Making Sense of Sensemaking: Understanding How Instructional Strategies Support Middle School Students' Engagement in the Sensemaking Process

By

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ABSTRACT

Studying student sensemaking has become an important lens through which to understand high-quality instruction. When students engage in the sensemaking process, they use observations and their prior knowledge to identify gaps or inconsistencies in their understanding, and then they collectively develop and test explanations to resolve this gap (Odden & Russ, 2018, 2019). In this dissertation, I addressed two understudied areas about the sensemaking process: how teachers' instructional strategies support different steps in the sensemaking process and how the sensemaking process guides students to integrate disciplinary knowledge, everyday experiences, and their observations during integrated STEM activities. Specifically, I sought to understand how instructional strategies, e.g., teachers' discourse moves and carefully designed instructional tasks, supported students' engagement in the sensemaking process during data investigations, a type of integrated STEM activity.

This dissertation is organized as three separate manuscripts. In my first study, I empirically investigated how the discourse moves of experienced middle school mathematics and science teachers initiated, sustained, and stopped different steps of the sensemaking process. I found teachers initiated the sensemaking process by highlighting something puzzling for students or by asking students to imagine a different scenario. The dynamic process of sensemaking, however, was not linear in the classroom discourse, but rather teachers and students entered, exited, and then returned to it. My findings from this study suggest that supporting the process of student sensemaking is a complex teaching practice and one fruitful area of research would be to study how to support teachers and students to transition through the steps of the sensemaking process.

In my second manuscript, a conceptual paper, I argued that there are potential problems with using current frameworks for designing integrated STEM activities, and that a sensemaking lens is necessary for designing, teaching, and studying integrated STEM activities. I described my new conceptual framework for integrated STEM, the Sensemaking Integrated STEM framework. It focuses on student thinking by specifically addressing how students generate knowledge resources during integrated STEM activities across instructional time and how students connect their knowledge resources as they make sense of integrated STEM problems.

My third manuscript is a design-based research study in which I used my new Sensemaking Integrated STEM framework to design a sixth-grade weather data investigation. I then empirically investigated how students responded to the instructional activities I designed to support students' sensemaking about variability in their local weather. I found students responded to the designed opportunities for sensemaking by brainstorming ideas and building upon other students' contributions. Looking at students' sensemaking explanations across the investigation, students integrated variability in temperature data with their ideas of weather phenomena and their everyday experiences. These findings suggest that the Sensemaking Integrative STEM framework is a productive lens for designing science data investigations to support students to connect their observations of variability in data with the phenomena that produced it.

The findings from across these three manuscripts provide insights into how teachers' discourse moves and the instructional tasks teachers use can support students' engagement in the sensemaking process. They show how the process of student sensemaking, with its

discrete and observable steps, provides a lens through which to study effective instructional strategies.

DEDICATION

This work is dedicated to my family.

Mom and Dad, I miss you and I wish you were here to celebrate this milestone with me. I know you would be very proud of me. Ana and Becky, you are the light of my life, and you inspire me every day to be a better person. Matt, you are my best friend and partner in life.

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LIST OF ABBREVIATIONS

Common Online Data Analysis Platform (CODAP)

Explaining Variability (EV)

Integrated Data Project (IDP)

Middle School-Earth and Space Sciences (MS-ESS)

National Oceanic and Atmospheric Administration (NOAA)

National Research Council (NRC)

Next Generation Science Standards (NGSS)

Student Sensemaking Talk (SST)

Teacher Discourse Moves (TDMs)

Chapter 1 Introduction

Evan, a sixth-grade student sitting in science class, is looking at a map of personal weather stations and a corresponding table that indicates the temperatures at 9:45 a.m. at various locations in his town. Students have noticed that two weather stations next to each other report very different temperatures, and they are engaged in a discussion to figure out why that could have happened. Evan says, "There has to be two weather stations on each of those because I just counted this side of the map where it has all the numbers on it and I got 19. Then, I counted all of those on the map and it has 19. So, these two must be right next to each other measuring the temperature. Wait! I think Elena's right about the sun thing because if you look at it from the way I'm looking at it, it kind of looks like 6 is more up than 51, but just by a slight difference. Then 57 is down. So, what if one was behind the house where the sun was? Wait, so, it's 9:50 in the morning? 57 got the most sun."

Evan is making connections between his observations of the weather station locations on the map and the representation of their reported temperatures in the data table. He is building on the idea of another student as he connects his experiences with the location of the sun in the morning with differences in temperature. Evan is engaged in the process of sensemaking: he is using his observations and prior experiences to brainstorm ideas so he can construct an explanation for something that is puzzling to him (Odden & Russ, 2019).

Studying how to support students like Evan to engage in sensemaking has become an important lens through which to understand effective, equitable, and high-quality instruction in K12 education (Fitzgerald & Palincsar, 2019; Kapon & Berland, 2023; Li & Schoenfeld, 2019; Schwarz et al., 2021; Windschitl et al., 2018). When students are sensemaking, they make connections between disciplinary ideas and their own experiences (Kapon, 2017;

Windschitl et al., 2018), generate knowledge (Chen & Techawitthayachinda, 2020; Li & Schoenfeld, 2019; Odden, 2021; Odden & Russ, 2019), and gain greater understanding of disciplinary practices (Fitzgerald & Palincsar, 2019; Li & Schoenfeld, 2019). Instruction that supports student sensemaking is both rigorous, i.e., focused on students learning disciplinary concepts and practices, and responsive, i.e., centered on student thinking and students' experiences (Hagenah et al., 2018; Li & Schoenfeld, 2019; Windschitl et al., 2018).

Supporting students' sensemaking, however, is a complex teaching practice (Fitzgerald & Palincsar, 2019; Hagenah et al., 2018; Leatham et al., 2015; Schwarz et al., 2023). It involves coordination between noticing students' ideas, teachers' discourse moves, and the selection of students' tasks and tools (Fitzgerald & Palincsar, 2019; Hagenah et al., 2018; Leatham et al., 2022). This coordination can be challenging for teachers, especially in the moment of teaching (Hagenah et al., 2018; Stockero et al., 2022; Windschitl et al., 2018). Understanding this complex teaching practice first requires the use of theoretical frameworks to define what students are doing when they engage in sensemaking.

To better define the construct of student sensemaking, Odden and Russ (2018, 2019) recently described sensemaking as a process in which students identify gaps or inconsistencies in their knowledge and then collectively develop and test explanations to resolve this gap in their understanding. As they make sense of something, students move through a series of steps. First, students collectively draw upon their prior knowledge and everyday experiences to know what they know. Then, they recognize or are supported by the teacher to recognize a gap in their knowledge. Next, they collaboratively brainstorm and connect their ideas into an explanation. The connections in this explanation are collectively critiqued and checked for coherence by the students. They may recognize another gap, and the process repeats until the gap in knowledge is resolved. This process can be observed through students' discourse, and it is characterized by (a) the students' use of prior knowledge and everyday experiences as resources, (b) the students' perceived goal of figuring something out, and (c) the collaborative use of student discourse to build and critique explanations (Odden & Russ 2018, 2019).

Little is known about how teachers' instructional strategies guide students through the steps of the sensemaking process in whole class discussions. Therefore, it is critical to explore how and why instructional strategies, e.g., instructional tasks, tools, and teachers' discourse strategies, support students to engage in this process. Because the sensemaking process occurs in a series of steps, it is possible that guiding students during each step requires different instructional strategies.

Statement of the Problem

So far, the sensemaking process has been studied within small groups of students (Hunter et al., 2022; Odden, 2021), during laboratory work (Hamnell-Pamment, 2024), and within a specific type of curriculum (Lowell et al., 2022). There are two important research areas, however, in which little is known about the sensemaking process: how teachers' instructional strategies support the different steps of the sensemaking process and how to support the sensemaking process in integrated STEM.

Teachers' discourse moves, the selection and sequencing of student tasks, and the use of scaffolding tools for students are instructional strategies that have all been associated with student sensemaking (Fitzgerald & Palincsar, 2019; Hagenah et al., 2018). For example, teachers' discourse that is open-ended and less authoritative encourages student sensemaking (Hagenah et al., 2018; Scott et al., 2006; Windschitl et al., 2018). Student sensemaking is also associated with tasks that are challenging and that fit together to guide students' developing conceptual understanding (Fitzgerald & Palincsar, 2019; Hagenah et al., 2018). Less is known, however, about how these instructional strategies guide students through the different steps of the sensemaking process, particularly in whole-class discussions. Effective, high-quality instruction supports student sensemaking (Fitzgerald & Palincsar, 2019; Kapon & Berland, 2023; Li & Schoenfeld, 2019; Schwarz et al., 2021; Windschitl et al., 2018). Therefore, it is critical to understand how teachers' instructional strategies guide the sensemaking process and how those strategies may differ among different steps of the process.

Furthermore, sensemaking has been used as a research lens in mathematics education (e.g., Leatham et al., 2015; Li & Schoenfeld, 2019; Mueller et al., 2014) and in science education (e.g., Kapon & Berland, 2023; Manz & Georgen, 2023; Windschitl et al., 2018), but less is known about supporting the sensemaking process in integrated STEM learning environments, such as engineering design challenges, socio-scientific issues, or data investigations. During integrated STEM instruction, it is essential for teachers to support students to make sense of the connections among STEM disciplines and the connections between the context of the investigation and the use of STEM disciplines (Honey et al., 2014; Roehrig et al., 2021), but little is known about how teachers' instructional strategies, such as teachers' discourse moves and the design of activities, would best support this integration. Integrated STEM activities have become commonplace in K-12 classrooms (McComas & Burgin, 2020; Moore et al., 2020), and so it is vital to begin remedying this gap.

Study Purpose

The purpose of this dissertation study is to understand how instructional strategies can support students to engage in the steps of the sensemaking process during data investigations, a type of integrated STEM activity in schools. To that end, this dissertation is organized into three chapters where each chapter is a separate manuscript related to the overarching research goal of understanding how to support students' engagement in the sensemaking process.

This dissertation study is part of a larger program of research, the Integrated Data Project (IDP), that investigates opportunities for collaboration between middle school mathematics and science teachers to teach statistical-based model inference (IDP, n.d.). Data collection occurred within this larger project's Institutional Review Board approval (Middle Tennessee State University Institutional Review Board Protocol 20-2088). Throughout this work, I maintained the privacy and anonymity of all participants, and I used pseudonyms when reporting about schools, teachers, and students.

Theoretical Grounding

High-Level Theoretical Framing

I approached this dissertation study through an underlying interpretivist-constructivist lens (Stinson & Walshaw, 2017). I view students' knowledge as being constructed in the social environment of the classroom and mediated through language (Chin, 2007; Vygotsky, 1978). Students engage in the sensemaking process in the collaborative, social environment of the classroom. In this social environment, teacher and student discourse supports students' collective sensemaking (Colley & Windschitl, 2016; Fitzgerald & Palincsar, 2019) and mediates their knowledge construction (Chin, 2007).

I took an interpretive approach in my analyses as I sought to understand how teacher discourse and instructional tasks supported students' engagement in the sensemaking process. As I explored teacher discourse, I did not separate it from the language used by both teachers and students and the situations in which the discourse occurred (Carlsen, 1991; Chin, 2007; Kayima & Jacobsen, 2020). Furthermore, in my findings, I used thick descriptions to tell the story of how students engaged in the sensemaking process (Creswell & Poth, 2025).

Researcher Positionality

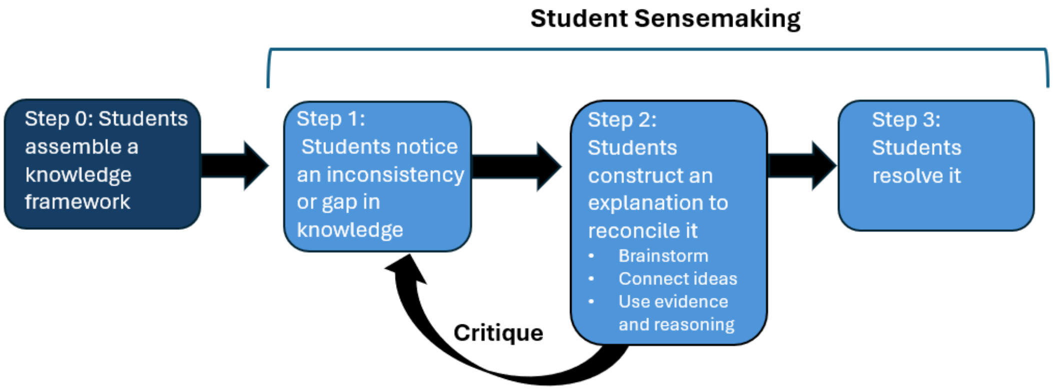
As I sought to understand how instructional strategies supported students to engage in the steps of the sensemaking process, I used my own experiences as a basis for my new understandings (Angen, 2000). I brought my experiences as a middle school (Grades 6-8) science teacher for twelve years and my experiences as an instructor of pre-service mathematics and science teachers to the analyses in this dissertation. These experiences, as well as my experiences as a former teacher at La Flor School where my design study occurred (Chapter 4), also informed the instructional choices I made.

Conceptual Framing of Sensemaking

Across these studies, student sensemaking is conceptualized as process with discrete and observable steps (Figure 1-1). Prior to engaging in the sensemaking process, students must first collectively assemble a shared knowledge framework (step 0, Figure 1-1; Odden & Russ, 2018). They do this by discussing, in small groups or as a whole class, what they know about the phenomenon or problem at hand as they draw upon their everyday experiences, their observations, and their prior knowledge. This shared knowledge framework helps students put all the ideas that may be useful for their understanding on the table, and it helps them focus their attention on any features of the phenomenon or problem they consider important (Odden & Russ, 2018).

Figure 1-1

The Process of Sensemaking



Note. Adapted from Odden, T. O. B., & Russ, R. S. (2018). Sensemaking epistemic game: A model of student sensemaking processes in introductory physics. *Physical Review Physics Education Research*, *14*(2), 020122. https://doi.org/10.1103/PhysRevPhysEducRes.14.020122

Students enter the process of sensemaking when they recognize, or are guided by the teacher to recognize, that something is puzzling or does not fit within their current shared knowledge framework (step 1, Figure 1-1; Odden & Russ, 2018, 2019). Students are now in the frame of trying to figure something out. They begin to brainstorm and connect their knowledge resources, i.e., those ideas they articulate in their initial knowledge framework and new ideas or observations, to build an explanation (step 2). As they make connections, students verbalize their evidence and reasoning. These connections are collectively tested and critiqued, which may lead to new gaps or inconsistencies (curved arrow). This cycle is repeated until students are satisfied with their explanation (step 3).

Dissertation Organization

My overarching research goal in this dissertation was to understand how instructional strategies support students' engagement in the sensemaking process. Each chapter in this dissertation is a complete manuscript that relates to this goal. In Chapter Two, I investigated how experienced middle grade mathematics and science teachers used teacher discourse moves to initiate, sustain, and stop the sensemaking process during whole class discussions. This manuscript will be submitted to the journal *Cognition and Instruction*.

I described the potential problems of using frameworks that only describe the disciplinary ideas or skills students engage in during integrated STEM activities in Chapter Three. I argued that a new student-centered sensemaking framework for integrated STEM is necessary to understand and develop teachers' integrated STEM instructional strategies so that researchers and practitioners can explore how and when students are thinking about disciplinary concepts and practices as they make sense of STEM problems.

In Chapter Four, I used this new sensemaking framework to design a sixth-grade weather data investigation in which students make sense of variability in their local weather data. I then asked the following research questions related to my initial design conjectures: (a) how does engaging in the sensemaking process support students to explain variability in local weather data, (b) how do students connect their knowledge resources as they make sense of variability in local weather data, and (c) how do students use epistemic tools from their mathematics class as they make sense of variability in local weather data. This manuscript will be submitted to the *International Journal of STEM Education*. The final chapter summarizes my findings across the three manuscripts.

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Chapter 2 Experienced Mathematics and Science Teachers' Discourse Moves to Support Middle School Students' Engagement in the Sensemaking Process

ABSTRACT: Effective teaching supports student sensemaking. Sensemaking is a process in which students move through a series of discrete steps observable in classroom discourse: first assembling what they know, then recognizing a gap in their understanding, and finally building and critiquing their explanations to resolve their knowledge gap (Odden & Russ, 2018). In this study, we investigated how experienced middle grade mathematics and science teachers used discourse moves to initiate, sustain, and stop the sensemaking process during whole class discussions. We found that students engaged in sensemaking talk by sharing their observations and ideas in all teachers' classrooms. During students' sensemaking talk, teachers' eliciting discourse moves such as asking for observations or ideas supported students to assemble a shared classroom knowledge framework that could potentially be used for students to engage in the sensemaking process. Teachers' initiating discourse moves of highlighting something puzzling for students and asking students to imagine a different scenario invited students to enter the sensemaking frame and start brainstorming. Teachers used the discourse moves of asking for explanation and pressing for reasoning to sustain the sensemaking process. Students' sensemaking talk stopped when teachers used discourse moves to change the topic or shift into more authoritative discourse. Viewing student sensemaking as a process with discrete steps makes visible the complexity of teachers' discourse practices.

1. Introduction

Effective teachers use instructional strategies that can support student sensemaking (Colley & Windschitl, 2016; Fitzgerald & Palincsar, 2019; Li & Schoenfeld, 2019; Stockero et al., 2022). Students engage in the process of sensemaking when they have opportunities in the classroom to draw on their prior knowledge to "figure something out" by building, testing, and revising their explanations (Odden & Russ, 2019a, p. 192). During sensemaking, students make connections between disciplinary ideas and their own experiences (Kapon, 2017; Thompson et al., 2016), generate knowledge (Chen & Techawitthayachinda, 2020; Li & Schoenfeld, 2019; Odden, 2021; Odden & Russ, 2019a), and gain greater understanding of disciplinary practices (Fitzgerald & Palincsar, 2019; Li & Schoenfeld, 2019).

Research suggests that student sensemaking is dynamic and fleeting, perhaps only occurring for minutes (Hutchison & Hammer, 2010; Odden & Russ, 2019b). Thus, one instructional challenge for teachers is how to begin and then sustain the process of student sensemaking (Odden & Russ, 2018). Teachers' discourse moves (TDMs), the intentional actions a teacher takes to participate in or guide the classroom discourse (Krussel et al., 2004), are one instructional strategy that supports students' sensemaking (Benedict-Chambers et al., 2017; Carpenter et al., 2020; Colley & Windschitl, 2016; Fitzgerald & Palincsar, 2019; Lowell et al., 2022). Discourse moves such as probing for student thinking, pressing students to explain their reasoning, and revoicing student contributions are examples of TDMs associated with sensemaking (Herbel-Eisenmann et al., 2013; Michaels & O'Connor, 2012; Tytler & Aranda, 2015; Windschitl et al., 2018).

Less is known, however, about how TDMs guide students through the sensemaking process (Lowell et al., 2022). As students engage in the sensemaking process, they move through a series of discrete steps observable in their discourse: first assembling what they know, then recognizing a gap in their understanding, and finally building and critiquing their explanations to resolve their knowledge gap (Odden & Russ, 2018; Odden & Russ, 2019a). TDMs that function to begin the sensemaking process, such as those that support students to use what they know to identify gaps in their knowledge, are likely to be different from those that support students to begin to critique their own and each other's explanations, but how TDMs guide students through the different steps of the sensemaking process is not well-studied. This gap in the literature motivated us to investigate how expert teachers use TDMs to guide students through the sensemaking process.

Data investigations, activities in which students analyze data for the purpose of answering an investigative question about real-world phenomena (Bargagliotti et al, 2020; Lee et al., 2022), offer an ideal context for exploring TDMs and sensemaking. Sensemaking is an integral part of data investigations because students are continuously using ideas from their prior knowledge, connecting those ideas to the data and analysis, and engaging in cycles of critique and judgment to generate knowledge (Arnold & Franklin, 2021; Wild & Pfannkuch, 1999). Supporting student sensemaking during data investigations is challenging for teachers (Elsayad et al., 2024), and so we chose to study how experienced sixth-grade science and mathematics teachers used TDMs to guide students through the sensemaking process.

Specifically, we asked the following research questions:

RQ1: During data investigations, how do experienced mathematics and science teachers use TDMs to initiate the process of students' sensemaking in whole-class discussions?

RQ2: How do these teachers' TDMs sustain the sensemaking process during whole-class discussions?

Because the sensemaking process is dynamic and short-lived, we also asked:

RQ3: What kinds of TDMs stop the sensemaking process during whole-class discussions?

2. Background

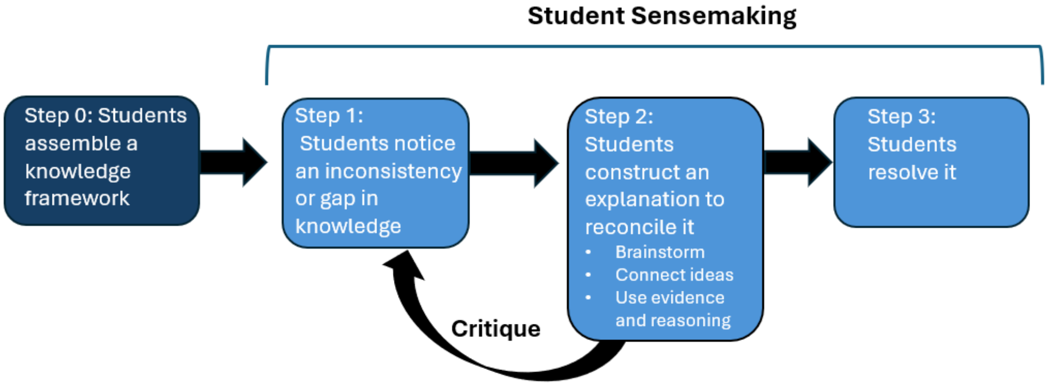
We begin by describing how students engage in the process of sensemaking and some of the TDMs associated with it. This study explored how students engage in sensemaking during data investigations, and so we end this section by briefly describing data investigations and what it means for students to make sense of data.

2.1 The Process of Sensemaking

The student sensemaking framework describes the process students engage in as they identify gaps or inconsistencies in their knowledge and then develop and test an explanation to resolve this gap in their understanding (Odden and Russ, 2018; 2019a; Figure 2-1). This process is characterized by (a) the students' use of prior knowledge and everyday experiences as resources, (b) the students' perceived goal of figuring something out, and (c) the collaborative use of student discourse to build and critique explanations (Odden & Russ, 2018, 2019a).

Figure 2-1

The Process of Sensemaking



Note. Adapted from Odden, T. O. B., & Russ, R. S. (2018). Sensemaking epistemic game: A model of student sensemaking processes in introductory physics. *Physical Review Physics Education Research*, *14*(2), 020122. https://doi.org/10.1103/PhysRevPhysEducRes.14.020122

Student sensemaking is built upon students' experiences and their prior knowledge (Kapon, 2017; Odden & Russ, 2018; Odden & Russ, 2019a). Before sensemaking occurs, students use their prior knowledge as resources to construct and articulate a knowledge framework as they work through what they know about the phenomenon or problem at hand (Step 0, Figure 2-1; Odden & Russ, 2018). In other words, students need time to collectively know what they know about something before they can identify any gaps in their knowledge. They do this by drawing on a combination of their formal knowledge and their everyday experiences as resources (Kapon, 2017). The development of this initial shared knowledge framework helps students put all the ideas on the table that may be useful to their understanding (Odden & Russ, 2018). This knowledge framework is transient because some of these ideas may be unused or discarded during sensemaking. As students work through their ideas, the articulation of this knowledge framework helps students focus their attention on any features of the phenomenon or problem they consider important (Odden & Russ, 2018). Once students have laid out their initial ideas, they are now primed to enter the process of sensemaking.

To begin sensemaking, students must first recognize, or be guided by the teacher to recognize, that something is puzzling or does not fit with what they know (Step 1, Figure 2-1; Odden & Russ, 2018, 2019a). They must be in a frame of trying to figure something out. Frames are the expectations, perceived goals, and choices students make when they are in classroom learning situations (Hutchison & Hammer, 2010). For example, students may be in an answer-giving frame or a completing homework frame (Hutchison & Hammer, 2010). These frames are dynamic and short-lived, perhaps on the order of minutes, and students may shift in and out of frames multiple times in the classroom as they interact with the teacher, other students, and classroom tasks (Hunter et al., 2021; Hutchison & Hammer, 2010; Odden & Russ, 2019a). When students engage in sensemaking, they are in a frame of trying to figure out something they recognize as puzzling or inconsistent with their current understanding. This perceived goal differentiates sensemaking from other ways students may perceive their role in the classroom discourse such as answer-making or reciting explanations (Odden & Russ, 2019a; Hunter et al., 2021).

One way to identify if students are entering into the sensemaking frame is by noting when students ask a question or make a statement about something they are uncertain (Odden & Russ, 2019b). Odden and Russ (2019b) described this type of student discourse as a vexing question because it not only begins the process of sensemaking but also motivates students to remain in the sensemaking frame. In students' discourse, these vexing questions often re-surface multiple times as students repeatedly return to them as they generate their explanations (Odden & Russ, 2019b, Hunter et al., 2020).

Although sensemaking can certainly occur entirely in a student's mind, it is through collaborative discourse that it can be observed in the classroom (Odden & Russ, 2019a). When students are in a frame of figuring something out, it often leads to sensemaking talk as students brainstorm out loud and make several initial claims. As students verbalize their claims, they begin to connect their claims into a "chain of ideas," often expressing their evidence and reasoning (Odden & Russ, 2019a, p. 192). This chain of ideas becomes an explanation that is expressed in the students' own words (step 2, Figure 2-1).

When this explanation is collectively scrutinized by students, more gaps or inconsistencies may be noticed and verbalized, as they test out the links between claims and evidence and consider whether it is coherent with what they already believe to be true. They may then further refine their explanation (Figure 2-1). This navigation between constructing an explanation and then critiquing it and checking its coherence is one of the main characteristics of sensemaking (Ford, 2012, Odden & Russ, 2019a). Students may move back and forth between explanation and critique several times until students are either satisfied with their explanation (step 3, Figure 2-1), or they give up in frustration.

Therefore, when students engage in the sensemaking process, they activate their prior knowledge, are in the frame of figuring something out, and alternate between constructing their explanation and critiquing it. This process can be observed through students' discourse. Defining sensemaking in this way, as an observable process with a beginning and an ending, allows the investigation of how and why instructional tasks, tools, and strategies support students to engage in this process (Odden & Russ, 2018). TDMs are one such instructional tool associated with supporting student sensemaking (Benedict-Chambers et al., 2017; Carpenter et al., 2020; Colley & Windschitl, 2016; Fitzgerald & Palincsar, 2019; Lowell et al., 2022), but little is known about how these tools function at different steps of the sensemaking process. In the next section, we describe the TDMs associated with supporting student sensemaking and the context of classroom discourse in which they occur.

2.2 Teachers' Discourse Moves Associated with Students' Sensemaking Talk

Several specific TDMs from the mathematics and science education literature have been associated with supporting student sensemaking (Table 2-1). TDMs are the intentional discourse actions a teacher takes to participate in or guide classroom discourse (Krussel et al., 2004). TDMs, also referred to as talk moves, are instructional tools that have specific properties related to the classroom discourse (Michaels & O'Connor, 2015). For instance, a probing TDM has the property of eliciting students' thinking, i.e., "What do you think is happening?" (Windschitl et al., 2018) and that property is different from the properties of other TDMs such as revoicing or pressing. As tools, TDMs are a means of accomplishing the intended learning goals of the teacher (Michaels & O'Connor, 2015). This means that the same TDM can be used to accomplish different purposes depending on the specific context of the classroom discourse (Hagenah et al. 2019; Herbel-Eisenmann & Breyfogle, 2005; O'Connor & Michaels, 2019). For example, a teacher could use the marking TDM, which draws attention to a student response as the teacher repeats it (Tytler & Aranda, 2015), to draw attention to a correct student response, i.e., "Shana said temperature was important. Good." A teacher could also use the same marking TDM, "Shana said temperature was important. Good," to draw attention to a student's response and then use it to elicit students' ideas, i.e., "How does that compare to what David said?"

TDMs, therefore, always function within a specific context of classroom discourse (Carlsen, 1991; Kayima & Jacobsen, 2020; O'Connor & Michaels, 2019).

Table 2-1

Examples of TDMs Associated with Student Sensemaking

TDM	Property	Connection to Literature
Probing for thinking	Elicits student thinking by asking them to verbalize it	(Herbel-Eisenmann et al., 2013; Windschitl et al., 2018)
Requesting clarification	Elicits student thinking by asking student to provide more information	(Tytler & Aranda, 2015; Lowell et al., 2022)
Asking to add on	Connects student thinking by asking students to engage with another student's discourse	(Michaels & O'Connor, 2012; Windschitl et al., 2018)
Teacher revoicing	Clarifies a student idea, focuses attention on an important idea, or connects an idea to academic language by the teacher rephrasing it	(Herbel-Eisenmann et al., 2013; Windschitl et al., 2018)
Marking	Draws attention to a student's response by repeating exactly what a student has said	(Tytler & Aranda, 2015)
Asking for student revoice	Connects student thinking by asking them to listen to one another and to restate student's discourse in their own words	(Herbel-Eisenmann et al., 2013; Windschitl et al., 2018)
Pressing for reasoning	Challenges some aspect of student's discourse by asking for examples, evidence, or how to test a claim	(Michaels & O'Connor, 2012; Tytler & Aranda, 2015; Windschitl et al., 2018)

TDMs are therefore used in different ways depending on the context. In a collective sensemaking context, TDMs function to focus the classroom discourse on students' ideas (Herbel-Eisenmann, 2005; Hagenah et al., 2019). TDMs that are used for focusing help students voice their ideas, and connect and compare them (Herbel-Eisenmann, 2005; Hagenah et al., 2019). These TDMs are open-ended in that they allow for multiple students to share their thinking and respond to other's thinking (Colley & Windschitl, 2016; vanZee & Minstrell, 1997). The TDMs in Table 2-1 can all function according to this purpose of eliciting student ideas, connecting them, and comparing them.

In contrast, an authoritative, non-interactional discourse pattern prescribes the direction of discourse, and the teacher's view is the one privileged and valued. In this case, the function of TDMs is to funnel the classroom discourse toward a correct answer based on the teacher's perspective or classroom textbook (Herbel-Eisenmann, 2005; Hagenah et al., 2019). Often teachers use close-ended TDMs in which students responded with short, pre-determined answers that are evaluated by the teacher (Scott et al., 2006; vanZee & Minstrell, 1997). Although the teacher may use some of the same TDMs as in the focusing discourse patterns, e.g. revoicing or requesting clarification, the goal of the discourse is to determine the correct answer. Therefore, during our analysis, we paid careful attention to the patterns of TDMs during whole class discussions; whether the pattern of TDMs functioned to focus the classroom discourse on students' ideas or whether they functioned to funnel students' ideas toward a particular answer.

To understand how TDMs functioned in supporting students' sensemaking, it is necessary to first identify places in the classroom discourse where students' sensemaking talk is occurring. Research suggests that classroom discourse associated with students' sensemaking talk is dialogic, interactional, and interanimated (Lowell et al., 2022; Scott et al., 2006). It is dialogic because students share and explore multiple ideas, and these ideas are viewed by the teacher and students as valuable contributions to the classroom discourse. Additionally, the discourse context is interactional in that it allows for the participation of multiple students with potentially different perspectives. It is not a dialogue between the teacher and a single student, but rather multiple students contribute their ideas. Finally, because connecting and critiquing ideas is an important part of the student sensemaking process, classroom discourse must also support the interamination of students' ideas (Lowell et al., 2022). Students' ideas are interaminated when they are clarified, compared, and elaborated upon through the classroom discourse, rather than simply noted or listed on the board (Lowell et al., 2022; Scott et al., 2006). Therefore, a whole-class discussion in which students are engaging in the sensemaking process would have multiple students sharing their ideas, and these ideas would be valued, compared, and criticized through the classroom discourse as students worked to figure something out (Lowell et al. 2022). These moments in the classroom discourse, when students were engaging in sensemaking talk in whole-class discussions, were the target of our analysis.

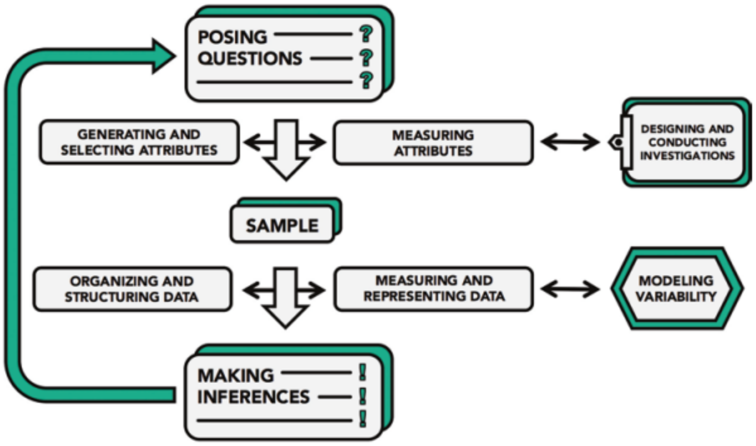
2.3 Data Investigations

Data investigations occur in a variety of K-12 disciplines: mathematics, science, social studies, and computer science (Lee et al., 2022). During data investigations, students analyze data for the purpose of answering an investigative question about real-world phenomena (Bargagliotti et al, 2020; Lee et al., 2022). These interdisciplinary classroom activities require teachers and students to coordinate ideas from mathematics, data science, and the context of the investigation (Cobb & Moore, 1997; Kjelvik & Schulteis, 2019; Wild et al., 2018). Because of this interdisciplinary nature, when students engage in data investigations, they have opportunities to make sense of the professional practices of scientists, data scientists, and statisticians, as well as applying content knowledge to make sense of the investigation's context.

Making sense of data requires students to be able to characterize and account for variability (Bargagliotti et al., 2020; Lehrer & English, 2018; Lehrer et al., 2020; Watson et al., 2022). Data modeling (Lehrer & English, 2018), which approximates the practices professional statisticians engage in as they describe and make sense of variability, provides a framework to conceptualize students' sensemaking work during data investigations (Figure 2-2).

Figure 2-2

Data Modeling



Note. From Lehrer, R., & English, L. (2018). Introducing children to modeling variability. In Ben-Zvi, D., Makar, K., Garfield, J. (Eds.), *International Handbook of Research in Statistics Education*. (pp. 229-260). Springer International Publishing. https://doi.org/10.1007/978-3-319-66195-7_7

As students experience the practices in each box in Figure 2-2, they have opportunities to make sense of variability. In the top half of Figure 2-2, students are making sense of the potential variability involved in the creation of their sample and how their decisions about what to measure, how to measure it, and the questions they want to answer are related to the design and execution of their investigation. The double arrows indicate that these practices are interrelated;

that is, the choices made in one area of practice, e.g., the choice of a particular attribute to measure, will affect the other areas of practice, e.g., how that particular attribute can be measured. As students create their data sample, they make sense of the expected variability generated by their question, the variability created by their choice of different attributes, and the possible variability inherent in how they measured their attributes.

In the bottom half of Figure 2-2, students are making sense of the variability in their actual sample of data and how their decisions about how to structure, display, and measure their data can lead to models of its variability. The double arrows indicate that these practices are also interrelated; for example, the choice of organizing the data using a distribution with bins will affect how the variability in that data can be measured. Before students begin to make inferences from their sample, they need to make sense of how to best organize their data using data displays, how to describe aggregate characteristics of their data, how to measure the center and spread of their data, and how to model variability by accounting for its sources using the context and the creation of the sample. As students make inferences from their sample, it often leads to posing new questions.

In the data investigations of this study, students have created a sample of measurements in their mathematics or science class, and they are making sense of the variability in their measurements by discussing how to organize and structure their data so that they can begin to make inferences about what they can claim as a typical measurement for that object.

3. Methods

3.1 Context and Participants

The data analyzed in this study were a subset of data from a larger study, the Integrated Data Project (IDP). Data were collected in a large, public middle school in the southeastern

United States, Heavenbow Middle School (Table 2-2). The average class size was twenty students.

Table 2-2

Participating School Demographics

	Heavenbow Middle School
Setting	Public middle school Grades 6 and 7
Enrollment	745
Student: Teacher Ratio	11:1
Student Demographics	59.9% White 26.8% Hispanic/Latino 2.8% Black or African American 2.0% Asian/Pacific Islander 5.0% Native Hawaiian 0.9% Native American

Note. School demographic information is from the U.S. and World News Report (n.d)

For this study, we chose a homogeneous sample (Patton, 2015) of four veteran teachers, two in mathematics and two in science (Table 2-3). The teachers were selected from among those involved in professional development through the IDP. These veteran teachers had many years of experience, and three of them also held leadership positions, i.e., instructional coach, department head, in their school. This sample allowed us to focus on the characteristics of teacher discourse that in-service, experienced middle school mathematics and science teachers used to support the sensemaking process during data investigations.

Table 2-3

Participating Teachers

Pseudonym	Content Area	Experience
Ms. Summers	Sixth Grade Mathematics	20 years, instructional coach, national board-certified teacher
Mr. Trumbull	Sixth Grade Mathematics	7 years, department head
Mr. Houston	Sixth Grade Science	26 years, department head, national board-certified teacher
Ms. Manchester	Sixth Grade Science	13 years

3.2 Data Investigations

As part of the Integrated Data Project, these teachers were video recorded as they taught the data investigations “Inventing Data Displays” in mathematics, and “How Do Plants Change as They Grow” in science (Table 2-4). The “Inventing Data Displays” unit was developed by Rich Lehrer (Lehrer et al., 2020). Both mathematics teachers had taught this unit for several years. The “How do Plants Change as They Grow” investigation was developed by the IDP to support students to make connections with content in the Data Displays unit in students’ mathematics classes, i.e., creating data displays and using them to make claims, explaining sources of variability in data. This data investigation was first enacted by Heavenbow science teachers in 2022. Both investigations had opportunities in the curriculum for students to engage in collective sensemaking by developing explanations and to publicly share, critique, and revise them. As part of the IDP, teachers taught these investigations from Fall 2021 to Spring 2023. Students experienced the mathematics investigation first, in the second quarter of the school year

(Nov. 2021) or early in the third quarter (Jan. 2023), and then the same students experienced the science investigation early in the fourth quarter (Mar. 2022 or Mar. 2023; Table 2-4).

Table 2-4

Mathematics and Science Data Investigations

Investigation	Class	Brief description	Teacher, when lesson was taught (number of lessons videorecorded)	Length of each class period
Inventing Data Displays	Grade 6 Mathematics	Students generate data by independently measuring the same object with a small 15-cm ruler and then create a way to display their class data. They then develop explanations for the variability in their measurements and explain how differences in their data displays resulted from different design choices.	Ms. Summers, Nov. 2021 (3) Mr. Trumbull, Jan. 2023 (4)	90 minutes 75 minutes
How Do Plants Change as They Grow?	Grade 6 Science	Students make observations about individual differences in Wisconsin Fast Plants and how they change as they grow. They measure their plants to generate quantitative data and create data displays to make claims about how plants grow. They then explain how different sources contribute to the variation in the data.	Mr. Houston, Mar. 2022, (1), Mar. 2023 (2) Ms. Manchester, Mar. 2022, (2), Mar. 2023 (2)	45 minutes 45 minutes

Note. Detailed descriptions of these investigations can be found on the Integrated Data Project website (Integrated Data Project, n.d.).

3.3 Data Collection

A member of the IDP team video recorded the classroom lessons during the mathematics and science investigations described above. The recordings were transcribed using the online transcription software, Otter AI, and then a team member reviewed and clarified the transcripts.

At times, researchers were also present in the classroom as co-teachers during the data investigations. As experienced educators and instructors of pre-service teachers, they also may have employed discourse strategies to support student sensemaking and so we included their discourse in my analysis.

3.4 Data Analysis

During analysis, we did not use transcripts of classroom discourse for coding, but rather we used the video recordings and the qualitative data analysis software, MaxQDA, to better understand the classroom context, i.e., what was occurring in the classroom, the intonations of the speakers, how the teacher moved in the room, how data was presented to the students, etc.. After coding was completed and we identified patterns across the data corpus, we used transcripts to illustrate representative examples of how teachers used TDMs to support students' sensemaking talk.

3.4.1 Identifying Students' Sensemaking Talk Episodes

The first author began the analysis by identifying those segments in classroom discourse when teachers engaged in whole class discussions. Brief analytic memos (Saldaña, 2009) were written for each whole class discussion to characterize the classroom discourse by noting patterns of discourse, whether multiple students contributed, the topic of discussion, etc. These analytic memos were used to understand how TDMs were situated in the context of classroom discourse and activities (Carlsen, 1991; Kayima & Jacobsen, 2020).

The first author then marked segments in the whole class discussions that resulted in student sensemaking talk (SST). These segments were moments in the whole class discussions when the classroom discourse was dialogic, interactive, or interanimate (Lowell et al., 2022; Scott et al., 2006); for example, places in the discourse where multiple students were contributing ideas, multiple ideas were shared, or students engaged with others' ideas. Because vexing questions are an indicator when students are engaging in sensemaking (Odden & Russ, 2019b), discourse segments when students asked questions were also marked.

These segments of classroom discourse, SST episodes, were the unit of analysis. Each episode was bounded by the teacher's discourse immediately preceding SST, typically a question, and the teacher's discourse immediately following the SST episode. Early in the analysis, the first author brought several samples of these SST episodes and other segments of whole class discussion that did not include SST to the IDP team. We discussed them until we came to consensus on their characterization as an SST episode.

As an example, Table 2-5 illustrates a segment of whole class discussion that was not coded as an SST episode. In this whole class discussion, Mr. Trumble asked for definitions of the word "data" and wrote the responses on the board.

Table 2-5

Whole Class Discourse Without SST

Row	Speaker	Discourse
1 **14:25**	Mr. T:	So, what would be some examples of data? Anyone? What would be an example of data you can think of? Also, I just said like four, so you know, raise your hands. What would be an example? Edwin?
2	Edwin:	Elephant toothpaste.
3	Mr. T:	Okay, so what would be the data you're collecting on that? You're right.
4	Edwin:	Oh, I wasn't there for that.
5	Mr. T:	Oh, okay. So, that would be an experiment. What would be the data that we'd be collecting in elephant toothpaste? Adrian?
6	Adrian:	So, how many people thought that elephant toothpaste was the best experiment.
7	Mr. T:	I'm going to summarize that as like opinions on things could be some data [writes on board]. So, like, like people's opinion on something, for example. Do you like elephant toothpaste? That sounds funny. Please don't use elephant toothpaste, that would be bad for your health. What would be another? Think simply. Do not have to be complex here. Marcelo?
8	Marcelo:	What the best McDonald's meal is
9	Mr. T:	Sure. What the best McDonald's meal is. Um, let's go just because I don't want to write a bazillion things. That's a great example. What's gonna give me an example of data that would be like numerical, since we said often they're a set of numbers? Ali?
10	Amelia:	Um, temperature.
11 **16:05**	Mr. T:	Yes. Yeah, we'll say yeah, temperature data, let's say temperature. For Alabama [writes on board]. That would be some data we could collect.

Although multiple students responded to Mr. Trumble's TDMs, this classroom discourse was more authoritative as Mr. Trumbull used TDMs to direct student responses to a desired outcome. For example, when students did not give a numerical example for data, Mr. Trumble specifically asked for one (row 9), and he used TDMs to re-word student responses in a more canonically correct manner (rows 7 and 11). In this segment, students did not engage with each other's ideas or ask questions.

In contrast, Table 2-6 shows the transcript of one SST episode from Ms. Manchester's science class. Ms. Manchester was asking questions about students' plant height measurements that had been written on sticky notes and displayed on the board in this whole class discussion.

Table 2-6

Example SST Episode in Ms. Manchester's Science Class

Row	Speaker	Discourse
1 **31:06**	Ms. M:	What kinds of things can we say now that it's [students' plant height measurements written on sticky notes] a little bit better organized? That was a good suggestion, Sky.
2	Dante:	That it's on a range of 4 to 35.
3	Ms. M:	Good. We have a range, and we can see it really easily over here, the smallest up to the biggest of 35. So, we can look at the range.
4		So, any other things we can notice from there?
5	Dante:	There are two outliers, kind of. Well, 3 outliers.
6	Ms. M:	What would you say the outliers are?
7	Dante:	28, 32, and 35.
8	Ken:	That's mine. You're just jealous that they're really big.
9	Dante:	They are outliers. Also, none of those are yours- yours is 22.
10	Ken:	Mine was 28.
11	Jose:	Mine was 22.
12	Ms. M:	So, maybe on the top [the larger numbers] we kind of see a jump.
13		Could we do something else to our line to make it, make some things stand out? Should we change it a little bit?
14	Sky:	We could, um, scale [voice trails off]
15	Dante:	Add some-what's it called?
16	Jose:	Lengths
17	Sky:	Scale
18	Dante:	Ana said the distance, the distance in between them. (Jose: Lengths). Yeah, the distance in between them.
19	Ms. M:	Ohhh, we don't have any gaps right now. If it's okay, we can add some gaps and we can, we can break it into two lines or we can extend on the next paper if you need to. [Dante rearranged data sticky notes on board]

20		And you can go, if you want to, Dante, you can just extend it to the next sheet to keep it all on one line. (Sky: No, keep it going)
21	Ken:	This is confusing. Now it looks like 35 is the last one.
22	Dante:	It is the last one.
23	Ms. M:	It is the last one
24	Ken:	Oh. The first one.
25	Ms. M:	Okay. So, what do we notice now that Dante changed something?
26	Sky:	That these are outliers [points to the smallest numbers]
27	Ms. M:	Ohhh, because before we said that these were outliers [pointing to the larger numbers]. Now Sky is saying, well, maybe the bottom ones are the outliers [pointing to the smaller number]. (Amir: I see gaps)
28		Oh. Yes. Okay. Amir says "I see gaps."
29		Does that help you see where we don't have any data?
33:23		

In this SST episode (Table 2-6), Ms. Manchester asked a series of open-ended questions in which many student responses were possible. She did not evaluate student responses, but rather asked students to clarify their ideas (rows 6, 13). Multiple students responded to her questions, and, in their responses, they used informal language and talked to one another (rows 15-18). This SST episode is bounded by her first open-ended question, "What kinds of things can we say now that it's a little bit better organized?" and ends with a closed-ended, yes/no, question (row 29). The length of this SST episode was 2 min 17 s.

We found these SST episodes in all four teachers' whole-class discussions (Table 2-7). Across all four teachers, the mean length of an SST episode was 2 min 5 s. The minimum length was 22 s and the maximum length was 5 min 35 s.

Table 2-7

SST Episodes in Whole Class Discussions

Teacher	Content Area	Number of SST episodes	Mean Length of an SST episode	Number of lessons recorded (year)	Total time video-recorded
Ms. Summers	Sixth Grade Mathematics	28	2 min 11 s	3 (2021)	4:07 hr (1 group of students)
Mr. Trumbull	Sixth Grade Mathematics	13	2 min 40 s	4 (2023)	5:07 hr (1 group of students)
Mr. Houston	Sixth Grade Science	21	1 min 26 s	1 (2022) 2 (2023)	2:46 hr (4 groups of students)
Ms. Manchester	Sixth Grade Science	10	2 min 23 s	2 (2022) 2 (2023)	3:41 hr (3 groups of students)

3.4.2 Characterizing Teacher and Student Discourse

The first author then characterized the TDMs and the students' discourse during each SST with a mixture of deductive and inductive coding. TDMs immediately prior to and during SST episodes were deductively coded by using descriptions of TDMs known to support student sensemaking from the extant literature, e.g., revoicing, pressing, marking, clarifying (Table 2-1). A sample of the TDM codes are in Table 2-8, with their description, examples from the data, and connection to the extant literature. Early in the coding process, samples of SST episodes were brought to the IDP team. Each team member coded the transcript using an initial draft of the codebook. We then discussed the codes, and the feedback was used to refine the codebook. Those sample SST episodes were then recoded with the updated codebook.

One extant code, probing for student thinking, was split into several different codes depending on the context of the teacher's discourse; for example, sometimes teachers were probing for student thinking about what they noticed. This discourse was coded as "asking for observations." At other times, teachers were probing for student thinking in general. This discourse was coded as "asking for ideas." See Appendix 2-A for the complete codebook.

Any teacher's utterances that did not fit these descriptions were inductively coded using their functions in the classroom discourse, e.g., highlighting a puzzle, focusing discourse, asking what if, etc. A sample of these inductive codes are included in Table 2-8. Teacher's utterances could have overlapping codes.

Table 2-8

Sample Codes for TDMs Immediately Prior To and During SST Episodes

Teacher Discourse Move Code	Action the teacher made to participate in or guide classroom discourse	Examples	Connection to TDMs and Sensemaking Literature
Sample of deductive codes:			
Asking for ideas	Makes a general request for students to express their thinking	"What were some things we did?" "Any thoughts?"	Probing for thinking (Herbel-Eisenmann et al., 2013; Windschitl et al., 2018), Eliciting student ideas (Carpenter et al., 2020)
Asking for observations	Requests students share what they notice or what they see	"What did you notice?" "What do you all see that goes in there?"	Probing for thinking (Windschitl et al., 2018), Explication questions (Benedict-Chambers et al., 2017)
Pressing	Challenges some aspect of student's discourse by asking for examples, evidence, or how to test a claim	"Be more specific. Why did they do what?" "I guess what I'm asking is: how do you know it's too low?"	Pressing (Michaels & O'Connor, 2012; Tytler & Aranda, 2015; Windschitl et al., 2018)

Teacher revoices	Rephrases a student's contribution. May add disciplinary language	"You're saying, if we were to graph them, that this section here, would be like [this]." "Zero to 30 centimeters? We might have a range that we might give them."	Revoicing (Herbel-Eisenmann et al., 2013; Windschitl et al., 2018)
Marking	Repeats what a student has said to emphasize it or for the whole class to hear	"Okay. Gregory noticed that there is a number line on it." Student: "Maybe they didn't follow the planting directions right." Mr. Houston: "They didn't follow the planting directions, possibly."	Marking (Tytler & Aranda, 2015)
Sample of inductive codes:			
Highlighting a puzzle	Asks students about something that may be unusual or confusing or that doesn't make sense	"Ohhh, because before we said that these were outliers [pointing to the larger numbers]. Now Sky is saying, well, maybe the bottom ones are the outliers [pointing to the smaller number]." "Actually my average falls in the three range, and no one said three, right? But the average, if we use mean, is three."	
Focusing Discourse	Emphasizes some aspect of the data, problem, or phenomenon to support student understanding	"Right. So that's what I'm saying. When I look up there, the 42 and the 96 look pretty close to the 110." "They called this column 120 and they said half the data is in this column. Do you see that, what Madeline is talking about?"	
Asking what if	Asks students to imagine a new scenario	"What if I had you guys measure again with the same instructions and same tool? What would happen?" "If Dora jumps again and she gets 20 jumps, where does the 20 go?"	

The first author rewatched the SST episode and inductively coded the students' utterances according to their functions in the classroom discourse, e.g., explains, adds on to an idea, gives evidence. A sample of these student codes are in Table 2-9. Students' utterances could have overlapping codes.

Table 2-9

Sample Student Codes During SST Episodes

Code	Action the student took to participate in classroom discourse	Examples
Makes an observation	Makes a statement about something the student sees about the data, data display, or phenomenon	"She put it from least to greatest." "My [plant's] leaves kind of looked white"
Makes a claim	Makes a statement about something the student thinks is true.	"Sometimes the plants didn't get as much light as other plants." "It [stem and leaf plot] really easily shows least to greatest."
Explains	Talks about why or how something occurs or why they are making a claim	"Because we had so many of these containers in one area, it was hard to squish them all in." "Because then, if you had like 20, it could go in either one.
Gives evidence	Talks about the data, data display or phenomenon in support of a claim	"Fewer people got in the 40s than in the 100s." "It's kind of difficult because we have 2 modes. There's two [plants] that grew 8 [cm] and there's two that grew 15 [cm].
Gives an alternative	Talks about an alternative idea to either the teacher's discourse or another student's discourse	Researcher: "I've got a bunch of zeroes. What do I do with these? Should I put them up in order here? Student: "No, you should stack them up."

		Student 1: “It more common to get 21 [cm for plant height]. Student 2: “Yeah, but most of the plants are smaller too so you have to average it.”

Finally, the SST episode was watched for a third time and the TDMs at the end of the SST episode were inductively coded (Table 2-10). There was one exception to this inductive coding. The code *closed question* was used for a TDM that invited a brief, factual response from the student (Erdogan & Campbell, 2008; vanZee & Minstrell, 1997).

Table 2-10

Sample of TDMs Ending SST Episodes

Teacher Discourse Move Code	Action the teacher made to guide classroom discourse	Example
Closed question	Asks for a yes or no response, or a factual response	“Can I quickly look at this and tell how many 135s there are?” “Did all plants grow in the same way?”
Changes topic	Switches the topic of classroom discourse from what students are talking about to a new topic	Student: “I see it like there’s a normal frequency and then there’s binned frequency. And if they have bins, it’s not going to be like the normal frequency on their graph.” Mr. Trumble: “I think that’s a good way of thinking about it. So, here’s what I’m going to do. I’m going to pass back several graded papers.”
Teacher explains	Provides explanation before students verbalize their ideas	Ms. Montgomery: “What did you notice?” Student: “Some grew taller than others.” Ms. Montgomery: “Some grew taller than others. If you look at, you know, this plant right here, we have a really tall one, really well developed lots of seed pods. And then we have one that did not do very well at all. So, if you're thinking about the question, How tall do Wisconsin fast plants grow? We're gonna have to look at a lot of plants, right?

		To try to figure out if you are going to answer that question. You can't just go off of one piece of data, right? Do we think all plants are growing and changing in the same way? No, they grow differently don't they?”
No follow up	Does not take up idea in student's discourse	Ms. Summer: “Somebody got what [as their measurement]?” Student: “42. It was probably inches. Ms. Summer: “Maybe.” [calls on another student]

To find patterns across the SST episodes, we created a spreadsheet that included the timestamps for each episode, the teacher and student codes, discourse examples, and short analytic memos. Student sensemaking is a process where students assemble prior knowledge, identify a gap in their understanding, and then build and critique explanations to resolve that gap (Figure 2-1; Odden & Russ, 2018, 2019a) and so we used this framework to look for patterns in TDMs across all the SST episodes.

4. Findings

The purpose of this study was to describe how expert teachers used TDMs to initiate, sustain, and stop student sensemaking talk during their data investigations. Through our analysis, we began to think of the process of student sensemaking during whole class discussions as a pathway. These expert teachers used TDMs to support students to start on the pathway of sensemaking, and SST occurred, but then in their discourse the teachers and students quickly veered off the path of sensemaking, and SST stopped. The dynamic process of sensemaking was not linear in classroom discourse, but rather teachers and students entered, exited, and returned to the pathway. Our analysis helped us see there were three ways these expert teachers used TDMs to support students to travel the pathway of sensemaking: *packing their bags*, *starting their* *journey*, and *prolonging their trip*. We briefly summarize them here and then, in what follows, we use three vignettes to describe them in greater detail.

In the first way of travelling the sensemaking pathway, teachers used TDMs to elicit students' observations or thinking. These eliciting TDMs included asking for observations, asking for ideas, and asking for comparison. We called this *packing their bags* to travel the sensemaking pathway because these TDMs supported students to collectively assemble their initial observations, ideas, and prior knowledge as a necessary preparatory step for the sensemaking process. Students needed to articulate what they knew about the problem or phenomenon before they could identify any gaps or inconsistencies in their knowledge. The TDMs of changes the topic or teachers explains stopped SST after students shared their observations or ideas, and students did not begin the sensemaking process. In these episodes, students packed their sensemaking bags by collectively sharing their ideas and observations but then did not have a classroom discourse opportunity to use those ideas to figure something out and go on the sensemaking journey.

The second way we saw TDMs used to travel the sensemaking pathway was when teachers employed initiating sensemaking TDMs to use students' ideas or observations to call attention to something puzzling or a gap that needed to be addressed. These initiating TDMs included highlighting a puzzle or asking what if. The TDM of focusing discourse was used in conjunction with these TDMs to draw students' attention to some aspect of their data. We called this *starting their journey* on the sensemaking pathway because these TDMs invited students to be in the frame of figuring something out, and students typically began the process of sensemaking by brainstorming and sharing their ideas. All four teachers used the TDMs of highlighting a puzzle or asking what if to invite students to figure something out. After the sensemaking journey started, however, students did not have discourse opportunities to fully develop, critique or revise their explanations. SST stopped when teachers used the TDMs of teacher explains or changes the topic.

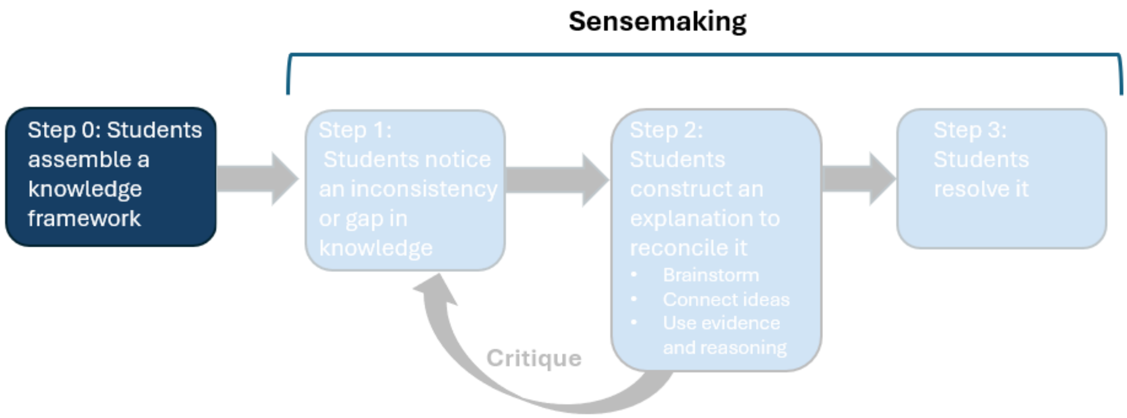
Finally, teachers employed sustaining sensemaking TDMs to support students to develop and critique their explanations. The TDMs of asking for explanation, asking for clarification, and asking for evidence supported students to develop their explanations. If a critique occurred, the teacher used the TDMs of pressing, asking what if, and focusing discourse to challenge students' ideas. We called this *prolonging the trip* on the sensemaking pathway because these TDMs helped students to develop their explanations and notice gaps or inconsistencies in them.

4.1 Packing Their Bags: What Do You Notice?

This vignette illustrates how Mr. Houston, a sixth-grade science teacher, used the eliciting TDM of asking for observations to support his students to make public their initial ideas about variability in the growth of their plants. The open-ended TDM of "what do you notice" was a common discourse move across all SST episodes. This eliciting TDM supported students to assemble their shared knowledge framework because it gave them the opportunity to collectively express what they knew (Figure 2-3).

Figure 2-3

Assembling a Knowledge Framework



Note. The shaded-out parts of this figure represent steps in the sensemaking process not evident in this vignette. Adapted from Odden, T. O. B., & Russ, R. S. (2018). Sensemaking epistemic game: A model of student sensemaking processes in introductory physics. *Physical Review Physics Education Research*, *14*(2), 020122. https://doi.org/10.1103/PhysRevPhysEducRes.14.020122

In Mr. Houston's class, students began the "How Do Plants Change as They Grow" data investigation by planting Wisconsin Fast Plants seeds (see Table 2-4 for investigation overview). Two or three students worked together as a group to plant three to four Wisconsin Fast Plant seeds in a single pot. Students measured their plant's height and counted any leaves, flowers, and seed pods every few days for three weeks as the plants grew, recording their data on individual data sheets.

This SST episode occurred during the first lesson after students' data collection was completed (Table 2-11). It lasted approximately 2 min 30 s. Mr. Houston began by asking students for their observations of the differences in the growth of their Wisconsin Fast Plants.

Table 2-11

Sensemaking Step 0: Noticing Difference in Plant Growth

Row	Speaker	Discourse	Code
1 **5:06**	Mr. H:	**What differences** [in plant growth] **did you notice? Can anybody want to share theirs? What differences?**	**Asking for observations** **Asking for comparison**
2	Kayli:	*Ours bent when it grew.*	*Makes an observation*
3	Mr. H:	**Some of the plants bent when they grew?** (student: mmhmm)	**Marking**
4		**Did all of them do that?**	**Follow up** **Asking for clarification** **Closed question**
5	Kayli:	*Two of them did.*	*Makes an observation*
6	Mr. H:	**Why do you suppose some of them bend and some of them do not?**	**Asking for explanation**
7	Jonathan:	*They're going towards the light.*	*Makes a claim*
8	Mr. H:	Ahhh. Okay. Let's raise your hand, wait. Is everybody with me? Leo, you with us? All right.	
9		**So, some are going towards light.**	**Marking**
10		**Do you guys know what that's called? When a plant goes and shoots toward the light?**	**Asking to make a connection**
11		There's a scientific term for that.	
12	Roberto:	*Photosynthesis?*	*Makes a claim*
13	Mr. H:	**That's when, that's how they make their own food.** **That's actually a phototropic, a phototropic response is what that's called.** Good.	**Teacher explains**
14	Jonathan:	*We note, uh, we noticed that some plants are way, or 10 times bigger than other plants.*	*Makes an observation*
15	Mr. H:	Okay, **so we noticed a lot of variation in the growth.**	**Teacher revoices**
16		**What can be some reasons behind that? Do you know?**	**Asking for explanation**
17	Jonathan:	*Well, I did notice that Mikes' plant was like sitting on top of another plant*. (Mr. H: Okay)	*Makes an observation*
18		*So that might have messed it up.*	*Makes a claim*
19	Mr. H:	**Maybe where they planted their seed and just didn't have enough room**, could be.	**Teacher explains**
20	Roberto:	*Like, the difference I noticed was Jonathan's was the biggest at first. It was giant. And then it was*	*Makes an observation*

		weird, because his like, stopped growing, and mine just grew more.	
21	Mr. H:	Maybe that will happen to him in real life because he is the tallest person in the room. He'll stop growing at some point, right. That happens to all of us.	
22	Jaime:	*I noticed that mine grew faster than most of yours.*	*Makes an observation*
23	Mr. H:	**Okay, so yours grew faster.** (Jaime: He moved 10, but [unintelligible]	**Marking**
24		**So, they grew at different speeds is what I'm hearing, right.**	**Teacher revoicing**
25		**Any other differences?**	**Asking for observations** **Asking for comparison**
26	Leo:	*Mine grew in an L shape.*	*Makes an observation*
27 **7:41**	Mr. H:	Okay. **So again, it leaned over to the side**.	**Teacher revoices**
28		**And maybe, I don't know, one of the reasons behind that. You might think about why that can happen. Okay, any other reasons?** [no students answer]	**Asking for explanation**
29		**All right. So, we, the answer to this is no, they did not grow in the same way. Right?** (Student: No.)	**Teacher explains**
30		Yeah. Okay. **Let's go to the next one** [slide]. **All right, I want you to watch this** [video]. **Did you notice that you some of you had some green bean looking things on your plants, anybody have those?**	**Changes topic**

Note. In this table, and in subsequent transcript tables, the bold type indicates a teacher's utterance that was coded. Its corresponding code(s) is shown in bold type to the right of the discourse. Italicized type indicates a student's utterance that was coded. Its corresponding code(s) is shown in italicized type to the right of the discourse. Utterances in plain text were not assigned a code. If utterances overlapped, they are shown in parentheses. Information in brackets was added by the authors to give information about the context of the discourse. The timestamps of the SST episode are in bold type, next to the first line of SST and the last line.

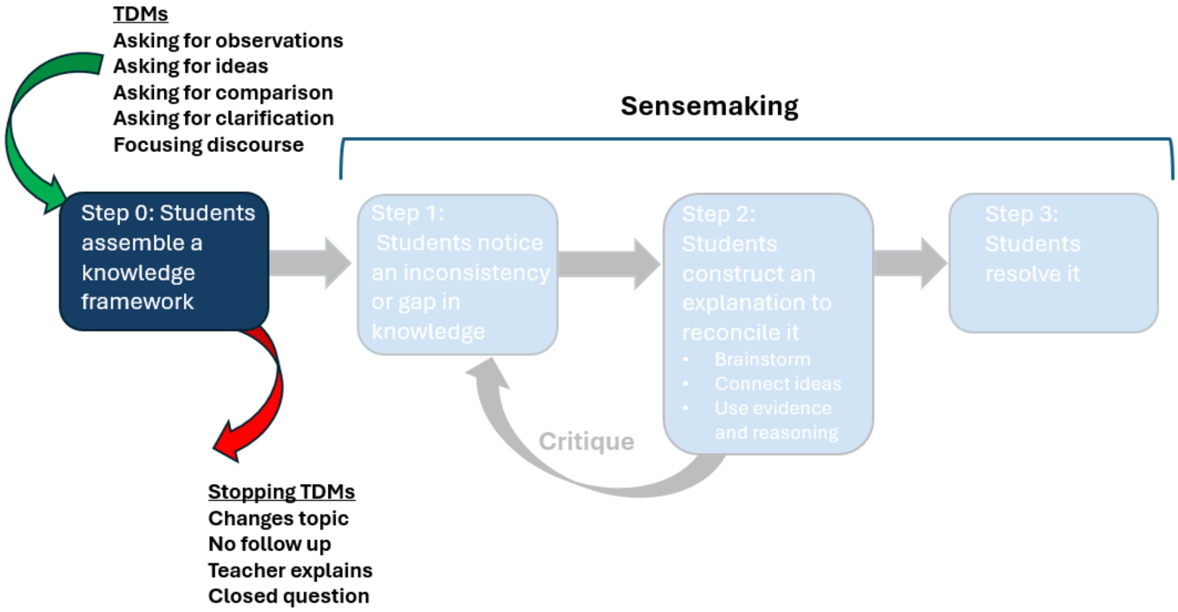
In this SST episode (Table 2-11), Mr. Houston asked an open-ended question (row 1) to elicit students' observations about differences in the growth of their plants. Multiple students responded to this TDM by sharing observations about variation in the shape of the plant growth (rows 2, 26), the height of the plants (row 14), the proximity of the plants (row 17), and the rate of plant growth (rows 20, 22). Mr. Houston marked these student contributions as important by repeating them (rows 3, 9, 23) or rephrasing them using the TDM of revoicing (rows 15, 24, 27). He also asked students to provide a reason for why those differences may have occurred (rows 6, 16, 28) but then used the TDM of teacher explains to answer his questions (rows 13, 19, 29). Mr. Houston stopped SST by using the TDM of changes topic. Here, multiple students shared their observations in response to his open-ended question, but those observations were not used for subsequent discourse or recorded for further use.

In this vignette, Mr. Houston *packed the bags* for student sensemaking by using an eliciting TDM, "what do you notice," so that multiple students could respond with their observations. This TDM functioned to open up the classroom discourse and gave the students an opportunity to participate in the dialogic discourse necessary for collective sensemaking to occur. It also focused students' attention on the variability of several characteristics of plant growth and provided a context for the data they collected. These student observations and ideas had the potential to be used as a shared knowledge framework for students to use if they had started on the pathway of sensemaking, but the SST episode ended without those observations being used in subsequent discourse.

Across the data corpus, the eliciting TDMs of asking for observations, asking for ideas, and asking for comparison occurred during SST episodes (Figure 2-4). Multiple students responded to these open-ended TDMs by sharing their noticings and thinking. Teachers also used the TDMs of asking for clarification and focusing discourse to further clarify and refine these ideas. For example, the next vignette of Mr. Trumbull's classroom contains examples of how he used asking for clarification and focusing discourse to refine his students' ideas (Tables 2-13 and 2-14).

Figure 2-4

Packing the Bags: Eliciting TDMs Used for Assembling a Shared Knowledge Framework



Note. This figure illustrates the process of sensemaking (Odden & Russ, 2018). The green arrow indicates the teacher discourse moves from across the data corpus used to support students to engage in a step of the sensemaking process. The red arrow indicates the teacher discourse moves from across the data corpus used to end student sensemaking talk.

Teachers used TDMs to elicit students' observations or ideas but did not use further TDMs to support students to start on the pathway of sensemaking. These SST episodes typically stopped with the teacher using TDMs to change the topic of discourse, not follow up with a student idea, or to provide an explanation (Figure 2-4).

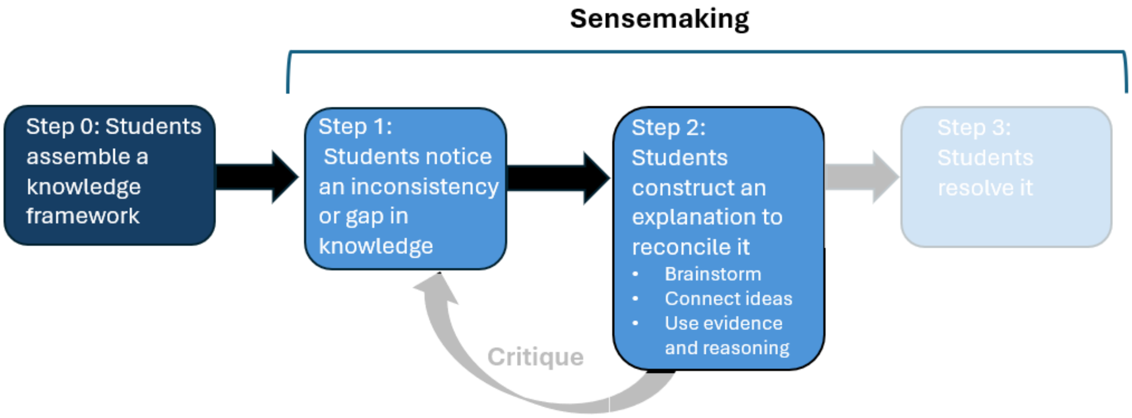
In the next vignette, we describe how a teacher employed TDMs to elicit students' observations and prior knowledge, packing the bags for the sensemaking journey, and then used one of those student observations to start on the pathway.

4.2 Starting Their Journey: Is My Arm Span Both 12 and 263?

This vignette describes two consecutive SST episodes, and we present them as a series of tables. Each episode is divided into several discourse segments determined by the content of the teacher and student discourse. The first SST episode lasted approximately 4 min, and its transcript and codes are presented in Tables 2-12 through 2-15. In this SST episode, Mr. Trumbull, a sixth-grade mathematics teacher, used TDMs to help his students to notice features of their measurement data and draw upon their prior knowledge about the word average as they assembled their shared knowledge framework and packed their bags for their sensemaking journey (Figure 2-5, step 0).

Figure 2-5

Initiating the Sensemaking Process



Note. The shaded-out parts of this figure represent steps in the sensemaking process not evident in this vignette. Adapted from Odden, T. O. B., & Russ, R. S. (2018). Sensemaking epistemic game: A model of student sensemaking processes in introductory physics. *Physical Review Physics Education Research*, *14*(2), 020122. https://doi.org/10.1103/PhysRevPhysEducRes.14.020122

The second SST episode immediately followed the first and lasted approximately 5 min. Its transcript and codes are presented in Tables 2-16 through 2-19. In this SST episode, Mr. Trumbull used one of the student's observations to highlight an inconsistency and then used TDMs to help students realize the need to explain the "weird" variability in their data (Figure 2-5, step 1). Mr. Trumbull supported his students to *start their journey* on the sensemaking pathway as he shifted the whole-class discussion from what the students observed about their measurements to developing initial explanations for the variability in their measurements (step 2, Figure 2-5).

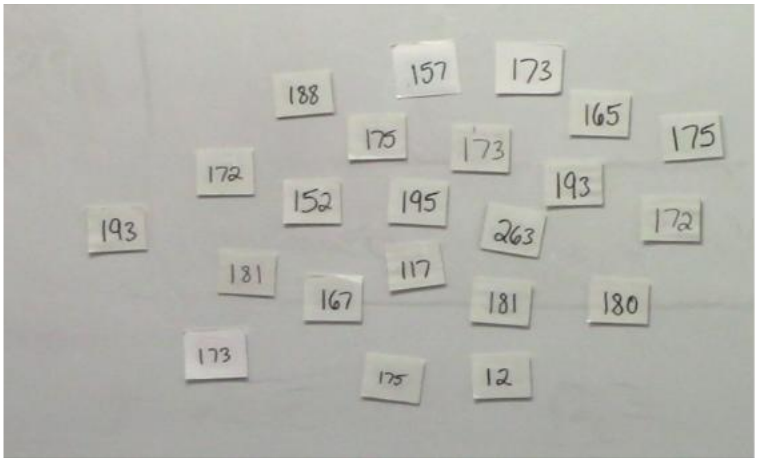
4.2.1 Packing Their Bags: What Do You Notice?

To begin the "Inventing Data Displays" data investigation, Mr. Trumbull had his students independently measure his arm span with a small, fifteen-centimeter ruler (see Table 2-4 for investigation overview). Students used these data throughout the unit on data and statistics. The following SST episodes occurred during the first lesson of the unit, and it was the first time students saw their collective measurement data.

Prior to initiating this whole class discussion, Mr. Trumbull displayed the students' measurements of his arm span on the board (Figure 2-6). He asked the students to take a moment to look at the data without discussing it with anyone. After thirty seconds, he directed the students to turn and talk with the people at their tables and share what they were noticing and what they were wondering. As the students discussed, Mr. Trumbull visited each group, listened, and occasionally asked students questions.

Figure 2-6

Students' Measurements of Mr. Trumbull's Arm Span



Mr. Trumbull then engaged the class in a whole class discussion. He began this SST episode by using the TDM of asking for observations to elicit discourse about what students noticed about their measurements (Table 2-12).

Table 2-12

Sensemaking Step 0: General Noticing

Row	Speaker	Discourse	Code
1 **43:46**	Mr. T:	Okay, a couple things I am hearing from tables. **Audrey, what was something you noticed?**	**Asking for observations**
2	Audrey:	*Uh. There was, uh, three 173s.*	*Makes an observation*
3	Mr. T:	So, **did anyone else notice that there were some repeated measures?**	**Follow up** **Asking for consensus** **Closed question**
4	Students:	*Yes.*	
5	Mr. T:	**She pointed out that there's three 173s.** Interesting.	**Teacher revoices**
6		**Are there any other repeated measures,** just out of curiosity?	**Asking for observations**
7	Student:	*There's two 172s.*	*Makes an observation*
8	Mr. T:	**Two 172s. Brandon?**	**Marking**
9	Brandon:	*175.*	*Makes an observation*
10	Mr. T:	**175 repeats, excellent!**	**Marking** **Evaluates student discourse**

Mr. Trumbull's use of the TDM of asking for observations began the assembly of the class's shared knowledge framework. He strategically asked Audrey to share her observation that there were three 173s to bring to the surface that there were repeated values (row 2). He then used the TDM of revoicing to repeat Audrey's observation for the class, and he explicitly added that they were repeated measures (rows 3, 6). This revoicing helped two additional students identify other repeated values for the class. Mr. Trumbull marked those contributions as valuable by repeating them and using the word "excellent" (row 10). This use of the TDM of asking for observations began to create a shared understanding of what the students knew about their data. Students began assembling their knowledge framework by collectively establishing that certain individual measurements repeat. By supporting students to notice these repeated values, Mr. Trumbull helped students see that there was structure in their data in the midst of its variability.

Mr. Trumbull continued using the TDM of asking for observations; this time focusing the class's attention on a student's idea that there was a group of values where measurements tended to occur (Table 2-13).

Table 2-13

Sensemaking Step 0: Noticing Patterns in the Data

Row	Speaker	Discourse	Code
11	Mr. T:	**But some of you noticed something else too with that. Not just repeated individual values** [voice trails off]. Norman?	**Asking for observations** **Focusing discourse**
12	Norman:	*There's a range like, well, most numbers are like 170 to 200, or whatever, give or take.*	*Makes an observation*
13	Mr. T:	**So, there's kind of some repetition within like a certain range. So, there's, we could say there's a lot of 170s to 200s.** Right? Interesting. Okay.	**Teacher revoices**
14		**Anyone else notice anything?**	**Asking for observations**
15		You know, actually. Danny, he said, I like how you said it. **What was like the first thing you look for?**	**Asking for observations**
16	Danny:	*I said like the range is from 12 all the way to like 263.*	*Makes an observation*
17	Mr. T:	Interesting. Here, actually, I'm gonna write some of these things on the board really quick. **So, he said, repeated values, he said, groups of values.** [writes "repeated values" "groups of values" on board]	**Teacher revoices**
18		Danny. I'm sorry. What did you say again?	
19	Danny:	*It's like they range from 12 to 263.*	*Makes an observation*
20	Mr. T:	**What do you mean by the word range there?**	**Follow up** **Asking for clarification**

21	Danny:	*It's like the smallest is 12 centimeters. Take the smallest, the number I got, and then the biggest number is 263.*	*Explains*
22	Mr. T:	[writes "smallest to largest (range)" on board] Interesting. **So, thinking about this really small to really big.**	**Teacher revoices**

The assembly of the class's shared knowledge framework continued as Mr. Trumbull shifted students' attention away from observations of individual values of measurements to making observations about groups of values (rows 13, 15). He used the TDM of focusing discourse to direct the class's attention to notice that not only individual values repeat, but there is repetition of values in a certain numerical range of the data (row 11). Mr. Trumbull revoiced Norman's contribution by saying "there's a lot of 170s to 200s" to emphasize this observation. He then used the TDM of asking for observations to specifically ask Danny (row 15) about his observation that the range is from 12 to 263, drawing the class's attention to another observation of the data as a whole. Mr. Trumbull followed up on Danny's observation by using a TDM of asking for clarification so that all students could hear what Danny meant by the word range (row 20).

This movement from thinking about data as individual values to viewing aggregate properties of the data is an important step in beginning to reason with data (Konold et al., 2015; Rubin, 2020). When Mr. Trumble used the TDMs of asking for observations, asking for clarification, and focusing, he intentionally supported the students to notice these patterns in the data. Then, he used TDMs of revoicing and marking to emphasize their importance as he recorded them on the board.

The class's shared knowledge framework now included the observations that some individual measurements repeated in the data, those repeated measurements occurred in a clump, and there was a large range of values. These student observations about frequency, density, and the range are all characteristics of their data that students will need to develop explanations for their data's variability.

Note that Mr. Trumbull often used the word "interesting" in his discourse after students have shared their observations (rows 5, 13, 17, 22). This word acknowledged students' discourse as valuable to the discussion without passing judgment on them, and therefore, positioned the students as the knowledge contributors. This TDM supported the dialogic and interactive classroom discourse necessary for student sensemaking.

In this next segment, Mr. Trumbull supported the assembly of a shared knowledge framework by helping students draw upon their prior knowledge and experience. He began by using the TDM of asking for ideas and students responded by talking about their prior knowledge of the word average and the "meh," a prior shared classroom understanding (Table 2-14).

Table 2-14

Sensemaking Step 0: Drawing in Prior Experience

Row	Speaker	Discourse	Code
23	Mr. T:	**And I'll take one more thought.** Marcelo?	**Asking for ideas**
24	Marcelo:	*The average is something like, between, um... I forgot now.*	*Makes a claim*
25	Mr. T:	[writes "average" on board] Now, **what do you mean by the word average?** Because it's a word that we throw up and around a lot in the world and in math, but if you were to define without just saying average, **what do you mean?**	**Follow up** **Asking for clarification**
26	Marcelo:	*It's kind of like the middle of all the numbers.*	*Explains*
27	Mr. T:	[writes "middle" under average on board] Okay. Santiago, **what were you gonna say?**	**Asking for ideas**
28	Santiago:	*The meh*	*Explains*

			Draws on experience
29	Mr. T:	**The what?**	**Asking for clarification**
30	Santiago:	*The meh, like we said before.*	*Explains* *Draws on experience*
31	Mr. T:	Oh! Yeah, we did say that! [writes “meh” under average on board] (*students: oh yeah, the meh, I remember tha*t)	
32		Yeah. Wait, Santiago, remind me. Nice. **Remind me what we meant by the meh**	**Follow up** **Asking for clarification**
33	Santiago:	*Like, uh, this was in Project Redshift, right?*	*Student question* *Clarifying*
34	Mr. T:	Yep. When we were doing astronomy, yeah. **What about it?**	**Follow up** **Asking for explanation**
35	Santiago:	*It was, uh, I forgot.*	
36	Mr. T:	Yeah, it's okay. **Help him out.**	**Asking to add on**
37		**What were we saying with that? Why, in Project Redshift, we do, we did something, we're kind of like, it's like the meh value?** Ember?	**Asking to make a connection** **Asking for explanation**
38	Ember:	*We were like, it's like, kind of close... with meh, it’s kinda like in the "mmm"*	*Explains*
39	Mr. T:	Yeah, I like it. **It’s like kind of** [gestures with hands]	**Teacher revoices**
40		Katalina, **were you going to add something to that?**	**Asking to add on**
41	Katalina:	*Umm, but, it's like... kind of where they’re all close to each other.*	*Explains* *Adds on to an idea*
42	Mr. T:	**Close to each other. Good**.	**Marking**
43		**Last thought, Timothy?**	**Asking to add on**
44	Timothy:	*Sometimes I'll think of like average as like, when I think of, like, height, let's say the average height is like something, let's just say, it’s six foot.* (Mr. T: Sure). *That's probably the most common number or the most common height for this certain group of people ‘cause* (Mr. T: Sure) [writes “common” under average on board].	*Explains* *Adds on to an idea*
45	Mr. T:	**Good. I love that. That’s great**.	**Evaluates student discourse**
46		**And I like our, I like our class definition of meh. It's like, yeah, it's like "ish" It’s basically that. Right?**	**Teacher revoices** **Asking for consensus**

This segment further develops the class’s shared knowledge framework by incorporating students’ prior knowledge of the word average. In row 23, Mr. Trumbull used the TDM of asking for ideas, a more general request for student thinking, and opened the discourse up to the whole class. In response, Marcelo made a claim that the average of this data is a certain value, or range of values (row 24). Mr. Trumbull wrote the word average on the board, and then, like when Danny used the word range, he used the TDM of asking for clarification so that all students could hear what Marcelo meant by average (row 25).

This clarification is important because students have experiences with the word average in everyday language (Konold et al., 2015). Students may not use the word to describe an aggregate property of the data but rather use it to describe a characteristic of a particular case or subset of cases; for example, students often view average as the most frequent case, or the case or clump of cases in the middle of a distribution (Konold et al., 2015). In fact, Marcelo explained that the average of the data is the middle of all the numbers (row 26). Mr. Trumbull acknowledged this idea by writing it on the board but did not use any other TDMs in response. He then used the TDM of asking for ideas so another student could share their thinking.

In response, Santiago drew upon a previous classroom experience and connected the meaning of average with the “meh” (row 28), and this word seemed to resonate with several students (row 31). Mr. Trumbull used the TDM of asking for clarification to bring into the classroom discourse how Santiago defined the “meh” from their previous project (row 32), but Santiago was unable to explain. At this point, Mr. Trumbull could have explained what the class meant by the “meh,” but he opened up the question to the class by using the TDM of asking for explanation (rows 36-37). Two more students participated in the discussion by explaining that the “meh” is a clump of data where the values are close together. Mr. Trumbull used the TDMs of revoicing and marking to emphasize this idea as valuable (rows 39, 42).

Mr. Trumbull asked for a final thought, presumably about the “meh,” using the TDM of asking to add on, but Timothy returned to the idea of average and described it as the most common value in a data set (rows 43 and 44). This is another common way students view the word average, as the most frequent case or mode (Konold et al., 2015).

In the following segment, Mr. Trumbull continued using the TDM of asking for ideas but then used several TDMs to end students’ sensemaking talk (Table 2-15).

Table 2-15

Sensemaking Step 0: Tension Between Dialogic and Authoritative Classroom Discourse

Row	Speaker	Discourse	Code
47	Mr. T:	**Norman, I lied about last thing, so really quick.**	**Asking for ideas**
48	Norman:	*Umm, the meh would mean more like an estimate than an average because the average is like, like, you take all the numbers together and find the exact average, like the exact* [voice trails off]	*Makes a claim* *Explains*
49	Mr. T:	Okay, so you don't... **you wouldn't say we should put the word estimate up here** [points to board].	**Follow up** **Pressing** **Asking for clarification** **Closed Question**
50	Norman:	*No. No.*	*Makes a claim*
51	Mr. T:	Can I, can I add? **I kind of like the word estimate.** **Can I say it's a "Mathy estimate"?** [writes “mathy estimate” under average on board]	**Pressing** **Asking for consensus** **Closed Question**
52	Norman:	*Yeah. It’s like a guesstimate* (*student: oh, yeah, guesstimate is good, another student: guesstimate sounds good*)	*Makes a claim* *Draws on experience*
53	Mr. T:	I think I [voice trails off] I hear y'all, I'm going to keep "Mathy Estimate."	
54 **48:11**		**But I like what you're saying, we're not just saying like ehh, it’s this. Why not. Whatever. We're saying, hey, we're gonna actually have a strategy to estimate something or to summarize something.** Good.	**Teacher revoices**

55	Mr. T:	So, really quick, y'all have noted some of these things. But why? **Here's the thing. We started this class by saying Hey, Mr. Roberts thought all these values are the same. Is he right?** (*multiple students: No*)	**Changes topic** **Closed question**
56		He's very wrong. Okay.	

Mr. Trumbull ended this SST episode by using one more open-ended TDM of asking for ideas. Norman responded by resisting the idea that the “meh” could mean average and claimed that the “meh” is an estimate, unlike the average, because the average is an exact number. It is possible that Norman held a view of average in the aggregate sense when he said, “you take all the numbers together and find the exact average” (row 48) and the idea that average could also be “ish” (row 46) or “kind of where they're close together” (row 41) was incongruent to his own knowledge framework. Mr. Trumbull used the TDM of pressing to challenge this idea, using a closed, yes/no, question. Norman disagreed with the idea of using the word estimate to describe average and repeated himself for emphasis (line 50). For the first time in this sensemaking episode, Mr. Trumbull explicitly asserted his epistemic authority by saying he liked the word estimate, and he asked Norman if “mathy estimate” could be an acceptable description for average, another closed question (line 51). Norman agreed, but he then made the claim that “guesstimate” was also a good description (line 52). Guesstimate is a word that students may have heard before in their prior experience, because several students agreed that guesstimate might be a good description. Mr. Trumbull once again explicitly asserted his epistemic authority by saying he was going to keep “mathy estimate” as a description although he acknowledged he heard the students' ideas.

This segment of discourse ended the SST episode and marked a transition from Mr. Trumbull using eliciting TDMs, i.e. asking for observations, asking for ideas, asking for clarification, that are open ended and position students as the knowledge contributors to using closed questions that require yes or no answers (rows 49, 51, 55). He also explicitly asserted his epistemic authority rather than marking student ideas as "interesting." At the end of this SST episode, Mr. Trumbull changed the topic of the discourse to refer to a question he had asked at the beginning of the lesson. All four teachers used TDMs of closed questions or changes topic to end SST episodes.

Throughout this SST episode, Mr. Trumbull used eliciting TDMs to support students in assembling their knowledge framework of noticing the smallest and largest values, which values repeated, and how to describe where there were clumps of values, *packing the bags* to start the process of sensemaking. About half the class, ten students, responded to these eliciting TDMs and contributed to the classroom discourse to assemble the class's shared knowledge framework. In this SST episode, Mr. Trumbull supported his students to *pack their bags* for traveling on the pathway of sensemaking by eliciting students' noticings, ideas, and prior knowledge. In the next SST episode, he supported them to *start their journey*.

4.2.2 Starting Their Journey: Something Is Weird Here

Mr. Trumble began the next SST episode, which immediately followed the previous one, by using an observation the students had just articulated in their shared knowledge framework to help students notice something puzzling and invite them to explain it (Table 2-16).

Table 2-16

Sensemaking Step 1: Highlighting an Inconsistency

Row	Speaker	Discourse	Code
1 **48:24**	Mr. T:	But I get what he's saying. **Is my arm span both 12 centimeters and 263 centimeters?** (*multiple students: No)*	**Highlighting puzzle** **Closed question**

2		**No, something is weird here because they should be the same. My arm span has a length to it.**	**Focusing discourse**
3		So, why, why are... **Can we agree that there's maybe some error?** (*Multiple students: Yes.*)	**Asking for consensus** **Closed question**
4		Yes. Well, **what do I mean when I say error, what do I mean when I say there is error? Edwin?**	**Asking for clarification**
5	Edwin:	*Something wrong.*	*Explains*
6	Mr. T:	**Something wrong, a mistake.**	**Teacher revoices**
7		So, **what are some possible reasons why there might be mistakes in these data? What, what could have caused this error?**	**Asking for explanation**

In the previous SST episode, students noticed the smallest and largest measurements in the data (Table 2-13, rows 19, 21). In this SST episode (Table 2-16), Mr. Trumbull used these measurements to highlight something puzzling about their measurements (row 1) and emphasized that the object they measured has a length and therefore all the measurements should be the same. He then linked this idea with the idea of error in the data (row 3). He explicitly asked a student to clarify the meaning of error so that all students understood the word. This sequence of TDMs set the stage for the students to figure something out and understand why there was a need to explain the variability in the data. He then used the TDM of asking for explanation to elicit students' ideas and start the brainstorming necessary for developing an explanation.

In the next two discourse segments (Tables 2-17 and 2-18), students generated several claims for why there may be variability in their measurements. As each student voiced their claim, Mr. Trumbull revoiced them to emphasize their contributions were valuable.

Table 2-17

Sensemaking Step 2: Brainstorming General Claims

Row	Speaker	Discourse	Code
8	Edwin:	*Someone probably just did the "meh" and got 12.*	*Makes a claim*
9	Mr. T:	So, **someone, can I say that as someone was just not being very careful.** (*Edwin: Yep*) [Mr. T. types on computer and projects his screen] Okay. Maybe they were rushing to through it [types]. Something like that? Sure. Brandon?	**Teacher revoices**
10	Brandon:	*Umm. We're not all robots. (*student*: yeah) We're not perfect.*	*Makes a claim*
11	Mr. T:	Yeah, **we're humans. Not robots**…[types on computer]	**Marking**
12		**What do you mean by that Brandon?**	**Follow up** **Asking for clarification**
13	Brandon:	*Everything we do, like* [voice trails off] *Nobody's perfect*. [voice trails off] *And yeah.*	*Explains*
14	Mr. T:	**Yeah, absolutely. Mistakes happen.** Sure.	**Teacher revoices**
15		**What else?** Javier?	**Asking for ideas**
16	Javier:	Oh, *we're not perfect. So like,*	*Makes a claim*
17	Mr. T:	That's what he just said.	
18	Javier:	*Yeah, I had something then Brandon took it.*	
19	Mr. T:	Okay, sorry…	

Students began by voicing general claims, e.g., people were not careful or made mistakes, about sources of error, or variability, in their measurement. Mr. Trumbull revoiced these ideas and made a public record of them by typing them.

Students then shifted from general claims about mistakes to more specific claims about the ways students could have measured (Table 2-18).

Table 2-18

Sensemaking Step 2: Brainstorming Claims About the Measurement Process

Row	Speaker	Discourse	Code
20	Mr. T:	...Katalina, go for it.	
21	Katalina:	*So, people forget things. I think that they might just be like, remember that 12? They might be just counting the rulers.*	*Makes a claim*
22	Mr. T:	Ooh. **And they could have forgotten a lot of things**. I mean, **how many of you while you were measuring kind of had a moment of like, shoot, I lost my train of thought? Anyone?** (student: *Ooh, I might have* [several students raise hands]) **Maybe forgotten where they were in their counting** [types on computer]	**Teacher revoices** **Asking for consensus**
23		**Katalina said another thing. They may have counted how many rulers, not centimeters** [types] Audrey?	**Teacher revoices**
24	Audrey:	*Umm. Like, you could have left a little space in between the rulers that you had.* (student: *yeah*)	*Makes a claim*
25	Mr. T:	**You're saying like if they were using two, they might have left some space?** Sure. Sure. Raven?	**Teacher revoices**
26	Raven:	*Since they were, like, cause like it'd be easier if it was like a long ruler maybe. But since they were like small rulers, we can't be perfect on where we place them.*	*Makes a claim* *Explains*
27	Mr. T:	Yeah. I don't know, **whose dumb idea was it to measure my arm span in tiny rulers?** Oh, it was mine. My bad. **That was a terrible measuring tool.** Right? That was a huge pain.	**Teacher revoices**
28		**What if you had used a yardstick or a tape measure that would've been way better?** Terrible measuring tool [types]. Hugh?	**Teacher explains**
29	Hugh:	*Well, mine was basically, it's like adding on to that.* (Mr. T: Sure.) *Your hands, since it's so tiny. Trying to keep it, like, precise, and not as moving.*	*Adds on to an idea* *Makes a claim*
30	Mr. T:	**So, you're saying I have weirdly small hands?** [students laugh]	**Asking for clarification**
31	Hugh:	*No, like with the ruler. Your hands could get, like, shaky while you're measuring? It could like move more or less of like a centimeter.*	*Explains*
32	Mr. T:	Sure. So, absolutely. Ember?	
33	Ember:	*Not everyone, like, starts at 100% the same spot. And at the end they could have ended it in a different place.*	*Makes a claim*

34	Mr. T:	Sure, **we knew it was fingertip to fingertip. But that's actually a little unclear**. Norman?	**Teacher explains**
35	Norman:	So, *you don't realize there's a little bit in the start before it gets to zero.* (Mr. T: Yeah.) *And they might have accidentally used that. Like, you can't just line up rulers, You have to, like, start it, like* [voice trails off] (*student: I hate that.*) *Yeah.*	*Makes a claim*
36	Mr. T:	Yeah, so **some people might have been really careful and like considered that little gap. Other people might have just counted it as part of it.** Sure. Timothy?	**Teacher revoices**

In response to Mr. Trumble's TDM of asking for explanation, several students made claims about sources of error, or variability, in their measurement process. This marks a shift from students thinking about variability in a general way, "we're not perfect," to thinking about specific causes of variability, "you could have left a little space in between the rulers". Additionally, Katalina connected the data, the measurement of twelve, to a possible reason for the error, counting the number of ruler length used, but no other students referenced the data. In these two discourse segments (Tables 2-17 and 2-18), the students appeared to be brainstorming, and Mr. Trumble used the TDM of revoicing to mark each claim as valuable, as well as typing a running list of student claims.

This brainstorming of ideas is important for sensemaking because it occurs as a precursor to generating explanations (step 2, Figure 2-5; Odden & Russ, 2018, 2019). These nascent ideas have the potential to be connected by students to develop a possible explanation. In the next segment, Timothy summarized the prior student ideas in the discourse by making a general claim that students used their measuring tools in different ways. He then connected this claim to evidence in the data, and, in response to Mr. Trumble's discourse moves, explained his reasoning (Table 2-19).

Table 2-19

Sensemaking Step 2: Beginning to Connect Ideas

Row	Speaker	Discourse	Code
36	Timothy:	*Kind of what Norman said. Like, people might have used their measuring tools in different ways. Like, has someone?*	*Adds on to an idea* *Makes a claim*
37		*Like, I would be like, let's start using the range. The person who got 12 definitely measured different than the person who got 263.*	*Explains* *Gives evidence*
38	Mr. T:	Timothy, **I’d like to hear about that a little bit more.**	**Follow up** **Asking for explanation**
39		**You said they might have used the tools different ways.**	**Teacher revoices**
40		**What were, what, how did you go about using it?** Do you want a ruler?	**Asking for clarification**
41	Timothy:	Yeah. *When I was measuring, I put the, I made sure to, like, put them line by line, or at least try my best to, like, keep not using the spaces, or the first little*	*Explains*
42	Mr. T:	[Interrupts] Here, one second. Because not everyone can see that. So, **what he was saying, like Norman said, there's a little gap in the beginning. So, Timothy was saying he was really careful to ignore that, or overcome, that gap and really carefully line it up**.	**Teacher revoices**
43		**And then you were just saying?**	**Asking for explanation**
44	Timothy:	*And then maybe the person who got 12, instead of doing centimeters, they counted the, each one of those. Sounds like something I would do, but I didn't do that.* (Mr. T: There you go.) *So, I was surprised. I’d probably end up getting that.*	*Makes a claim*
45 **53:39**		*But they might have just measured different than some of the other people.*	*Explains*
46	Mr. T:	Sure. **Or how many of you used one ruler?** Raise your hand. Really? Oh, yeah. I was gonna say a couple of y’all did.	**Closed question**
47		**How many of you used two?**	**Closed question**
48		There are some differences. Did? Well, this is a silly question. **Some of you did this: some of you laid it out and then flipped it and flipped it. Valid strategy**. (Student: There you messed up.) Well, I know, I'm not trying too hard here, right? **But that's a good strategy. Some of you did this: marked it with your finger, slid it,**	**Teacher explains**

	marked it with your finger. Those are different ways.	
	I have one more question that I really want to hear from y'all. What about the thing that you were measuring? Tell me about that. I mean, I know it was me, but like, elaborate.	**Changes topic**

Timothy claimed that the different ways students used their measuring tool was the source of variability in the measurements. He used the range of measurements as an example, specifically referring to the twelve and 263 measurements. Mr. Trumble responded by asking Timothy to explain further about his claim. Timothy explained his process for using the ruler to measure and then returned to Katalina's claim that the measurement of twelve was a result of counting the number of ruler lengths used (row 44). The TDMs of closed question, teacher explains and changes topic stopped this SST episode.

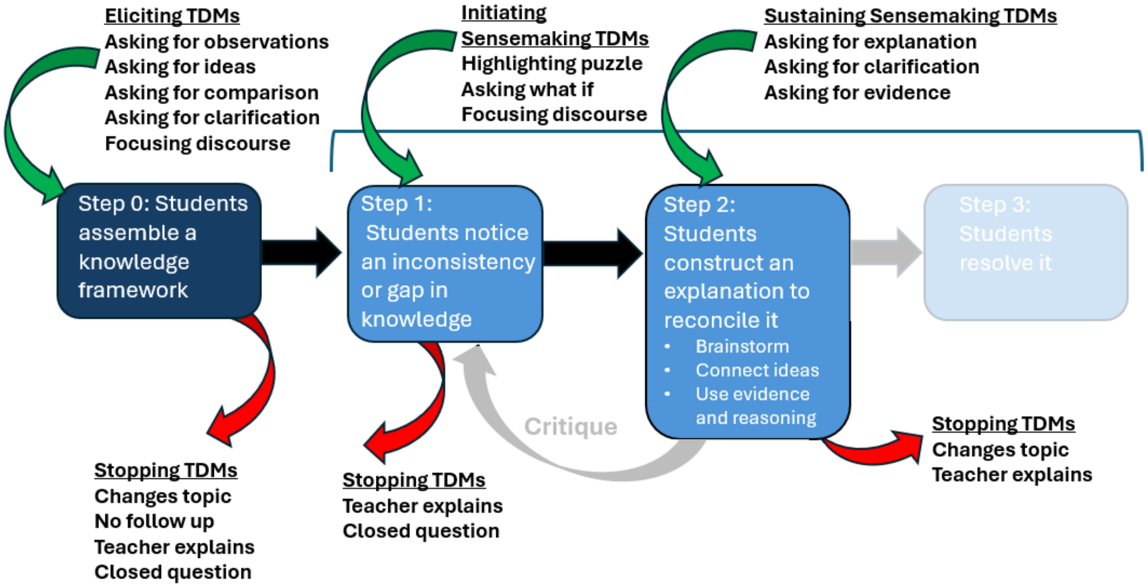
Here, Timothy began to connect all the different claims into an explanation for the measurement error, or variability, in their data, and explained his reasoning by providing evidence from the data. He had started on the pathway of sensemaking. At that point, there was an opportunity to further build on his explanation by thinking about other ways students used the measuring tool and how those methods could correspond to the data generated; for example, by thinking about the small gap on the end of the ruler and connecting it to variability in the measurement data. The SST episode stopped, however, and the discourse topic changed, and the students veered off this pathway of sensemaking.

In this vignette, Mr. Trumbull used sustaining sensemaking TDMs to shift students from seeing a need to figure something out to beginning to develop an explanation. These sustaining TDMs included asking for explanation and asking for clarification. Multiple students responded by brainstorming ideas, which Mr. Trumble consistently revoiced and noted in the class's public record. Timothy began to connect those ideas into an explanation and provided some evidence, i.e., counting ruler flips to generate the measurement of 12, but the topic of the classroom changed before the students had an opportunity to scrutinize Timothy's explanation and provide further evidence and critique.

Across the data corpus, the initiating sensemaking TDMs appeared in all four teachers' SST episodes. These TDMs included highlighting a puzzle and asking what if as teachers invited students to begin figuring something out and *start their journey* on the sensemaking pathway (Figure 2-7). The TDM of focusing discourse, when teachers emphasized some aspect of the data, problem or phenomenon, also occurred and helped students to understand the gap or inconsistency (see Table 2-16, row 2 for an example of focusing discourse that functioned in this way). Sustaining TDMs included asking for explanation, asking for clarification, and asking students for evidence for their claim (Figure 2-7).

Figure 2-7

Starting the Journey: Initiating TDMs and Sustaining TDMs to Begin the Sensemaking Process



Note. This figure illustrates the process of sensemaking (Odden & Russ, 2018). The green arrows indicate the teacher discourse moves from across the data corpus used to support students to engage in steps 0-2 of the sensemaking process. The red arrows indicate the teacher discourse moves from across the data corpus used to end student sensemaking talk.

Next, we explore how a teacher *prolonged students' trip* on the sensemaking pathway by using a recurrent question about the use of scale in a student-generated data display, and using the TDMs of pressing, asking what if, and focusing discourse to support one student to critique his explanation. We also provide discourse evidence from a later science investigation to show how at least one student from this mathematics class used these ideas about scale as a resource to make sense of a data display in science class.

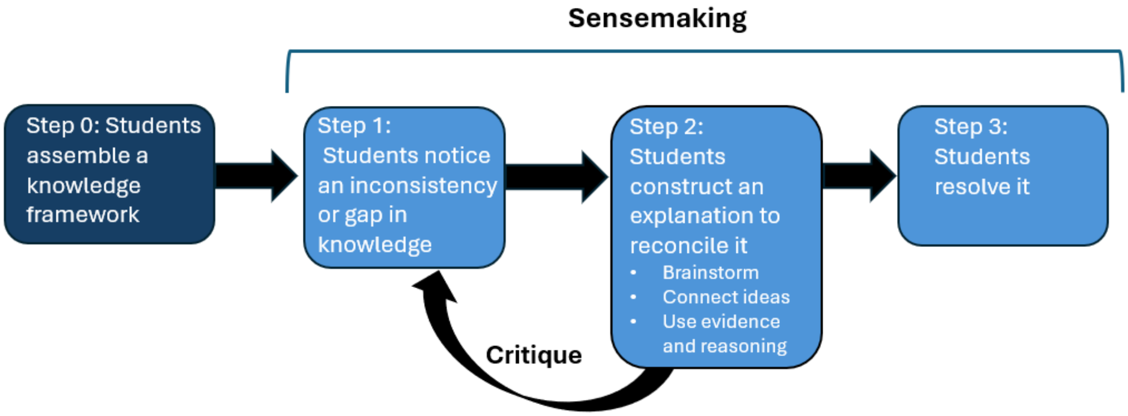
4.3 Prolonging Their Trip: Is This a Mistake or On Purpose?

This vignette describes how Ms. Summer, a sixth-grade mathematics teacher, used a recurrent question, "does it look like they made a mistake?", and the TDMs of pressing and asking what if to *prolong her students' trip* on the sensemaking pathway. The vignette includes four SST episodes across two class periods, and it illustrates the dynamism and complexity of classroom sensemaking as teachers and students start on and veer off the sensemaking pathway. As in the previous vignette, each episode is divided into a series of discourse segments determined by the content of the teacher and student discourse, and these segments are presented in a series of tables. We first give an overview of this vignette and then describe it in detail.

In the first SST episode (Tables 2-20 and 2-21), Ms. Summer began the lesson by using an eliciting TDM to help students pack their bags for the sensemaking pathway by noticing an important feature, the use of gaps where there were no measurements, on a strategically chosen student data display (Figure 2-8, step 0). She then helped the students to start on the sensemaking pathway by highlighting a puzzle: was it a mistake on the display to have a place where there were no numbers? (Figure 2-8, step 1).

Figure 2-8

The Process of Sensemaking



Note. Adapted from Odden, T. O. B., & Russ, R. S. (2018). Sensemaking epistemic game: A model of student sensemaking processes in introductory physics. *Physical Review Physics Education Research*, *14*(2), 020122. https://doi.org/10.1103/PhysRevPhysEducRes.14.020122

In the second SST episode (Tables 2-22 through 2-24), which was in the middle of the lesson, Ms. Summer returned to the question of whether the display author made gaps where there were no numbers on purpose and she asked students to explain whether it was important to do so (Figure 2-8, step 2). In this SST episode, Ms. Summer prolonged the students' trip on the sensemaking pathway by using the TDM of pressing to challenge a student's explanation that the gaps were a waste of space (Figure 2-8, critique). Near the end of the lesson, in the third SST episode (Table 2-25), Ms. Summer returned to the same strategically-chosen student data display and used the TDM of asking what if to continue their trip on the sensemaking pathway by helping her students imagine an alternative and explain why including gaps on a data display might be useful (Figure 2-8, step 1).

The fourth SST episode happened near the end of the lesson on the following day. We present only a portion of this SST episode, the discourse segment about the use of gaps (Table 2-26). Ms. Summer again used the TDMs of pressing and what if to start students on the sensemaking pathway and challenge a student's idea that using gaps in a data display was a waste of space. In this SST episode, there is evidence that at least some students resolved the puzzle of whether it was a mistake to include gaps on a data display (Figure 2-8, step 3).

The final SST episode we present in this vignette occurred five months after Ms. Summer's lesson. This SST episode occurred in Mr. Houston's science class when students were discussing their plant measurement data (Table 2-27). It illustrates how one student from Ms. Summer's class connected her prior mathematical knowledge of the use of gaps with their use on a data display in science class. It suggests that, for at least this student, using gaps on a data display made sense.

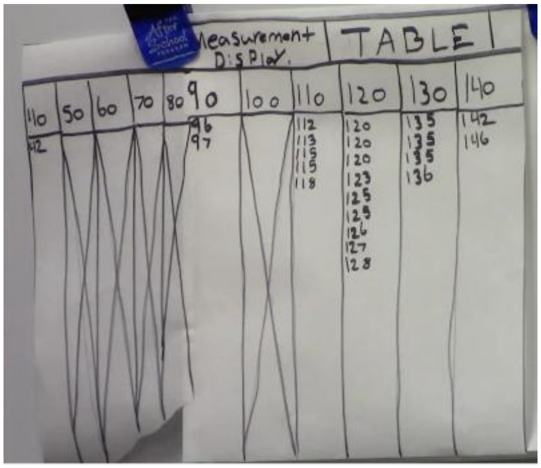
4.3.1 Packing Their Bags: What Do You Notice?

Prior to this lesson, Ms. Summer's students worked in groups of two to three to create a display of their individual measurements of a pool noodle (see Table 2-4 for overview). Ms. Summer told the students the display should help a person answer the question, "how long is the noodle?", but she did not give them any further instructions about how they should construct it. The day before this lesson, the students observed one another's displays and wrote down what they noticed about each one.

This lesson began with Ms. Summer presenting Nolan's data display. Nolan was a student from another class, and these students had not yet seen his data display (Figure 2-9). Like the first two vignettes, this SST episode started with Ms. Summer asking for student observations, "what do you notice?," to support students to assemble their shared knowledge framework (Table 2-20). This SST episode lasted approximately 1 min 36 s., and it includes discourse segments in Table 2-20 and Table 2-21.

Figure 2-9

Nolan's Data Display



easurement DiSPlay. TABLE

40	50	60	70	80	90	100	110	120	130	140
42					96		112	120	135	142
					97		113	120	135	146
							115	120	135	
							115	123	136	
							118	125		
								125		
								126		
								127		
								128		

Table 2-20

Sensemaking Step 0: Noticing a Unique Feature in a Student Data Display

Row	Speaker	Discourse	Code
1 **3:26**	Ms. S:	I want you to take a look at the other one that you guys haven't seen that happened in the day while you weren't here. You've made observations on all the others, but, so let's turn and look right here at this one. Can y'all see it? No? [walks over, gets data display (Figure 9), and holds it in front of class.]	
2	Leo:	*That one kind of looks like ours.*	

3		Ladies, **do you notice anything?** Madeleine?	**Asking for observations**
4	Madeleine:	*Um, they put the 50s, 60s, 70s, and 80s, but they marked it out. And the 100s.*	*Makes an observation*

Madeleine responded by observing that the display author included certain categories, i.e., the 50s, 60s, and 100s, but the display author marked them out (row 4). As in other SST episodes, the TDM of asking for observations began to create a shared understanding of what the students knew about this data display, packing their bags for sensemaking. It supported students to attend to a characteristic of the data display, the marked-out sections, and to collectively establish that this display had categories where there were no measurement data. This observation prepared the class for Ms. Summer's next discourse move because it drew students' attention to the marked-out sections.

4.3.2 Starting Their Journey: Does It Look Like They Made a Mistake?

Next, Ms. Summer highlighted a puzzle, "does it look like they made a mistake?", to start her students on the journey on the sensemaking pathway (Table 2-21).

Table 2-21

Sensemaking Step 1: Highlighting a Puzzle

Row	Speaker	Discourse	Code
5	Ms. S:	**So, does it look like they made a mistake?**	**Follow up Highlighting puzzle Asking to make a claim**
6	Mylah:	[Shakes head side to side, no]	
7	Celine:	*Mmmhmm* [shakes head up and down, yes]	*Makes a claim*
8	Mrs. S:	**Mylah says, No. Celine says, yes.**	**Marking**
9		**Do you think they put that there on purpose or on accident?**	**Highlighting puzzle Asking to make a claim**
10	Multiple	*On purpose.*	*Makes a claim*

	students:		
11	Ms. S:	**I hear on purpose.** Ray? [waits 10 seconds]	**Marking**
12		You stick it back up when it comes back to you. Okay, Justine?	
13	Justine:	*I think they did that on purpose.*	*Makes a claim*
14		*And it looks like they thought they were counting by tens and they started by, by the tens part where the lowest numbers were and where it was the last one.*	*Explains*
15	Ms. S:	**Thumbs up or thumbs down. You agree or disagree with Justine?** [several students put their thumbs up]	**Follow up** **Asking for consensus**
16		**Jay, what do you think?**	**Asking to make a claim**
17	Jay:	Uh. I don’t know.	
18	Mrs. S:	You don’t know. Ray?	
19	Ray:	*You don’t know what they’re measuring in. Like, what if they’re measuring in inches or something? Because it doesn’t have centimeters.*	*Makes an observation*
20	Ms. S:	So, science teachers, I’m sure you appreciated that. [teachers in room laugh]. **There are no centimeters on here. That is important.**	**Teacher revoices**
21	Leo:	*It almost looks like it was taped on, right here.*	*Makes an observation*
22	Ms. S:	**Maybe he ran out of paper or something**. I don’t know.	**Teacher explains**
23 **5:02**		**But so, we feel like he did it on purpose** [some students nod head for yes] And, were you saying something about, **Julia said he counted by 10 from the first number.**	**Teacher revoices**
24		**Look at his first number. 42. This is y'all's data**, okay. So, if you don't mind, **I'm going to stick this one up there like that for now.**	**Focusing discourse** **Changes topic**
25		**Alright. You have your notetaker out...**	**Changes topic**

Students responded to this TDM of highlighting a puzzle with opposing claims (rows 6, 7). Ms. Summer marked their contributions without evaluating them and repeated her question. In response, Justine then made a claim that the author of the display added those categories on purpose and explained her reasoning (row 13-14). Ms. Summer did not evaluate her ideas but continued the open-ended discourse by using the TDM of asking for consensus to visually check if students agreed or disagreed with Justine's claim (row 15). After two students made unrelated observations, Ms. Summer used the TDMs of revoicing and focusing discourse to summarize Justine's ideas. This SST episode ended when Ms. Summer changed the topic of the classroom discourse (row 25).

At this point, Ms. Summer did not evaluate Justine's claim or reasoning, and she left the question open as to whether it was on purpose or not (row 23). These TDMs supported the dialogic and interactive classroom discourse necessary for student sensemaking. These open questions, whether the author of the display left gaps where there were no measurements on purpose and why they chose to do so, reoccurred in subsequent classroom discourse and functioned as vexing questions (Odden & Russ, 2019b) to prolong students' sensemaking about the use and importance of using scale on data displays.

4.3.3 Prolonging Their Trip: Where Would They Put Their 42?

Ms. Summer and her students then discussed the data displays created by student groups. They talked about how certain displays allowed one to see the order of the measurements, their frequency, and how they were grouped or binned. After approximately 50 minutes of discussion, Ms. Summer returned to Nolan's data display (Figure 2-9). Nolan's data display was the only one that clearly showed the gap between 42 and the other measurements and thus indicated the scale of the measurements. Ms. Summer began this SST episode by asking a student to revoice the class's initial ideas (Table 2-22). This SST episode lasted approximately 3 min, and it includes the discourse segments in Table 2-22 through Table 2-24.

Table 2-22

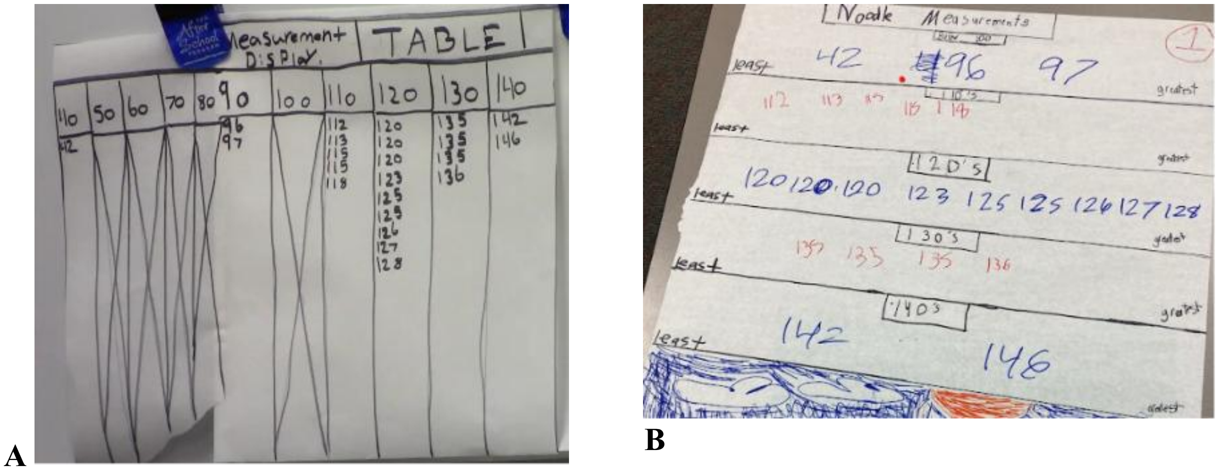
Sensemaking Step 2: Explaining Where to Put the 42

Row	Speaker	Discourse	Code
1 **55:53**	Ms. S:	Okay. We put one last one to look at right here. We, uh, **what did y'all say about this**? I'm having trouble remembering.	**Asking for student revoice**
2	Mylah:	*Oh, we said that: so, you had first pointed out that the 50, 60,70, and 80 were there, and you asked if they put it there on purpose. And Celine said no and I said yes. But then Justine pointed out why they put it on there on purpose*.	*Explains*
3	Ms. S:	So, we have talked about it. **What do you think about it? Important or not important?** (*Multiple students: Important*.)	**Asking for ideas** **Asking for opinion**
4		**Wasted space or a good use of space**? [Students talking over each other] (*Some students: good use of space. Some students: waste of space*)	**Asking for opinion**
5	Jay:	*They could have used so much space if they would have not used those columns.*	*Makes a claim*
6	Ms. S:	Okay, **where would they have put their 42?**	**Follow up** **Pressing** **Asking for explanation**
7	Jay:	*Well, they could have, like, just made a single column for it (*student: yeah*) Like they did. Instead of making different columns that aren't very useful.*	*Explains* *Gives alternative*
8	Ms. S:	Oh. **It is kinda like, kinda like what you did** [points to Jay's data display (Figure 10B)]**. You grouped the 42 with the 96.**	**Focusing Discourse**
9	Jay:	*Yeah! Yeah, they were, all of those were meant to be below 100.*	*Explains*

In response to Ms. Summer's TDM, Mylah accurately recounted the discussion that happened at the beginning of the lesson (row 2). Then, Ms. Summer shifted students from thinking about whether the display author used marked-out columns on purpose to thinking about whether the marked-out columns were an important choice, "a good use of space," or maybe a choice that "wasted space" (row 3-4). Jay responded by claiming that the marked-out columns were a waste of space (row 5). Ms. Summer did not evaluate his claim but instead pressed Jay for his reasoning by asking, “where would they put their 42?” This question was critical because it identified “42” as a measurement of importance. Nolan’s display was the only one to show any numerical gaps between measurements and thus it communicated information about their variability. All other student data displays in this class placed the measurement 42 next to 96. Jay responded by explaining his reasoning further (row 7). Like Mr. Trumbull, Ms. Summer did not evaluate Jay’s claim or explanation in order to support the dialogic discourse necessary for student sensemaking (row 6, 8). Then, she focused the class’s attention on Jay’s display and supported the students to make a comparison (Figure 2-10B).

Figure 2-10

Student Data Displays



Note. Nolan’s data display is in panel A and Jay’s data display is in panel B.

Next, Ms. Summer prolonged the students’ trip on the sensemaking pathway by using the TDM of pressing to critique Jay’s claim that 42 should be grouped with 96 (Table 2-23).

Table 2-23

Sensemaking: Critiquing the Explanation Part 1

Row	Speaker	Discourse	Code
11	Ms. S:	**Because this says** [pointing to data display, Figure 10B], **42 is kind of close to 96, just like 142 is kind of close to 146**.	**Focusing discourse** **Pressing**
12	Jay:	*Well, yeah, they're below a certain amount of numbers.*	*Explains*
13	Ms. S:	**Are they close to each other***?* (Another student*: not really*)	**Pressing**
14	Jay:	*Like. Like. Okay. So, here's 42.* [gestures with left hand] *Here's 40* [gestures with right hand]. *Here's 96*. [gestures farther with right hand] *So, they're, eeeh, this far apart*. [gestures widely with both hands.]	*Explains*
15	Ms. S:	**They are how far apart?**	**Pressing**
16	Jay:	*This far apart.* [gestures widely with both hands.]	*Explains*
17	Ms. S:	**Okay. So, do I need to show that they are far apart or not?** [some students in class laugh]	**Focusing discourse** **Pressing**
18	Jay:	*No! They're not exactly right next to each other, like,* [gestures smaller with both hands]	*Explains*
19	Ms. S:	**You have them right next to each other.**	**Pressing**
20	Jay:	*They're not, in a number scale, if you went from 1* [gestures with left hand] *to 96*, [gestures with right hand] t*hey're not close to each other.*[makes a sweeping gesture with right hand].	*Explains*
21	Ms. S:	**Oh, I see you leaving some gaps for them.** [gestures widely with hands] (*Jay: Yeah*)	**Teacher revoices**
22		**There's a distance in between them** [makes same gesture]	**Teacher revoices** **Pressing**
23	Jay:	*Yes, in between the two numbers.*	*Explains*
24	Ms. S:	**But we don't think that we need to show that? We think that 42 is as close to 96 as 142 is to 146.**	**Pressing**
25	Jay:	*If you, if you take all three of those numbers together* [makes a circle gesture with both hands] *and put them here,* [uses left hand and gestures above desk] *they're all below 100* [uses right hand and gestures high above desk] *so why not just put them in a group together?* [makes a circle gesture, midway above desk]	*Student Question* *Posing Alternative*
26		*Because they are all below a certain level.*	*Explains*
27	Ms. S:	**That is a choice you made, right?**	**Focusing discourse**
28	Jay:	*Yeah.*	

Ms. Summer began this discourse segment by using the TDM of focusing discourse to help students see that Jay's data display communicated that "42 is kind of close to 96, just like 142 is kind of close to 146." She made a series of pressing discourse moves to support Jay and the other students to see that there is a distance between 42 and the other numbers and it might be important to communicate that distance in a data display (rows 13-24). This series of pressing TDMs functioned as a critique of Jay's explanation and supported Jay to clearly articulate his thinking for the whole class. Jay responded by posing an alternative idea (row 25). Because most of the measurements were above 100, Jay grouped the three smaller measurements together, because they "are all below a certain level" (row 26). Instead of evaluating his response, Ms. Summer validated Jay's idea by saying it was a choice he made as the author of his display.

The SST episode continued as Ms. Summer asked students to imagine a different scenario to provide another reason for including gaps where there were no measurements and to further challenge Jay's idea that showing gaps on a data display was a waste of space (Table 2-24).

Table 2-24

Sensemaking: Critiquing the Explanation Part 2

Row	Speaker	Discourse	Code
29	Ms. S:	Okay, and remember, we said, **Gregory came in and measured 102, where would that go on yours?**	**Pressing** **Asking what if**
30	Jay:	*Well, we didn't measure one that was just for 100.*	*Explains*
31	Ms. S:	**Should you have?**	**Pressing**
32	Jay:	*We didn't have a reason to. There wasn't one there.*	*Explains*
33	Ms. S:	Okay.	

34	Jay:	*We didn't have one below 110 and above 100.* [gestures with hands]	*Explains*
35 **58:31**	Ms. S:	Okay, **Do y'all want me to keep pushing on Jay?** (*students: yes!*)...	**No follow up**
36		**Could I have put that, could I have put Gregory's new measurement on Wilson's** [points to data display],	**Closed question**
37	Student:	Yeah.	
38	Ms. S:	**Because of what he called his groups, right**?	**Closed question**
39		**Can I put it on this one** [points to another data display]**? If Graham measured 105, is there room for it on here?**	**Closed question**
40		**Let's talk about 42.**	**Changes topic**

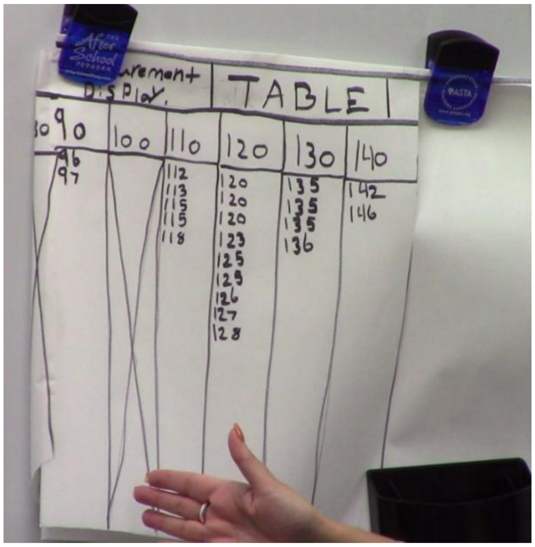
Here, Ms. Summer shifted the students' thinking from showing the distance between measurements on data displays to thinking about using gaps as a means to hold a place for future measurements by asking them to imagine a new student with a new measurement to add to the class data. Jay continued to claim there was no reason to use gaps, but Ms. Summer did not explicitly evaluate his claim (row 33). Then, she used closed questions to compare Jay's display with two others, and these closed questions ended the SST episode.

This TDM of asking what if prolonged students' trip on the pathway of sensemaking because it helped students imagine another reason why including gaps between numbers could be useful. Although Ms. Summer used closed questions to end this SST episode, those questions helped students make comparisons across the students' data displays.

The class then talked for ten minutes about the outlier of 42 and why it may have occurred. Ms. Summer returned to Nolan's data display for a final time, and folded part of it back to exclude the outlier (Figure 2-11). This is the third SST episode discussing the gaps shown on Nolan's data display and it lasted approximately 1 min 30 s. Ms. Summer began focusing the students' attention on the data display with the outlier removed (Table 2-25).

Figure 2-11

Nolan's Modified Data Display



urement Display. TABLE

90	100	110	120	130	140
96 97		112 113 115 115 118	120 120 120 123 125 129 126 127 128	135 135 135 136	142 146

Table 2-25

Sensemaking Step 1: Imagining a Different Scenario

Row	Speaker	Discourse	Code
1 **69:56**	Ms. S:	But how about now [shows data display with one side folded back (Figure 11)] **How about now when I took the 42 out of this data set?**	**Asking what if**
2		**Nolan still did some things that the rest of us didn't do**. Ray?	**Asking for observations** **Asking for comparison**
3	Ray:	*He still put the 90s together and then closed off the 100s since there's no 100s. And then, so you can tell that 90 is a little bit farther away from that.*	*Makes an observation* *Makes a claim*
4	Ms. S:	**Yeah, he left, he left the gap for the hundreds.**	**Teacher revoices**
5		**If, like, if we combined class data from like B block, maybe they did have some in the hundreds. See that.**	**Asking what if**
6		**How do you feel about that? Do you think it's important that we leave a place to hold the 100s that might have been later or the 80s?**	**Asking for opinion**

7		**Where do you think Nolan would have started if there hadn't been a 42**	**Asking what if**
8	Multiple students:	*With the 90s. He would have just started with the 90s.*	*Makes a claim*
9	Mylah:	*He wouldn't have had that many boxes about the, in between the [unintelligible]*	*Makes a claim*
10	Jay:	*He still would have had the 100s*	*Makes a claim*
11	Ms. S:	**So, thumbs up or thumbs down. It's important to leave gaps or not important?**	**Asking for opinion** **Closed question**
12	Students:	*Not important* (*other students: important*)	*Makes a claim*
13	Student:	*It's in between.*	
14	Ms. S:	**We're still at a so-so?**	**Closed question**
15 **71:28**		**Is it so-so, because it's distracting to see all this empty space? Is it distracting you?**	**Closed question**
16	Students:	Yes	
17	Jay:	*It's wasteful of paper.*	*Makes a claim*
18	Ms. S:	**Okay, that's the goal is to distract you. That's the goal for this to say: Hey, I'm sticking out here. No friends.**	**Teacher explains**

Here, Ms. Summer sustained the sensemaking process by asking students to imagine a different scenario: what if they took the outlier of 42 out of the data set? Then, she asked them to compare that modified data display with the other displays in the room. Ray responded by observing that Nolan grouped the 90s together and left a space for the 100s. He claimed that showing this gap on the modified data display indicated the distance between the measurements (row 3). Ms. Summer revoiced Ray's observation for the class and then used the TDM of asking what if again by having the students to imagine they combined their data with another class. She used the TDM of asking what if a third time and asked the students to imagine where Nolan would have started if there had not been a measurement of 42.

By asking students to imagine these different scenarios, Ms. Summer helped her students test the connections of their collective explanation for Nolan's gaps in between numbers. Ray connected the gap between numbers with the data display communicating the distance between numbers (row 3), and multiple students voiced their understanding that the low measurement of 42 necessitated the gap (rows 8-9); however, some students continued to think it was not important to leave gaps (rows 12-13, 17). Ms. Summer ended this SST episode by asserting her epistemic authority and explaining the importance of leaving a gap for the outlier of 42.

4.3.4 End of Their Journey: We Literally Just Explained This

The final SST episode from Ms. Summer's class illustrates how, for at least some students, the use of gaps made sense, and they reached the end of the sensemaking journey. It occurred on the following day when Ms. Summer asked a few students how many hours they had slept the previous night to create a small data set, and then she asked each group of students to draw a data display on their table using that data. She did not give any further instructions about how they should draw it.

After a few minutes, she asked the class to gather around one group's data display. This SST episode began by Ms. Summer by asking for student observations, "I need one notice," about the student's display. The class spent a few minutes sharing what they noticed. Table 2-26 shows the discourse segment near the end of this SST episode.

Ms. Summer began this discourse segment by recreating another student's data display so that her students could make a comparison between one that showed the gaps in between data points and one that did not.

Table 2-26

Sensemaking Step 3: Possible Resolution

Row	Speaker	Discourse	Code
26 **53:21**	Ms. S:	**I saw this.** [writes on desk]	**Focusing discourse**
27	Jay:	*That's what Leo's was.*	*Makes an observation*

28	Wilson:	*Yeah, that's what Leo wrote*	*Makes an observation*
29	Leo:	*We did all the numbers in between including like 5, 6, 7, 8, 9, 10.*	*Explains*
30	Ms. S:	**How is this different than that?** [pointing to the display she wrote and a group's display]	**Asking for observations** **Asking for comparison**
31	Students:	[Several students talking at once].	
32	Jay	*You are just showing the numbers that are there. Like, you're just showing the numbers, not the numbers in between.*	*Explains*
33	Ms. S:	Okay. **Did I ask everyone how long they slept?**	**Focusing discourse**
34	Jay	*No, not everyone. You only asked certain people.*	*Explains*
35	Ms. S:	Yeah, my sample size was kind of small. **But what if, now I asked Bonnie, how long did she, did you sleep? And she said, 6.**	**Asking what if**
36		**What are you going to do? Start completely over?**	**Pressing**
37	Jay	*No, you have to write 6 in between those.*	*Makes a claim*
38	Ms. S:	**But isn't it helpful that they're the same size, that I can see that it's more?**	**Follow up** **Pressing**
39	Wilson:	*I mean, if you ask that, we already have this already [points to data display written on desk] And if you ask that all we have to do is (Jay: But that's why, but that's why)*	*Makes a claim*
40	Ms. S:	**You just put a check mark there.**	**Pressing**
41	Jay	*That's why you're supposed to, like, write it. That way you don't have to go back to the teacher and do it more.*	*Explains*
42	Ms. S:	**But did you?**	**Pressing**
43	Jay	No.	
44	Ms. S:	**Do you think you might remember to do that next time?**	**Closed question**
45	Jay	*Well, I mean, we would do it if we have the numbers.*	*Makes a claim*
46	Ms. S:	**Only if you had the numbers?**	**Teacher revoices**
47	Jay	Yeah.	
48	Ms. S:	**You wouldn't show that nobody slept for six hours?**	**Pressing**
49	Jay:	*No, because it's a waste of space.*	*Explains*
50	Wilson:	*Dude. We literally just explained this. If she* [Ms. S] *asks her* [Bonnie] *when we're already done, and she says 6, we don't have to restart.*	*Gives alternative* *Explains*

		She just reaches to that [points to data display on desk] *and checks it.*	
51 **55:07**	Ms. S:	Okay, but, **I don't think none or zero gets enough credit in this world. I think it's okay that we show no one slept for six hours tonight.**	**Focusing discourse**
52		**Tonight, could you sleep for six hours?** (students: yeah)	**Asking for prediction** **Closed question**
		Yeah? Me too.	
53		**Yeah, and then we would have a spot to put that, right?**	**Closed question**
54		**What did y'all call this yesterday?**	**Changes topic**

Leo responded by explaining that he included all the numbers in between the first data point and the next on his data display (row 29). This provides evidence that, for Leo, creating gaps on his data display where there were no measurements made sense to him because he chose to include them in his data display. Ms. Summer then emphasized his explanation by asking the whole class to share their observations on the differences between the two data displays. Jay explained that, unlike Leo's, the other display "just showed the numbers that are there."

Next, Ms. Summers asked the students to imagine a scenario where new data was generated (row 35), similar to an example Ms. Summers had used on the previous day (row 29, Table 2-24). Jay continued to claim that he would only use the data given in the data set because doing otherwise wasted space (row 49) as Ms. Summers used several pressing moves for him to articulate his thinking. For Jay, the connection between leaving gaps on a data display because one could add subsequent data later on still did not make sense. Another student, however, critiqued Jay's explanation and gave an alternative explanation (row 50). This discourse provides evidence that for Wilson the connection between using gaps as a means to hold a place for future data made sense.

This vignette illustrates the dynamism and complexity of classroom sensemaking. Ms. Summers and her students entered and exited the pathway of sensemaking about using scale on a data display several times over a 90-minute lesson, and they returned to the sensemaking pathway again on the following day.

Next, we present a final SST episode to provide further evidence that, for at least another student in Ms. Summer's class, using gaps on a data display made sense (Table 2-27). This SST episode occurred five months later in Mr. Houston's science class. In this discourse segment, the students in Mr. Houston's class were directing the researcher to arrange their plant height measurements into a data display. Mylah, from Ms. Summer's class, used prior knowledge from her mathematics class to make sense of creating a gap where there were no height measurements.

Earlier in this SST episode, students had suggested the researcher re-arrange the plant height measurements in bins of five. The researcher began this discourse segment by highlighting a puzzle: what should they do when a bin has no plant height measurements?

Table 2-27

Sensemaking Step 3: Possible Resolution

Row	Speaker	Discourse	Code
7 **27:22**	Researcher:	**And then I don't have anything from 25. I'm sorry, 26 up to 30**. (student: So, you skip that column.) **But I have a 30 and a half.**	**Focusing discourse** **Highlighting a puzzle**
8		**So, tell me where to put this.**	**Asking for ideas**
9	Students:	[students talking over each other]. *You could... Maybe make a column...*[unintelligible]	*Brainstorming*
10	Student 1:	*If there was one that could be between 26 to 30, leave a space for that, and put that one there*	*Explains*
11	Researcher:	Okay, **so you're saying I should not put it here? That I should leave a space even though I don't have anything there**? [gestures to board]	**Teacher revoices**

12	Student 1:	Yeah.	
13	Researcher:	**Is that okay?**	**Asking for consensus**
14	Students:	Yeah. Yes.	
15	Student 2:	*In that case, it's an outlier.*	*Makes a claim* *Makes a connection*
16	Researcher:	Now, **why, why is it important for me to leave that space?** Because I don't have any measurements there?	**Asking for explanation**
17	Student 1:	*It's because if you had that there it wouldn't truly go there, because it's 26-30, not 26-35.*	*Explains*
18	Researcher:	**Any other thoughts about why this gap needs to be here?**	**Asking for ideas**
19		**What does that help us see?**	**Asking for explanation**
20 **28:22**	Mylah:	*And, if, like, between the 30 and the 20, if there ends up being a number in between those, we can place it there.*	*Explains*
21	Researcher:	**So, if we had another plant that, or if we measured it again, and some of these other ones grew a little taller or something like that.**	**Teacher explains**

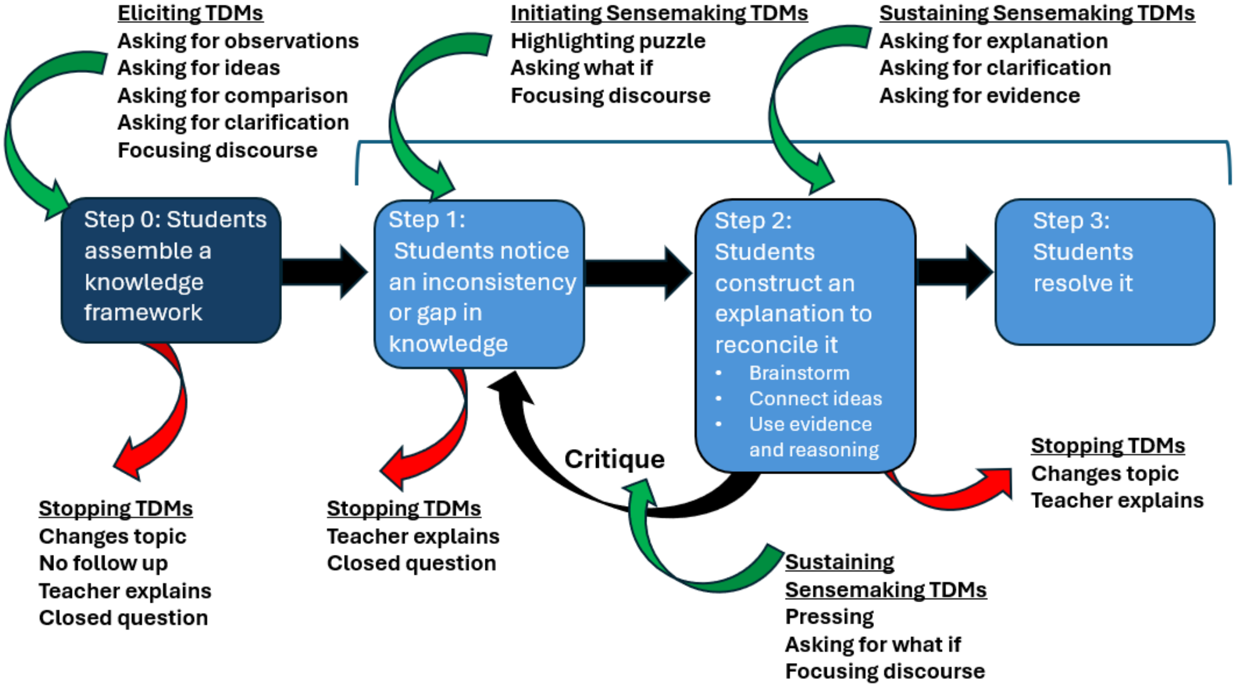
Several students responded with their ideas about leaving a gap for the empty bin (rows 7, 9, 10). The researcher then asked students to explain why that was important. One student gave a concrete reason for leaving a gap for the empty bin (row 17). The researcher did not evaluate the students' discourse but continued to ask them for their ideas. Mylah, from Ms. Summers' class, explained that the empty bin was a means to hold a place for future plant height measurements (row 20). Her discourse provides additional evidence that traveling the entire sensemaking pathway with Ms. Summers resulted in Mylah making sense of why leaving gaps on a data display was important.

Across the data corpus, sustaining sensemaking TDMs guided students to develop their explanations and notice gaps or inconsistencies in them. The TDMs of asking for explanation, asking for clarification, and asking for evidence supported students to develop their explanations.

If a critique occurred, the teacher used the TDMs of pressing, asking what if, and focusing discourse to challenge students' ideas. (Figure 2-12).

Figure 2-12

Prolonging Their Trip: Eliciting, Initiating, and Sustaining Sensemaking TDMs



Note. This figure illustrates the process of sensemaking (Odden & Russ, 2018). The green arrows indicate the teacher discourse moves from across the data corpus used to support students to engage in the steps of the sensemaking process. The red arrows indicate the teacher discourse moves from across the data corpus used to end student sensemaking talk.

5. Discussion and Implications

In this study, we sought to understand how experienced mathematics and science teachers used TDMs to initiate and sustain the process of sensemaking about data in whole-class discussions. We found that students engaged in sensemaking talk in all four mathematics and science classrooms, and there were three ways these expert teachers used TDMs to support students to travel the sensemaking pathway. Eliciting TDMs guided students to collectively share their observations and thinking, i.e., to *pack their bags* for sensemaking. In those episodes in which students *started their journey* into the sensemaking process, the initiating TDMs of highlighting something puzzling for students and asking students to imagine a different scenario invited students to enter the sensemaking frame and students began brainstorming their ideas. Finally, TDMs sustained sensemaking by asking students to develop explanations and challenging students to notice gaps or inconsistencies in them, i.e., *prolonging their trip*.

We also wondered how TDMs stopped the sensemaking process for students. Students' sensemaking talk stopped when TDMs functioned to invite only a brief response, i.e., a closed question, change the topic of discourse, or switch to more authoritative classroom discourse, i.e., the TDM of teacher explains. Although these TDMs temporarily halted SST, at times teachers used TDMs to initiate SST again, as seen in the second and third vignettes. The steps of the sensemaking process were not always temporally linear in the classroom discourse.

For the remainder of this section, we discuss three main takeaways from our analysis. First, eliciting TDMs, e.g., "what do you notice" or "any thoughts," supported students to verbalize their ideas and observations as a shared knowledge framework. This finding is not surprising because many practitioner resources for science and mathematics teachers emphasize the importance of using teacher talk to surface student thinking, e.g. Michaels & O'Connor, 2012; Stein et al., 2008; Windschitl et al., 2018. Second, all four teachers used initiating sensemaking TDMs, e.g., "is my arm span both 12 and 263 cm," to invite students to figure something out that originated from a student contribution. This type of discourse move established a need for making sense of the observations or ideas students contributed (Leatham et al., 2022) and framed the purpose of students' classroom discourse as making sense of something. Third, TDMs often stopped the sensemaking process at various points, but sometimes teachers and students re-entered the process later on in the classroom discourse. Steps of the sensemaking process were not linear in the classroom discourse but were organized around making progress on an idea. We end this section with some possible limitations of our study.

5.1 TDMs Guided Students to Create a Shared Knowledge Framework

Probing for student thinking, clarifying student contributions, and restating or revoicing their ideas are discourse moves associated with sensemaking in the literature (Herbel-Eisenmann et al., 2013; Lowell et al., 2022; Windschitl et al., 2018). We found that these discourse moves were used by the expert teachers in this study, and we argue that these eliciting TDMs guided students to create a shared knowledge framework composed of their observations and prior knowledge that had the potential to be used in the sensemaking process. For example, Mr. Trumbull's classroom discourse used TDMs to strategically invite students to share their observations of the data and their prior experiences with terms like "the meh," range, and average. As he elicited these ideas, he asked students to clarify them so that there could be a shared classroom understanding of students' contributions. Both Mr. Trumbull and Ms. Summer then used a student's observation from this shared knowledge framework to support students to begin the sensemaking process.

One common eliciting TDM was asking students to share what they noticed about their data or the phenomena, e.g., differences in plant growth. This discourse move occurred in all three of the vignettes presented here and in multiple SST episodes in all four teacher's classrooms. Using the eliciting TDM of "what do you notice," often in conjunction with "what do you wonder," is becoming a common instructional strategy to support sensemaking in middle school mathematics classrooms (Rumack & Huinker, 2019). These open-ended TDMs positioned students as creators of the class's shared knowledge framework, and they supported the dialogic and interactional discourse (Lowell et al., 2022; Scott et al., 2006) necessary for collective sensemaking.

Additionally, the teacher can anticipate the students' observations and responses surfaced through the TDMs of asking students to notice and wonder. Teachers can select instructional objects to support students' engagement in the sensemaking process (Rumack & Huinker, 2019). We argue this occurred in Ms. Summer's classroom when she brought in a student's data display from a different class and asked students to share what they noticed about Nolan's data display, the only one that displayed the mathematical quality of scale. Her students verbalized their observations about data display and created a knowledge framework, and then Ms. Summer leveraged their observations to support them to enter into the sensemaking process to figure out what using scale on a data display communicated.

The observations and ideas surfaced by these eliciting TDMs sometimes remained unconnected to subsequent discourse. For example, in Mr. Houston's vignette, students shared observations about several important differences in plant growth: the shape of the growth, the height of the plants, the proximity of the plants, and the rate of plant growth, but then they moved on to the next activity without working with these ideas. In this SST episode, students created a shared knowledge framework with these observations, but the shared knowledge framework was not utilized further. These isolated SST episodes, in terms of their idea work, occurred in all the classrooms in this study. This finding is consistent with other work that suggests teachers use TDMs to support students to share and, perhaps, clarify their ideas, but do not use subsequent TDMs to build on and critique those ideas (Berland and Hammer, 2012; Harris et al., 2012; Lowell et al., 2022).

5.2 TDMs Invited Students to Figure Something Out or Imagine an Alternative

All teachers used TDMs to highlight an inconsistency or something puzzling in the shared knowledge framework of the class. These initiating sensemaking TDMs functioned to invite students to enter the sensemaking process and be in the frame of figuring something out. They signaled to the class that something strange is going on and positioned the students as the ones who will figure it out. This framing is important because it expands sensemaking opportunities for the class so that all students can participate in brainstorming and contribute their ideas in the classroom discourse (Schwarz et al., 2021). For example, in response to Mr. Trumble's initiating sensemaking TDM, ten different students contributed to the classroom discourse and had their ideas recorded as valuable contributions (see section 4.2.2)

Initiating sensemaking TDMs also positioned students to make progress on important disciplinary ideas. Leatham et al. (2022) characterized the types of discourse moves that initiate student sensemaking as grapple tosses. Grapple tosses function to explicitly reveal a collective need for students to make sense of something from the classroom discourse with the instructional goal of connecting it to an important disciplinary idea. In Mr. Trumble's vignette, he used a student's observation that the values for his arm span included 12 and 263 and explicitly revealed a need for the students to figure out this large range by saying "something is weird here because they should be the same. My arm span has a length to it" (Table 2-16, row 2**).** From his subsequent classroom discourse, we argue that his instructional goal was for students to engage in the statistical practice of characterizing variability**.** Likewise, Ms. Summers used a student's observation that certain columns were marked on a data display and made explicit the need to figure out if “they put that there on purpose or on accident” (Table 2-21, row 9) and the reasons for why they did so. From Ms. Summer’s actions and discourse, we argue that her instructional goal was for her students to discuss how the quality of scale communicated something on a data display. In both teachers’ classrooms, initiating TDMs positioned students as the ones who were generating ideas to make progress on these ideas.

5.3 TDMs Supported a Non-Linear Sensemaking Process in Classroom Discourse

In this study, TDMs guided students to enter, exit, and re-enter the sensemaking pathway. This was seen in Ms. Summer’s classroom as the class returned to making sense of using gaps on Nolan’s data display repeatedly across the lesson. Instances of students’ sensemaking talk were non-sequential but were related by the topic of making sense of scale across the lesson. Schwarz et al. (2021) called these instances in the classroom discourse sensemaking moments. Like our study, they found that non-sequential student sensemaking moments were sometimes linked together across the lesson by students’ work on an idea or related ideas.

Both our work and the work of Schwarz et al. (2021) illustrate the complexity and opportunity for teachers supporting students to engage in the sensemaking process. Students’ sensemaking talk is dynamic. It stops suddenly when TDMs such as closed questions or authoritative discourse shift the discourse context away from being open and dialogic. Students can, however, return to the sensemaking pathway and resume making progress on disciplinary ideas.

Viewing sensemaking as a process with discrete observable steps is a productive lens to study the complexities of how TDMs function to support student sensemaking in whole class discussions. This lens allowed us to explore the TDMs teachers used at different steps of the sensemaking process. The next step in this research would be to understand how to support pre-service or beginning teachers to learn how to use TDMs to transition from one step to another. Teachers often use TDMs to elicit students' thinking but find it challenging to work with students' discourse contributions to make progress on ideas (Harris et al., 2012; Lowell et al., 2022; Schwarz et al., 2021). Professional development or teacher education materials focused on the steps of the sensemaking process and the associated TDMs may help break down this complex teaching practice and help beginning teachers view sensemaking as a process to work through with their students.

Another implication of this work is teachers' use of the TDM of focusing discourse in many of the steps of the sensemaking process. This TDM supported students to pay attention to some aspect of the data or phenomenon. We suspect that focusing discourse was perhaps too coarse of a code, and thus future work could examine whether there are nuances to how teachers use discourse moves to help students see important features of the data or phenomenon.

5.4 Limitations

The findings in this study described the discourse practices of a small number of experienced middle school mathematics and science teachers. We intended to give the reader a realistic account of how these teachers used discourse moves to support their students' sensemaking talk and engagement in the sensemaking process, but we acknowledge these findings cannot be generalized beyond these teachers and students. Other teachers and those in instructional contexts different from data investigations may support students to engage in the sensemaking process using TDMs not discussed here.

Another limitation of this study is that we did not know the instructional goals teachers had for their discourse moves. We were unable to interview teachers or have them review the videos of their lessons. Future work would include interviewing teachers or using stimulated video recall to understand what teachers intended with their discourse moves and how they expected their students to respond.

6. Conclusion

In this study, teachers' eliciting discourse moves supported students to make public their ideas and observations during data investigations. These discourse moves are important because they help students to collectively know what they know about their data and its context. This shared knowledge framework has the potential to be used by students as they engage in the sensemaking process. For example, in this study, teachers used the students’ ideas and observations as a basis to point out gaps or inconsistencies in understanding. These initiating discourse moves highlighted a puzzle or asked students to imagine a what if scenario, and they provided opportunities for students to enter into the process of sensemaking and begin generating explanations. To sustain the sensemaking process, teachers used discourse moves to support students to develop their explanations and challenge them to notice gaps or inconsistencies. These findings suggest that highlighting a puzzle for students or asking them to imagine a different scenario are important discourse moves to initiate student sensemaking because they establish a need for students to make sense of the observations or ideas students contributed.

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Appendix 2-A

Table 2A- 1

Codebook for Teacher Discourse Moves to Initiate and Support Sensemaking

Teacher Discourse Move Code	Action teacher makes to participate in or guide classroom discourse	Examples	Connection to TDMs and Sensemaking Literature
Deductive codes:			
Asking for ideas	Makes a general request for students to express their thinking	"What were some things we did?" "Any thoughts?"	Probing for thinking (Herbel-Eisenmann et al., 2013; Windschitl et al., 2018), Eliciting student ideas (Carpenter et al., 2020)
Asking for observations	Requests students share what they notice or what they see	"What did you notice?" "What do you all see that goes in there?"	Probing for thinking (Windschitl et al., 2018), Explication questions (Benedict-Chambers et al., 2017)
Asking for comparison	Asks students to make a claim about similarities/differences	"Let's take a look at this one. Similar or totally different?" "Which ones [data displays] jump out and help us see which measurements are very far away?"	Probing for thinking (Herbel-Eisenmann et al., 2013; Windschitl et al., 2018)
Asking to make a claim	Asks students to make a statement the student thinks is true	"Does it look like they made a mistake?" "Do you have any hypotheses why it died?"	Probing for thinking (Herbel-Eisenmann et al., 2013; Windschitl et al., 2018)
Pressing	Challenges some aspect of student's discourse by asking for examples, evidence, or how to test a claim	"Be more specific. Why did they do what?" "I guess what I'm asking is: how do you know it's too low?"	(Michaels & O'Connor, 2012; Tytler & Aranda, 2015; Windschitl et al., 2018)

Asking for evidence	Asks students to reference the data, phenomenon, or data display to explain their thinking	“What makes you say that when you look at this display?” “So, where do you think it might be? Come show me.”	(Michaels & O’Connor, 2012; Tytler & Aranda, 2015; Windschitl et al., 2018)
Teacher revoices	Rephrases a student’s contribution. May add disciplinary language	“You’re saying, if we were to graph them, that this section here, would be like [this].” “Zero to 30 centimeters ? We might have a range that we might give them.”	Revoicing (Herbel-Eisenmann et al., 2013; Windschitl et al., 2018)
Marking	Repeats what a student has said to emphasize it or for the whole class to hear	“Okay. Gregory noticed that there is a number line on it” Student: “Maybe they didn’t follow the planting directions right.” Mr. Houston: “They didn’t follow the planting directions, possibly.”	Marking (Tytler & Aranda, 2015)
Asking for student revoice	Asks another to student to restate student’s discourse	“What do you think Michael means by that?” “Can someone summarize what Danny just said? How do we read this stem and leaf situation here?	Revoicing (Herbel-Eisenmann; 2013)
Follow up	Teacher discourse closely related to what a student just said, often overlaps with other codes	Student: “I think it would be bigger.” Ms. Summer: “Bigger. What would cause our numbers to be bigger	Follow up (Windschitl et al., 2018)

		than what the length actually is.”	
Asking for clarification	Asks student to provide more information or interpretation so that it is clear what the student meant	“What do you mean by that-most common number?” “Did all of them do that [bend toward the light]?”	Requesting clarification (Tytler & Aranda, 2015; Lowell et al., 2022)
Asking to add on	Asks students to engage with another student’s discourse	“There’s another measure of center, right? What’s the other one?” “Help him out. What were we saying about that?”	Add on (Michaels & O’Connor, 2012)
Inductive codes:			
Asking for prediction	Asks students to make a prediction	“What do you think their measurements are going to look like?” “Anybody think it could be smaller?”	
Asking what if	Asks students to imagine another possibility	“What if I had you guys measure again with the same instructions and same tool? What would happen? If Dora jumps again and she gets 20 jumps, where does the 20 go?	
Asking to make a connection	Requests students to share prior ideas talked about in class or from across school disciplines	“Imagine a plant that was right under the light and one right on the edge. Where do you think they would fall in the data up here? “What would you say another way to look at it? Another measure of center?” [science teacher]	
Asking for consensus	Asks whole class if they all agree or disagree with what a student or teacher has said	“Is everyone okay with that, if I start to order it?” “Would you agree with that?”	
Asking for opinion	Asks students what they think about an idea a student has proposed using informal language	“How do y’all feel about that? Do you like it or not?” “We have an idea to group them by tens. Any thoughts on that?”	
Highlighting puzzle	Asks students about something that may be unusual, or confusing,	“Ohhh, because before we said that these were outliers [pointing to the larger numbers]. Now Sky is saying, well, maybe the bottom ones are the outliers [pointing to the smaller number].”	

	or that doesn't make sense	"Actually my average falls in the three range, and no one said three, right? But the average, if we use mean, is three."
Focusing discourse	Teacher discourse that supports students to understand what the teacher is asking or that highlights some aspect of the data, problem, or phenomenon	"Right. So that's what I'm saying. When I look up there, the 42 and the 96 look pretty close to the 110." "They called this column 120 and they said half the data is in this column. Do you see that, what Madeline is talking about?"

Table 2A- 2

Codebook for Student Discourse During SST Episodes

Student Discourse Code	Action the student takes to participate in classroom discourse	Examples
Makes an observation	Makes a statement about something the student sees about the data, data display, or phenomenon	"She put it from least to greatest." "My [plant's] leaves kind of looked white"
Makes a claim	Makes a statement about something the student thinks is true.	"Sometimes the plants didn't get as much light as other plants." "It [stem and leaf plot] really easily shows least to greatest.
Explains	Talks about why or how something occurs or why they are making a claim	"Because we had so many of these containers in one area, it was hard to squish them all in." "Because then, if you had like 20, it could go in either one."
Gives evidence	Talks about the data, data display or phenomenon in support of a claim	"Fewer people got in the 40s than in the 100s." "It's kind of difficult because we have 2 modes. There's two [plants] that grew 8 [cm] and there's two that grew 15 [cm].
Gives an alternative	Talks about an alternative idea to	Researcher: "I've got a bunch of zeroes. What do I do with these? Should I put them up in order here?

	either the teacher’s discourse or another student’s discourse	Student: “No, you should stack them up.” Student 1: “It more common to get 21 [cm for plant height]. Student 2: “Yeah, but most of the plants are smaller too so you have to average it.”
Brainstorming	Multiple students speaking at the same time to share ideas	Ms. Summer: “Why didn't I just have one person measure and trust that answer? Student 1: “Because you, he or she could have gotten it wrong”, Student 2: “Because we're different, yeah,” Student 3: “All of our brains work differently”, Student 4: “Everybody has a different length that they got. Or some people could have gotten the same.”
Makes a comparison	References two or more ideas, data displays, or processes in their discourse	“I kind of think it is a mixture between me and their group, then those two, because those two put it in a group, but our group put it least to greatest, from least number in the group to the greatest number in the group.”
Makes a connection	Makes a connection between idea and another discipline’s idea	[in science class] “We could use median and mean.” [in science class] “You could do one of those little charts. I know they're called something, where like, how many there are, are like stacked, a bar chart?
Adds on to an idea	Relates their discourse to previous student discourse, provides more details or explanation	Student 1: “Kind of adding on to that. When you [Mr. Trumbull] were like reaching.” Student 2: “Yeah, you could have stretched out differently” Student 1: “So, instead of a value is like 14 through 16, not 14.” Student 2: “I see it like there’s a normal frequency and then there’s binned frequency. And if they have bins, it’s not going to be like the normal frequency on their graph.”
Connects phenomenon	Connects the phenomenon under investigation with a disciplinary idea or practice	“Since you weren’t staying perfectly still, it could have changed the measurements. The way you had your arms.” “I think it can be smaller because they could, like, they could line up their noodle and ruler incorrectly, and so like the noodle could end up like right here [gestures with hands] and so, like it could be smaller.”

Highlights a puzzle	Indicates something confuses or puzzles them. Asks why something occurred	“Why did they put multiplication?”[referring to a student data display] “I noticed that they, I couldn’t really tell what they were saying from over a hundred and less than 130” [referring to a student data display]

Table 2A- 3

Codebook for Teacher Discourse Moves Ending SST Episodes

Teacher Discourse Move Code	Action teacher makes to guide classroom discourse	Example
Closed question	Asks for a yes or no response, or a factual response	“Can I quickly look at this and tell how many 135s there are?” “Did all plants grow in the same way?”
Changes topic	Switches the topic of classroom discourse from what students are talking about to a new topic	Student: “I see it like there’s a normal frequency and then there’s binned frequency. And if they have bins, it’s not going to be like the normal frequency on their graph.” Mr. Trumble: “I think that’s a good way of thinking about it. So, here’s what I’m going to do. I’m going to pass back several graded papers.”
Teacher explains	Provides explanation before students verbalize their ideas	Ms. Montgomery: “What did you notice?” Student: “Some grew taller than others.” Ms. Montgomery: “Some grew taller than others. If you look at, you know, this plant right here, we have a really tall one, really well developed lots of seed pods. And then we have one that did not do very well at all. So, if you're thinking about the question, How tall do Wisconsin fast plants grow? We're gonna have to look at a lot of plants, right? To try to figure out if you are going to answer that question. You can't just go off of one piece of data, right? Do we think all plants are growing and changing in the same way? No, they grow differently don’t they?”
No follow up	Does not take up idea in student’s discourse	Ms. Summer: “Somebody got what [as their measurement]?” Student: “42. It was probably inches.

		Ms. Summer: “Maybe.” [calls on another student]
No response from students	Gives wait time and no one answers. Repeats question or asks it in a different way and students do not respond	“Where does that [making food for plant] happen?” [waits 6 seconds] “Where does photosynthesis happen?” [waits 2 seconds] “Does it happen in the flower, the seed pods, the stem, or the leaves?” [waits 7 seconds] “What do plants have that make them green?”
Evaluates student discourse	Marks student’s idea as “good” or correct	“Okay. Some of the leaves were real wilty. Good.” “I like that thought.”

Chapter 3 The Sensemaking Integrated STEM Framework: Addressing the "When" and "How" of Integrated STEM

ABSTRACT: Integrated STEM activities, e.g., engineering design challenges, model-eliciting activities, data investigations, have become commonplace in K-12 science and mathematics classrooms. In this conceptual paper, I describe some of the typical frameworks used to design integrated STEM activities. I argue that these frameworks are problematic because they describe *what* disciplinary knowledge and skills students use, but not *how* students generate knowledge using them and make sense of the connections among them. I then describe my new framework, the Sensemaking Integrated STEM Framework, that focuses on student thinking; specifically addressing how students generate knowledge resources during integrated STEM activities across instructional time and how students connect their knowledge resources as they make sense of integrated STEM problems. As a research lens, this new framework for integrated STEM allows the exploration of new questions about how and when students engage in disciplinary thinking as they experience integrated STEM activities

1. Introduction

Although integrated STEM activities have become commonplace in K-12 classrooms (McComas & Burgin, 2020; Moore et al., 2020), the question of what exactly integrated STEM is remains difficult to conceptualize, with a number of frameworks used to describe it (Dare et al., 2022; English, 2016; Moore et al., 2020; Roehrig, Dare, Ellis, & Ring-Whalen, 2021; Sgro et al., 2020). This lack of consensus makes it difficult to understand how to support integrated STEM teachers' development of successful teaching strategies (Dare et al., 2022; Honey et al., 2014).

Many of these integrated STEM frameworks focus on the disciplinary knowledge and practices students need to know (Moore et al., 2020). Integrated STEM is frequently conceptualized as an interaction among disciplinary knowledge and practices during STEM activities (Tytler et al., 2021). These framings focus on what disciplinary ideas students will use or learn from each STEM discipline as students experience the integrated STEM activity, and these frameworks are often used as a lens to develop curricula for teachers and students. Because they focus on what students will learn, these discipline-centered ways of conceptualizing integrated STEM may hide how students develop their understandings or engage in the creation of approximations of disciplinary practice. In fact, little is known about how teachers support students in making sense of ideas and practices from multiple disciplines during integrated STEM activities (Honey et al., 2014; Roehrig, Dare, Ellis, & Ring-Whalen, 2021). Thus, the knowledge of student thinking necessary for developing productive teaching strategies in integrated STEM education may be underexplored when using these discipline-centered framings.

In this paper, I argue that a new student-centered framework for integrated STEM is necessary to understand and develop teachers' integrated STEM teaching strategies so that researchers and practitioners can explore how and when students are thinking about disciplinary concepts and practices as they make sense of STEM problems. Viewing integrated STEM from a student-centered perspective, instead of a discipline-centered one, allows the investigation of new questions about the development of productive teaching strategies for teachers to use during integrated STEM activities. For example, how do teachers use discourse moves to support student sensemaking as students use concepts and practices from multiple STEM disciplines? How do teachers know when to ask questions so that students productively reach for ideas and practices that are often disconnected from one another in schools? The investigation of these types of research questions could lead to the development of productive discourse strategies in integrated STEM.

I begin with a description of some common conceptual frameworks for integrated STEM and explain how they are typically used to develop integrated STEM curricula. I then describe my proposed student-centered framework for integrated STEM focused on students making sense of STEM problems and discuss some potential implications for using this sensemaking framework for research and teaching.

2. Frameworks of Integrated STEM

Integrated STEM in the classroom typically refers to educational experiences that utilize more than one domain of science, technology, engineering, or mathematics (STEM; Moore et al., 2020) with the goal of student learning. Interdisciplinary STEM or integrative STEM are other terms used in the literature that are conceptually similar to integrated STEM (Roehrig, Dare, Ellis, & Ring-Whalen, 2021). It is a widely held view in the literature that integrated STEM activities in the classroom require the context of complex, real-world problems (Moore et al., 2020), but there continues to be discussion about how many STEM disciplines are required for it to be considered integrated STEM (Martín Páez et al., 2019; Sgro et al., 2020), how the disciplines need to interact in the instructional space (Chalmers et al., 2017; Kelley & Knowles, 2016; Leung, 2020), and what type of knowledge is produced through integrated STEM activities (Stohlmann et al., 2012; Tytler et al., 2021).

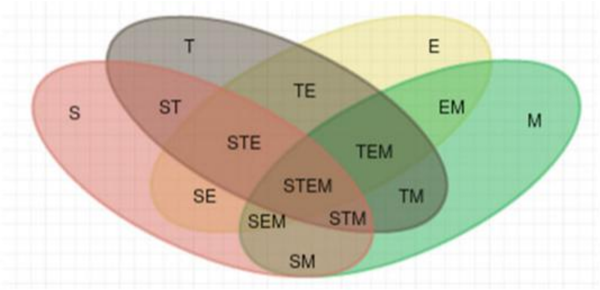
Although there continues to be discussion about exactly how to conceptualize integrated STEM, many frameworks for integrated STEM describe the different disciplinary concepts and practices students are expected to learn and use during an integrated STEM activity (Moore et al., 2020). Because these framings focus on the different disciplinary ideas necessary to plan integrated STEM activities, I characterize them as discipline-centered frameworks. In the following section, I briefly describe several of these discipline-centered frameworks to highlight their focus on developing integrated STEM curricula from a perspective of combining the ideas and practices of individual STEM disciplines, i.e., they address what STEM knowledge or practices need to be included. I then discuss what these framings may fail to address when students experience integrated STEM activities.

2.1 Discipline-Centered Frameworks: Addressing the "What" of Integrated STEM

Discipline-centered frameworks of integrated STEM describe the ideas and practices of the STEM disciplines utilized during an integrated STEM educational activity. One simple framework to represent this disciplinary interaction uses a Venn diagram in which circles represent the STEM disciplines and various regions of overlap represent their integration (Figure 3-1). This perspective conceptualizes integrated STEM as regions of overlap where domain-specific ideas or practices from particular STEM disciplines are used in some combination to solve a problem (Vasquez, 2015). For instance, integrated STEM could be a combination of disciplinary ideas from science and mathematics, or it could be a combination of ideas from technology and engineering. This basic framework does not specify which particular ideas and practices are needed from the various STEM disciplines but only distinguishes between integrated STEM activities, where the regions overlap, and disciplinary activities, the non-overlapping regions.

Figure 3-1

Venn Diagram Model of Integrated STEM



Note. The letters S, T, E, and M indicate the disciplines of science, technology, engineering, and mathematics, respectively. The overlapping circles show possible disciplinary combinations for integrated STEM activities. From "Quantitative Reasoning and its Role in Interdisciplinarity," by R. Mayes, 2019, in B. Doig, J. Williams, D. Swanson, R. Borromeo Ferri, and P. Drake (Eds.), *Interdisciplinary mathematics education: The state of the art and beyond*, p. 115.

Other discipline-centered models of integrated STEM are more specific regarding which knowledge and practices are utilized in the regions where the STEM disciplines overlap (Table 3-1). For example, Chalmers et al. (2017) described integrated STEM classroom activities as using the "big ideas of STEM" (p. S27). Big ideas are "key ideas that link numerous discipline understandings into coherent wholes" (p. S27), and these ideas relate to content, such as evolutionary theory, variables, and number line models, or disciplinary practices, such as experimenting, mathematical reasoning, and systems thinking. Thus, each STEM discipline has its organizing ideas and methods of understanding.

Table 3-1

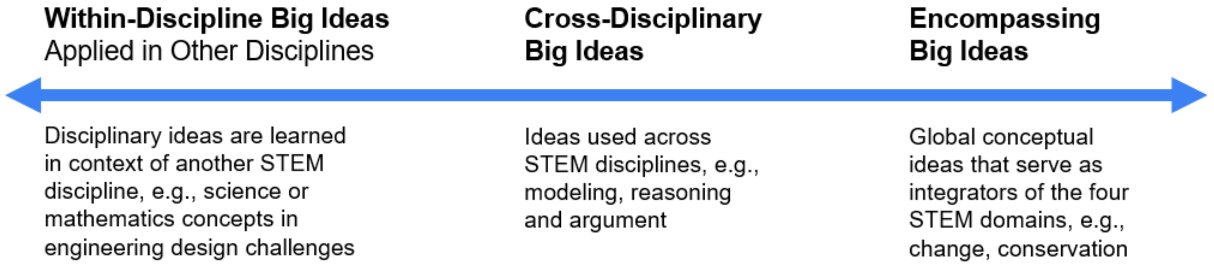
Examples of Discipline-Centered Frameworks of Integrated STEM

Conceptual Frameworks	Interaction of Different STEM Disciplines in Classroom Activities	Description of Suggested Curriculum Unit
Big Ideas of STEM (Chalmers et al., 2017)	Different key disciplinary **ideas**	Students design a multi-terrain rescue vehicle using the big ideas of gears, speed, and torque (science), ratios (mathematics), in the context of an engineering design project (engineering).
STEM Learning (Kelley & Knowles, 2016)	Disciplinary **practices** of scientific inquiry, technological literacy, engineering design, and mathematical reasoning	Students use 3D printing technology to create engineering-designed bio-mimicry solutions in the context of entomology. Students use mathematical modeling to predict and assess the performance of designs.
Boundary Crossing STEM Pedagogy (Leung, 2020)	**Problem-solving processes** of different STEM disciplines	Students use sketch-mapping (geography), bone identification (biology), modeling (mathematics), and an app to estimate circumference (technology) to solve the problem of estimating the weight of a dinosaur from a simulated fossil bone.

These big ideas of STEM interact on a continuum (Figure 3-2). At one end, integrated STEM activities can be designed so discipline-specific ideas are applied in other disciplines. One STEM discipline acts as a context for the application of another discipline's big idea(s); for example, a science big idea like gravity could be explored through an engineering design challenge. In this case, using engineering as the context provides a more meaningful and relevant way to learn the key science idea of gravity.

Figure 3-2

Big Ideas of STEM



Note. The arrow shows a continuum of interactions among the key ideas of science, technology, engineering, and mathematics. Adapted from "Implementing "Big Ideas" to Advance the Teaching and Learning of Science, Technology, Engineering, and Mathematics (STEM)," by C. Chalmers, M. Carter, T. Cooper, and R. Nason, 2017, *International Journal of Science and Mathematics Education*, *15*, p. S26.

In the center of the continuum are the big ideas located in at least two STEM disciplines. These cross-disciplinary ideas are shared across STEM disciplines; for example, using models, logical reasoning and evidence-based argument, and identifying and elucidating patterns are key ideas in multiple STEM disciplines. In this case, integrated STEM activities would highlight the similarities and differences in the use of these cross-disciplinary ideas across the disciplines. For instance, the uses of mathematical models in science, technology, engineering, and mathematics could be explored in an integrated STEM activity.

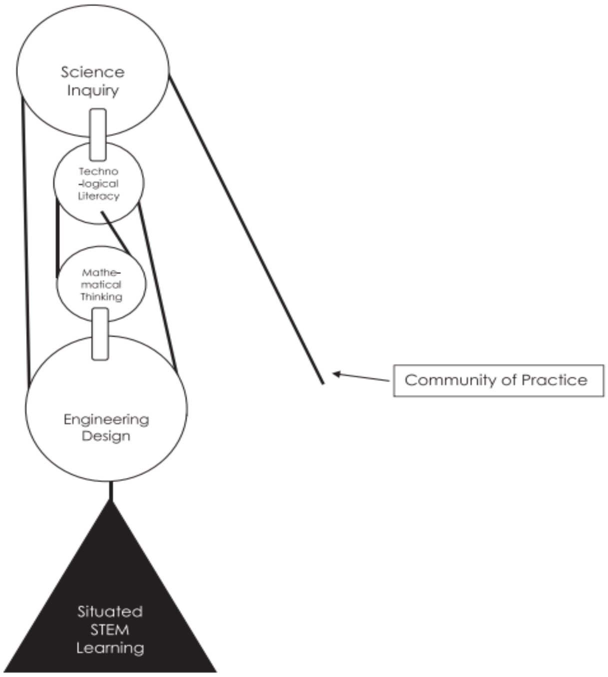
At the far end of the continuum are the encompassing big ideas. These ideas are either conceptual and contain many applications across all STEM disciplines, for example, conservation, representations, and change, or they address important problems facing humanity, such as sustainability, environmental impacts, and climate change. These global ideas aid in the design of activities that seek to integrate all four STEM domains.

This perspective conceptualizes integrated STEM as the interaction of disciplinary key ideas. Chalmers et al. (2017) used this framework to support the design of integrated STEM curriculum units (Table 1). Integrated STEM units can be designed to contextualize disciplinary big ideas by situating them in another discipline or connect disciplinary big ideas by highlighting their cross-disciplinary or global nature. This framework emphasizes how to select STEM *disciplinary ideas* to develop effective integrated STEM activities.

Instead of using organizing ideas, Kelley and Knowles (2016) described integrated STEM classroom activities as the interaction of four discipline-specific practices (Figure 3-3). In this framework, students use the practices of engineering design, scientific inquiry, mathematical thinking, and technological literacy to solve a problem or design challenge (Table 3-1). This problem or design challenge is situated in an authentic real-world context and learning occurs through the application of these practices as part of a community of practice. The practice of engineering design is used to design, construct, and test a prototype during a design project. The design process provides opportunities for both scientific inquiry and mathematical reasoning to occur because it allows for the application of "science knowledge and inquiry as well as provides an authentic context for learning mathematical reasoning for informed decisions" (Kelley & Knowles, 2016, p. 5). Technological literacy is used to construct the material objects of the design project and to investigate how those objects could impact human society.

Figure 3-3

Conceptual Framework for STEM Learning



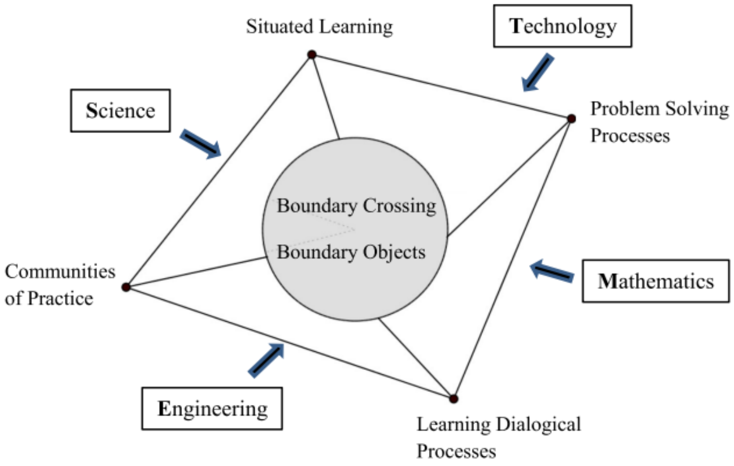
Note. Each pulley represents a practice of science, technology, engineering, or mathematics. The STEM practices are connected by a rope, which represents a community of practice. The entire system is designed to enact situated STEM learning. From "A Conceptual Framework for Integrated STEM Education," by T. R. Kelley, and J. G. Knowles, 2016, *International Journal of STEM education*, *3*(11), p. 4.

Kelley and Knowles (2016) suggested that STEM educators understand and use these STEM practices to develop integrated STEM activities. They used this framework to design an integrated STEM curriculum unit in which students used the engineering design process and 3D printing technology to create bio-mimicry solutions in a scientific context of entomology (Table 3-1). Mathematical modeling was used to predict and assess the performance of the designs. This perspective, therefore, emphasizes what types of *STEM practices* could be used to design integrated STEM activities.

Instead of viewing integrated STEM as an interaction of key ideas or multiple disciplinary practices, Leung (2020) argued that problem-solving processes connect the STEM disciplines (Table 3-1). In this framework, integrated STEM classroom activities are situated in a real-world problem-solving context and occur as part of a community of practice consisting of teachers and students. Situated learning and communities of practice therefore form two corners in Figure 3-4. A STEM problem serves as the boundary object, an abstract or concrete entity that can both "articulate meaning and address multiple perspectives" (Leung, 2020, p. 3). The act of boundary crossing integrates the STEM disciplines because different problem-solving processes in the STEM disciplines are used to solve the STEM problem of interest in the classroom activity. These processes are the third corner in Figure 3-4. These problem-solving processes within the STEM disciplines overlap and so students need to identify, coordinate, and apply the different STEM practices used during problem-solving as part of a dialogical process, the fourth corner in Figure 3-4, during which learning occurs.

Figure 3-4

Boundary Crossing STEM Pedagogy



Note. This model shows that boundary objects are at the center of integrated STEM. From "Boundary Crossing Pedagogy in STEM Education," by A. Leung, 2020, *International Journal of STEM Education*, *7*(1), p. 5.

Like the previous frameworks, Leung (2020) described an example of how a boundary-crossing perspective could be used to design an integrated STEM unit (Table 3-1). In this case, high school teachers and students formed a community of practice to develop an integrated STEM unit around a simulated archeological dig site. The boundary object was the problem of estimating the weight of a dinosaur from simulated fossil bones, and it involved problem-solving processes from biology, mathematics, and technology. The curriculum developed from this framework emphasizes what *problems* should be chosen to develop integrated STEM activities.

These discipline-centered frameworks focus on the disciplinary knowledge and skills that are used in integrated STEM activities, either through the general interactions of STEM domains, the more specific interactions of cross-disciplinary concepts and practices, or the use of STEM problems as mediators for the interaction of STEM domains. These frameworks are useful for describing and planning the concepts, practices, and tasks targeted in integrated STEM activities, and they are often reported as a framework used to develop integrated STEM curriculum units. They address *what* students should know and, therefore, take a more curricular perspective of integrated STEM.

2.2 Potential Problems with Discipline-Centered Frameworks

Discipline-centered frameworks, however, do not indicate *when* and *how* students connect knowledge and skills of different disciplines as they experience integrated STEM activities (Tytler et al., 2021). By conceptualizing integrated STEM as interactions of disciplinary ideas or practices, how students develop their understandings or how they engage in the creation of approximations of disciplinary practice may be hidden. These framings do not address student thinking or the experiences of students as they engage in integrated STEM activities. This lack of attention to students' experiences is problematic because knowledge of student thinking and how they engage with disciplinary content is a critical component of effective teaching (Ball et al., 2008; Shulman, 1987).

Furthermore, students have ways of thinking during integrated STEM activities that are difficult to predict (English, 2022; Lehrer & Schauble, 2021). For example, students may engage in more sophisticated modes of thinking during integrated STEM activities than researchers anticipate. English (2022) described how fifth-grade students' use of data representations and quantitative reasoning during an integrated STEM investigation exceeded the researchers' expectations based on their knowledge of the students' curriculum. The students' invented data displays included several stacked bar graphs, a topic that was not included in their curriculum. Students also engaged in more sophisticated quantitative reasoning than expected when they made predictions about lava flow time using their scientific knowledge of viscosity and environmental factors. In this case, students' invented solutions and the connections they made with prior knowledge were not anticipated. This knowledge of student thinking during this investigation could help teachers develop instructional strategies that facilitate students' use of quantitative reasoning (English, 2022).

Students may also have unanticipated responses and ways of thinking as they experience integrated STEM activities that may cause challenges for intended instruction. Lehrer and Schauble (2021) described the unexpected problems an experienced elementary teacher had during an integrated STEM activity in which students were developing their mathematical knowledge of coordinates and mapping using the science context of studying plants in a prairie ecosystem. Students responded to the task with unexpected solutions that reflected their engagement with the science context, but those solutions conflicted with the teacher's mathematical agenda. The teacher struggled to support her students' mathematical thinking as she intended because her students were thinking about this task in ways that she had not anticipated. Understanding the range of students' potential responses and their ways of thinking about integrated STEM activities are necessary for the productive integration of multiple STEM disciplines (Lehrer & Schauble, 2021). Discipline-centered frameworks do not address the ways students think about integrated STEM, and this could be problematic for effective instruction and student learning.

Additionally, discipline-centered frameworks ignore the development of student thinking. These framings are silent on how to sequence integrated STEM instruction in an activity coherently or across several integrated STEM activities so that students develop their disciplinary thinking over time. This lack of coherence in integrated STEM activities can result in a shallow understanding of disciplinary practices (McComas & Burgin, 2020; Tytler et al., 2019).

Discipline-centered frameworks, therefore, do not address how students are making connections among disciplinary ideas as they experience STEM activities, their possible invented solutions, or how students draw upon prior knowledge and skills, either from school experiences or from everyday life. This knowledge of student thinking is necessary to develop effective instructional strategies (Ball et al., 2008; Shulman, 1987). Therefore, an integrated STEM conceptual framework is needed *alongside* these discipline-centered framings to explore how students make sense of STEM problems, when they engage in disciplinary thinking as they experience integrated STEM activities, and how those experiences develop students' thinking over time. In the following section, I address this gap by proposing a framing of integrated STEM that describes how students reach for disciplinary ideas in different ways across time as they make sense of integrated STEM problems.

3. Integrated STEM from a Student Sensemaking Perspective

3.1 Addressing the "When" and "How" of Integrated STEM

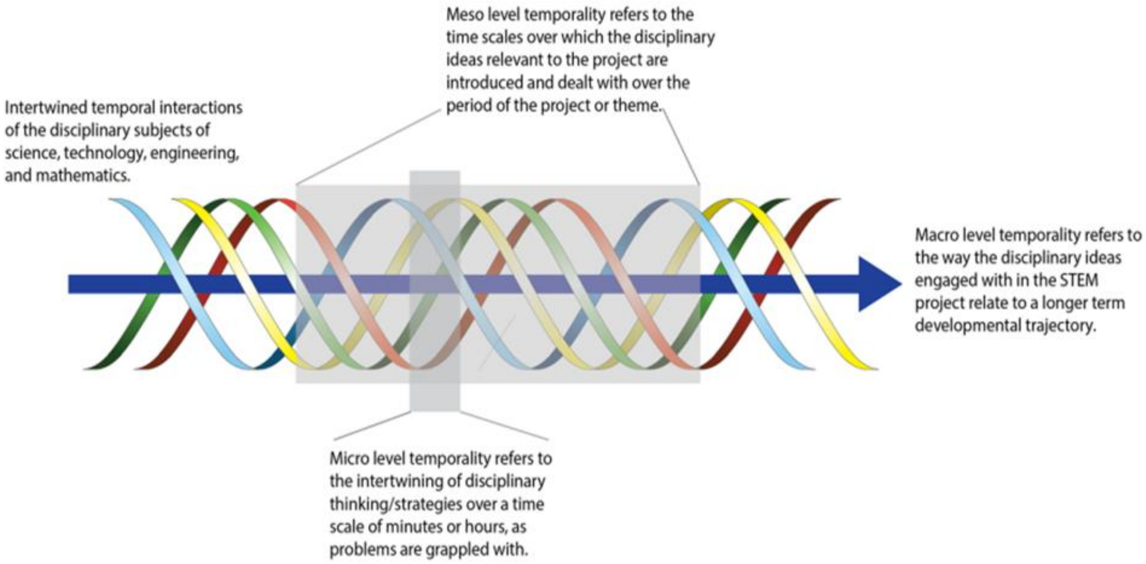
Integrated STEM is used to encompass a wide range of classroom activities in K-12 science and mathematics classes (McComas & Burgin, 2020). Activities such as model-eliciting activities (Baker & Galanti, 2017), engineering design challenges (Kelley & Knowles 2016; Roehrig, Dare, Ring-Whalen, & Wieselmann, 2021), socio-scientific issues (Owens & Sadler, 2020), and data investigations (Kjelvik & Schultheis, 2019) can all be considered examples of integrated STEM classroom activities because they are centered around complex, authentic problems that approximate the problems STEM professionals address in the real world. STEM problems require students to coordinate knowledge and methods from multiple STEM disciplines and to use various representations to reduce the complexity of the real world (Pleasants, 2020).

As students work to develop solutions to these STEM problems, they draw upon the ideas, practices, and representations they have experienced in different classes and at different times. In other words, in the moment of problem-solving, students may utilize ideas about constructing graphs they experienced in mathematics class last year along with a concept from science class they heard about today. Or they may use an in-the-moment invented mathematical strategy in mathematics class to describe the data from a test of their engineering design that occurred yesterday.

There is, therefore, a temporal aspect to how students experience school disciplinary thinking during integrated STEM activities (Tytler et al., 2021). At a *micro-level time scale* of minutes or hours, students recognize or are guided to recognize that multiple disciplinary ideas or practices are needed to grapple with a problem (Figure 3-5). At a *meso-level time scale*, these ideas may be learned or newly generated over several days or weeks during the length of a STEM investigation or project, or at a *macro-level time scale*, these disciplinary ideas could have been learned months or years earlier. Furthermore, at a macro-level time scale, integrated STEM activities should develop disciplinary ideas in coordinated ways across grade levels as part of a learning trajectory (Tytler et al., 2021). This framing, therefore, emphasizes *when* students draw from disciplinary ideas and practices as they experience integrated STEM activities. By conceptualizing integrated STEM on a temporal scale, student thinking can be explored across instructional timescales as students grapple with aspects of an integrated STEM problem in the moment of experiencing it, as students solve a problem over the course of an integrated STEM investigation or project, and as students experience integrated STEM learning over a long-term learning trajectory.

Figure 3-5

A Temporal Model of Integrated STEM

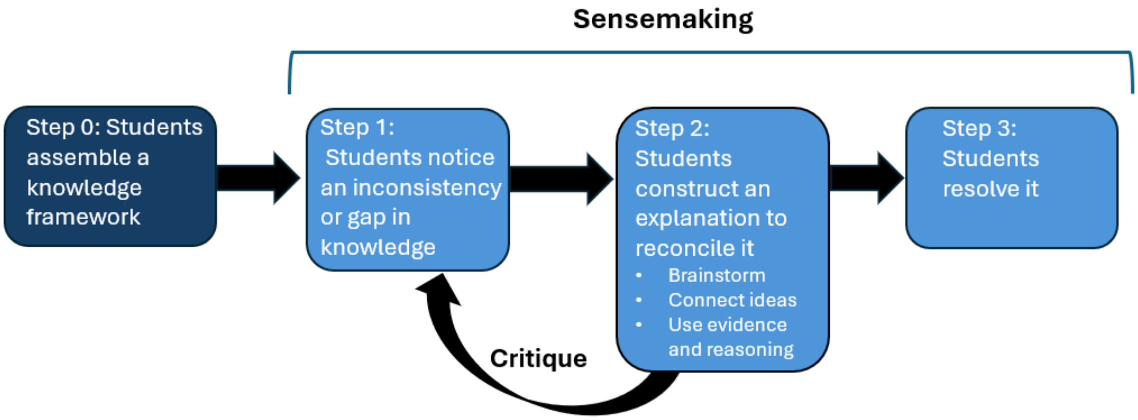


Note. The red, blue, yellow, and green lines represent the intertwined interactions of the science, technology, engineering, and mathematics disciplines. The blue arrow represents the passage of time. From “Rethinking Disciplinary Links in Interdisciplinary STEM Learning: A Temporal Model,” by R. Tytler, V. Prain, and L. Hobbs, 2021, *Research in Science Education*, *51*, p. 7.

This temporal framework alone, however, does not address *how* students interact with disciplinary thinking as they experience STEM problems beyond suggesting that STEM disciplinary thinking becomes somehow intertwined during the STEM activity. Therefore, I propose that the intertwining of STEM disciplinary thinking happens when students are making sense of STEM problems. This sensemaking process (Odden & Russ, 2018, 2019a) occurs when students recognize a gap in their understanding of some aspect of a STEM problem and work to build an explanation to resolve it (Figure 3-6).

Figure 3-6

The Sensemaking Process



Note. Adapted from Odden, T. O. B., & Russ, R. S. (2018). Sensemaking epistemic game: A model of student sensemaking processes in introductory physics. *Physical Review Physics Education Research*, *14*(2), 020122. https://doi.org/10.1103/PhysRevPhysEducRes.14.020122

Before sensemaking can occur, students begin by using their prior knowledge as resources to construct and articulate what they know about an aspect of a STEM problem (Step 0, Figure 6; Odden & Russ, 2018). This knowledge framework comes from a mixture of intuitions from their everyday experiences and their prior knowledge (diSessa, 1993; Kapon, 2017; Odden, 2021). This pre-sensemaking step is the first place where students could reach for ideas and practices from different disciplines they encountered from prior educational experiences as they work to know what they know about a STEM problem.

Students then recognize, or are guided by the teacher to recognize, that something is puzzling or does not fit with what they know (Step 1, Figure 3-6; Odden & Russ, 2018, 2019a). The goal of figuring something out leads to students using some of the resources they have previously assembled in their knowledge framework to brainstorm and make several initial claims. As students verbalize their claims, they begin to connect them into a "chain of ideas," often expressing their evidence and reasoning (Odden & Russ, 2019a, p. 192). This chain of ideas becomes an explanation that is expressed in the students' own words (step 2, Figure 3-6). This step in the sensemaking process is where disciplinary thinking can become intertwined, or integrated. Students have opportunities to integrate ideas and practices from different disciplines as they work together to brainstorm, connect their ideas, and articulate their evidence reasoning.

When this explanation is collectively scrutinized by students, more gaps or inconsistencies may be noticed, as they test out and critique the links between their claims and evidence and consider whether the explanation is coherent with what they already believe to be true. Here is another opportunity for students to utilize ideas and practices from different disciplines as they critique their explanations.

As they test their explanation, students may further refine their ideas. They may move back and forth between explanation and critique several times until they are either satisfied with their explanation (step 3, Figure 3-6), or they give up in frustration. The sensemaking process results in knowledge building (Odden, 2021; Odden & Russ, 2019a) and this knowledge may be used as a further resource for subsequent sensemaking.

Therefore, as students experience integrated STEM problems, they have opportunities to draw upon and connect ideas and practices from different disciplines as they engage in the sensemaking process. The temporality of these disciplinary resources for sensemaking and how students can be supported to utilize them become an important consideration to understand and best support student learning during integrated STEM activities. Students use disciplinary thinking: 1) during *micro-level integration* as they engage in the process of sensemaking to figure out aspects of STEM problems in the moment of the lesson, 2) during *meso-level integration* over the length of the investigation or project as they coherently generate and build on new knowledge related to the STEM problem and make connections as the project or problem unfolds, and 3) during *macro-level integration* over months or years as they develop more sophisticated strategies and explanatory tools for solving STEM problems (Table 3-2). In the following sections, I discuss each of these components in further detail and briefly describe how each could be used as a lens to study integrated STEM teaching and learning.

Table 3-2

Sensemaking Integrated STEM Framework: Addressing the When and How of Integrated STEM

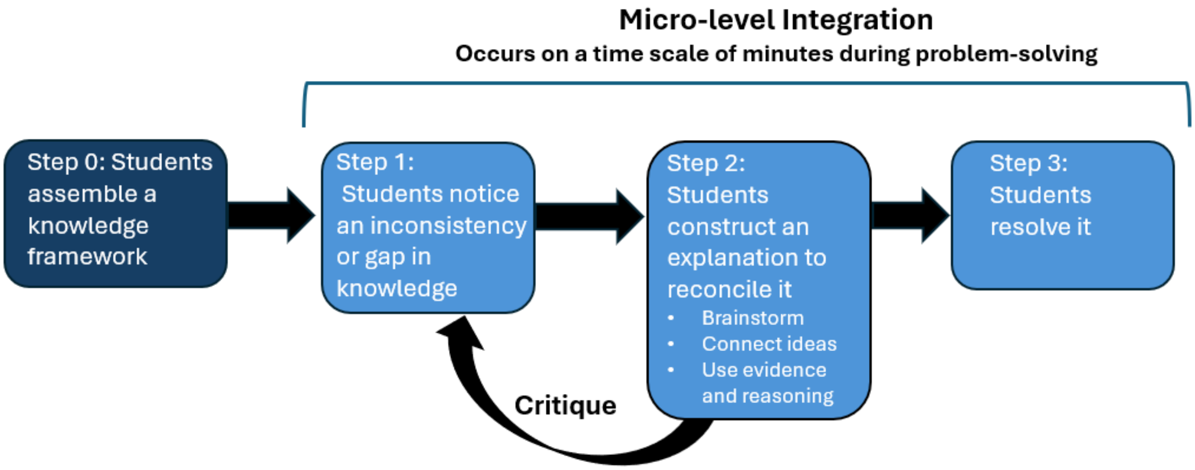
	Time scale of students' experiences with ideas from different disciplines	How student sensemaking may integrate ideas from different disciplines
Micro-level integration	In the moment of problem-solving (minutes or hours)	Students reach for ideas from different disciplines during the process of sensemaking as they build, revise, and critique explanations.
Meso-level integration	Over the course of the investigation, unit, or project (days or weeks)	Students coherently build on new knowledge and connect it to ideas of different disciplines in their explanations.
Macro-level integration	Across the school year or grade levels (months or years)	As they develop more sophisticated explanations, students routinely reach for ideas from different disciplines as explanatory tools.

3.2 Micro-level Integration

At the micro-level time scale, integration of disciplinary ideas occurs as students grapple with aspects of a STEM problem. Because STEM problems require knowledge and methods from multiple disciplines and are situated in the complexity of the real world (Pleasants, 2020), these problems provide many opportunities for students to grapple with gaps or inconsistencies in their knowledge or experiences. During micro-level integration, students engage in the sensemaking process as they try to "figure something out" and build explanations to make sense of these gaps in knowledge (Odden & Russ, 2019a, p. 199). Students generate new knowledge or make new connections with their prior knowledge as they construct their sensemaking explanations (Figure 3-7).

Figure 3-7

Micro-Level Integration



Note. The blue boxes describe the steps in the sensemaking process. This process is adapted from Odden, T. O. B., & Russ, R. S. (2018). Sensemaking epistemic game: A model of student sensemaking processes in introductory physics. *Physical Review Physics Education Research, 14*(2), 020122. https://doi.org/10.1103/PhysRevPhysEducRes.14.020122.

As they build their explanations, students reach out for disciplinary ideas and practices to connect them to the phenomenon of the problem. Sensemaking explanations may occur within disciplinary boundaries as students draw upon ideas from a single discipline, or they may occur across disciplinary boundaries as students use prior knowledge from multiple disciplines. These explanations are then critiqued and refined, either individually or collectively, as students develop new understandings (Odden & Russ, 2018; Odden & Russ, 2019a).

As an example of students' micro-level integration, Venville et al. (2004) described students' experiences as they participated in an engineering design challenge. Venville and colleagues explored the sources of knowledge students drew upon as they made design decisions to build the best-performing solar boat. In the following illustration of micro-level integration, Kevin and Jin-ming were trying to solve an aspect of their integrated STEM problem: determining the best circuit of solar cells to maximize the boat's power output. As they worked, they discovered an inconsistency in their knowledge, which caused them to reach out for science concepts to construct and test a new explanation:

> Kevin and Jin-ming were pleased with their initial combination of two cells in series and one in parallel because they recorded a high reading of 1600 mA for the current and 1.5 V for the voltage. During classroom trials, Kevin tinkered with several combinations of solar cells. When he set up five 400 mA solar cells in series, he said he, "blew the water out of the tank" with a voltage of 2.9 V and a higher current than all their previous readings. Jin-ming said he didn't understand how they got a higher current reading because, "in series that isn't supposed to happen." Kevin consulted the design and technology teacher who reminded him that resistance causes the voltage to go down and the voltage overcomes the resistance. The students realised that for the loaded motor the voltage was more critical. They did further trials to confirm this. They concluded that a series circuit would increase the voltage to compensate for the load. The students also discovered through trials that a parallel circuit has more joints than a series circuit, therefore more resistance and drains more power. (Venville et al., 2004, p. 125)

Kevin and Jin-ming were surprised they measured a higher current reading when the solar cells were in series than when they were in a combination of series and parallel. This inconsistency in their understanding of circuits caused them to reach out to their teacher for more information. The students began to make sense of this inconsistency when the teacher reminded them of the science concept of resistance and its relationship to voltage. The students then "realised that for the loaded motor the voltage was more critical," and began to build their explanation. To critique their newly built explanation that a series circuit has less resistance and produces a higher voltage, they did more trials to try to confirm it. Their explanation also led to the new knowledge that a series circuit has fewer joints than a parallel circuit and, therefore, less resistance.

This vignette illustrates micro-level integration because, over the timescale of a single lesson, the students were figuring out an inconsistency in their knowledge that puzzled them. The students built an explanation to resolve this gap by integrating the science concept of resistance and its relationship to voltage into the engineering design of their solar boat. They then tested the coherency of their explanation by doing further trials. Their sensemaking resulted in an explanation for why they decided to use solar cells in series as the circuit for their solar boat design.

Studying integrated STEM at this micro-level scale provides a useful lens to explore how students interact with disciplinary knowledge and methods in the immediate act of figuring out an aspect of a STEM problem (Tytler et al, 2021). During this in-the-moment time scale, researchers can investigate the types of knowledge students draw upon as they engage in problem-solving, the ways students connect their observations and knowledge of phenomena, disciplinary concepts, and disciplinary practices, and the reasoning students use as they develop and critique their explanations.

Furthermore, because micro-level integration occurs during the act of teaching, researchers can explore how this knowledge of student thinking informs teachers' instruction; for example, they can investigate how teachers work with student ideas as students build, share, and revise their explanations during integrated STEM activities. Finally, teachers can think about ways to help students uncover surprising gaps or inconsistencies in their knowledge. These gaps could be designed into problem-solving tasks, or they could be uncovered through teacher and student discourse.

3.2 Meso-level Integration

Students interact with disciplinary thinking over the course of an integrated STEM investigation, unit, or project at a meso-level scale of days or weeks (Tytler et al., 2021). Throughout an investigation, students engage in multiple episodes of sensemaking as they figure out aspects of a STEM problem. These aspects could include prototype testing as in the case of Kevin and Jin-ming, creating graphs, interpreting and analyzing data, or developing explanations for phenomena. As students construct their sensemaking explanations, they generate new knowledge or apply their knowledge in new ways (Odden & Russ, 2019a). Over the course of the STEM activity, students could coherently use this knowledge-building as resources to develop subsequent explanations and to make progress on the STEM problem they are solving. Meso-level integration, therefore, refers to students making sense of how their problem-solving activities fit together (Table 3-2).

For example, English (2022) described an investigation that illustrates how students experienced an integrated STEM investigation that supported both micro-level and meso-level integration through a sequence of problem-solving tasks. In this study, fifth-grade students were asked to solve the problem of predicting evacuation times for a village at the base of a newly discovered volcano. Students experienced a series of sensemaking tasks as they first made sense of the scale of their model, then developed data displays to make sense of their data and finally used their data displays to predict the best evacuation times for a volcano taller than the one represented by their model. Each task supported students to engage in micro-level integration as they figured out an aspect of the problem, and students then used the new ideas they generated as a resource to support sensemaking in the next task.

The sequence of tasks described in English (2022) appeared to facilitate meso-level integration, but sometimes students have unanticipated difficulties taking up ideas across integrated STEM tasks. Lehrer and Schauble (2021) described how a teacher used three different representations across two days of instruction as students investigated the problem of locating their research plants after a prairie burn. First- and second-graders needed to coordinate their ideas about how to reliably locate their plants using their memories of walking on the prairie, a two-dimensional paper map with an “x” to mark each of their research plants, and a hoop on the floor using stuffed animals to represent their research plants across several days of instruction. These different representations of the large space of the prairie were difficult for students to connect because the first representation was from their perspective, the second was a two-dimensional representation of a large space, and the third was from a bird’s-eye perspective (Lehrer & Schauble, 2021). The teacher in this case struggled to support the development of her students’ mathematical ideas because of the differences in her choices of representations for the prairie (Lehrer & Schauble, 2021). This example illustrates the importance of meso-level integration and of attending to how students make connections among integrated STEM tasks across the duration of the investigation or project.

Meso-level integration occurs as students use new knowledge generated through sensemaking as resources to develop subsequent explanations in coherent ways. By studying integrated STEM at this meso-level scale, researchers and practitioners can explore the new knowledge students generate and how students use that knowledge to build new understandings across the course of the integrated STEM investigation or project. Teachers can also look for the challenges that exist for students as they import ideas from one aspect of solving a STEM problem to subsequent tasks.

Additionally, by using meso-level integration as a research lens, researchers and practitioners can explore how teacher discourse can support students in connecting their ideas across integrated STEM investigations or projects. Practitioners and teacher educators can explore the knowledge teachers need to sequence activities, tasks, and discussions so that they can support students to reach for disciplinary ideas and practices just in time for when they need it to engage in sensemaking. Because this disciplinary knowledge is taught in most schools through a siloed approach, researchers can study the best methods to coordinate instruction among science, mathematics, and technology teachers.

3.3 Macro-level Integration

Students experience the ideas and practices of multiple STEM disciplines over a school year or across grade levels (Tytler et al., 2021). Macro-level integration describes how students' sensemaking explanations become more sophisticated over the school year or across grade levels as they develop their use of disciplinary ideas. During macro-level integration, students reach for more and more disciplinary ideas and practices as explanatory tools and develop their abilities to engage in sensemaking as a problem-solving strategy (Table 3-2).

Students engage in sensemaking during micro-level integration and generate new knowledge or apply their knowledge in new ways. They then use this new knowledge as a resource as they connect it to other disciplinary ideas during meso-level integration. Students could have learned those disciplinary ideas earlier in the school year or at a previous grade level. Macro-level integration occurs as students develop the ability to reach for previously learned disciplinary ideas as explanatory tools when they need them to solve STEM problems. During macro-level integration, students make sense of when, why, and how to apply disciplinary knowledge and practices as they solve integrated STEM problems.

As an example of macro-level integration, Lehrer et al. (2020) described a sequence of units designed for students to make sense of variability. Students began by inventing data visualizations to make sense of measurement variability (i.e., measurement error) when each student measured the same object. In the following two units, students created measures of center and measures of variation to characterize the distribution of their class measurements. Then, they investigated sampling variability and began to make sense of probability. Next, students developed models of variability by creating computerized random generators that accounted for both measurement and sampling variability. Finally, students made sense of variability in natural systems by modeling sampling variation from a local pond. In every unit, students made sense of variability by developing their own explanations (e.g., data visualizations, procedures for calculating measures of center, and explanatory models of variation) and sharing them with the class for critique and revision.

This sequence of units illustrates macro-level integration because students' explanations of variability drew upon ideas that had been developed across the whole school year. As one of their instructional design principles, Lehrer et al. (2020) stated "students must come to see how the particulars of their activities make sense cumulatively in light of their overarching goal of generating and critiquing knowledge" (p. 4). Thus, this sequence of units was designed so that students made sense of how and why they used disciplinary ideas (e.g., measures of center and distributions) and when to apply them so that they deepened their explanations of variability (e.g., developing models of variability and in their investigations of pond ecology). Throughout these units, generating and critiquing knowledge, or sensemaking, became a problem-solving strategy for students that led to more sophisticated explanations for variability.

This macro-level perspective of students' sensemaking can be used to investigate what disciplinary ideas students import across integrated STEM investigations and how students' use of those ideas becomes more sophisticated. One criticism of integrated STEM education is that students' scientific and mathematical knowledge is not developed in a systematic way (McComas & Burgin, 2020; Roehrig, Dare, Ring-Whalen, & Wieselman, 2021; Tytler et al., 2019). Students often use mathematics as a tool in integrated STEM activities and do not have opportunities to develop deeper conceptual thinking (Mayes, 2019; Roehrig, Dare, Ring-Whalen, & Wieselmann, 2021; Tytler et al., 2019). McComas and Burgin (2020) argued that in elementary STEM lessons "there are few opportunities [for students] to *learn* scientific and mathematical principles, values, and methods" (emphasis in original, p. 17). By considering macro-level integration, the best methods to systematically support the development of students' disciplinary ideas over time as they engage in sensemaking can be investigated. For example, Zhao and Schuchardt (2021) described levels of science sensemaking and mathematical sensemaking when students experienced mathematical equations in science classes. Each level in their framework described a more sophisticated understanding of using mathematical equations to explain scientific phenomena. Like the carefully sequenced units to support students' explanations of variability, these descriptions of student thinking could be purposefully used to support the systematic development of students' conceptual understanding of the mathematical ideas in science equations and their understanding of how science equations explain the mechanisms of science phenomena.

Furthermore, researchers and curriculum designers can also study how the development of students' thinking in integrated STEM activities aligns with standards and curricula in science, mathematics, and technology classes. How teachers coordinate and sequence disciplinary ideas and practices across school years and grade levels so that students have access to the necessary disciplinary resources to develop their sensemaking explanations during integrated STEM activities can be explored, as can the types of tasks that best support macro-level integration.

In summary, the sensemaking process occurs during all three levels of integration: micro-, meso-, and macro-level, but each level is different from the others in two distinct ways. First, as students experience micro-, meso-, and macro-level integration, there are temporal differences in how students may draw upon the knowledge resources they use during their sensemaking explanations. Micro-level integration describes the knowledge resources students use in the moment of grappling with an aspect of a STEM problem. Meso-level integration describes the knowledge resources students coordinate across multiple opportunities for sensemaking during the STEM activity. Finally, macro-level integration describes the knowledge resources students draw upon from earlier in the school year or earlier grade levels. There is, therefore, a temporal aspect to students' potential knowledge resources during the sensemaking process.

Second, from the perspective of designing STEM curricula, there is a difference in the desired outcome of the students' sensemaking process during micro-, meso-, and macro-level integration. When students experience micro-level integration, the desired outcome of the sensemaking process is for students to figure out an aspect of a STEM problem. During meso-level integration, the desired outcome of the sensemaking process is for students to develop new connections among the aspects of a STEM problem across the activity. When students experience macro-level integration, the desired outcome of the sensemaking process is for students to develop their abilities to reach for previously learned disciplinary ideas as explanatory tools when they encounter STEM problems. Therefore, the intended instructional outcome of students' experiences with micro-, meso-, and macro-level integration is an important distinction among the three levels.

Conclusion

This student-centered integrated STEM conceptual framework describes how students reach for disciplinary ideas in different ways across time as they make sense of integrated STEM problems. As a research lens, it allows the exploration of new questions about how and when students engage in disciplinary thinking as they experience integrated STEM activities. What sources of knowledge are students drawing on as they experience integrated STEM activities? How do students connect the phenomena of a STEM problem with disciplinary concepts and practices? What challenges exist for students as they import knowledge from one problem-solving task or integrated STEM investigation or project to use in subsequent problem-solving? How can teachers support the development of disciplinary knowledge across integrated STEM activities? These questions about how students experience integrated STEM activities and how they reach for disciplinary ideas are difficult to explore with discipline-centered integrated STEM frameworks. I propose this student-centered sensemaking framework for integrated STEM to facilitate the investigation of some of these questions.

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Chapter 4 Making Sense of Variability: A Middle School Weather Data Investigation

ABSTRACT: In this design-based research study, we developed a science data investigation for sixth-grade students in which students used ideas from both their science and mathematics classes to make sense of variability in their local weather data. We used two theoretical frameworks, the Sensemaking Integrated STEM Framework and the Explaining Variability construct, to create activities that provided opportunities for students to experience something puzzling or inconsistent in strategically selected sets of their local weather data. To understand how students responded to these sensemaking opportunities about variability, we asked: (a) how did students explain variability in their local weather data as they engaged in the sensemaking process, (b) how did students connect their knowledge resources as they made sense of variability in local weather data, and (c) how did students use epistemic tools from their mathematics class as they made sense of variability in local weather data. We inductively analyzed the classroom discourse and students' artifacts to show how students explained variability in their local weather data. Throughout the weather data investigation, we found that students engaged in the sensemaking process to explain variability by integrating variability in temperature data with their ideas about weather phenomena, such as wind, wind direction, precipitation, shade, clouds, the position of the sun, and length of time the sun shines. Students made some connections across activities in the weather data investigation that we anticipated, but supporting students to make other connections was more challenging. For example, most students connected variability in temperature data with heat transfer from the sun, but only a few students connected this variability with specific mechanisms of heat transfer. Finally, we found evidence that students used their prior mathematics concepts of order, count, and measures of center as epistemic tools to make sense of variability in temperature data by organizing their data

and making aggregate properties of their data visible. Our findings offer implications that the Sensemaking Integrative STEM framework and the Explaining Variability construct are productive lenses for designing science data investigations to support students to connect variability in data with the phenomena that produced it. Furthermore, when students are given instructional opportunities to reach for statistical ideas from mathematics, these opportunities support students to use those ideas as epistemic tools for generating knowledge.

1. Introduction

Students in K-12 science classrooms need opportunities to engage in the science and engineering practices of collecting, analyzing, and interpreting data (NGSS, 2015; NRC, 2012). Authentic participation in these practices requires students to coordinate ideas about data visualization and statistics from mathematics class and content knowledge about mechanism and phenomena from science class in order to develop new conceptual understandings about natural phenomena (Kjelvik & Schultheis, 2019; Manz et al., 2020). It is challenging, however, to design science investigations that explicitly support students to do this kind of interdisciplinary coordination of ideas (Lehrer & Schauble, 2010; Manz et al., 2020).

Explaining variability is a core practice of interpreting data in both science and statistics, and to explain the sources of variability in data requires this interdisciplinary coordination of statistical ideas and contextual knowledge (Cobb & Moore, 1997; Lehrer et al., 2020). Therefore, science investigations in which students are asked to explain the variability they encounter as they collect, analyze, and interpret their data supports them to authentically connect data visualization and statistical practices with understanding phenomena (Hunter-Thomson, 2022; Lehrer & English, 2018; Lehrer et al., 2020).

To explain variability, students first need to recognize the differences in data, and then they need to organize and structure those differences so that aggregate qualities of the data can be observed (Scott, 2024). Students use their observations of the data and their ideas about the phenomenon to construct explanations that account for sources of variability. Therefore, to design science investigations in which students explain variability in their data, teachers and researchers must understand student thinking and how students make sense of differences in data and how they make sense of connecting those differences with the phenomena under investigation.

For this design-based research study, we developed a new conceptual framework, the Sensemaking Integrated STEM framework, to design a science data investigation in which students use ideas from both their science and mathematics classes to make sense of variability in their local weather data. This framework describes how students make sense of STEM problems as they connect disciplinary ideas in the moment of experiencing a STEM problem, across the length of a STEM investigation or activity, and over the course of the school year. In this paper, we share our initial design conjectures based on this framework and show how these ideas guided the first iteration of our sixth-grade weather data investigation. We then show how students' engagement in the sensemaking process during this weather data investigation supported their explanations of variability.

2. Conceptual Frameworks

Two conceptual frameworks guided our initial design and analysis of the weather data investigation. We developed a new conceptual framework for integrated STEM, the Sensemaking Integrated STEM framework, because, in our design, we intended to focus on how and when students connected disciplinary ideas from science and mathematics during the weather data investigation. Most conceptual frameworks for integrated STEM in the literature focus on the concepts and skills from the different STEM disciplines the students will use in the activity (Tytler et al., 2021). We argue that, while these integrated STEM frameworks are useful, they fail to address student thinking and sensemaking during integrated STEM activities. The Sensemaking Integrated STEM framework describes how students connect ideas from the different STEM disciplines when they engage in the sensemaking process. We used this framework to design opportunities for students to engage in sensemaking about their local weather data, and we used it to develop an instructional sequence of activities across the weather data investigation to support students to connect the knowledge they generated through sensemaking.

We employed a second framework, the Explaining Variability (EV) construct, to inform our design and analysis of what students were making sense of during the weather data investigation. Making sense of data requires students to be able to characterize and account for variability (Bargagliotti et al., 2020; Lehrer et al., 2020; Watson et al., 2022). Our research group, the Integrated Data Project (IDP), developed this theoretical construct for studying the progression of student thinking as they move from simply recognizing variability to quantifying and structuring it, and then explaining its sources and developing models for variability. We used this framework to design opportunities for students to recognize, structure, and explain the variability in their local weather data. In this section, we describe both frameworks in greater detail.

2.1 The Sensemaking Integrated STEM Framework

Integrated STEM problems are complex, authentic problems that approximate those that STEM professionals experience in the real world. Integrated STEM problems are "*amalgams* of intersecting sub-problems", and these sub-problems require knowledge and methods from individual STEM disciplines to address them (Pleasants, 2020; p. 838, emphasis in original). When students experience integrated STEM problems in school, they must coordinate the knowledge generated from these sub-problems to address the larger one. For example, Pleasants (2020) discussed a hypothetical STEM problem in which students were asked to improve the design of the levee protecting their community to prevent likely future floods. To solve this

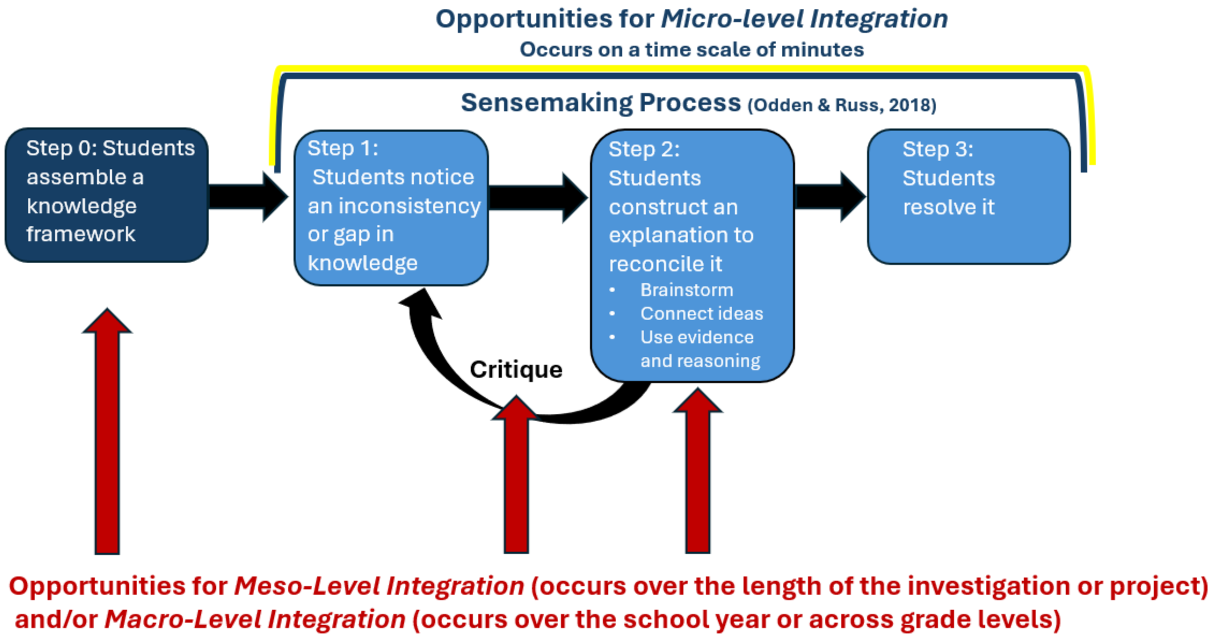
STEM problem, students would need knowledge and methods from science to investigate the sub-problem of where and why the local river flooded. They would need knowledge and methods from mathematics to analyze historical data sets of river water levels to investigate the sub-problem of predicting the probabilities of future high-water levels, and they would need knowledge and methods from engineering to address the sub-problem of designing a cost-effective levee. To address this integrated STEM problem, students would then connect all the knowledge generated from these sub-problems to create a report that described and justified their design. Students would need to make sense of the amalgam of knowledge generated by these sub-problems to create a possible solution.

Frameworks for developing integrated STEM activities often fail to address how students make these kinds of necessary connections because they focus on the disciplinary knowledge and skills students will learn and use as they experience the activity (Tytler et al., 2021). In other words, these frameworks are discipline-centered because they describe *what* disciplinary knowledge and skills students use, but not *how* students generate knowledge using them or *when* they make sense of the connections among them. For example, discipline-centered frameworks may focus on developing integrated STEM activities using key ideas from science, technology, engineering, and/or mathematics (e.g., Chalmers et al., 2017), important practices of the STEM disciplines (e.g., Kelley & Knowles, 2016), or problem-solving processes of the STEM disciplines (e.g., Leung, 2020). Discipline-centered frameworks fail to address how students make connections among disciplinary ideas as they experience the amalgam of sub-problems of integrative STEM activities, how they might invent possible solutions to sub-problems, or how students draw upon their prior knowledge and skills, either from their school experiences or from everyday life. This knowledge of student thinking and sensemaking is necessary to develop effective instruction (Colley & Windschitl, 2016; Fitzgerald & Palincsar, 2019; Li & Schoenfeld, 2019; Stockero et al., 2022).

Therefore, for this design study, we developed a new framework, the Sensemaking Integrated STEM framework, to guide our design of a weather data investigation (Figure 4-1). This framework is grounded in two existing frameworks from the literature. First, there is a temporal aspect of how students experience disciplinary ideas during integrated STEM activities (Tytler et al., 2021). At a *micro-level time scale* of minutes, students interact with disciplinary ideas or practices as they grapple with a problem. At a *meso-level time scale*, these ideas may be learned or newly generated over several days or weeks during the length of a STEM investigation or project, and at a *macro-level time scale*, these disciplinary ideas could have been learned months or years earlier. Second, students make connections among disciplinary ideas, their prior knowledge, and their everyday experience during the process of sensemaking (Odden & Russ, 2018, 2019a). Unlike discipline-centered frameworks, the Sensemaking Integrated STEM framework focuses on student thinking; addressing how students generate knowledge resources during integrated STEM activities across instructional time and how students connect their knowledge resources as they make sense of integrated STEM problems.

Figure 4-1

Sensemaking Integrated STEM Framework



Note. The light blue boxes, bracketed by the yellow line, describe the steps in the sensemaking process. Step 0, assembling a knowledge framework is a necessary preparatory step for the sensemaking process. Micro-level integration describes opportunities for students to connect disciplinary ideas in classroom moments when students are engaged in the sensemaking process (steps 1-3). The red arrows indicate steps when there are opportunities for meso-level integration, i.e., steps in which students could coherently connect ideas generated by the sensemaking process over the length of the investigation or project, and steps when there are opportunities for macro-level integration, i.e., steps in which students could use prior disciplinary knowledge as epistemic tools. The sensemaking process is adapted from Odden, T. O. B., & Russ, R. S. (2018). Sensemaking epistemic game: A model of student sensemaking processes in introductory physics. *Physical Review Physics Education Research, 14*(2), 020122. https://doi.org/10.1103/PhysRevPhysEducRes.14.020122.

This framework describes the sensemaking process (Odden & Russ, 2018, 2019a) as students attempt to figure out an aspect of an integrated STEM problem. Research suggests that this sensemaking process occurs on a time scale of minutes (Hutchison & Hammer, 2010; Odden & Russ, 2019b), and it is through sensemaking at this micro-level time scale that students have opportunities in the classroom to make connections among their observations, different disciplinary ideas, and their everyday experiences (blue boxes, Figure 4-1). Although the sensemaking process can and certainly does occur in an individual's mind (Klein et al., 2006; Odden & Russ, 2019a), this framework assumes the process of student sensemaking is visible in the classroom when students are engaging in collaborative discourse with the teacher and with each other.

Prior to engaging in the sensemaking process, students must first collectively assemble a shared knowledge framework (step 0, Figure 4-1; Odden & Russ, 2018). They do this by discussing, in small groups or as a whole class, what they know about the phenomenon or problem at hand as they draw upon their everyday experiences, their observations, and their prior knowledge. As students develop this initial shared knowledge framework, it helps them put all the ideas that may be useful for their understanding on the table, and it focuses their attention on any features of the phenomenon or problem they consider important (Odden & Russ, 2018). These ideas are the potential knowledge resources students possess for sensemaking (diSessa, 1993; Kapon, 2017). This shared assemblage of ideas allows students to know what they know about something before they begin sensemaking.

Students enter the process of sensemaking when they recognize, or are guided by the teacher to recognize, that something is puzzling or does not fit with their current shared knowledge framework (step 1, Figure 4-1; Odden & Russ, 2018, 2019a). Students are now in the frame of trying to figure something out. They begin to brainstorm and connect their knowledge resources, i.e., those ideas they articulated in their initial knowledge framework or new ideas and observations, to build an explanation (step 2). As they make connections, students verbalize their evidence and reasoning. These connections are collectively tested and critiqued, which may lead to new gaps or inconsistencies (curved arrow). This cycle is repeated until students are satisfied with their explanation (step 3). This sensemaking process results in new knowledge or new connections made to prior knowledge (Odden, 2021).

During the sensemaking process, students experience micro-level integration of disciplinary knowledge, everyday experiences, and the observations they make during the integrated STEM activity because students take their fragmented knowledge resources, connect them up, and collectively test those connections. Each sub-problem has opportunities for the sensemaking process to occur as students grapple with various aspects of the integrated STEM activity. For example, in the hypothetical STEM problem given above, to make sense of why the river floods in one location instead of another, students could use every day experiences of swimming in the river to understand the force of flowing water, their observations of pictures of the flooded levee, and their science knowledge of velocity, erosion, and deposition to build and refine their explanation for where and why the river floods. Designing for micro-level integration requires understanding how to provide opportunities for students to be in the frame of figuring something out, and how to support them to build and critique their explanations.

Students experience meso-level integration when they have opportunities during the sensemaking process in which they can coherently connect the knowledge resources generated across the length of the investigation or project (red arrows, Figure 4-1). Students experience meso-level integration when the ideas generated from one aspect of the problem are logically used as part of the knowledge framework necessary for making sense of another aspect of the problem. For example, using the hypothetical situation discussed above, students could have made sense of where and why the river floods so they could use those ideas to develop criteria for searching through historical records. Or students could experience meso-level integration when they use the ideas they generated through sensemaking to build and critique subsequent explanations for other aspects of the problem. Designing for meso-level integration, therefore, refers to understanding how students make sense of fitting their problem-solving activities together.

Students experience macro-level integration when they have opportunities during the sensemaking process to use prior disciplinary knowledge developed over the school year or across grade levels as epistemic tools (red arrows, Figure 4-1). Epistemic tools are physical, symbolic, or discursive artifacts that support knowledge building (Kelly & Cunningham, 2019). Artifacts become epistemic tools through their repeated use and when users understand the specific knowledge building contexts in which they are used. For example, Kelly and Cunningham (2019) discussed how students' sketches for prototype-building became epistemic tools when students used them to communicate their ideas to one another. The symbolic artifact of a sketch became a knowledge constructing tool across multiple engineering design activities to identify variables and their interactions.

Continuing to use the hypothetical example above, students could use mathematical measures of center and measures of variance as epistemic tools to generate knowledge about historical river flooding. The need for these epistemic tools would be apparent to the students and would arise naturally from their knowledge building. During the sensemaking process, students may critique how epistemic tools are used; for example, critiquing the choice of a particular measure of center in the context of the data. Detailed sketches of levees could also be used as an epistemic tool when students provide evidence for the most cost-effective levee. During macro-level integration, therefore, students make sense of when, why, and how to apply disciplinary knowledge and practices as they solve integrated STEM problems.

In summary, the sensemaking process occurs during all three levels of integration: micro-, meso-, and macro-level, but each level is different from the others in two distinct ways. First, as students experience micro-, meso-, and macro-level integration, there are temporal differences in how students may draw upon the knowledge resources they use during their sensemaking explanations. Micro-level integration describes the knowledge resources students use in the moment of grappling with a sub-problem. Meso-level integration describes the knowledge resources students coordinate across multiple sub-problems as they solve integrated STEM problems. Finally, macro-level integration describes the knowledge resources students draw upon from earlier in the school year or earlier grade levels. There is, therefore, a temporal aspect to students' potential knowledge resources during the sensemaking process.

Second, from the perspective of designing STEM curricula, there is a difference in the desired outcome of the students' sensemaking process during micro-, meso-, and macro-level integration. When students experience micro-level integration, the desired outcome of the sensemaking process is for students to figure out a sub-problem. During meso-level integration, the desired outcome of the sensemaking process is for students to develop new connections among the knowledge they generate from their solutions of the sub-problems across the activity. When students experience macro-level integration, the desired outcome of the sensemaking process is for students to develop their abilities to use disciplinary epistemic tools when they encounter STEM problems. Therefore, the intended instructional outcome for students' experiences with micro-, meso-, and macro-level integration is an important distinction among the three levels.

The Sensemaking Integrated STEM framework allowed us to design for the orchestration of students' experiences through the amalgam of sub-problems in our weather data investigation. It helped us think about how to design activities for students to have opportunities for micro-level integration, i.e., engage in the sensemaking process, about weather phenomena and weather data, opportunities for meso-level integration, i.e., making connections among the weather data activities, and opportunities for macro-level-integration, i.e., using ideas from mathematics class during sensemaking.

2.2 Explaining Variability

To inform our design and analysis of what students were making sense of during the weather data investigation, we employed the EV construct. Variability is omnipresent in the natural world, and describing and accounting for it is a key scientific practice to understand natural phenomena (Lehrer & English, 2018; Lehrer et al., 2020). This practice requires students to understand that variability is present in both the attribute itself and how that attribute is measured. Understanding how to characterize and account for variability is challenging for students (Lehrer et al., 2020; Watson et al., 2022)

Our research team, the IDP, has developed the EV construct to describe student thinking as they move from simply noticing variability and qualitatively describing it to the more abstract performances of quantifying variability and coordinating data and phenomenon to explain it (Table 4-1). Sixth-grade students, the participants in this study, are not expected to exhibit the highest levels of the EV construct, model distribution and model competition, because those levels are aligned with seventh-grade standards; therefore, those levels are not included in this table. For the entire EV construct, see Appendix 4-A.

Table 4-1

Explaining Variability Construct: Levels 1-4

Level	Student Performances	Example
EV 4: Difference Explained Students construct explanations that account for sources of variability. Students use data AND phenomenon to construct the explanation or include multiple variables.	Students: 4c: develop an explanation of a process or mechanism to explain variation.	I think the plants under the grow light would be the taller ones on the right side of the data display, but the ones on the edge of the light are on the left side.
	4b: Coordinate variation in a measured attribute with variation in another relevant attribute to partition data and explain variation in the measured attribute.	“Let’s make different graphs for samples inside the wild space and outside the wild space. Then we can see if there’s more clover inside or outside.”
	4a: build correspondence among measurement procedure, phenomenon, and data to explain variation	“I think the only way you’d get a measurement that low is if you used inches and the rest of the class used cm.”
EV 3: Difference Structured Students structure a collection of measures as a distribution and measure distributional features with statistics. Students rely on data only with no connection to the phenomenon.	Students: 3c: relate measures of variability that describe a distribution to events or processes	“The first fruit fly adults hatched 3 days before the last fruit fly adult, so the range was 4 days. 80% of the adults hatched on the second day of the hatching period.”
	3b: relate measures of center that describe a distribution to events or processes	“The median number of hairs on our collection of Fast Plants was 11.”
	3a: display measures of an attribute in a way that makes aggregate properties of the collection visible	“According to our class weather data, the bins with the typical temperature are 60 degrees to 69 degrees and 70 degrees to 79 degrees.”

	3a-: order measures to use aggregate properties of the collection	The Bermuda grass was the most, and dandelions were the least. The other one was in the middle.
EV 2: Difference Measured Students develop or appropriate a measure and apply it to a collection.	Students: 2c: question if reliable claims can be made with variable data	"There's no way to tell how tall the plants are because they all grew different heights."
	2b: anticipate variability in measurements (without structure)	"Even if we all measure the same plant, we won't get the same number just from our mistakes."
	2a: develop/appropriate a measure of an attribute and ordering the collection on that measure	"Four plants had true leaves on day 8, and five plants had true leaves on day 9, and one that sprouted died before it had true leaves."
EV 1 Difference Described Students describe qualitative differences in a collection.	Students: 1d: describe variation across different samples	These plants in the mowed area spread out but these plants in the wild space grow taller but don't spread out.
	1c: brainstorm or make initial conjectures about sources of variability	Maybe some of the plants got more sun or water, so they grew more.
	1b: observe/describe/draw qualitative differences in a collection	"Some of the Fast Plant seeds sprouted on day 2, some sprouted on day 3, and some didn't sprout at all."
	1a: do not expect variability	"If all those plants grow in the exact same conditions, they should grow to the same height."

Note. Adapted from "An Examination of Variability: Using Construct Measurement to Develop an Interdisciplinary Assessment, *"* by F.C. Scott, 2024, (Publication No. 31336083). [Doctoral dissertation, Middle Tennessee State University]. ProQuest Dissertations and Theses Global.

Students’ baseline thinking, level 1a, is not to expect variability in their data, e.g., “if all those plants grow in the exact same conditions, they should grow to the same height.” Above level 1a, students in EV levels 1b-1d notice and qualitatively describe variability. They begin to make conjectures to explain qualitative differences, i.e., “maybe some of the plants got more sun or water, so they grew more.” After students notice variability, they need to have opportunities to develop a way to quantify attributes of the phenomenon of interest. At EV Level Two, students quantify the phenomenon of interest by developing or appropriating a measure of an attribute and then ordering the collection on that measure. Students at EV Level 3 structure their measures as a distribution and notice aggregate qualities of their data, e.g., clumps or gaps. They begin to use statistics, e.g., measures of center and variability, to describe aggregate properties of their measures. At EV Level Four, students account for sources of variability in their explanations. In their explanations, students coordinate evidence from their data with evidence from the phenomenon they measured. They also coordinate variation across measured attributes to partition the data.

With these two conceptual frameworks in mind, we developed three design conjectures for the first iteration of the weather data investigation. We briefly describe them here and then illustrate how we used them in our design in the next section. First, students need opportunities to engage in sensemaking about variability in their local weather data during the investigation. As they engage in the sensemaking process, we conjectured that students would experience micro-level integration as they used resources of their prior knowledge, observations, and everyday experiences to notice gaps in their knowledge, brainstorm, connect their ideas, and develop explanations for variability in their data. Second, there should be opportunities for students to connect the knowledge resources they generated through sensemaking as resources to explain variability in subsequent sensemaking. We hypothesized that these opportunities would support students to experience meso-level integration as they *coherently* built on new knowledge as the weather data investigation unfolded. Finally, there should also be targeted opportunities for students to draw upon prior knowledge from their mathematics class as they made sense of variability in their weather data. We conjectured that these opportunities would support students to experience macro-level integration as they were encouraged to reach for ideas from mathematics as epistemic tools.

Specifically, through the enactment of our design, we sought to understand:

RQ1: How does engaging in the sensemaking process, i.e., micro-level integration, support students to explain variability in local weather data?

RQ2: How do students connect their knowledge resources, i.e., meso-level integration, as they make sense of variability in local weather data?

RQ3: How do students use epistemic tools from their mathematics class, i.e. macro-level integration, as they make sense of variability in local weather data?

3. Design of Weather Data Investigation

3.1 Context

This design study was part of a larger project, the IDP. This study occurred in a private school, La Flor School, in the southeastern United States (Table 4-2). At this small preK-8 school, there is one middle grade (6-8) mathematics teacher and one middle grade (6-8) science teacher. There are two classes for sixth-grade students, and, in Spring 2024, there were sixteen students in one class and seventeen students in the other. The names reported here for students, teachers, and the school are pseudonyms.

Table 4-2

La Flor School Demographics

	La Flor School
Setting	Private school pre-K through Grade 8
Enrollment	271
Student: Teacher Ratio	12:1
Student Demographics	69.7% White 20.7% Hispanic/Latino 3.7% Black or African American 3.3% Asian/Pacific Islander 2.6% Two or more races

Note. School demographic information is from the U.S. and World News Report (n.d)

The IDP team partnered with Ms. Quitman, the mathematics teacher, in January 2024 to introduce a curriculum for statistical mode-based inference to her and her students. The IDP team taught three statistical units on data displays, measures of center, measures of variability to both classes of sixth-grade students in February-March 2024.

We began work with our partner science teacher, Dr. Lahaina, in March 2024. Dr. Lahaina was in his second year of teaching at La Flor School. He expressed interest in having us develop a data investigation for his sixth-grade students.

The weather data investigation design addressed this middle grade Next Generation Science Standard (NGSS) performance expectation related to weather and the collection of data:

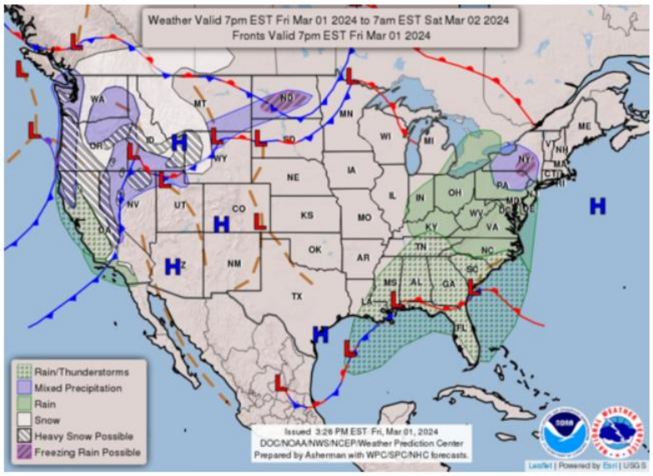
> MS-ESS2-5 Collect data to provide evidence for how the motions and complex interactions of air masses result in changes in weather conditions (NGSS, 2013).

We chose this standard for our design for three reasons. First, Dr. Lahaina was teaching about weather late in the Spring 2024 semester and he expressed interest in us developing a new investigation for his weather unit. Second, the IDP team had worked with another school partner where sixth-grade students collected weather data from a school weather station as part of their weather unit every year. Students collected daily temperature, humidity, pressure, and wind speed data but then did not use it for any further purpose. Based on this and our experiences with middle grade teaching, we reasoned collecting daily weather data was a common occurrence in middle grade classrooms and there was a need for developing an investigation in which students explored the data they collected.

Third, and more importantly, for students to authentically address this standard, there must be opportunities to grapple with explaining variability. Weather, unlike climate, is defined by its variability: weather at a given location is always changing over time. The clarification statement for this standard indicates that examples of data provided to students could be weather maps, diagrams, and visualizations or it could be from laboratory experiments (NGSS, 2013). This standard is often addressed with activities in which students look at weather maps of the United States (Figure 4-2).

Figure 4-2

Typical Way of Presenting School Weather Data



Note. Screenshot from the National Oceanic and Atmospheric Administration (NOAA) Weather Prediction Center (https://www.wpc.ncep.noaa.gov/noaa/noaa_archive.php?month=03&day=01&year=2024&format=gif&lang=english&cycle=00&reset=no)

But to make claims about changes in weather conditions using data as evidence, students need opportunities to explore sources of variability in weather variables like temperature, humidity, wind direction etc. at a fixed location across time. Exploring variability in this way requires students to use disciplinary ideas from science and mathematics class. Data always contains variability (Cobb & Moore, 1997) so students need to think about the variability inherent in any weather data and where that variability comes from. This standard asks students to use data as evidence and so students need to make sense of how to use data as evidence and what counts as good evidence. Students need to problematize how they could observe the motions of air masses through data and how that data shows the movement of air masses. In this standard, therefore, there is an amalgam of potential sub-problems for students to grapple with and connect ideas from science and mathematics class.

We developed the weather data investigation in March and April 2024. During the two weeks of instruction in science class in May 2024, the first author was the principal teacher of the weather data investigation. The principal investigator of the IDP was present and occasionally interjected questions and comments during whole group instruction. The first author, principal investigator, and Dr. Lahaina monitored and facilitated small-group instruction.

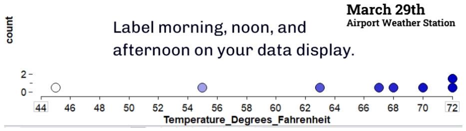
The weather data for this investigation came from an online website, Weather Underground (https://www.wunderground.com/), because La Flor School did not have access to a school weather station. This online service provides weather data from a large network of local personal and commercial weather stations, including ones near La Flor School. It provides weather data: temperature, humidity, wind speed, etc., at ten-minute increments. Weather data was collected from this website from March 1 to April 26, 2024, and entered in a spreadsheet by a member of the IDP team.

3.2 Design of Instructional Sequence

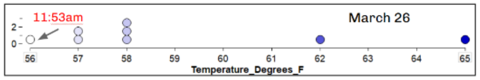
We designed five lessons for the weather data investigation to be taught across seven days. Table 4-3 provides an overview of our conjectures about how activities in our design provided opportunities for students to engage in the sensemaking process and how those activities also supported the students' development of explaining variability. In the following paragraphs, we explain our design as it was first enacted at La Flor School, describing how we designed for students to engage in sensemaking about variability, i.e., *micro-level integration*, connect their knowledge resources across lessons, i.e., *meso-level integration*, and need epistemic tools from mathematics, i.e., *macro-level integration*. We also describe how we supported the students to develop their explanations of variability, beginning with students observing variability (EV 1; Table 4-1), and ending with them constructing explanations for variability (EV 4; Table 4-1). The instructional materials we developed, e.g., student handouts, formative assessments, and slides, can be found in Appendix 4-B.

Table 4-3

Weather Data Investigation

Activity	Opportunities for Sensemaking	Opportunities for Explaining Variability
Lesson 1 **How do we describe and measure weather?** (1 day)	Students begin creating a shared knowledge framework of what they know about the weather and how to measure it.	Students make qualitative observations about the weather (EV 1b) and discuss how to quantify observed qualities (EV 2b).
Lesson 2 **What's the temperature?** (1.5 days)	Students notice different temperatures are reported for the same moment in time in their town. They brainstorm explanations, sources of variability, for what may affect the temperature (*micro-level integration*). Students use ideas from mathematics, making data displays and using measures of center, to figure out the temperature for their town (*macro-level integration*)	 April 22nd at 9:45am Students notice variability in temperature data (EV 1b) and create a data display to provide evidence for a single temperature that should be reported on a weather app (EV 3). Students match sources of variability with locations on a data display (EV 4a)
Lesson 3 **What's typically the warmest part of the day?** (1.5 days) .	 Students figure out why noon is not the warmest part of the day (*micro-level integration*) as they make claims about the mechanism, i.e., heat transfer, that causes the temperatures to vary across the day. They make connections between the weather and a physical model of radiation, convection, and conduction (*meso-level integration*).	 **March 29th** Airport Weather Station Label morning, noon, and afternoon on your data display. Students notice variability in temperature data across a school day (EV 1b) and develop explanations about the mechanisms for this source of temperature variability (EV 4c)

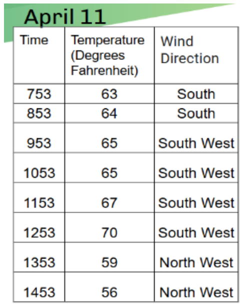
Lesson 4
What other factors influence the temperature during the day? (1.5 days)
.



What is going on here??

Students make sense of two discrepant events in their local temperature data (*micro-level integration*).

They connect information about air masses (video given as homework), cloud cover, and precipitation to differences in temperature data across the day (*meso-level integration*).



April 11

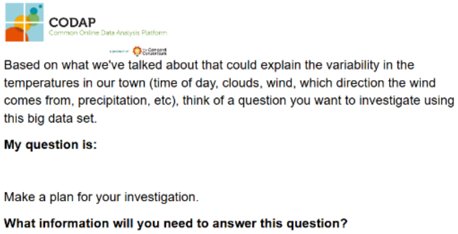
Time	Temperature (Degrees Fahrenheit)	Wind Direction
753	63	South
853	64	South
953	65	South West
1053	65	South West
1153	67	South West
1253	70	South West
1353	59	North West
1453	56	North West

Students notice variability in other weather variables (EV 1b) and use their observations to coordinate variability in temperature with differences in cloud cover, precipitation, and wind direction data (EV 4b).

Lesson 5
In our town, what factors influence the temperature in the Spring? (1.5 days)

Students use sources of variability discussed throughout the investigation, e.g., time of day, cloud cover, precipitation, wind direction (*meso-level integration)* to make sense of a large data set of local weather variables.

They create data displays and use statistics as epistemic tools to help answer their question (*macro-level integration*).



Based on what we've talked about that could explain the variability in the temperatures in our town (time of day, clouds, wind, which direction the wind comes from, precipitation, etc), think of a question you want to investigate using this big data set.

My question is:

Make a plan for your investigation.

What information will you need to answer this question?

Students investigate their own weather question by creating a data display using CODAP (EV 3) and partition the data to make claims about how variables of their choosing affect temperature data in the Spring (EV 4b).

3.2.1 How Do We Describe and Measure Weather?

Students began our weather data investigation by walking outside and writing down their descriptions of the weather at that moment. We planned this as our first activity for two reasons. First, we anticipated that these qualitative observations would support students to connect weather variables like temperature, humidity, precipitation, cloud cover, and wind speed to their own everyday experiences of being outdoors and experiencing the weather. As we discussed their descriptions of the weather, we listed their ideas on chart paper. We conjectured that this initial activity would begin the creation of a shared class knowledge framework of the qualities used to describe the weather, the preparatory step in the sensemaking process, that we could build on and refer to across the unit.

Additionally, we expected students would share conflicting qualitative descriptions of the weather, i.e., "It was cool outside," "I thought it was warm." We wanted to support students to notice the variability in their weather descriptions, i.e., observing differences in a collection (EV level 1b; Table 4-1), and to provoke a discussion about how to quantify the quality of feeling the air temperature with their bodies that the students experienced outside (EV 2a; Table 4-1). To build on this discussion, we used different tools to measure the temperature at that moment in the classroom: a Galileo thermometer, radial thermometer, mercury thermometer, and digital thermometer. We conjectured this discussion would support students to anticipate variability from the use of different measurement tools (EV 2b; Table 4-1). We explicitly referenced an activity from their mathematics class several months prior, when the students measured an object with two different measurement tools, to connect the idea of measurement error they experienced in mathematics class with the measurement of weather variables in science class.

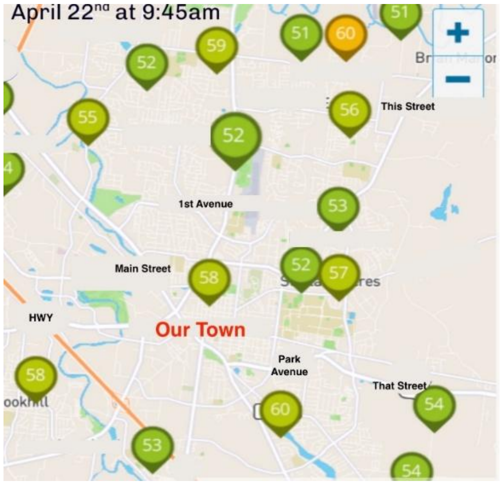
3.2.2 What's the Temperature?

We began this lesson by showing students a picture of a personal weather monitoring station and asking students if anyone had one at home. We explained that the data they would be working with came from a website, the Weather Underground, that collected information from these types of personal weather stations. Because students had not actually collected the data they were going to work with during the investigation, we wanted to be certain students understood where their data came from.

We then showed students a screenshot from the Weather Underground that contained temperature data from around their school at a single point in time and asked them to share what they noticed (Figure 4-3). We wanted to give students an opportunity to create a shared knowledge framework, i.e. step zero in the sensemaking process, by voicing their observations about this new representation of temperature data. We hoped students would notice the range of values, the different colors in the display, and aspects of the map of their town, i.e., the street names and bodies of water.

Figure 4-3

Lesson Two: Example of Temperature Data Shown to Students



Note. Adapted from a screenshot taken from the weather app, Weather Underground (https://www.wunderground.com/).

We anticipated students would notice the temperature measurement of 51 near the measurement of 60 (Figure 4-3). The proximity of these two measurements highlighted a puzzle for the students to make sense of: how could the temperature be 51 and 60 at that location at the same time? We conjectured this question, coming from students' observations, would support students to enter into the sensemaking process, i.e., step one in Figure 4-1. This question then led to students brainstorming possible sources of variability, the second step in the sensemaking process (Figure 4-1). We noted student ideas about possible sources of variability on chart paper because we wanted to further develop this prior knowledge, written in the students' own words, and connect it to conventional science explanations for generating weather patterns. As students experienced micro-level integration in this activity, we hoped students would begin to make connections between observing differences in data values and conjecturing about the mechanisms or phenomena that created them.

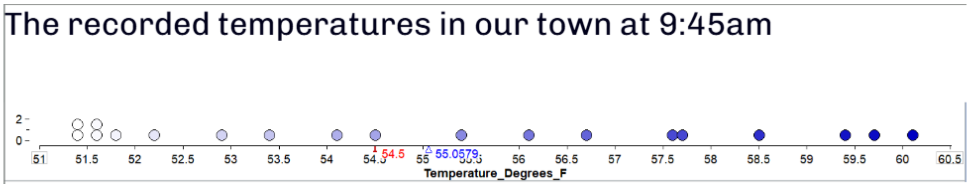
Next, students made a claim about what temperature should be reported as the temperature for that specific time on a weather app. Dr. Lahaina told us that the students were not familiar with claim, evidence, reasoning activities so we planned to explicitly introduce those terms to the students. We also provided some sentence stems on the student handout to support students to complete this activity (see Appendix 4-B).

This activity was an opportunity for students to experience macro-level integration as they connected ideas from mathematics class they experienced several months prior to providing evidence and reasoning for their claim in science class. Artifacts such as creating data displays and calculating measures of center become epistemic tools through their use in specific contexts (Kelly & Cunningham, 2019). Therefore, we wanted to build correspondence with an earlier actvity in the students' mathematics class in which they all independently measured the same object and then were asked to make a claim about the true length of the object. In this mathematics activity, students created their own data displays of the measurements and then discussed how qualities like order, count, bins, and scale emphasized certain aspects of the data. They used statistical tools, i.e., measures of center, to provide evidence for their claim of the true length of the object. In our weather data activity, students did the same type of thinking: using variable measurement data to create their own data display and then make a claim for the true temperature of the town. By asking students to make a claim about a single temperature that should be reported on their phone app, we intended that students would see a need for using the measures of center as an epistemic tool to provide evidence for their claim. We also hoped students would not all choose the same measure of center as their evidence so students could discuss the mathematical reasoning behind their choice.

For the final activity in this lesson, students looked at the temperature data at a single moment in time as a dot plot (Figure 4-4). Students were familiar with dot plots from their mathematics class. Using the list of sources of variability students generated at the beginning of the lesson, we asked them to make a claim about where they would find each source on the dot plot; for example, where did they expect the weather stations that were in the shade to be on the data display? Students did a similar activity in mathematics class in which they made claims about where sources of measurement error, e.g., using the inch side of the ruler instead of the centimeter side, corresponded to locations on their data display. We conjectured this activity in science supported students to begin explaining variability by building correspondence between the phenomena, i.e., factors that affect temperature such as clouds, proximity to asphalt, etc., and the temperature data they observed (EV level 4a; Table 4-1).

Figure 4-4

Lesson Two: Dot Plot of Temperatures at a Single Moment in Time

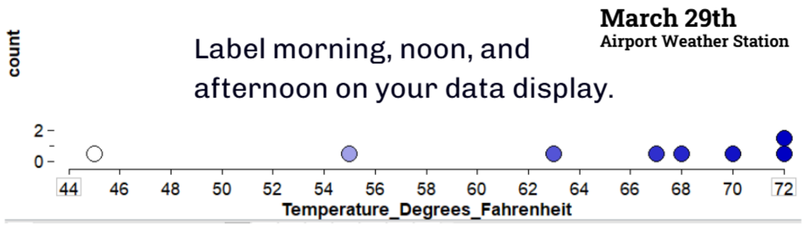


3.2.3 What's Typically the Warmest Part of the Day?

To start this lesson, students would be given a dot plot of temperature measurements across a school day and asked to label morning, noon, and afternoon (Figure 4-5). On their handout, we would ask them: "What caused all this variability?". Students were to do this individually and then we planned to have a whole-class discussion. We chose this representation of the temperature data rather than a more typical temperature across time graph because middle grade students do not study bi-variate graphs until seventh grade, and because students were already familiar interpreting and creating dot plots from their mathematics class.

Figure 4-5

Lesson Three: Dot Plot of Temperatures Across the Day at a Single Location



We chose this activity because we wanted to continue to support students to think about how data corresponds to a phenomenon, and because thinking about the variability of the temperature across the day is an entry point to explaining mechanisms of heat transfer (EV 4c; Table 4-1). Students often think that noon is the warmest part of the day because they learn that the sun is at its highest position in the sky at noon, and we anticipated some students would label the highest temperatures on the dot plot as noon. We also anticipated some students would claim afternoon is the warmest part of the day because of their everyday experiences with warm temperatures after school.

We expected most students to say that the sun caused the variability of temperatures across the day, but we did not think most students would discuss the mechanism. On a typical sunny day, the warmest temperatures of the day on Earth's surface are in the afternoon due to the combination of heat transfer from radiation, conduction, and convection.

Dr. Lahaina had discussed mechanisms of heat transfer with his students a few weeks prior to the weather data investigation, and we wanted students to experience meso-level integration by connecting a physical model of these mechanisms with increases in temperature across the school day. We created this physical model to represent the sun heating up the Earth (Figure 4-6). In this model, we used an incandescent light bulb to represent the sun and a tray of potting soil to represent the ground. We used an infrared thermometer to take temperature readings of four metal disks: two disks, one painted black and one silver, on the soil under the light to represent heat transfer through radiation, one in the air above the light to represent heat transfer through warm air rising, i.e., convection, and one on the counter that we moved onto the soil to represent heat transfer through conduction. We included a black disk because we anticipated students would claim one of the sources of variability for temperature would be weather stations near dark asphalt.

Figure 4-6

Lesson Three: Physical Model of Heat Transfer

Before we turned on the light, we took a temperature reading of each disk to represent nighttime when we expected no differences in temperature. We then turned on the light and took the temperature every two minutes for a total of ten minutes. We hoped this physical model would make the heat transfer mechanisms more concrete for the students and help them connect the variability of the temperature data across the day with the mechanisms of radiation, conduction, and convection (EV 4c; Table 4-1).

Students explained the variability in temperatures across the day by drawing their own explanatory models. Students explained their own models to others and then we discussed them as a whole class. This discussion provided evidence about how students were experiencing meso-level integration as they connected the physical model with their own ideas about mechanisms of heat transfer.

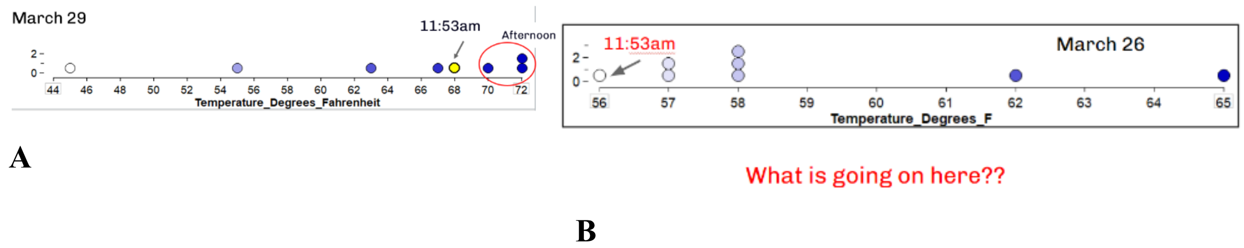
As an exit ticket for this lesson, we developed a formative assessment to gather information about students thinking about temperature variability and heat transfer (see Lesson 3 Formative Assessment in Appendix 4-B). This assessment explained a scenario in which two students disagreed on their interpretation of where noon should be located on a dot plot of temperature data. Students were asked to indicate which student they agreed with and explain, in terms of heat transfer and weather, why they agreed with that particular student.

3.2.4 What Other Factors Influence the Temperature During the Day?

We started this lesson by showing students a dot plot of temperature data when noon was the coldest temperature of the school day and asking them to report what they noticed (Figure 4-7B). We conjectured students would use the resources they generated in the previous lesson, e.g., the Earth typically gets gradually warmer across the school day, noon is not the coolest temperature of the day, to consider these data as a discrepant event. A discrepant event is a situation that is inconsistent with what one would expect (Gonzalez-Espada et al., 2010; Wright & Govindarajan, 1992), and we hoped students would find this dot plot inconsistent with their shared knowledge framework, i.e., step one in the sensemaking process. We designed this activity as a moment for both students' meso-level integration and micro-level integration. As students experienced meso-level integration, we conjectured they would use the resources they developed in the previous lesson to recognize a gap in their understanding, and this moment would also support students to be in the sensemaking frame as they began to figure out this inconsistency.

Figure 4-7

Lesson Four: Conflicting Dot Plots

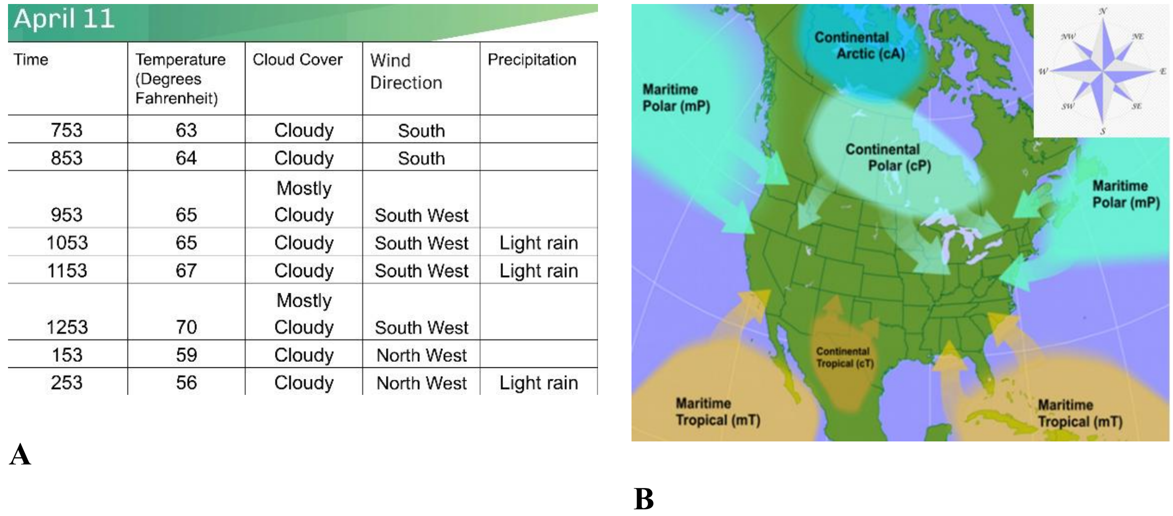


We anticipated students would begin brainstorming ideas, e.g., precipitation, cloud cover, wind speed, to explain why noon was the coldest temperature of the school day; therefore, we prepared a table of the actual data for these variables in advance so that they could use that data as evidence for their claims (see instructional materials in Appendix 4-B). We hoped our discussion of these other weather variables would support students to notice their variability (EV 1b) and use their observations to coordinate variability in temperature data with differences in cloud cover and precipitation (EV 4b, Table 4-1). We conjectured students would experience meso-level integration later on in the weather data investigation as they used some of the sources of variability generated by this activity to design their own weather data mini-investigation in Lesson 5 (Table 4-3).

Next, we showed students another discrepant event in their weather data: a day when the afternoon was not the warmest part of the day (Figure 4-8A). This activity was another opportunity for students to experience meso-level integration and micro-level integration. In the previous discrepant event, when noon was the coldest temperature, precipitation and cloud cover were likely explanations for that weather pattern. We wanted students to test those explanations using these data (Figure 4-8A) and see that cloud cover and precipitation were similar during the warm and cool parts of the school day.

Figure 4-8

Lesson Four: Connecting Temperature Data with the Movement of Air Masses



April 11

Time	Temperature (Degrees Fahrenheit)	Cloud Cover	Wind Direction	Precipitation
753	63	Cloudy	South	
853	64	Cloudy	South	
953	65	Mostly Cloudy	South West	
1053	65	Cloudy	South West	Light rain
1153	67	Cloudy	South West	Light rain
1253	70	Mostly Cloudy	South West	
153	59	Cloudy	North West	
253	56	Cloudy	North West	Light rain

A

B

Note. Image in panel B adapted from materials from Penn State Department of Meteorology and Atmospheric Science, Lesson 3: Global and Local Controllers of Temperature (https://courses.ems.psu.edu/meteo3/l3_p5.html).

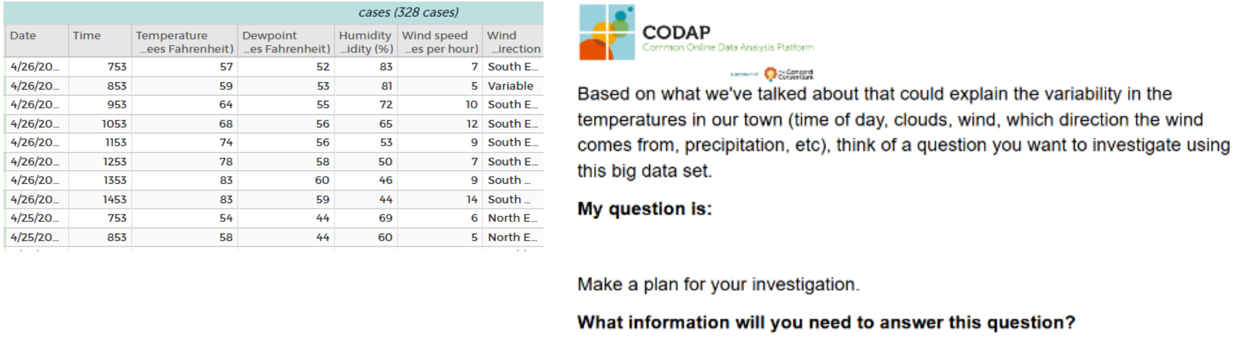
We also expected the students to notice the change in wind direction when the cooler temperatures occurred. We conjectured this would support students to use their observations to coordinate variability in temperature with differences wind direction (EV 4b; Table 4-1). Next, we showed students a map of the air masses that affect the weather in the United States and asked students to describe terms like “polar” and “maritime” in their own words (Figure 4-8B). Then, we posed the question, “which air mass might have moved into our town?”. Earlier in the week, we assigned students to watch a short video about air masses and their movements. We hoped to support students to make a connection between the change in wind direction with the movement of an air mass and how that change could be observed in the temperature data. This activity directly addressed the NGSS (2015) standard that asks students to collect data to provide evidence for how the movements of air masses can change weather conditions.

3.2.5 In Our Town, What Factors Influence the Temperature in the Spring?

Our final lesson in the weather data investigation asked the students to think about all the sources of variability that affected the local temperature data we had discussed in the previous lessons. Then, they used a large set of local weather variables collected in March and April, to design their own data investigation using CODAP, an online data analysis platform (Figure 4-9). Previously, students had been introduced to CODAP in their mathematics class.

Figure 4-9

Lesson Five: Exploring Your Own Question Using Local Weather Data



cases (328 cases)

Date	Time	Temperature …ees Fahrenheit)	Dewpoint …es Fahrenheit)	Humidity …idity (%)	Wind speed …es per hour)	Wind …irection
4/26/20…	753	57	52	83	7	South E…
4/26/20…	853	59	53	81	5	Variable
4/26/20…	953	64	55	72	10	South E…
4/26/20…	1053	68	56	65	12	South E…
4/26/20…	1153	74	56	53	9	South E…
4/26/20…	1253	78	58	50	7	South E…
4/26/20…	1353	83	60	46	9	South …
4/26/20…	1453	83	59	44	14	South …
4/25/20…	753	54	44	69	6	North E…
4/25/20…	853	58	44	60	5	North E…

Based on what we've talked about that could explain the variability in the temperatures in our town (time of day, clouds, wind, which direction the wind comes from, precipitation, etc), think of a question you want to investigate using this big data set.

My question is:

Make a plan for your investigation.

What information will you need to answer this question?

Students developed their investigative question and thought about the data they would need to answer it before they had access to CODAP. We hoped this would help students focus their attention on the relationship between their question and the sources of variability we had discussed. In this activity, we conjectured students would experience meso-level interaction because they could use the weather ideas we developed earlier, e.g., cold air masses move into our local area, precipitation affects temperature, as a knowledge framework to develop their investigative question and make their claim.

We also planned this activity to be an opportunity for students to experience macro-level interaction. Using CODAP, students created a data display (EV 3; Table 4-1) and made claims about how variables of their choosing affected the temperature in the Spring (EV 4b; Table 4-1). We hoped students would use CODAP data visualization and measures of center tools as epistemic tools to organize, structure, and explain variability in a large data set.

4. Methods

4.1 Data Sources

For each day of instruction, we video-recorded the classroom activities during the weather data investigation. We set up one video camera to capture whole-class discussions and activities and to record any slide presentations or information written on the board. A member of the IDP team transcribed the audio from these recordings using the qualitative data analysis software, MaxQDA. The transcriptions were checked by the first author for accuracy and completeness.

We also collected student artifacts, e.g., hand-written and digital data displays, student handouts, and formative assessments, from all students to serve as additional data sources. We anonymized all students' work, and then we digitized these artifacts and returned them to Dr. Lahaina.

4.2 Analysis

The first author began the analysis by watching video recordings of each lesson. Brief analytic memos (Saldaña, 2009) were written for each video to characterize the classroom activities and discourse by noting patterns of discourse, the content of the discourse, and the activities of the students and teacher (Carlsen, 1991). These analytic memos allowed us to get a broad understanding of what was occurring in the classroom during each lesson.

Next, the first author began an inductive analysis of the video recordings and the students' artifacts. In our initial design conjectures, we hypothesized our design of this weather data investigation would support students to engage in the sensemaking process about variability, connect knowledge resources, and use epistemic tools from mathematics. Therefore, the first author looked for evidence of these design conjectures in students' classroom discourse and in students' work (Sandoval, 2014). For example, when students are engaging in the sensemaking process, they are sharing and exploring multiple ideas and multiple students are contributing to the discourse (Lowell et al., 2022; Scott et al., 2006); therefore, we targeted those instances we found in the classroom discourse to understand how the lesson activity, teacher discourse, and student responses interacted. We specifically designed lessons three, four, and five (Table 4-1) to support students to connect knowledge resources across lessons. Therefore, we inductively analyzed the knowledge resources students used and how they used them in their classroom discourse and their artifacts. Finally, we conjectured that students would use the mathematical ideas of order, count, grouping, scale, and measures of center we had introduced to them two months prior as epistemic tools to generate knowledge. Therefore, we sought to understand how students were using these ideas in their classroom discourse and artifacts in response to the lesson activities. We looked across both classes to determine the relative frequency of students' ideas. For our findings, we used our analyses to develop a narrative account to describe how students responded to each of our initial design conjectures.

5. Findings

For this weather data investigation, we developed three initial design conjectures: (a) students need opportunities to engage in the sensemaking process about variability, (b) students need opportunities to connect the knowledge resources they generated through sensemaking to explain variability, and (c) students need targeted opportunities to draw upon prior knowledge from their mathematics class to make sense of variability. In this section, we share how students responded to these sensemaking opportunities as they explained variability in their local weather data and what we have learned during the first iteration of this weather data investigation. Rather than presenting our findings in the order of our instructional sequence, we present our findings using three themes that correspond with our design conjectures: *how students engaged in sensemaking about variability*, *how students connected resources generated by sensemaking to explain variability*, and *how students used epistemic tools from mathematics to explain variability*. We briefly summarize our findings here, and then we describe them in greater detail by providing examples of classroom discourse and student artifacts.

We designed our activities so that students would have opportunities to make sense of variability in temperature values in each lesson (Table 4-3). As they engaged in the sensemaking process, we conjectured that students would experience micro-level integration when they used resources of their prior knowledge, observations, and everyday experiences to notice gaps in their knowledge, brainstorm, integrate their ideas, and develop explanations for variability in temperature values. We found students responded to our designed opportunities for sensemaking by brainstorming ideas, building upon other students' contributions, and, very infrequently, critiquing other students' ideas. Looking at students' sensemaking explanations across the investigation, students integrated variability in temperature data with ideas of weather phenomena: wind, wind direction, precipitation, shade, clouds, the position of the sun, and length of time the sun shines. To a lesser extent, students integrated variability in temperature data with the heat transfer mechanisms of radiation, conduction, and convection. In their sensemaking explanations, we also saw students integrating variability in temperature data with prior experiences of how vehicles measure the temperature and their own daily activities.

In our design, we wanted students to coherently build on their new knowledge about explaining variability in temperature data as the weather data investigation progressed. Therefore, we designed opportunities for students to experience meso-level integration so that students could connect the resources they generated through the sensemaking process across different activities. We found supporting students to coordinate and connect ideas about variability across the activities was challenging. For example, we planned in our design to connect students' ideas about when the warmest part of the day occurred with data generated from a physical model of the mechanisms of heat transfer (Lesson Three; Table 4-3). It was challenging to help students coordinate their ideas about variability across the different types of models: the variability in temperatures shown on the dot plot and the variability of the temperature data of the representations in the physical model. Furthermore, it was difficult to support students to connect the variability in temperatures across the day to the relationships of radiation, convection, and conduction in their explanatory model. Discussing these ideas with students took longer than we anticipated.

Lastly, we designed targeted opportunities for students to draw upon prior knowledge from their mathematics class to make sense of the variability in their local weather data. These opportunities for students to experience macro-level integration would guide them to reach for ideas from mathematics as epistemic tools to support their generation of new knowledge. We found students used some mathematical concepts in science as epistemic tools to organize and structure the variability in temperature values in their pen-and-paper data displays. For example, students created a variety of data displays by ordering the values and indicating their frequency. They used the mode, and to a lesser extent, the mean and median, to determine the most typical temperature value. Students continued to invent measures of center, a practice that was encouraged in their mathematics class, by using a combination of calculated values for mode, mean, or median, as a way to communicate the most typical value. In their writing and discourse, there was evidence that students viewed these mathematical ideas as epistemic tools because students explained how data displays and their measures of center told them something or helped them figure something out. When students used technology, i.e., the online data analysis platform, CODAP, it was less obvious how they used ideas from mathematics class to connect their data work with explaining a weather phenomenon.

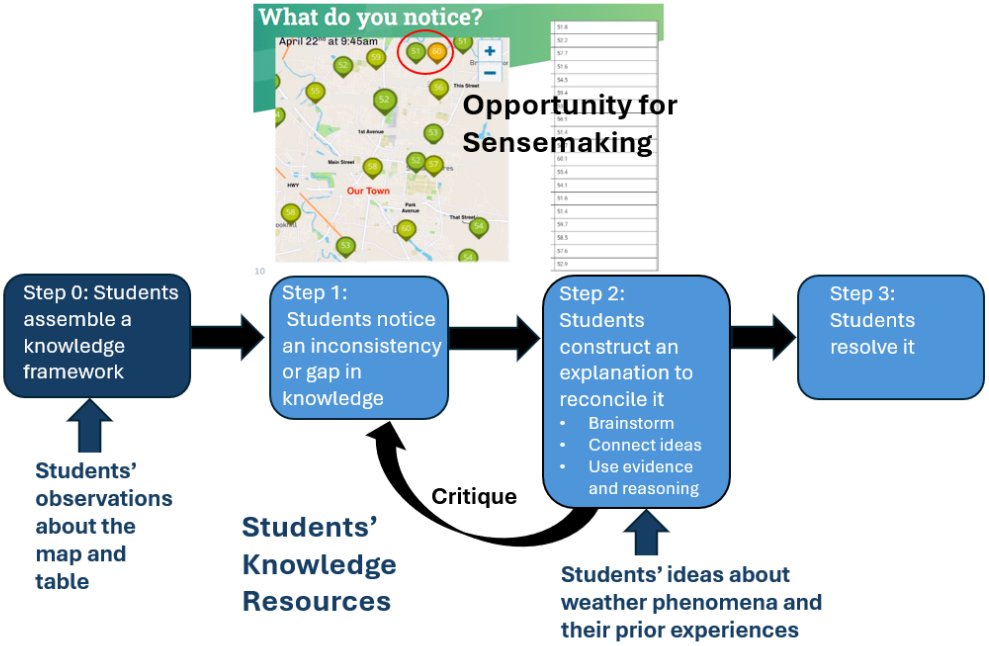
5.1 How Students Engaged in Sensemaking About Variability

We designed several opportunities for students to engage in sensemaking about variability in temperature data. Students developed an explanation for why similar locations at a single moment in time could have different temperatures (Lesson Two; Table 4-3). They figured out why temperatures varied across the school day and why noon was not the hottest part of the day (Lesson Three; Table 4-3). Lastly, students developed explanations for two different discrepant events to figure out why afternoon temperatures were colder than morning temperatures (Lesson Four; Table 4-3). During these lessons, we conjectured students would experience micro-level integration as they used resources of their prior knowledge, observations, and everyday experiences to notice gaps in their knowledge, brainstorm and then develop explanations for the variability in their temperature data.

In this section, we use several transcripts from one of these lessons, when students observed the temperature data in their town at one moment in time (Lesson Two), to describe how students engaged in the sensemaking process (Figure 4-10). First, students created a shared knowledge framework about the temperature data by verbalizing their observations of the map and data table (step zero; Figure 4-10). The instructor then used one of the students' observations to highlight a puzzle, i.e., step one in the sensemaking process. In response, students began to develop an explanation by making connections between the variability in the temperature data and their knowledge of weather phenomena and prior experiences.

Figure 4-10

Micro-Level Integration: The Sensemaking Process

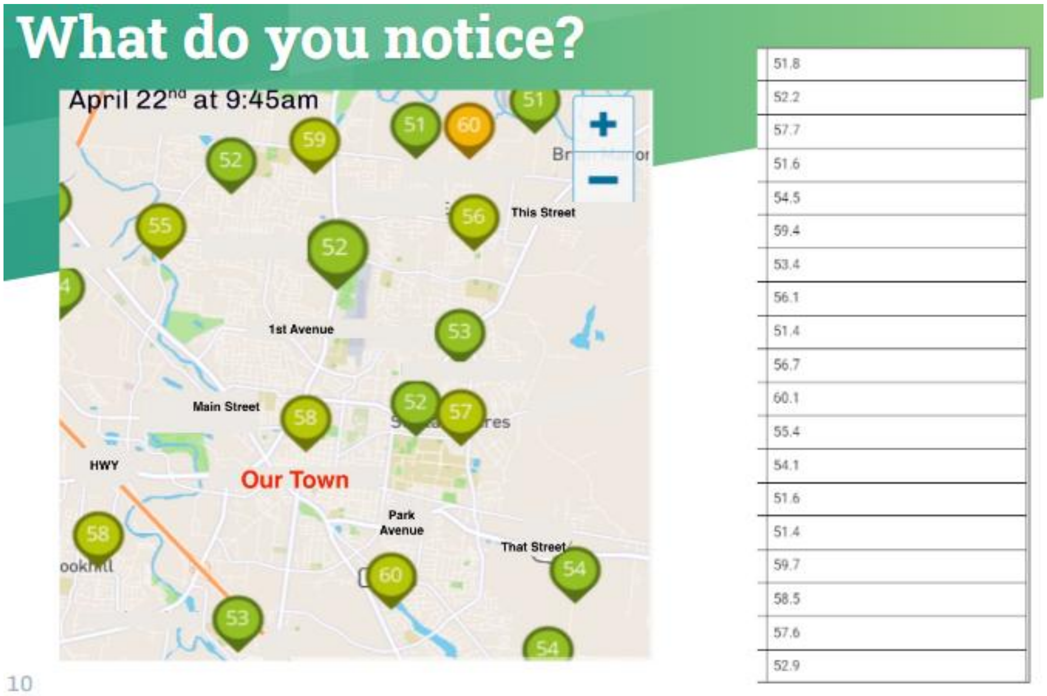


5.1.1 Noticing Variability

We began Lesson Two by showing students a screenshot of the weather station temperatures for their town at a single moment in time next to a table of the data (Figure 4-11). Students thought about what they noticed, shared their observations with their table group, and then they shared their observations in a whole class discussion.

Figure 4-11

Lesson Two: "What's the Temperature?" Slide



What do you notice?

April 22nd at 9:45am

51.8
52.2
57.7
51.6
54.5
59.4
53.4
56.1
51.4
56.7
60.1
55.4
54.1
51.6
51.4
59.7
58.5
57.6
52.9

Note. Adapted from a screenshot taken from the weather app, Weather Underground (https://www.wunderground.com/). The names of the weather stations have been removed from the table on the right to protect the privacy of the participants.

Students began by creating their shared knowledge framework as they talked about their observations and ideas (Table 4-4). One of their observations led Mrs. K, the instructor and first author, to highlight a puzzle in the temperature data. This discourse move invited students to begin the sensemaking process.

Table 4-4

Lesson Two: Students' Observations About the Temperature Map

Row	Speaker	Discourse
1	Mrs. K:	Alright, let's hear some things that you have noticed up here and maybe some questions you have because I heard some questions too out there about this. I would like some people who I have not heard from this morning. So, what have you noticed? Samara?
2	Samara:	*All of them are in the 50's or 60's*
3	Mrs. K:	Okay, so all those numbers are in the 50's and with a 60 in there, 50 or 60. What do you think those numbers mean? That was your question, Savannah, wasn't it?
4	Savannah:	*Well, I was confused because like it, like where it says like our town in your list says 51.8 but the spot right where, like right near where it says our town says 58 instead of 51 so.*
5	Mrs. K:	Oh, okay alright, so you were noticing how on the right side [the weather station table of values]
6	Savannah:	*There was one temperature, but it was different from the other one.*
7	Mrs. K:	So, I see that. I will tell you these blue [pointed to the data table], those are the weather stations, but we might not necessarily know which station is which one so [pointed to the map].
8	Savannah:	*So, well, I know, I'm talking about like how there's like a 50 or 52 next to the blue, but then it looks like on the map with all those like, what are the little like pink points with the numbers on it?*
9	Mrs. K:	So, these are the locations of those weather stations, and what do you think, so this number 58 can we find a number that maybe rounds to 58 over there?
10	Savannah:	*58.5*
11	Evan:	*You got 57.7 at number three.*
12	Mrs. K:	So, we have this one, do we have any other ones?
13	Student:	*There's also a 58.5 around* [unintelligible].
14	Mrs. K:	58.5
15	Student:	*58.5, 57.6, 59.7*

16	Mrs. K:	Yeah, so there’s a 58 here there’s a 58 there and so we don’t know if this weather station [pointed to data table]is this 58 [pointed to map] or it could be that 58. Evan?
17	Evan:	*Um, so what I noticed is that like you have this golden 60 but then the other ones are not really golden.*
18	Mrs. K:	Oh yeah, why do you think that is?
19	Evan:	*Because, well those two temperatures looked like they were tooken [sic] on the same street.*
20	Mrs. K:	These two right here? [pointed to map]
21	Evan:	*Yeah.*
22	Mrs. K:	Yeah. How can that happen? How could you have the temperature at 9:45 on April 22nd in our town be 51 and 60 at the same time?
23	Evan:	*Wind. Wind made it, like cause on the weather app you just like open it and you're like 'oh it's 45 degrees' but if you go down a little it says 'but the wind makes it feel like it's like 36’. Well, what if the, what if it was actually 60 but the wind made it feel like it was 51?*

Note. In this table and in subsequent transcript tables, student discourse is italicized. Information in brackets was added by the authors to give information about the context of the discourse. If speakers’ utterances overlapped, they are shown in parentheses.

When students were asked what they noticed, they shared observations about the values on the map (row 2), the values in the weather station table (row 4), the colors on the map (row 17), and the locations of the values (row 19). They also shared their ideas about how the values on the map corresponded with the values in the weather station table (rows 6-16). Both classes shared similar observations and ideas.

Before students can explain variability, they must first be able to notice it (EV level 1b; Table 4-1). This activity guided students to share their observations about the variability they noticed in the temperature values and the representation of them, e.g., the different colors on the map, the correspondence between the map and the table. Through this sharing, students verbalized their knowledge framework of what they knew about the data. The creation of this collective knowledge framework is a necessary step before the sensemaking process can begin (Odden & Russ, 2019a).

In our plan for this lesson, we hoped students would notice the difference in temperature values near one another. Evan shared an observation about the proximity of the values (row 19; Table 4-4) and students in the second class made similar observations and comments. Mrs. K then used these student observations to highlight something that students might want to figure out and, therefore, invite them to enter into the sensemaking process (row 22, Table 4-4).

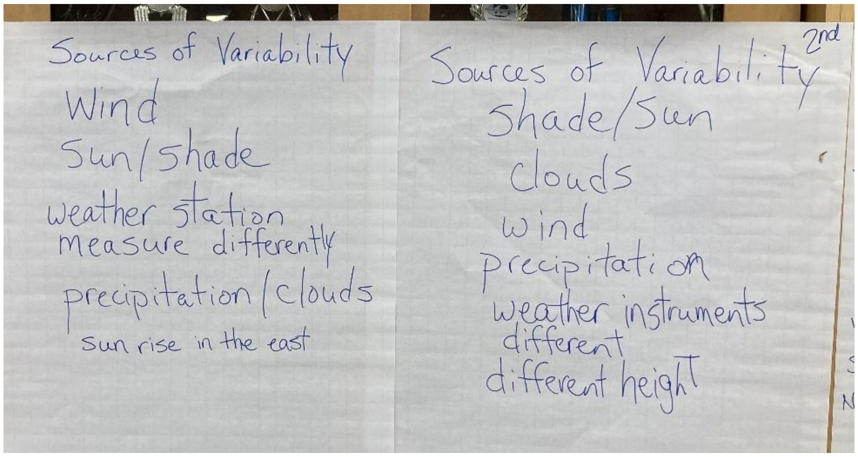
5.1.2 Connecting Variability in Temperature Data with Phenomena and Prior Experiences

After students were invited to engage in the sensemaking process, they started to brainstorm possible explanations for the differences in temperature values (row 23; Table 4-4). As they did so, this activity provided an opportunity for micro-level integration to occur as students connected the variability in temperature data with their knowledge of phenomena and their knowledge from their own prior experiences.

This activity supported students to brainstorm initial conjectures about sources of variability in the temperature values (EV level 1c; Table 4-1). Students in both classes connected differences in temperature data with the phenomena of differences in wind, amount of sun or shade, precipitation, clouds, altitude, and the position of the sun (Figure 4-12).

Figure 4-12

Students' Ideas About Sources of Variability in Temperature Data



Sources of Variability
Wind
Sun/shade
weather station measure differently
precipitation/clouds
sun rise in the east

2nd
Sources of Variability
Shade/Sun
clouds
wind
precipitation
weather instruments different
different height

In Tables 4-5 and 4-6, we show how Evan added on to another student's idea and then connected the variability in temperature values with the sun's position in the sky. Next, other students worked to understand and critique his claim. Evan's claim was that the temperatures values that are on the right side of the map are greater than the ones next to them on the left side because the sun rises in the east.

Table 4-5

Micro-Level Integration: Connecting Variability in Temperature Data with the Sun's Position

Row	Speaker	Discourse
1	Evan:	*. . . Wait! I think Elena's right about the sun thing because, if you, if you look at, if you look at it from the way I'm looking at it, it kind of looks like 6 is more up than 51 but just by a slight difference. Then 57 is down, so what if, like, one was behind the house where the sun was or one [voice trailed off] Wait, so it's 9:50 a.m.?*
2	Mrs. K:	9:45 in the morning, uh huh.
3	Evan:	*57 would get more sun.*
4	Mrs. K:	So, you think based on their location.
5	Evan:	*Yeah.*

6	Mrs. K:	Mhm, so if we imagine this is the East where the sun rises, this is the West [pointed to the map].
7	Evan:	*And I think 60 is yellow because it got the most sun.*
8	Mrs. K:	Oh. Okay.
9	Dr. J:	Does everyone, I want to make sure everyone understands what Evan is saying. Could someone else say what Evan is describing and if he's right, what would be kind of, what would we expect to see on that map? Mrs. K, yeah you pick who, I just wanted to hear someone else say what Evan was saying.
10	Linda:	*Um, I think Evan's saying like that the golden 60 right there since it's bright yellow-ish that it is going to have more sun and uh since there is like two shades of green.*
11	Student 2:	*Yeah, I was going to ask if green counts.*
12	Mrs. K:	Two shades of green.
13	Savannah:	*The higher numbers are like a more lime green and the lower numbers are more of a moss green.*
14	Mrs. K:	Okay, alright. Is that what Evan is saying? I think Evan has a claim.
15	James:	*But like, how Evan is saying, how the 60 is yellow, and it means it must be getting the most sun. The higher numbers will be brighter colors than some of the lower numbers, so like 52 has a green and 58 has more of a yellowish green so it is showing how much sun it got with the color.*

Evan started by adding on to what Elena said about the variability in temperatures two minutes earlier. Elena previously said, “So, it's like the sun. So, if they take the temperature at a house and the house is blocking the sun in their backyard then it will be cooler then if it was, like, right out, and the sun was, like, hitting it directly.”

Here, Evan agreed with Elena's explanation of sun and shade differences, and he started to explain the evidence he saw in the temperature data on the map to support her explanation (row 1). He then made a claim that the differences in temperature values were related to the location of the weather stations and the sun's position in the morning (rows 1, 3, and 7). His last statement that “60 is yellow because it got the most sun” confused other students because both Linda and James subsequently focused on the color of the temperature value rather than its location on the map. Linda and James may have been thinking about the colors on the map and how they indicate the amount of sun and higher temperatures (rows 10 and 15) rather than

Evan's mechanistic explanation of why some of the weather stations reported higher temperatures than others. This confusion indicates the importance of asking students to repeat or summarize other students' ideas so that all students in the class understand the ideas that other students are sharing.

In response to this confusion, Mrs. K asked Evan to elaborate on his claim (Table 4-6). Evan then connected the school's location on the map to the motion of the sun in the morning and explained how that motion would affect specific weather stations on the map.

Table 4-6

Micro-Level Integration: Critiquing Connections

Row	Speaker	Discourse
1	Mrs. K:	That's not what you're saying? Maybe try one more time, Evan.
2	Dr. J:	Alright everyone, listen to Evan really closely.
3	Evan:	*Okay, guys. So, the sun rises in the West.*
4	Mrs. K:	The East. (Dr. J: Wait hang on, yeah.) Hold on, The East, The East.
5	Evan:	*The East, I don't know my directions. But, if the star [on the map] is us [the school's location] then the sun must be rising from right here [pointed to map], so if the sun isn't rising, is rising from right there, the closest ones to it are the 54, 51, and 60. The 60 is the highest temperature, and 51 looks like it is behind something and then 51 and the 51 behind it is a little bit slanted.*
6	Mrs. K:	51 [pointed to map].
7	Evan:	*So, yeah, so then I feel like 60 got sun and the two 51s didn't.*
8	Mrs. K:	Alright. So, we got some ideas. Andrew?
9	Andrew:	*I get what he is saying like it is going to be on the East, the 60 could be in front of the 51 and it could get more sun, and it could add more temperature. Still doesn't explain why the 51 in front of it is getting less Sun than that.*
10	Mrs. K:	So, it is really tough to know because we just have the map. Right? We're not. We don't have the birds eye view here, and we are just up here with the map. So, I hear sun, shade differences. I hear wind. I hear weather stations measure differently and have different ways of measuring uh that the temperatures differently, and Savannah has one more?

11	Savannah:	*Uhm, like, what about precipitation? You might have precipitation over in the next town but the, but there's no precipitation here in our town and the way that, like the way that like rain or snow or whatever comes, you might get it faster or slower than like other places.*

Andrew responded by repeating Evan's explanation to indicate that he understood what Evan was proposing, but then he critiqued his explanation by pointing out an inconsistency in Evan's explanation (row 9). Evan and Andrew were engaged in the sensemaking process of constructing an explanation and then critiquing it (Figure 4-10). Mrs. K, however, did not follow up on Andrew's critique, and she gave a short explanation to resolve the inconsistency. This was a missed opportunity for sustaining sensemaking because it did not give Evan or the other students in the class time to further refine Evan's explanation. Supporting students to engage in sensemaking takes time; they need time to brainstorm and time to think about and critique one another's ideas. This tension between allowing time for student thinking and the pacing of each lesson was apparent throughout this first iteration of our design.

In addition to connecting variability in temperature data with phenomena, students also connected variability in temperatures with their prior experiences. Andrew connected the variability in the temperature data with the differences he experienced with the technology in his parents' cars (Table 4-7).

Table 4-7

Micro-Level Integration: Connecting Variability in Temperature Data with Prior Experience

Row	Speaker	Discourse
1	Mrs. K:	Oh, so we don't really know where these weather stations are. Is that what you're saying? Some might be in the sun, but some might be in the shade. Is that, so you think that is a possibility? Anybody else's ideas, Andrew, have an idea back there?

2	Andrew:	*Yeah um, you said that's a weather station right, that little thing right* there [pointing to the table] *that you said was a thermometer.*
3	Mrs. K:	That, Dr. Lahaina’s?[picked up indoor thermometer]
4	Andrew:	*Yeah. What if it didn't include wind, what if, like, it didn't count cause my dad has a car and my dad's car and mom's car are different because one counts the wind as temperature and one doesn't. So, the 51 could've included the wind but the 60 maybe didn't include the wind.*
5	Mrs. K:	Oh, so you're saying that these weather stations might be different and the way that they include the wind or not include the wind.
6	Andrew:	*And their temperature*.
7	Mrs. K:	The way they figure out what the temperature is might be different? (Andrew: *Yeah.*) So different weather stations.
8	Dr. J:	That sounds a little bit like in your math class where some of you measured the pot whenever you measured the height of the tree. Some of you did not measure the pot when you measured the height of the tree. Is that what you were saying Andrew, that maybe the way the weather station measures the temperature could be slightly different?
9	Andrew:	*Mhhm.*
10	Mrs. K:	I'm gonna say: weather stations measure differently [wrote on chart paper]

This integration of new ideas with students’ everyday experiences is an important component of the sensemaking process (Odden & Russ, 2019a). Andrew integrated the idea of variability caused by how the attribute, i.e., temperature, was measured with his experiences with his parents’ cars (row 2 and 4). This activity supported Andrew to make a claim about the variability inherent in the measurement process (EV level 2b; Table 4-1). Dr. J then connected this idea to a prior experience that all students had in the mathematics class.

Students also connected differences in temperature values with their prior experiences in other lessons in the investigation. For example, during lesson three, a student explained that noon was the warmest temperature of the day “because that is when we go out for recess and I have noticed it is like the hottest kind of around noon.” Another student explained that the afternoon was the warmest part of the day “because it is usually really hot when we are going to the car. It is usually really warm and we have this like thing in my car where you can see the temperature outside, and like it was almost like 90 degrees.” At other times in the investigation, students connected variability in temperature values with the activities of playing soccer and going swimming (rows 14-22; Table 4-9) and watching the news (row 14; Table 4-10). In these examples, students connected their observations of variability in temperature data with their own daily activities.

In summary, students responded to our designed opportunities for sensemaking by integrating variability in temperature data with their ideas of weather phenomena: wind, precipitation, shade, clouds, and the position of the sun. We also saw students integrating variability in temperature data with their prior experiences of how vehicles measure the temperature and their own daily activities.

5.2 How Students Connected Resources Generated Through Sensemaking to Explain Variability

Students experience meso-level integration when they have opportunities during the sensemaking process in which they can coherently connect the knowledge resources generated across the length of the investigation. We designed several of these opportunities for students in this investigation. In this section, we use transcripts and student artifacts to show how students responded to three of these opportunities for meso-level integration. First, we describe how students integrated variability in temperature data with the mechanisms of heat transfer (Lesson 3; Table 4-3). This lesson had students figuring out where to label morning, noon, and afternoon on a dot plot, reviewing the mechanisms of heat transfer, observing a demonstration of a physical model of heat transfer, and then drawing their own explanatory model. We then gave students a formative assessment to gain an understanding of how they integrated ideas about heat transfer with variability in temperatures across the day. We initially conjectured students would use ideas generated by making sense of when the warmest part of the day occurred and connect them to their prior knowledge of radiation, convection, conduction and to the data from a physical model of heat transfer. We found it was challenging to support students to coordinate and connect ideas across the different types of models: the variability in temperature shown on the dot plot, the representations of heat transfer in the physical model and the temperature data from the model, and the relationships of radiation, convection, and conduction in the explanatory model.

Second, we show how students integrated variability in temperature data with the movement of air masses (Lesson 4; Table 4-3). This activity had students noticing variability in temperature data on a day when the afternoon was not the warmest part of the day. We initially conjectured students would use a knowledge resource that they developed in the previous lesson, i.e., their understanding of why afternoon was the warmest part of the day, to recognize a gap in their understanding, and this moment would support students to be in the sensemaking frame as they began to figure out this inconsistency. They would then integrate ideas about wind direction and air masses with differences in temperature data across the day. There is evidence that at least some students made these connections.

Third, we describe how students integrated variability in the large data set with the weather phenomena and sources of variability, e.g., time of day, clouds, wind direction, precipitation, etc., we discussed throughout the investigation (Lesson 5; Table 4-3). We conjectured that students would use the sources of variability they discussed throughout the investigation to make sense of a large data set of local weather variables. We found that students wrote about a variety of weather phenomena, but it was challenging for them to integrate ideas of weather phenomena with the evidence they created from the large data set.

5.2.1 Connecting Variability in Temperature Data with Heat Transfer

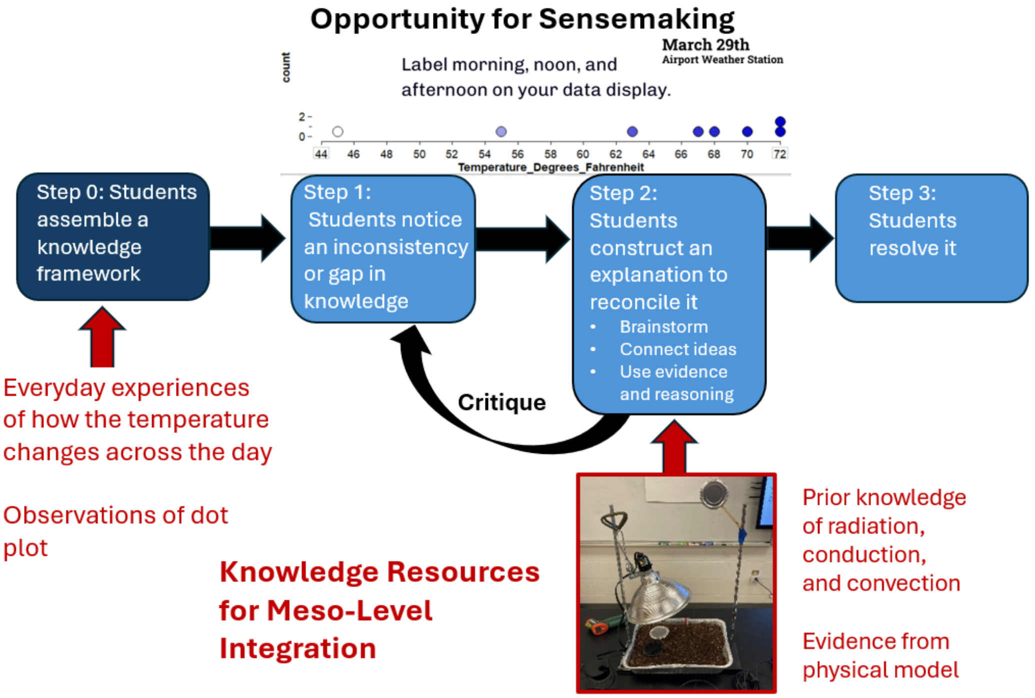
We started this lesson by asking students to individually write down a claim about where they would label morning, noon, and afternoon on a dot plot of temperatures across a school day and then write about what caused the variability in temperatures (see Appendix 4-B). After five minutes, students shared their claims and reasoning in a whole-class discussion. All students agreed that the two lowest temperatures occurred in the morning. Some students then claimed that the two highest temperatures should be labeled noon, while other students claimed that area of the dot plot should be labeled as afternoon. Students in both classes made similar claims.

Students drew on their everyday experiences to justify their claim. They related the variability in temperatures to their daily activities. For example, Mary said "So, 45 [on the dot plot is morning]. When you wake up in the morning, it is not as warm and then it builds temperature." Another student justified noon as the warmest temperatures on the dot plot by saying, "Yeah, because that is when we go out for recess and I have noticed it is like the hottest kind of around noon." Another student responded by saying "I would say that afternoon [is the warmest time of the day] because it is usually really hot when we are going to the car. It is usually really warm and we have this like thing in my car where you can see the temperature outside, and like it was almost like 90 degrees." These everyday experiences of temperature differences across the day resulted in conflicting claims.

We hoped students would verbalize these conflicting claims because this inconsistency would provide an opportunity for sensemaking (Figure 4-13). We conjectured this activity would be an opportunity for meso-level integration as we supported students to connect the variability in temperature data across the day with their prior knowledge of heat transfer. To do this, we reviewed the mechanisms of heat transfer with the students and then we used a lamp and metal disks positioned in various places, e.g., on the soil, suspended in the air, to provide a physical model of heat transfer in the classroom. We took the temperature of these disks with an infrared thermometer every two minutes for a duration of ten minutes and a student wrote the temperatures on the board (Figure 4-14).

Figure 4-13

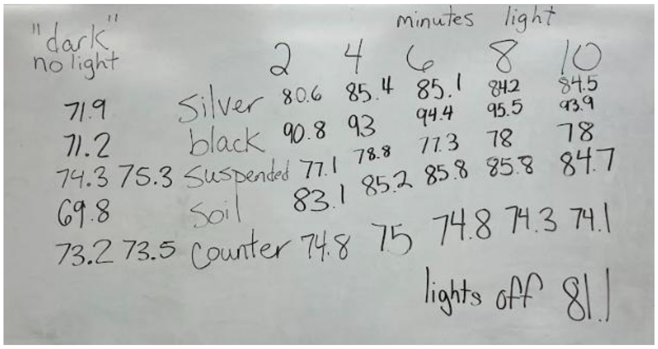
Meso-Level Integration: Connecting Temperature Variability Across the Day with Mechanisms of Heat Transfer



After we demonstrated the physical model, the class period ended so students were told to draw their own explanatory model of heat transfer as homework (see Lesson 3 in Appendix 4-B). The temperatures from the physical model were left on the board so that students could use it as evidence in the following day's discussion (Figure 4-14).

Figure 4-14

Temperature Data from Physical Model



"dark" no light			minutes light				
			2	4	6	8	10
71.9		Silver	80.6	85.4	85.1	84.2	84.5
71.2		black	90.8	93	94.4	95.5	93.9
74.3	75.3	Suspended	77.1	78.8	77.3	78	78
69.8		Soil	83.1	85.2	85.8	85.8	84.7
73.2	73.5	Counter	74.8	75	74.8	74.3	74.1

lights off 81.1

When we returned the following day, students shared their heat transfer models with their table groups. Mrs. K monitored their small group discussions, and, because students struggled to explain conduction as a method of heat transfer in their models, she began a whole-class discussion and drew a model of heat transfer as she talked through it with the students.

The classroom discourse reported in Table 4-8 occurred in the middle of this whole-class discussion, when Mrs. K and the students were talking about conduction and convection. Similar classroom discourse occurred in both classrooms.

Table 4-8

Excerpt from Whole-Class Discussion About Heat Transfer

Row	Speaker	Discourse
1	Mrs. K:	And so, right here [pointed to picture on screen] is where we have conduction usher in with our little warm weather there. In our [physical] model, where is the data that helps support that? Where is the evidence that things warm up through conduction?
2	Savannah:	*The soil got progressively warmer and if it, like, like* [voice trailed off], *or even the black little disc because it's, like, that might better represent*

the road or whatever, but I feel like the color, that definitely shows conduction, with the soil warming up.

3 Mrs. K: And, um, with the other class, we actually took the countertop one [held up the silver disk], we turned off the lights, and we put it on the soil for two minutes [pointed to board]. And that was its temperature after two minutes. So, we took the countertop one, we turned off the lights, we set it on the soil and, (Savannah: *Without the light on*?) without the light on, and we took its temperature after two minutes ["lights off" in Figure 4-14].

4 Savannah: *It probably warmed up by 6 or 7 degrees.*

5 Mrs. K: 7 degrees-ish. (Student: *On the dot.)* On the dot. So, and so, that was which process?

6 Savannah: *Conduction.*

7 Mrs. K: Conduction. Alright, so we have radiation [pointed to drawing on screen], we have the ground getting really warm. It takes a while because we didn't jump up to 95 right away [pointed to data on board], it took a while to warm up. Then, we have conduction with this air [pointed to a drawing on screen]. Now, what happens to that air when it is getting warmer, and warmer, and warmer? Air is a fluid. What happens to warm things, fluids, when they heat up?

8 Student: *They boil.*

9 Mrs. K: They boil. And that boiling means that [voice trailed off] What is boiling? Not quite yet

10 Savannah: *Convection is occurring.*

11 Mrs. K: Convection is occurring because as those, as that air heats up, it rises up. When you see things boiling, that's what you're seeing, the water heating up from the bottom of the pan, rising up. Coming up. Then, it rises up, and like Savannah said, that is going to be some convection.[drew on screen]. Think about your water cycle. You're thinking. As this warm air rises up, it has got some water vapor in it. What could it form as it rises up and cools off? What could it form?

12 Timothy: *The clouds.*

13 Mrs. K: It could form a cloud. Could form a cloud.

14 Savannah: *Could we add this to our worksheets?*

15 Mrs. K: Sure. Once that air rises up, cool air is going to come down and replace it. Because that would be strange if we had no air down by the ground, so it's a cycle. Which one of our variables here in our data would be, would give us evidence for convection? That the temperature is getting warmer higher up. Which one would give us evidence? Someone I haven't heard from [paused]. Talk to your neighbor. Which one is the evidence that this is going on?[Students talked to table partners for 1 minute]

16 Mrs. K: Alright, I think I have heard some really good ideas. Maybe Mary's group here could, they had some really good ideas. Mary, do you think you could recap what your group was talking about?

17 Mary: *Um, like the suspended one because the um convection like the air like the heat rises.*

18	Mrs. K:	Okay, so you're saying that the suspended one because heat rises. And what happened to the suspended one's temperature at the end?
19	Mary:	*It got hot. It got warmer.*
20	Mrs. K:	It got warmer compared to the?
21	Mary:	*Counter.*
22	Mrs. K:	The countertop one. And, so, all of this takes time.

Mrs. K began by asking students to explain how the temperature data from the physical model supported the claim that conduction occurred. Savannah struggled to connect the temperature data from the physical model with conduction, so Mrs. K focused the students' attention on the "lights off" condition that was tested in the other class (row 3). In this excerpt, Mrs. K did most of the explaining, rather than the students. The classroom discourse was more authoritarian rather than the dialogic discourse necessary for the sensemaking process. Note the relatively short student responses compared to the long discourse segments of the instructor.

Students entered the sensemaking frame, however, when Mrs. K asked them about a possible everyday experience they might have had (Table 4-9). This transcript excerpt immediately followed the excerpt in Table 4-8.

Table 4-9

Connecting Convection with Prior Experiences

Row	Speaker	Discourse
1	Mrs. K:	So, we have in the morning when the Sun comes up, we have what? [pointed to screen] When the Sun comes up?
2	Students:	*Radiation.*
3	Mrs. K:	Radiation. Then, that radiation is heating the?
4	Students:	*The ground.*
5	Mrs. K:	The ground. Then, after a while that ground gets really hot and that air does what?
6	Student:	*Convection.*
7	Mrs. K:	So, sometimes you can see those convection currents. Have you ever looked at a really hot road and you see these little shimmers?
8	Students:	*Yeah. Yeah.* (Savannah: *Like it almost looks like fake water on the road*)

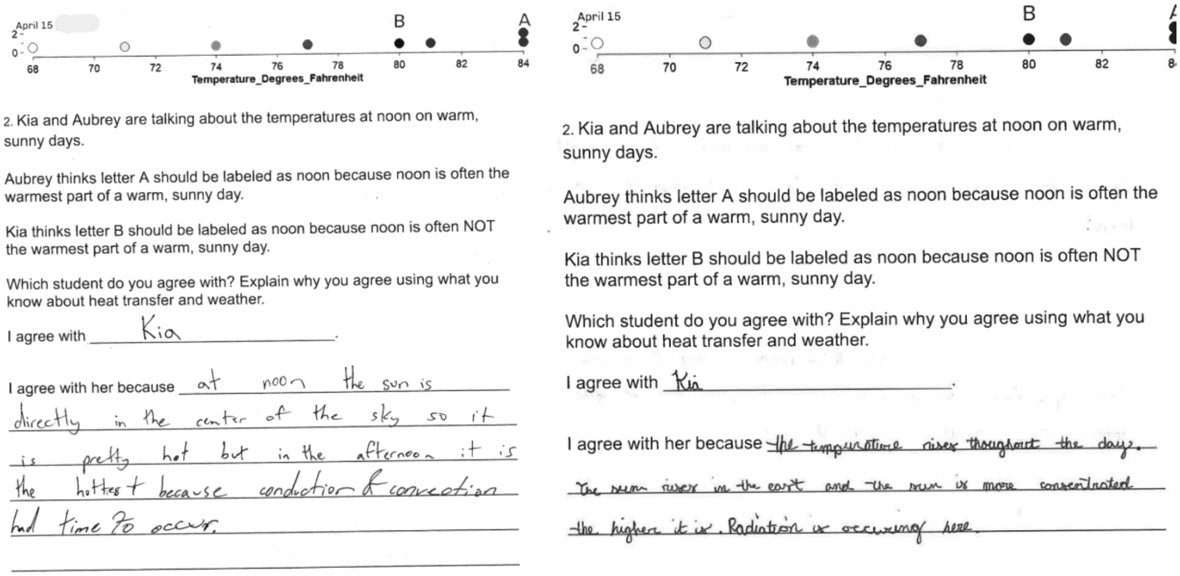
9	Mrs. K:	Yes, yes.
10	Savannah:	*That's always super like* [paused]. *Wait, how does that do that*?
11	Mrs. K:	How does that happen?
12	Student:	*Because it is so hot outside.*
13	Mrs. K:	It's because the air is so hot next to the road, and convection is happening.
14	Andrew:	*Yeah, I was playing this soccer game and we played on turf, which, when it gets hot outside, it gets super-hot and it burns your feet. I'll just see that everywhere, like everywhere I look. I'm just like, my feet!*
15	Mrs. K:	Yeah, and what's, like, the temperature up by your head?
16	Andrew:	*It's like 90.*
17	Mrs. K:	It's like 90, but the temperature down by your feet?
18	Andrew:	*It's like ten thousand!*
19	Mrs. K:	Ten thousand! [laughed]
20	Andrew:	*60 million!*
21	Evan:	*So, I agree with Andrew because my, uh, I have two people in my family who have pools. We go swimming at their house during the fourth of July, and we get out of the pool to jump in and it's like owww!*
22	James:	*You just like levitate over the pool and fall in.*
23	Mrs. K:	Yeah, so, conduction. That's pretty powerful down there.

Here, Mrs. K connected the process of convection with an experience students might have had (row 7). Savannah then entered the sensemaking process and wondered how those shimmers occurred. A students made the claim that it occurred because "it is so hot outside," and Mrs. K added on to that claim by saying it was the hot air next to the road. Andrew then connected his prior experiences with playing soccer on artificial turf with convection currents (row 14). Evan and James added on further to this explanation by giving the example of hot concrete by the pool (row 21). This student discourse suggests that some students were integrating the mechanisms of conduction and convection with their prior experiences of hot ground temperatures.

We also gave students a formative assessment following this lesson to get an understanding of their thinking about the variability of temperatures across the day and mechanisms of heat transfer (Figure 4-15). Most students agreed with the hypothetical student Kia who said that the warmest temperatures were in the afternoon, and most students explained the afternoon temperatures were the hottest because the sun had more time to warm the Earth. For example, Weston wrote a typical response: “I agree with Kia. I agree with her because the sun warms up the Earth and the longer it shines the warmer the temperature is.”

Figure 4-15

Examples of Formative Assessment



2. Kia and Aubrey are talking about the temperatures at noon on warm, sunny days.

Aubrey thinks letter A should be labeled as noon because noon is often the warmest part of a warm, sunny day.

Kia thinks letter B should be labeled as noon because noon is often NOT the warmest part of a warm, sunny day.

Which student do you agree with? Explain why you agree using what you know about heat transfer and weather.

I agree with Kia.

I agree with her because at noon the sun is directly in the center of the sky so it is pretty hot but in the afternoon it is the hottest because conduction & convection had time to occur.

2. Kia and Aubrey are talking about the temperatures at noon on warm, sunny days.

Aubrey thinks letter A should be labeled as noon because noon is often the warmest part of a warm, sunny day.

Kia thinks letter B should be labeled as noon because noon is often NOT the warmest part of a warm, sunny day.

Which student do you agree with? Explain why you agree using what you know about heat transfer and weather.

I agree with Kia.

I agree with her because the temperature rises throughout the day. The sun rises in the east and the sun is more concentrated the higher it is. Radiation is occuring here.

A **B**

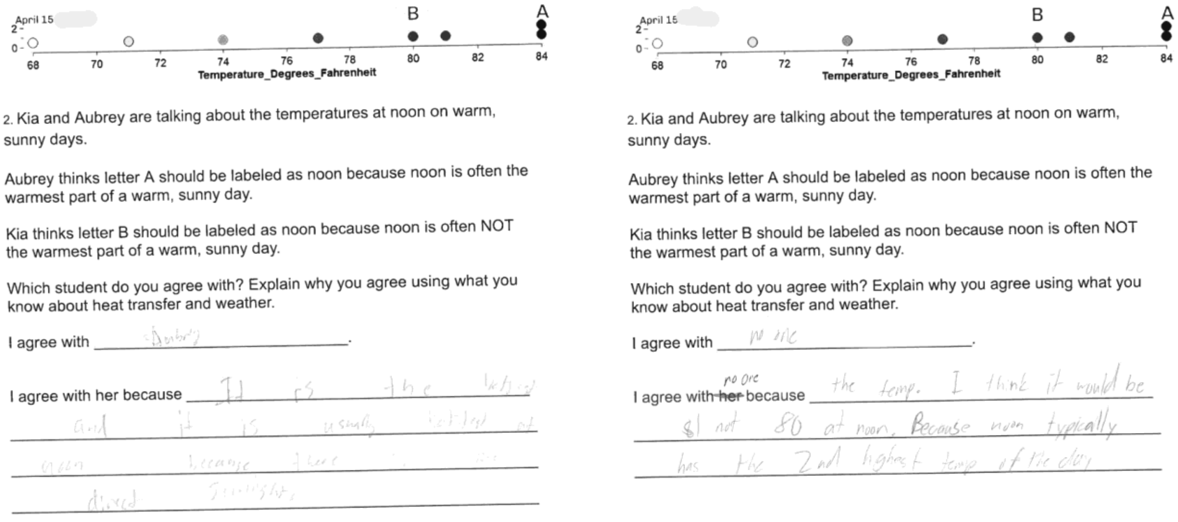
Note. In A, Madeline wrote: “I agree with Kia. I agree with her because at noon the sun is directly in the center of the sky so it is pretty hot but in the afternoon it is the hottest because conduction and convection had time to occur.” In B, Savannah wrote: “I agree with Kia. I agree with her because the temperature rises throughout the day. The sun rises in the east and the sun is more concentrated the higher it is. Radiation is occurring here.”

Three students integrated the mechanisms of heat transfer with variability in temperatures across the day. For example, Madeline wrote “in the afternoon it is the hottest because conduction and convection had time to occur" (Figure 4-15A). Riah discussed all three mechanisms of heat transfer: "I agree with Kia. I agree with her because in the afternoon, that's when the peak time of radiation, convection, and conduction. The sun is also usually at its highest and hottest, at least as I have examined going home after school." Riah also connected temperature variability with her everyday experience of going home after school. Savannah connected radiation with rising temperatures, but did not write about conduction and convection (Figure 4-15B). These responses indicate that at least some students integrated the variability of temperature data across the day with the mechanisms of heat transfer.

Of the three students who wrote that they agreed with the hypothetical student Aubrey and indicated that the highest temperatures were at noon, one student used her everyday experience in her explanation. Taryn explained, "I go outside for recess around noon and I feel as though it is hottest at noon." The two other students explained their reasoning using the position of the sun causing the most direct sunlight at noon. For example, Timothy wrote, "it is usually hottest at noon because there is most direct sunlight (Figure 4-16A). The instructor, Mrs. K, briefly discussed the position of the sun at noon and how the direct rays of the sun are concentrated on a smaller area of the Earth's surface at noon. There was not much time to discuss this idea further and this reference may have confused the students.

Figure 4-16

Alternative Student Ideas



2. Kia and Aubrey are talking about the temperatures at noon on warm, sunny days.

Aubrey thinks letter A should be labeled as noon because noon is often the warmest part of a warm, sunny day.

Kia thinks letter B should be labeled as noon because noon is often NOT the warmest part of a warm, sunny day.

Which student do you agree with? Explain why you agree using what you know about heat transfer and weather.

I agree with Aubrey.

I agree with her because It is the hottest and it is usually hottest at noon because there is most direct sunlight.

A

2. Kia and Aubrey are talking about the temperatures at noon on warm, sunny days.

Aubrey thinks letter A should be labeled as noon because noon is often the warmest part of a warm, sunny day.

Kia thinks letter B should be labeled as noon because noon is often NOT the warmest part of a warm, sunny day.

Which student do you agree with? Explain why you agree using what you know about heat transfer and weather.

I agree with no one.

I agree with ~~her~~ no one because the temp. I think it would be 81 not 80 at noon. Because noon typically has the 2nd highest temp of the day

B

Note. In A, Timothy wrote: “I agree with Aubrey. I agree with her because it is the hottest and it is usually hottest at noon because there is most direct sunlight.” In B, Andrew wrote: “I agree with no one. I agree with no one because the temp. I think it would be 81 not 80 at noon. Because noon typically has the 2nd highest temp of the day.”

Andrew did not agree with either hypothetical student (Figure 4-16B). It appears he viewed the temperature dot plot as a pattern where the highest temperature value is during the afternoon, and the second highest value is typically noon. This example was an unexpected way students could connect the temperature data from the dot plot and the phenomena, and it indicates the value of using formative assessments to understand what all students are thinking.

In summary, it was challenging to support students to coordinate and connect ideas about variability across the different types of models: the variability in temperatures shown on the dot plot and the variability of the temperature data of those representations. And then it was difficult to support students to connect the variability in temperatures to the relationships of radiation, convection, and conduction in the explanatory model. There is evidence, however, that students connected the data of the highest temperatures in the afternoon with the length of time the sun is in the sky. A few students explained the mechanism by referring specifically to radiation, convection, and conduction.

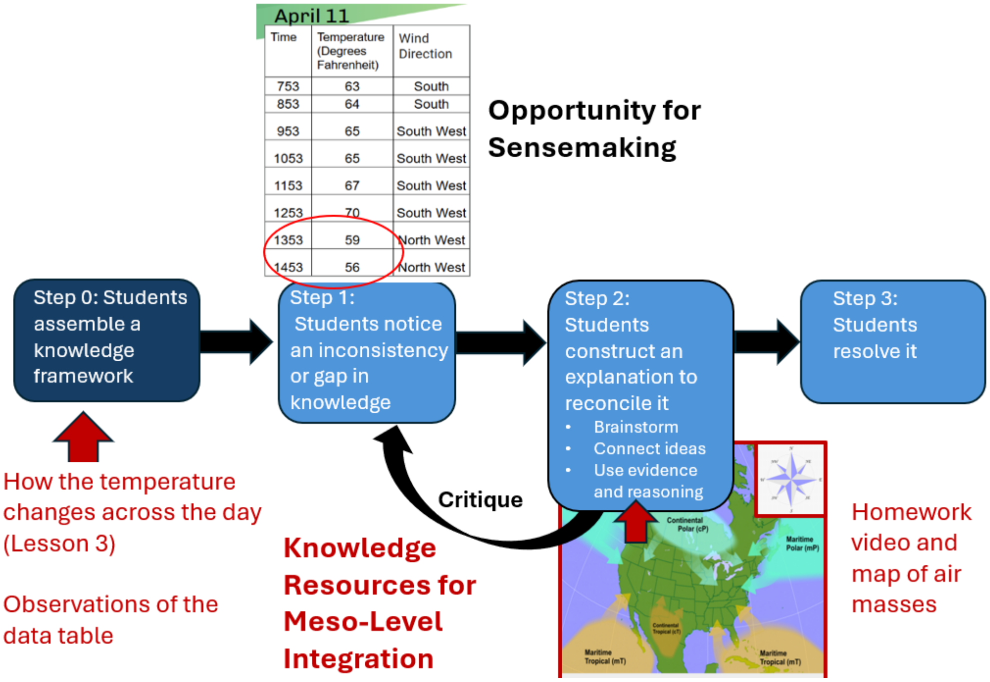
This lesson also took longer than we anticipated, and we had to spend additional time we did not expect reviewing mechanisms of heat transfer. We, therefore, had less time for the next lesson. For the second iteration of this investigation, this lesson needs several days to fully develop these ideas and the connections among them. Instead of a classroom demonstration, students could collect temperature data from a similar physical model in small groups. This change may support them to make stronger connections between the representations, the data they collect, and the mechanisms of heat transfer.

5.2.2 Connecting Variability in Temperature Data with the Movement of Air Masses

We began this activity by showing students a table that indicated temperatures from across the school day and the wind direction (Figure 4-17). At this point in the investigation, students had discussed variability of temperature values at one moment at time and across the school day. They had just briefly discussed the temperature data from a day when noon had the coldest temperatures of the day, and they had made claims that it might be due to clouds and rain. We conjectured that the temperature data from this day, one that had afternoon temperatures as the coldest, would provide an opportunity for students to begin the sensemaking process because the temperature data was inconsistent with the pattern of warmer temperatures in the afternoon (Figure 4-17). As they entered the sensemaking process, we wanted to support students to integrate the variability in the temperature data with ideas from a video about the movement of air masses they had watched for homework the night before.

Figure 4-17

Meso-Level Integration: Connecting Temperature Variability Across the Day with Movements of Air Masses



April 11

Time	Temperature (Degrees Fahrenheit)	Wind Direction
753	63	South
853	64	South
953	65	South West
1053	65	South West
1153	67	South West
1253	70	South West
1353	59	North West
1453	56	North West

The classroom discourse reported in Table 4-10 occurred at the beginning of the class period, after a short summary of sources of variability that might stop temperatures from increasing across the day. Similar classroom discourse occurred in both classes.

Table 4-10

Whole-Class Discussion About Air Masses

Row	Speaker	Discourse
1	Mrs. K:	And so, we are going to think about one more [source of variability]. And that was, this is April 11th. Looking at our data [pointed to data table], we have our time, we have our temperature. And what do you notice at the end of the day? What do you notice in the afternoon? What has happened?
2	Carmen:	*The temperature goes down by like twenty.*
3	Mrs. K:	Twenty degrees. That is a lot. About 15, 20. A lot. What else do you notice at the end of that day?
4	Andrew:	*The wind changes.*
5	Mrs. K:	The wind changes. Where does it change?
6	Andrew:	*It goes from Southwest. So, it goes from like...that would be like... So, this is like Northwest. No, that would be East. Cause this would be East, and that's West, and this is South. It went from here to here.*
7	Mrs. K:	Alright, and so. And it's important when we think of the wind direction, it's the wind-the direction the wind comes out of. So here, the wind is, in the morning, the wind is coming from the South [gestured toward herself], to use Andrew's [gesture]. And then in the afternoon, it is coming from the[gestured away from herself] (Student: *Aww* [gasped], *I know what happened!* [excited]. Another student: *I know!*) North.
8	Andrew:	*Is it the maritime polar, whatever? So, like, yeah, the wind is coming from the South, and it gets like those like continental tropical, maritime tropical winds, it gets all those warm winds. And then, it, becomes, like the polar winds, and then they come in and it makes like a* [paused] (Savannah: *a cold front or*) *a cold front or a warm front.*
9	Mrs. K:	A cold front. (Another student: *Air masses*). So perhaps, perhaps, because really we just have the data, perhaps this cold dry air continental polar coming from the North [pointed to map]. We're the star there, our state. Perhaps that air moved in and we had a [paused].
10	Student:	*Cold front.*
11	Mrs. K:	Cold front (Student: *Yes.*). And right now, our weather is warm and moist, where do you think our, the air is coming from right now? Right now?
12	Carmen:	*From, like, the South*
13	Mrs. K:	From the South. And you can check that on the weather app to see which direction the winds are coming from.
14	Evan:	*What, umm. So there's also this thing on the weather map on the news like it's warm fronts and cold fronts. And whenever there is a tornado, they meet and create the tornado.*
15	Mrs. K:	We have this cold dry air coming down [pointed to map]. We have this warm moist air coming up [pointed to map]. They meet and we might have a tornado [clapped hands].

16	Andrew:	*What, so, like I have got the continental, the maritime, it means like land/water. And we have got polar and tropical, like warm and cold. We've got Arctic??* [excited]
17	Mrs. K:	This is the super cold air up above the North Pole [pointed to map]. So that's the super cold air, way up there.
18	Mrs. K:	Alright, so we have one more source of variability now to think about. One more. And on our list here [pointed to sources of variability list on chart paper], you put wind as sort of one of our sources. So, we have where that air is coming from. Where that wind is coming from.

Mrs. K began by supporting students to assemble their shared knowledge framework. Two students shared critical observations: the temperature decreased in the afternoon, and the wind changed. Andrew then described how he thought the wind direction changed (row 6). Mrs. K clarified his description by pointing to the map as she used his gestures. In response, one student audibly gasped and excitedly said they knew what happened (row 7). Two students, Andrew and Savannah, constructed a sensemaking explanation by connecting the direction of the wind, the temperatures of the winds, warm or cold, and the weather term cold front (row 8). Carmen then predicted that the wind was coming from the south at that moment because their weather was warm and moist (row 12). Evan then made a connection between cold fronts and warm fronts from his everyday experiences of weather maps on the news and tornados (row 14). Andrew then asked a question to further clarify his connection between words on the map and their meaning (row 16).

This discourse suggests that Andrew, Savannah, Evan, and Carmen were all engaging in meso-level integration as they made sense of a puzzling exception to the typical pattern of increasing temperatures in the afternoon. They were integrating the variability in temperature values with their observations of direction of the winds from the data table and their knowledge of wind, air masses and fronts. It is unclear whether all students were making these connections because Mrs. K changed the topic of the discourse so that students would have time to complete the last lesson in the investigation.

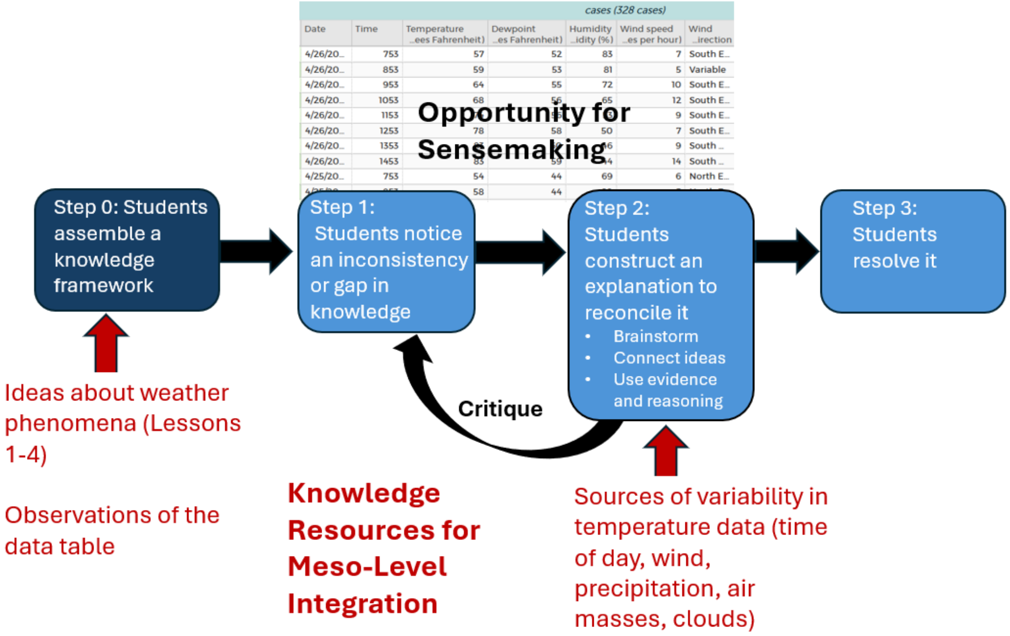
In summary, this activity addressed the NGSS (2015) performance expectation that asks students to collect data to provide evidence for how the movements of air masses can change weather conditions. There is evidence from the classroom discourse that some students connected the variability in temperature values with the change in wind direction and the movement of air masses (rows 7-9, 12, 14). Additionally, one student chose to investigate this question using the large data set: "if the wind is coming from the equator will it bring warm air?" (see Figure 4-27), and this suggests she connected the movement of air masses with changes in temperature.

5.2.3 Connecting Variability in a Large Data Set with Weather Phenomena

We designed opportunities for meso-level integration in the final lesson of the weather data investigation. We asked students to write their own investigative question and then use a large data set of weather variables from March and April to answer it (Lesson 5, Table 4-3). We conjectured the large data set would provide students with opportunities to engage in the sensemaking process when they noticed gaps in their knowledge as they created ways to visualize and organize the data using CODAP (Figure 4-18). As they engaged in sensemaking, students would integrate their observations of variability in the large data set with possible sources of variability and weather phenomena we had discussed throughout the investigation. We found that students wrote about a variety of weather phenomena we discussed, but it was challenging for them to integrate ideas of weather phenomena with the evidence they created from the large data set.

Figure 4-18

Meso-Level Integration: Connecting Variability in a Large Data Set with Weather Phenomena and Sources of Variability



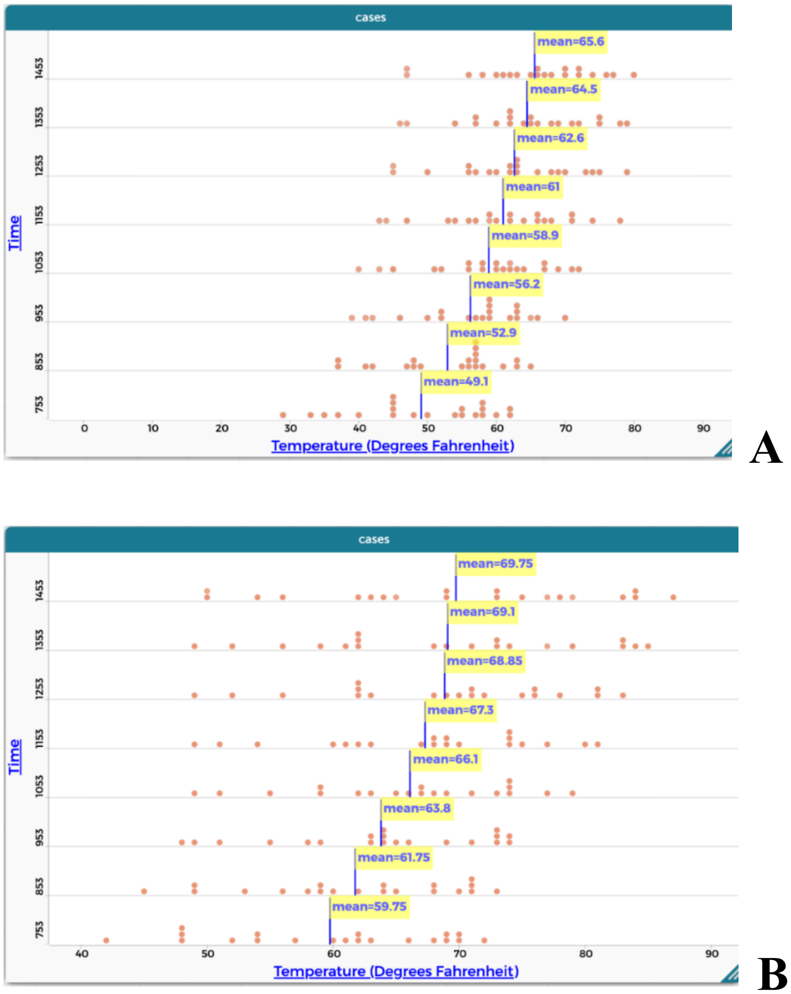
cases (328 cases)

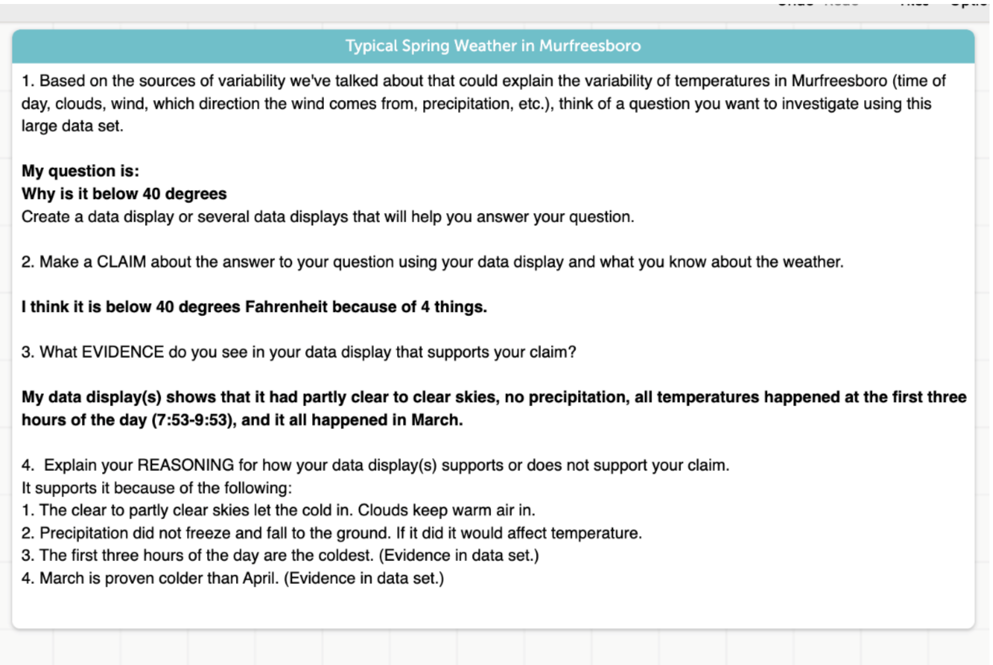
Date	Time	Temperature ...ees Fahrenheit)	Dewpoint ...es Fahrenheit)	Humidity ...idity (%)	Wind speed ...es per hour)	Wind ...irection
4/26/20...	753	57	52	83	7	South E...
4/26/20...	853	59	53	81	5	Variable
4/26/20...	953	64	55	72	10	South E...
4/26/20...	1053	68	56	65	12	South E...
4/26/20...	1153	[illegible]	[illegible]	[illegible]	9	South E...
4/26/20...	1253	78	58	50	7	South E...
4/26/20...	1353	[illegible]	[illegible]	[illegible]	9	South ...
4/26/20...	1453	83	59	[illegible]	14	South ...
4/25/20...	753	54	44	69	6	North E...
[illegible]	[illegible]	58	44	[illegible]	[illegible]	[illegible]

Many students wrote about weather phenomena we had discussed earlier in the investigation when they explained their claim, evidence, and reasoning (see also the CODAP work of Eden and Marilyn in section 5.3.3). Here, we show how Andrew connected low temperatures in the morning with several weather phenomena we had previously discussed in the the weather data investigation (Figure 4-19).

Figure 4-19

Lesson Five: Andrew's CODAP Data Display and Claim, Evidence, and Reasoning




Typical Spring Weather in Murfreesboro

1. Based on the sources of variability we've talked about that could explain the variability of temperatures in Murfreesboro (time of day, clouds, wind, which direction the wind comes from, precipitation, etc.), think of a question you want to investigate using this large data set.

My question is:
Why is it below 40 degrees
Create a data display or several data displays that will help you answer your question.

2. Make a CLAIM about the answer to your question using your data display and what you know about the weather.

I think it is below 40 degrees Fahrenheit because of 4 things.

3. What EVIDENCE do you see in your data display that supports your claim?

My data display(s) shows that it had partly clear to clear skies, no precipitation, all temperatures happened at the first three hours of the day (7:53-9:53), and it all happened in March.

4. Explain your REASONING for how your data display(s) supports or does not support your claim.
It supports it because of the following:
1. The clear to partly clear skies let the cold in. Clouds keep warm air in.
2. Precipitation did not freeze and fall to the ground. If it did it would affect temperature.
3. The first three hours of the day are the coldest. (Evidence in data set.)
4. March is proven colder than April. (Evidence in data set.)

Note. Andrew's data display A shows the temperature values from March. His data display B shows the temperature values from April.

Andrew made a claim that it was below 40 degrees in the spring because of four weather phenomena: clear skies, lack of precipitation, time of day, and month. He was one of the few students who connected his investigative question with multiple weather phenomena. Andrew's words suggest he engaged in meso-level integration because he integrated variability in temperature values in the large data set with sources of variability, cloud cover, precipitation, and time of day, we discussed earlier in the investigation. He elaborated on his reasoning about these phenomena by connecting temperature variability with cloud cover and the lack of frozen precipitation, but he did not save any data displays that provided evidence for these claims.

Andrew did reference two data displays he created to provide evidence for his claims that low temperatures occurred at specific times of the day and during March. He partitioned the data by time of day and by month to create these two data displays (Figure 4-19 A and B). Andrew indicates a measure of center, the mean, for each time of day in his two data displays. His words of "evidence in the data set" shows that Andrew was explaining variability at a high level, EV 4b, when he partitioned the data and used it to explain why the lowest temperatures occurred in the spring, but from his words it is difficult to know exactly what resources he was using. It is apparent from Andrew's, and the other students' CODAP work, that they did not fully integrate their ideas of weather phenomena with the evidence they created from the large data set (see section 5.3.3 for more examples of students' CODAP work).

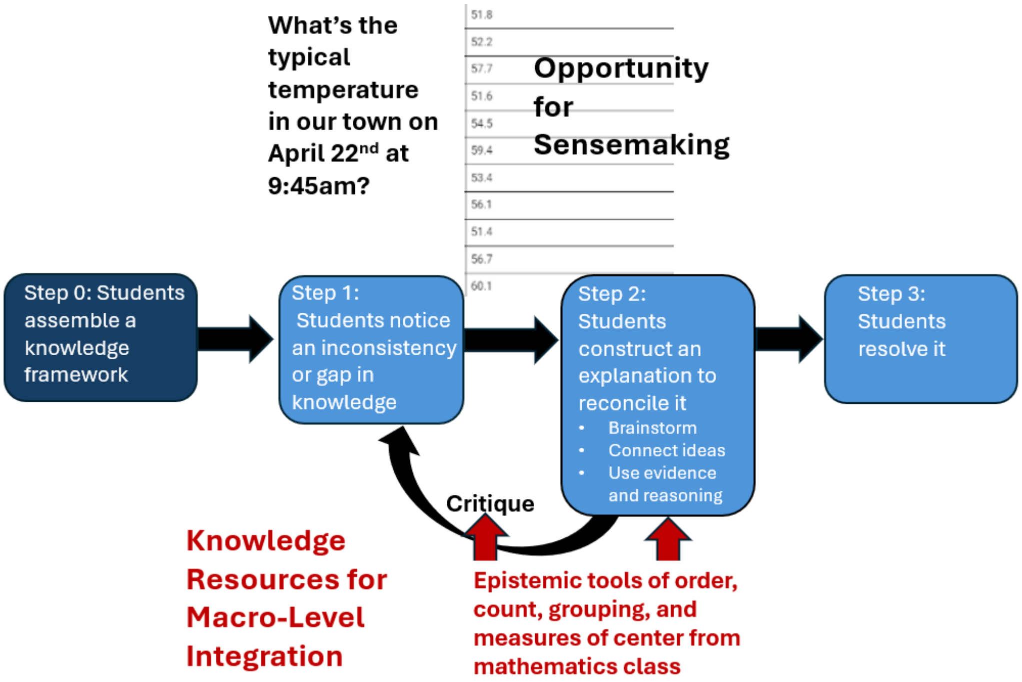
In summary, students responded to our designed opportunities for meso-level integration by making some connections across activities in the weather data investigation. Most students connected variability in temperature data with heat transfer from the sun and a few students connected the specific mechanisms of heat transfer with temperature variability. There is evidence that some students integrated variability in temperature values with their observations of the data and their prior knowledge of wind, air masses and fronts. In their CODAP work, many students wrote about weather phenomena we had discussed earlier in the investigation. We found supporting students to make these connections across activities to be challenging and we did not anticipate the amount of time it took. We will focus on understanding how to strengthen these connections and plan for more time to do it in our next iteration of the weather data investigation.

5.3 How Students Used Epistemic Tools from Mathematics to Explain Variability

We designed targeted opportunities for students to draw upon prior knowledge from their mathematics class when they drew a data display and made a claim for the temperature to be reported for their town on an app (Lesson 2; Table 4-3) and when they created a data display using CODAP to answer their own investigative question (Lesson 5; Table 4-3). We sought to understand how the students used epistemic tools from their mathematics class to visualize, structure, and explain variability in their local weather data (Figure 4-20). We found students used the mathematical concepts of order, count, and grouping in their pen-and-paper data displays as epistemic tools to organize their data and make aggregate properties of their data visible. Students also calculated measures of center, typically the mode, as an epistemic tool to determine and justify their claims for the typical temperature. Although all students created CODAP data displays to answer their investigative questions, it was less obvious how they used ideas from mathematics class to connect their data work with explaining a weather phenomenon.

Figure 4-20

Macro-Level Integration: Connecting Concepts from Mathematics Class with Visualizing Variability and Describing a Typical Temperature

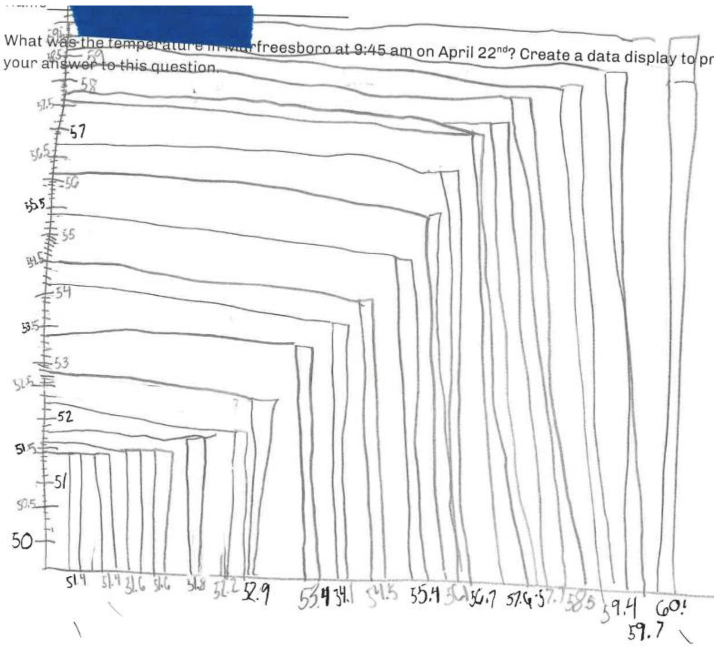


5.3.1 Order, Count, and Grouping

When students created their pen and paper data displays to make sense of the variability of temperatures in their town, they used many of the ideas developed in their mathematics class. These ideas included using the qualities of order, count, and grouping to emphasize certain aspects of the data. For example, the temperature data was given to the students in an unordered list, and almost all students ordered the values from least to greatest, or less frequently, from greatest to least. A few students created a data display by simply listing the values from least to greatest, including the repeated ones. Elena created a more complex data display to highlight order, a case value display, in which she plotted each value in order (Figure 4-21).

Figure 4-21

Lesson Two: Elena's Case-Value Display to Show Order



Name [redacted]

What was the temperature in Murfreesboro at 9:45 am on April 22nd? Create a data display to pr
your answer to this question.

CLAIM: A statement you believe is true.

I think the temperature was 57.9

EVIDENCE: Data or factual information that supports your claim.
For example: The mean is...
My data display shows...

The mean is 57.9

REASONING: Explaining how or why your evidence supports your claim.
For example: This evidence supports my claim because...
This evidence shows... because...

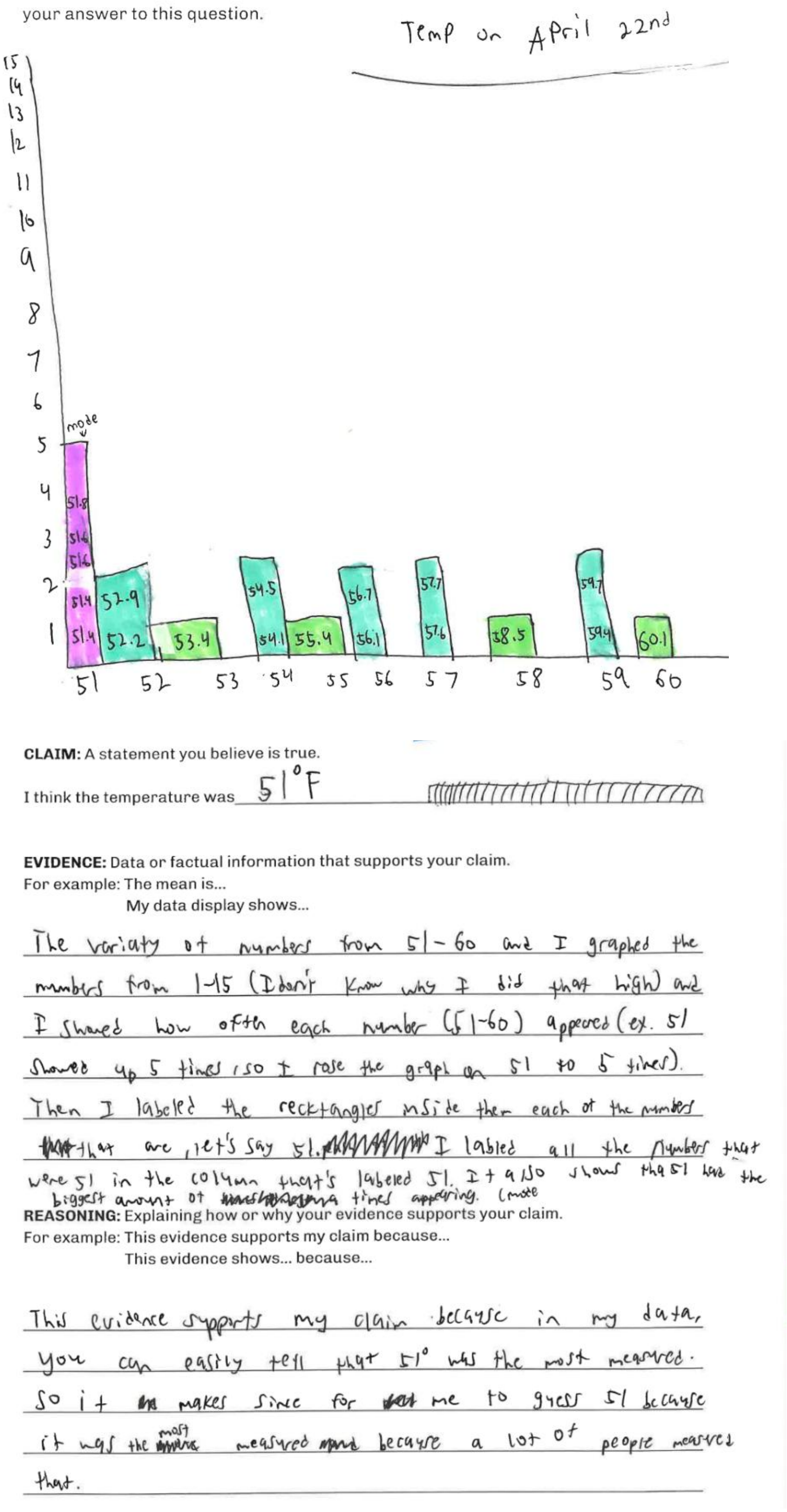
The evidence shows it's 57 because I calculated the Mean and I got 57. If you look at my graph you can tell it should be 57.9

Because the temperature values were given to the students as decimal numbers, students used a variety of strategies when they ordered their temperature values. Some students ordered the values exactly as listed as Elena did in Figure 4-21 (and see Figure 4-25). Other students rounded the numbers and ordered the values as rounded whole numbers (Figure 4-24). Several students ignored the decimal part of the number completely and ordered the numbers as whole numbers (Figure 4-22). When we gave the students the list of temperature values, we did not expect this variety of strategies. These strategies became fruitful during the students' whole class discussion, however, because students used them to discuss differences in how they arrived at their claims for the typical temperature.

Most students created data displays in which they included both order and count. For example, Riah created a data display in which she ordered the temperature values as whole numbers and indicated their count by the height of the bars (Figure 4-22). Other students used X's (Figure 4-24) or made dot plots (Figure 4-25) to indicate the frequency of temperature values in the data set. This use of order and count made aggregate properties of the data visible, e.g., the mode and range, for students.

Figure 4-22

Lesson Two: Riah's Data Display Using Order and Count



your answer to this question.

Temp on April 22nd

CLAIM: A statement you believe is true.

I think the temperature was 51°F

EVIDENCE: Data or factual information that supports your claim.
For example: The mean is...
My data display shows...

The variaty of numbers from 51-60 and I graphed the numbers from 1-15 (I don't Know why I did that high) and I shwed how ofteh each number (51-60) appered (ex. 51 showed up 5 times, so I rose the graph on 51 to 5 times). Then I labeled the recktangles inside them each of the numbers that are, let's say 51. I labled all the numbers that were 51 in the column that's labeled 51. It also shows tha 51 have the biggest amount of times appearing. (mode

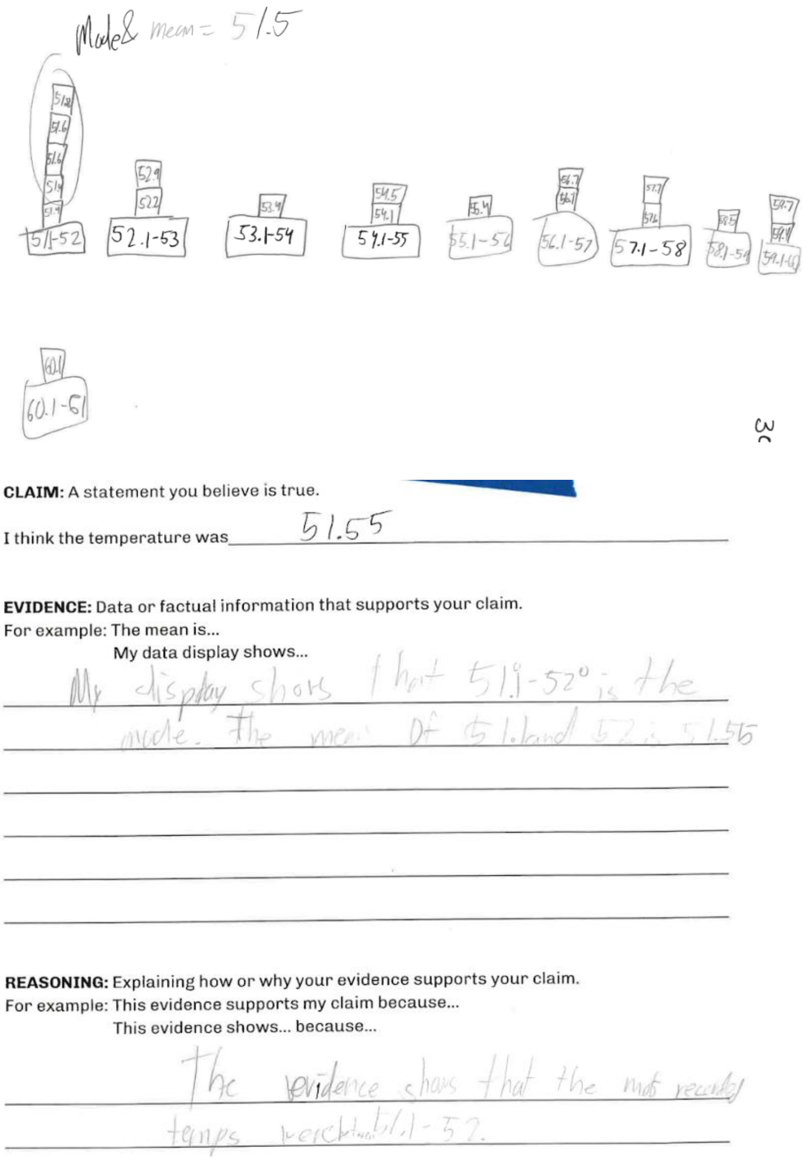
REASONING: Explaining how or why your evidence supports your claim.
For example: This evidence supports my claim because...
This evidence shows... because...

This evidence supports my claim because in my data, you can easily tell that 51° was the most measured. So it makes since for me to guess 51 because it was the most measured because a lot of people measured that.

A few students also included groupings, or bins, to display their data. For example, instead of rounding the temperature values or ignoring the numbers after the decimals, Andrew created equal-sized bins to group the temperatures by their decimal values (Figure 4-23).

Figure 4-23

Lesson 2: Andrew's Use of Bins



CLAIM: A statement you believe is true.

I think the temperature was 51.55

EVIDENCE: Data or factual information that supports your claim.
For example: The mean is...
My data display shows...

My display shows that 51.1-52° is the mode. The mean of 51.1 and 52 is 51.55

REASONING: Explaining how or why your evidence supports your claim.
For example: This evidence supports my claim because...
This evidence shows... because...

The evidence shows that the most recorded temps were btwn 51.1-52.

Although we kept the instructions for this activity deliberately vague, i.e., “create a data display to provide evidence for you answer to this question,” we found students used the mathematical concepts of order, count, and grouping they had developed several months prior in mathematics class. This suggests that students found these ideas useful as tools to organize the variability in their data and to make visible some of its aggregate properties, e.g., the mode and the range. The variety of ways students created their data displays, e.g., using color, dots, X’s, bars, lines etc., provides further evidence that it was the mathematical ideas of order, count, and to a lesser extent, grouping, that they found useful, rather seeing this activity in science class as replicating the idea of a correct data display from mathematics class.

Most students used their data displays as a way to determine an aggregate property of the data, typically the mode, and to justify their claim of the mode as the typical temperature. Like Riah and Andrew, they often wrote that their data display showed them the mode of the temperature data, and that was the evidence they used to justify their claim.

5.3.2 Measures of Center

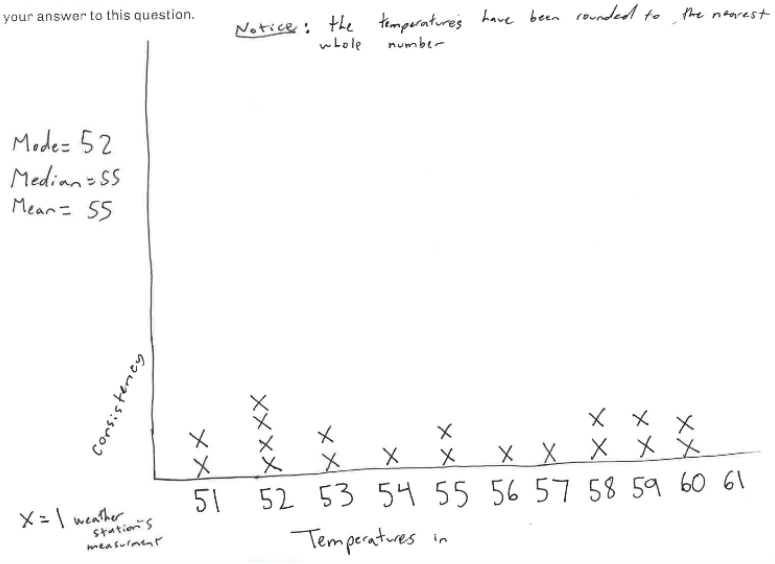
In their mathematics class, students had opportunities to describe their own invented measures of center to characterize a typical measurement. In this weather data investigation, a few students continued to invent their own measure of center. For example, Alex, the student who grouped his data by decimals, claimed the temperature on the app should be 51.55 because his “display shows that 51.1-52 is the mode. The mean of 51.1 and 52 is 51.55.” He then found the mean of the bin range with the greatest count. In this case, Alex used the concept of bins as a tool to find the mode, and he used the size of his bins to find the typical temperature.

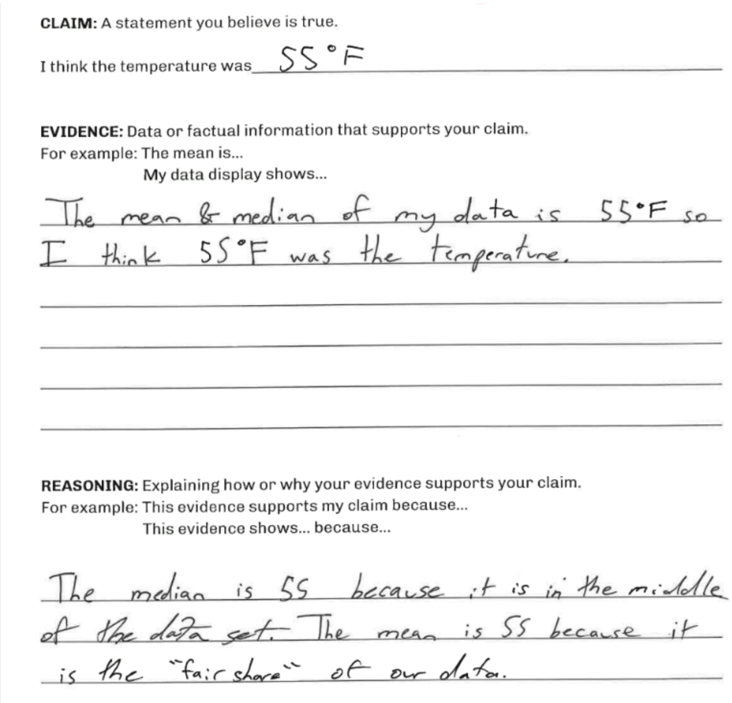
Most students, however, named and calculated at least one statistical measure of center, e.g., mean, median, or mode, to justify their claim about the typical temperature in their town. Most students used the mode for the typical temperature and, if they justified their choice, they explained they chose it because most people measured it, or because it occurred most often. For example, Riah indicated the mode on her data display and claimed the temperature was 51 (Figure 4-22). She justified her choice of the mode by explaining, "this evidence supports my claim because in my data, you can easily tell that 51° was the most measured so it makes sense for me to guess 51 because it was the most measured because a lot of people measured that" (Figure 4-22). Her words of "in my data, you can easily tell" suggest that she viewed her data display as a tool that communicated to her the typical temperature.

We conjectured this activity would support students to discuss the mathematical reasoning behind their choice of measure of center and we saw evidence of this when several students calculated multiple measures of center to justify their claims. For example, Marilyn calculated all three statistics (Figure 4-24). She made the claim that 55 was the typical temperature because "the mean & median of my data is 55° F so I think 55° was the temperature". She explained her reasoning by writing that "the median is 55 because it is in the middle of the data set" and "the mean is 55 because it is the 'fair share' of our data." Marilyn reasoned that the similarity between the mean and median provided evidence that it was the best value to claim as the typical temperature.

Figure 4-24

Marilyn's Use of Mean and Median





CLAIM: A statement you believe is true.

I think the temperature was 55°F

EVIDENCE: Data or factual information that supports your claim.
For example: The mean is...
My data display shows...

The mean & median of my data is 55°F so I think 55°F was the temperature.

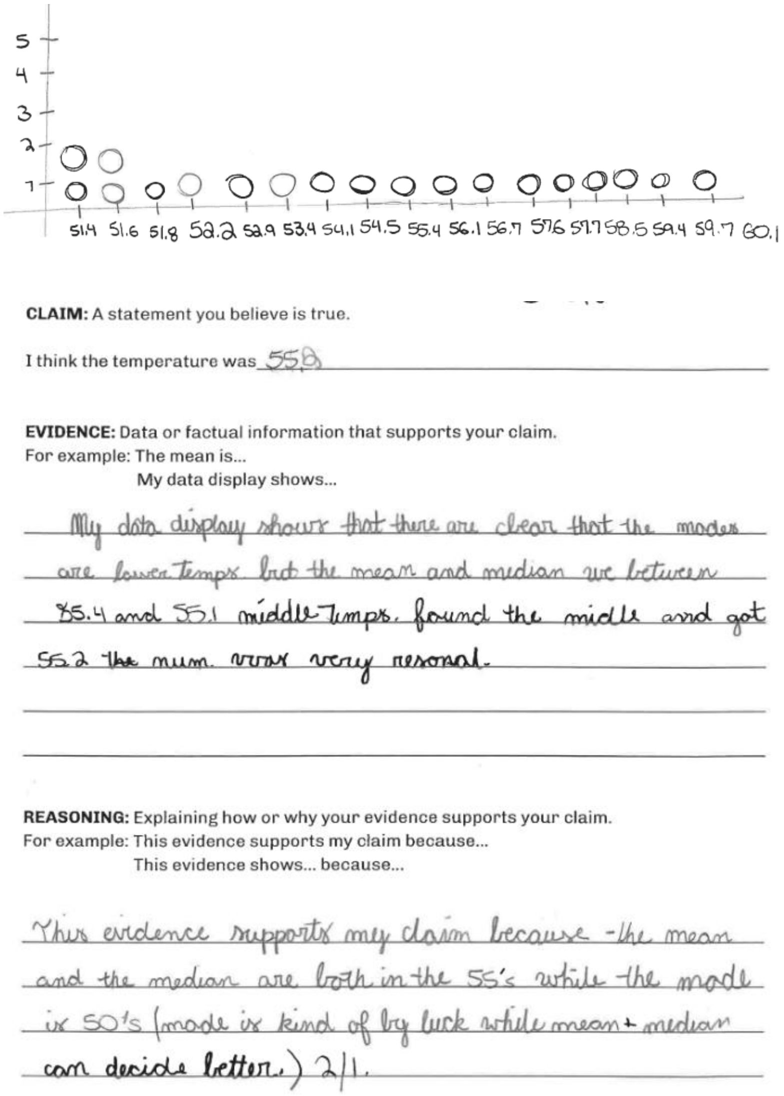
REASONING: Explaining how or why your evidence supports your claim.
For example: This evidence supports my claim because...
This evidence shows... because...

The median is 55 because it is in the middle of the data set. The mean is 55 because it is the "fair share" of our data.

Savannah more explicitly explained her reasoning for using the mean and median rather than the mode. She created a dot plot of the exact temperature values (Figure 4-25). She claimed the typical temperature was 55.2 because "my data display shows that there are clear that the modes are lower temps. but the mean and median are between 55.4 and 55.1 middle temps. [I] found the middle and got 55.2. The num. was very resonal [reasonable]". To determine the typical temperature, Savannah invented a measure of center by finding the middle number between her calculated mean and median.

Figure 4-25

Savannah's Reasoning for Mean and Median



CLAIM: A statement you believe is true.

I think the temperature was 55.8

EVIDENCE: Data or factual information that supports your claim.
For example: The mean is...
My data display shows...

My data display shows that there are clear that the modes are lower temps but the mean and median we between 55.4 and 55.1 middle temps. found the midle and got 55.2 the num. was very resonal.

REASONING: Explaining how or why your evidence supports your claim.
For example: This evidence supports my claim because...
This evidence shows... because...

This evidence supports my claim because the mean and the median are both in the 55's while the mode is 50's (mode is kind of by luck while mean + median can decide better.) 2/1.

Savannah explained how this evidence supported her claim by writing “the mean and the median are both in the 55’s while the mode is 50’s (mode is kind of by luck while mean + median can decide better) 2/1” (Figure 4-25). Savannah used all three measures of center to describe the distribution. Like Marilyn, she reasoned that the similarity between mean and median provided better evidence for the typical temperature. She viewed the most measured temperatures, or mode, as happening “by luck.”

Savannah elaborated further on her reasoning during a whole class discussion when students had an opportunity to share their claims, evidence, and reasoning (Table 4-11).

Table 4-11

Savannah’s Discourse Critiquing the Mode as a Measure of Center

Row	Speaker	Discourse
1	Savannah:	*I think it reminds me of something, like when we did the measuring.*
2		*I’ve thought about it and it’s like, the mode is almost used by luck. Well, not by luck, but, like, it might not be the most, like, I guess the proper way to find the number.*
3		*Because like, it's like, you get two other numbers for like, the median and the mean*
4		*It's just like, it can help you decipher it. If that makes sense?*

Even though Savannah viewed the mode as not the most “proper way find the number,” Savannah saw all three measures of center as ways to help her “decipher” the typical temperature (row 4). This suggests Savannah viewed calculating the measures of center as a means to help her answer the question of what was typical. Artifacts such as calculating measures of center become epistemic tools through their use in specific contexts (Kelly & Cunningham, 2019), and Savannah appears to be connecting calculating measures of center in the context of measuring in mathematics class (row 1) with using them in this context of finding the typical temperature in science class.

Evan also verbalized using the measures of center to figure something out. Immediately prior to Savannah's discourse, he discussed how he combined multiple mathematical strategies to determine the typical temperature (Table 4-12).

Table 4-12

Evan's Invented Strategy to Find the Typical Temperature

Row	Speaker	Discourse
1	Mrs. K:	Alright, so you rounded, and you got 52 as that mode, and that was the temperature that you put on your weather app - 52. So, we have 51, we have 52, we have 55. Alright, now, Evan?
2	Evan:	*I put 54.5, and give me a sec. So, I put all of the measurements.*
3		*I put the range equal to 9. I rounded all of my numbers, and I got the range as 9, I got the median as 55, and I got the mode as 52, and then I got the mean as 55.*
4		*So, the median and the mean are both the same. So, that gives me an idea on which area it probably is in.*
5		*So, it is probably like 55 through 53, and then, I cut the range in half and got 4.5.*
6		*Then, I looked at my meter paper and if it had any 54.5s. And you have one right here. One right here.*

Evan claimed the typical temperature was 54.5, and for his evidence, he calculated the range, median, mode, and mean of the rounded temperature values (row 3). Evan viewed calculating those statistics as a way to give him "an idea on which area it [the typical temperature] probably is in" (row 4), and then he made a claim of where on the distribution he thought the typical temperature occurred (row 5). This suggests he viewed these mathematical ideas as a tool to find something out. Like Savannah, he used all three measures of center to describe the distribution of the temperature measurements in his data display, but he also used a measure of variability, the range.

Interestingly, Evan then divided the range by two and used that number to find a specific weather station on the "meter paper" that reported a temperature that matched his calculated mid-range (row 6). He was the only student that connected a measure of center back to the "meter paper" and the specific weather stations. This suggests that Evan was connecting his value for the typical temperature with a physical weather station that could have produced it.

In summary, we designed this lesson to find a single temperature to report on an app so that students would experience macro-level integration and use some of the mathematical concepts in science as epistemic tools to organize and structure the variability in temperature values at a single moment in time. We found that students created a variety of data displays by ordering the values and indicating their frequency. Students used the mode, and to a lesser extent, the mean and median, to determine the most typical temperature value. Students continued to invent measures, often using a combination of calculated values for mode, mean, or median, as a way to communicate the most typical value. In their writing and discourse, students explained how data displays and their measures of center told them something or helped them figure something out.

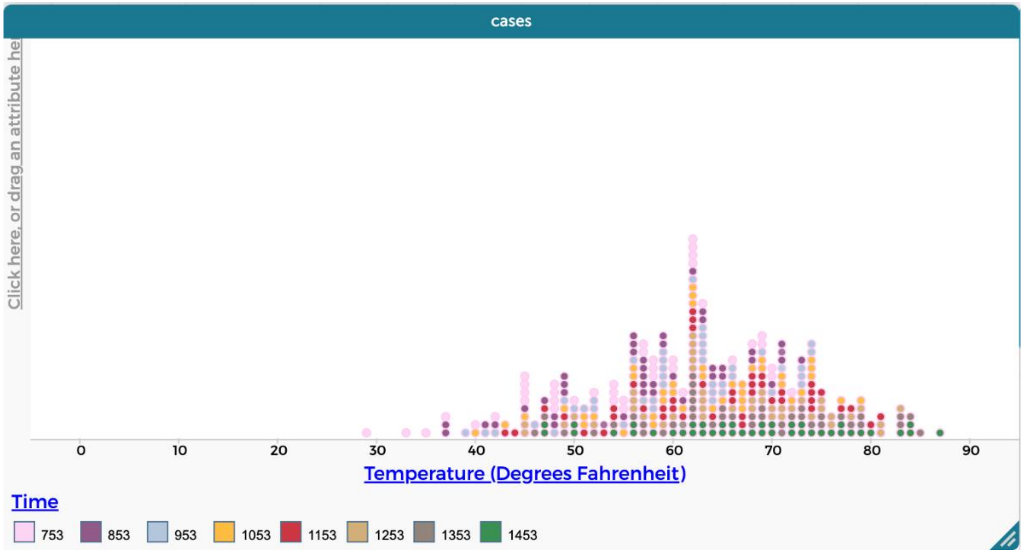
5.3.3 CODAP Data Displays

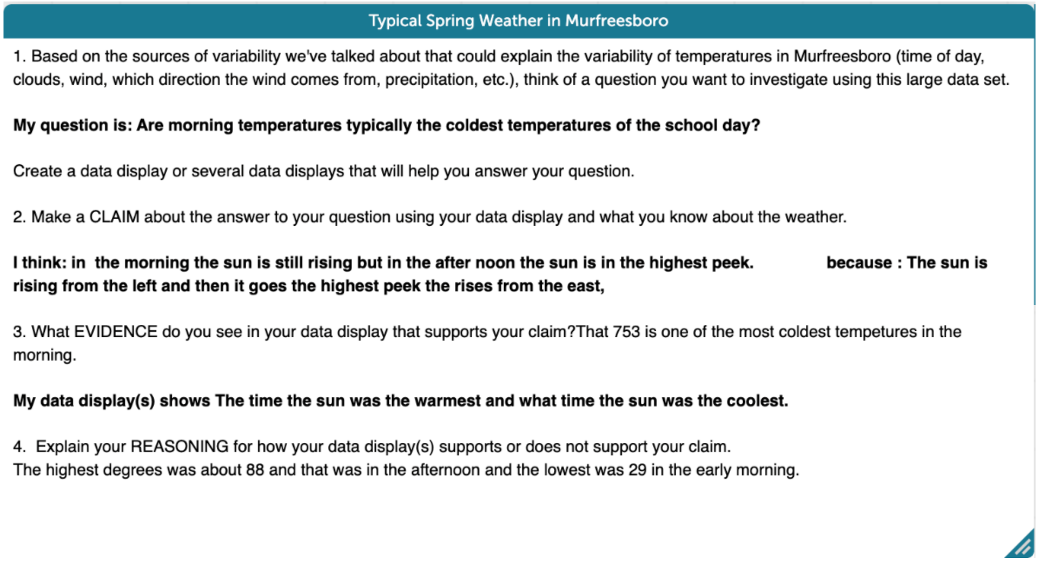
In the final lesson of the weather data investigation, students used a large set of local weather variables collected in March and April and CODAP to design their own data investigation. We conjectured this activity would provide opportunities for students to experience macro-level integration as they used knowledge and skills from mathematics class to organize, structure, and explain variability in a large data set. We found that all students made data displays using at least two variables from the data set to organize and structure the data. Many students did not complete the claims, evidence, and reasoning part of the assignment and so it was difficult to determine their reasons for the choices they made as they created their data displays. If they completed the entire assignment, we found students used individual values from their data displays as evidence for their claim rather than describing aggregate qualities of the data. Most students did not use measure of center tools on their data display or reference measures of center in their explanations.

Many students made a data display like Eden's in which she partitioned the data using two different variables (Figure 4-26). Unlike other students, Eden used a phenomenon we had talked about earlier in the lesson and information she generated from her data display to explain the answer to her question. Eden's investigative question was one we had listed as a possible choice for investigation: "are morning temperatures typically the coldest of the school day?" (Figure 4-26). For her data display, Eden created a dot plot of all the temperatures in the data set and used a color-coded key to indicate the time of day they were recorded.

Figure 4-26

Eden's CODAP Data Display and Claim, Evidence, Reasoning




Typical Spring Weather in Murfreesboro

1. Based on the sources of variability we've talked about that could explain the variability of temperatures in Murfreesboro (time of day, clouds, wind, which direction the wind comes from, precipitation, etc.), think of a question you want to investigate using this large data set.

My question is: Are morning temperatures typically the coldest temperatures of the school day?

Create a data display or several data displays that will help you answer your question.

2. Make a CLAIM about the answer to your question using your data display and what you know about the weather.

I think: in the morning the sun is still rising but in the after noon the sun is in the highest peek. because : The sun is rising from the left and then it goes the highest peek the rises from the east,

3. What EVIDENCE do you see in your data display that supports your claim?That 753 is one of the most coldest tempetures in the morning.

My data display(s) shows The time the sun was the warmest and what time the sun was the coolest.

4. Explain your REASONING for how your data display(s) supports or does not support your claim.
The highest degrees was about 88 and that was in the afternoon and the lowest was 29 in the early morning.

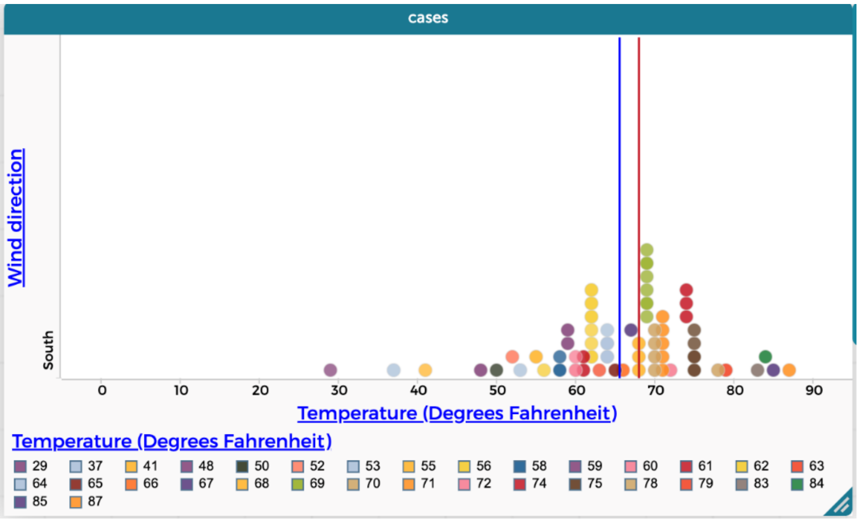
Eden answered her question by drawing upon her knowledge of the motions of the sun across the day, a phenomenon we had discussed earlier in the investigation (Figure 4-26). She then stated that "753 is one of the most coldest tempetures [temperatures] in the morning" and explained that her data display showed "the time the sun was the warmest and what time the sun was the coolest." Eden used the maximum and minimum of the data on her data display to explain her claim: "the highest degrees was about 88 and that was in the afternoon and the lowest was 29 in the early morning."

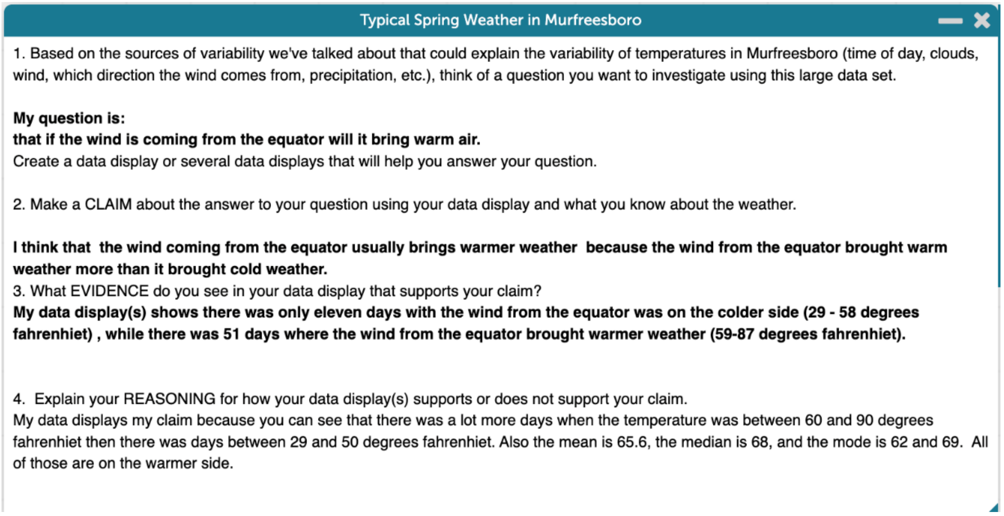
Eden's work suggests she attempted to explain why temperatures are typically colder in the morning by connecting the phenomenon of the sun moving across the sky with the two extreme values on her data display. Many of the students used individual values from their data display like Eden rather than using aggregate qualities of the data, e.g., measures of center or range, as their evidence or in their reasoning.

If they calculated them, few students used the aggregate qualities, i.e., measures of center, from their CODAP display as evidence in their explanation. For example, Andrew used a measure of center in his CODAP display that we discussed earlier (Figure 4-19), but he did not reference it in his explanation. Marilyn was one of the few students who connected a measure of center from their CODAP display with the phenomena they were investigating in their explanation (Figure 4-27).

Figure 4-27

Marilyn's CODAP Display and Claim, Evidence, and Reasoning





1. Based on the sources of variability we've talked about that could explain the variability of temperatures in Murfreesboro (time of day, clouds, wind, which direction the wind comes from, precipitation, etc.), think of a question you want to investigate using this large data set.

My question is:
that if the wind is coming from the equator will it bring warm air.
Create a data display or several data displays that will help you answer your question.

2. Make a CLAIM about the answer to your question using your data display and what you know about the weather.

I think that the wind coming from the equator usually brings warmer weather because the wind from the equator brought warm weather more than it brought cold weather.
3. What EVIDENCE do you see in your data display that supports your claim?
My data display(s) shows there was only eleven days with the wind from the equator was on the colder side (29 - 58 degrees fahrenhiet) , while there was 51 days where the wind from the equator brought warmer weather (59-87 degrees fahrenhiet).

4. Explain your REASONING for how your data display(s) supports or does not support your claim.
My data displays my claim because you can see that there was a lot more days when the temperature was between 60 and 90 degrees fahrenhiet then there was days between 29 and 50 degrees fahrenhiet. Also the mean is 65.6, the median is 68, and the mode is 62 and 69. All of those are on the warmer side.

Marilyn investigated the relationship between wind coming from the direction of the equator and the temperatures in March and April (Figure 4-27). In Figure 4-27, Marilyn partitioned the data by creating a display of all temperature values reported (horizontal axis) when the wind direction was from the south (vertical axis), and she calculated the mean and the median using the CODAP tools (red and blue lines). In her explanation, she defined colder air (29-58 degrees) and warmer air (59-87 degrees), and she compared the number of temperature values in each grouping. This suggests she is considering an aggregate property of her data display by focusing on the large "clump" of values above 60 degrees (Figure 4-27). It also suggests she viewed her data display in relation to the phenomenon of wind blowing from the south because in her writing she connected warmer air from the equator with specific temperature values from her data display. This suggests Marilyn engaged in meso-level integration because she connected variability in temperature values in the large data set with the movement of air masses, a phenomenon we had discussed earlier in the investigation. In her explanation, she explicitly stated the values for three measures of center and connected them to the phenomenon of being "on the warmer side."

It is difficult to tell if many of the students were using ideas from mathematics as tools to generate answers for their investigative questions. Many students used CODAP to make data displays that contained a relationship between two or more weather variables. Several students used individual values from their data display as evidence for their claims like Eden. Only a few students used aggregate qualities of their data display as evidence or in their explanation as Marilyn did. Andrew, for example, partitioned the data according to month and time of day and then, using the CODAP tools, indicated the mean of each time of day on his data display (Figure 4-19).

For the second iteration of this investigation, this activity might be more informative about students' thinking if students created their data displays and wrote their explanations working in pairs. As students verbally negotiate the choices they make, their thinking would be more visible to observers. Additionally, we did not have time for students to share their investigative questions and displays in small groups or as a whole class. In the next iteration, we should plan more time for students to share what they had learned from their investigative questions so that we could have more evidence about their thinking through their discourse.

6. Discussion and Implications

In this design study, we used two theoretical frameworks, the new Sensemaking Integrated STEM framework and the Explaining Variability construct, to design a weather data investigation for sixth-grade science students. We then made design conjectures about how the opportunities for student sensemaking about variability would function. To understand how students responded to these sensemaking opportunities in our initial design, we had three specific research questions: (a) how did students explain variability in their local weather data as they engaged in the sensemaking process, (b) how did students connect their knowledge resources as they made sense of variability in local weather data, and (c) how did students use epistemic tools from their mathematics class as they made sense of variability in local weather data.

We found that, throughout the weather data investigation, students engaged in the sensemaking process. They responded to the activities by brainstorming ideas and attempting to connect those ideas with their prior experiences to figure out something that was puzzling to them in the weather data. During the sensemaking process, students explained variability in their weather data by integrating variability in temperature data with their everyday experiences and their ideas about weather phenomena, e.g., wind direction, precipitation, shade, clouds, the position of the sun, and length of time the sun shines. In this first iteration, however, it was challenging to support students to experience meso-level integration and connect knowledge resources across activities in the investigation during their sensemaking. There was evidence that some students made the connections we planned for, but it is unclear from their discourse and artifacts whether most students experienced the meso-level integration we had anticipated.

Addressing our third research question, we found evidence, especially in students' pen-and-paper data displays, that students used their prior mathematics concepts of order, count, and to a lesser extent grouping, as epistemic tools to make sense of variability in temperature data. Students used these epistemic tools to organize their data and make aggregate properties of their data visible. They also used measures of center from their mathematics class, typically the mode, as an epistemic tool to determine and justify their claims for the typical temperature.

For the remainder of this section, we discuss three implications from this study. First, we argue that the Sensemaking Integrative STEM framework and the Explaining Variability construct are productive lenses for designing science data investigations to support students to connect variability in data with the phenomena that produced it. As we designed this investigation, we used these frameworks to select the type of variability in their local weather data we wanted students to make sense of and then we thought about students' likely knowledge resources they would use in their sensemaking explanations, the connections they might make among those resources, and the timing of how those resources were introduced. Second, we discuss implications for developing sensemaking opportunities for students to routinely reach for statistical ideas from mathematics class and how this supports students to use those ideas as epistemic tools for generating knowledge. Third, we discuss the challenges we experienced designing for meso-level integration and their implications for our next iteration of the weather data investigation. We conclude this section with some possible limitations of this design study.

6.1 Designing Science Data Investigations Using the Sensemaking Integrated STEM Framework and the Explaining Variability Construct

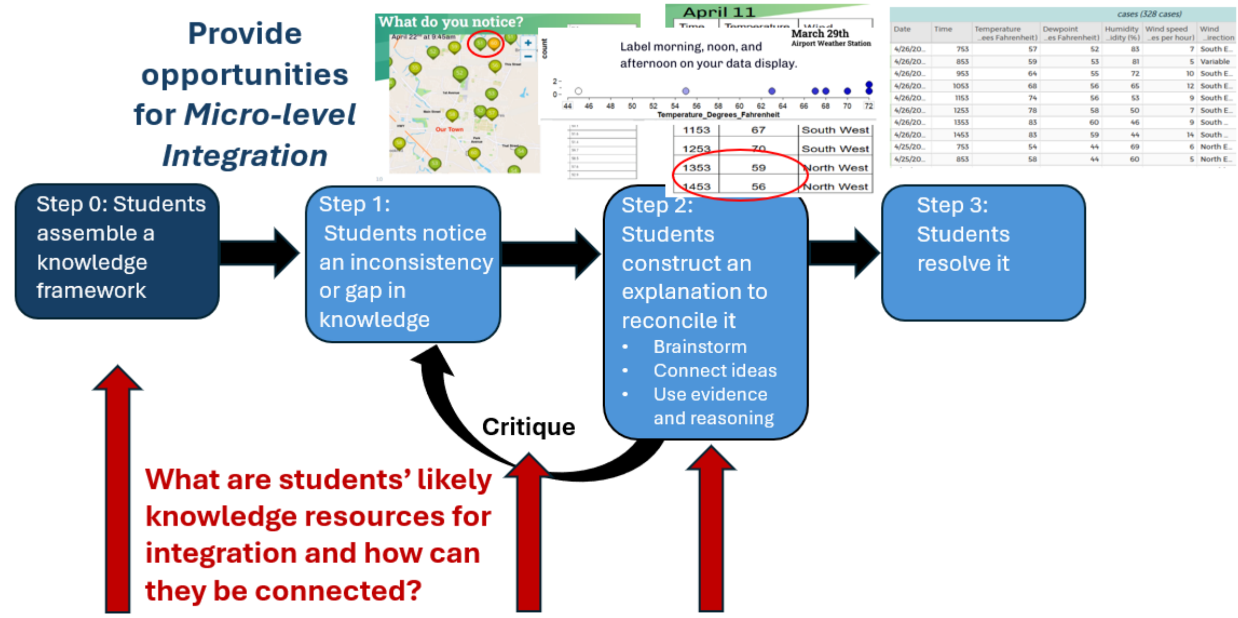
The Sensemaking Integrated STEM Framework was developed to understand how students generate knowledge resources as they engage in sensemaking during integrated STEM activities and how students connect those knowledge resources as they make sense of integrated STEM problems. We used this framework to design activities that provided opportunities for students to experience something puzzling or inconsistent in a strategically selected set of their local weather data. These activities helped students engage in micro-level integration as they entered the sensemaking process and brainstormed ideas to try to explain the puzzling variability in the data. As they developed their explanations for variability, we anticipated students' likely knowledge resources, i.e., their prior knowledge and everyday experiences of weather phenomena, and we conjectured how students would connect these resources to develop their explanations of variability.

We used our second theoretical framework, the Explaining Variability construct, to focus our design on what we wanted students to make sense of. It informed our selection of the temperature data we wanted to highlight for students, and it allowed us to structure the activities so that students would experience all levels of the explaining variability construct (Levels 1-4; Table 4-1). In the weather data investigation, we sequenced activities so students would develop more complex explanations of variability during sensemaking: first they made sense of variability in temperature data at a single moment in time, then they made sense of variability in temperature data across the school day, and finally, they made sense of variability in temperature data across two months in the spring.

These two frameworks could be used to design other science data investigations and study students' thinking as they develop explanations for sources of variability in data. First, researchers and curriculum designers would plan opportunities for students to engage in the sensemaking process about sources of variability in their data (top half of Figure 4-28). These opportunities would support students to notice a puzzle or gap in their observations of, or understanding about, the data.

Figure 4-28

Designing Science Data Investigations Using the Sensemaking Integrated STEM Framework



Then, researchers and curriculum designers would plan for the likely knowledge resources students would use as they assembled their knowledge framework about what they noticed about the data (step 0), brainstormed and connected their ideas about data, statistics, and phenomena as they explained the possible sources of variability (step 2), and critiqued their explanations (bottom half of Figure 4-28). Students would be guided to draw upon knowledge resources from mathematics class, e.g., creation of data displays, measures of center and variability, or probability, in their engagement of sensemaking so that they experienced macro-integration. The opportunities for sensemaking would also be connected, i.e., meso-level integration, so that students made progress on developing more complex explanations for variability and greater understanding of science phenomena.

After researchers enacted their design, they could study the types of knowledge resources students used and the ways students connected them or did not connect them. Instructional strategies, such as teachers' discourse moves or teaching routines, could be developed and studied to support students' integration of ideas about data, statistics, and phenomena at different steps in the sensemaking process. The sequencing of students' knowledge resources could also be studied so that students made conceptual progress as they engaged in sensemaking about data.

These two frameworks allowed us to design for the orchestration of students' experiences through the amalgam of sub-problems in our weather data investigation. Although we have used them to design science data investigations, we hope other researchers and curriculum designers find them useful to design other types of integrated STEM activities, e.g., engineering design challenges, model-eliciting activities, socio-scientific issues, etc.

6.2 Making Sense of Variability with Epistemic Tools from Mathematics

Students make sense of the variability inherent in data from natural phenomena when they engage in creating data displays, determining measures of center, and determining measures of variability (Hunter-Thomson, 2022; Lehrer et al., 2020). These activities allow students to generate their own knowledge claims about the natural world and justify their reasoning (Lehrer et al., 2020). For these statistical activities to become epistemic tools for students, they need opportunities to routinely use them across disciplinary boundaries and understand the specific knowledge building contexts in which they are used (Kelly & Cunningham, 2019; Lehrer et al., 2020).

Two activities in our weather data investigation supported students to use statistical ideas from mathematics class to make their own claims about their local weather data: students used pen-and-paper data displays and measures of center to make sense of temperature variability at a single moment of time, and students used CODAP data displays and measure of center tools to make sense of variability in a large weather data set to answer their own investigative question. In their discourse and written explanations, students viewed these mathematical ideas as helping them see something in their data or figure something out. Some students used invented strategies to determine measures of center to make claims, which suggests that they were not following a procedure, but rather thinking about calculating their own aggregate property of the data. The need to use ideas from mathematics class arose naturally for these students because it became apparent to them in the activity that they needed them to organize the data and determine some aggregate property of the data to make a claim about the typical temperature.

Our work suggests that students should routinely have these kinds of opportunities to explain the variability in their data by creating their own data displays and determining measures of center in their science investigations. Artifacts like creating data displays and determining measures of center become epistemic tools for students only through their repeated use (Kelly & Cunningham, 2019). Moreover, these artifacts must be used by students for knowledge construction, rather than students using them as a procedure, i.e., “we always calculate the average of our data in science.”

Students should also have opportunities to collectively share and justify their use of these epistemic tools from mathematics class so that students become accountable to others in the class for their knowledge construction (Kelly & Cunningham, 2019). In the weather data investigation, we did not have time for students to share their CODAP work and explain how their data displays answered their investigative question. This might explain why their use of concepts from mathematics is less obvious than when students made pen-and-paper displays and had the opportunity to discuss their different ideas.

6.3 Challenges with Meso-Level Integration

There were several opportunities for students to experience meso-level integration and connect knowledge resources across activities in our weather data investigation. For example, we initially conjectured students would use ideas generated by making sense of when the warmest part of the day occurred and connect those ideas to their prior knowledge of radiation, convection, conduction and to the data from a physical model of heat transfer. We found it was challenging to support students to coordinate and connect ideas across the data model, physical model, and explanatory model. We suspect there are at least two reasons why these challenges occurred: first, students had to develop multiple explanations of variability in temperature data at the same time, and second, it was challenging for students to quickly make sense of the connections between the representations in the physical model and the phenomena in the explanatory model.

Students had to coordinate explanations for variability in temperatures across the day shown on the dot plot (Figure 4-5) with explanations for variability in temperatures collected during the physical model (Figure 4-14). In the physical model, students had to make sense of variability in temperature values across the period of time we collected the data and across different locations, e.g., the counter, the soil, and the suspended disk, where we collected the temperature data. We did not give students enough time to notice and explain the variability in the data from the physical model or to coordinate their explanations with the variability in temperatures across the day.

Second, we did not give the students enough time to make sense of the connections between the representations in the physical model and the phenomena in the explanatory model. For example, we asked students to understand that the suspended disk in the physical model represented a column of air above the ground in the explanatory model. Students' understanding of the alignment between models is an important consideration when designing science investigations (Manz et al., 2020; Manz & Georgen, 2023). In this case, all students did not have enough time to fully make sense of the connections we assumed would occur. Mrs. K ended up doing most of the explaining in this lesson, rather than the students developing their own explanations.

Finally, we did not anticipate the amount of time that it took for these sensemaking discussions. When students are engaged in the sensemaking process, they need time to notice, think, and share their ideas with others (Odden & Russ, 2018). We had a finite amount of time for the weather data investigation allocated by the La Flor School science teacher. We found that, as our investigation progressed, we had less and less time to develop the ideas in the lessons that occurred at the end of the investigation, and we had less time to support students to connect their ideas across the activities. Other researchers have indicated that they have found a tension between the amount of time it takes for supporting students to connect ideas across activities and the benefits from sensemaking (Manz & Georgen, 2023).

We have two takeaways from these challenges for the revision of this weather data investigation. First, we must take care when selecting multiple models for potential sensemaking across activities. There can be too much variability for students to attempt to make sense of, and students may not understand the connections between models without considerable support from the teacher. Second, when students engage in the sensemaking process, it takes time to share and develop their explanations. We will need to carefully consider the pacing of the activities in this investigation for our next iteration.

6.4 Limitations

This design study reported on findings from the first iteration of the enactment of the weather data investigation. We acknowledge that our findings cannot be generalized beyond these groups of students, but we intended to give readers rich descriptions of the choices we made in the design and the theoretical frameworks we used to make them. We also described in detail how students responded to the activities in this investigation in both anticipated and unanticipated ways. We will use these findings to further refine our design conjectures for the next iteration of this design study.

The analyses of students' discourse and artifacts were conducted solely by the first author. This limits the conclusions that can be drawn from these findings. We plan to have robust conversations about the findings in this dissertation manuscript with our research group before it is submitted for publication.

7. Conclusion

Science investigations in which students are asked to explain the variability they encounter as they collect, analyze, and interpret their data supports them to authentically connect data visualization and statistical practices with understanding phenomena (Lehrer & English, 2018; Lehrer et al., 2020; Hunter-Thomson, 2022). In our weather data investigation, we used the Sensemaking Integrated STEM framework to design activities that provided opportunities for students to experience something puzzling or inconsistent in a strategically selected set of their local weather data. We used the Explaining Variability construct to focus our design on what we wanted students to make sense of. Our findings suggest that using these two frameworks to provide opportunities for students to make sense of variability are productive lenses in which to create science data investigations to support students to connect data visualization and statistical practices with understanding phenomena.

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Appendix 4-A

Table 4A- 1

Explaining Variability Construct

Level	Student Performances	Example
EV 6: Model Competition Students compare competing models for the same distribution of observed values.	Students: 6b: develop and apply criteria for assessing relative fit and validity of competing models.	“I think that is important for the model to produce the extreme values because those matter when we think about change over long periods of time.”
	6a: compare competing models of observed distribution.	“In my first model, plant heights varied from generation to generation, but all the variability was just by chance. In the second model, I included the effects of differences in light.”
EV 5: Model Distribution Students develop a model that accounts for the distribution observed.	Students: 5c: proposed model revisions in light of model evaluation.	“I changed the model to get more spread in the distribution of plant heights by adding another component.”
	5b: evaluate model results.	“When I ran the model with different starting times for growth, the heights that we modeled had the same bell-shape as the heights we found in our data. But there was more spread in our data than was predicted by the model.”
	5a: develop a probability model of process accounting for distribution. OR Develop a probability model of probability structure for discrete outcomes.	“Each Fast Plant started its growth at a little bit of a different time. All of them started out at 0 mm, which is why all of the heights are stacked up on the left side of the graph early in the growth cycle. Bast as the plants began to grow, we began to see a bell-shaped curve, showing that most of the plants had a similar height, although a few were shorter and a few were taller than average. So,

		when I built my model, I used a spinner to show the chance of starting the growth spurt earlier or later.”
EV 4: Difference Explained Students construct explanations that account for sources of variability. Students use data AND phenomenon to construct the explanation or include multiple variables.	Students: 4c: develop an explanation of a process or mechanism to explain variation.	I think the plants under the grow light would be the taller ones on the right side of the data display, but the ones on the edge of the light are on the left side.
	4b: Coordinate variation in a measured attribute with variation in another relevant attribute to partition data and explain variation in the measured attribute.	“Let’s make different graphs for samples inside the wild space and outside the wild space. Then we can see if there’s more clover inside or outside.”
	4a: build correspondence among measurement procedure, phenomenon, and data to explain variation	“I think the only way you’d get a measurement that low is if you used inches and the rest of the class used cm.”
EV 3: Difference Structured Students structure a collection of measures as a distribution and measure distributional features with statistics. Students rely on data only with no connection to the phenomenon.	Students: 3c: relate measures of variability that describe a distribution to events or processes	“The first fruit fly adults hatched 3 days before the last fruit fly adult, so the range was 4 days. 80% of the adults hatched on the second day of the hatching period.”
	3b: relate measures of center that describe a distribution to events or processes	“The median number of hairs on our collection of Fast Plants was 11.”
	3a: display measures of an attribute in a way that makes aggregate properties of the collection visible	“According to our class weather data, the bins with the typical temperature are 60 degrees to 69 degrees and 70 degrees to 79 degrees.”
	3a-: order measures to use aggregate properties of the collection	The Bermuda grass was the most, and dandelions were the least. The other one was in the middle.
EV 2: Difference Measured	Students: 2c: question if reliable claims can be made with variable data	“There’s no way to tell how tall the plants are because they all grew different heights.”

Students develop or appropriate a measure and apply it to a collection.	2b: anticipate variability in measurements (without structure)	“Even if we all measure the same plant, we won’t get the same number just from our mistakes.”
	2a: develop/appropriate a measure of an attribute and ordering the collection on that measure	“Four plants had true leaves on day 8, and five plants had true leaves on day 9, and one that sprouted died before it had true leaves.”
EV 1 Difference Described Students describe qualitative differences in a collection.	Students: 1d: describe variation across different samples	These plants in the mowed area spread out but these plants in the wild space grow taller but don’t spread out.
	1c: brainstorm or make initial conjectures about sources of variability	Maybe some of the plants got more sun or water, so they grew more.
	1b: observe/describe/draw qualitative differences in a collection	“Some of the Fast Plant seeds sprouted on day 2, some sprouted on day 3, and some didn’t sprout at all.”
	1a: do not expect variability	“If all those plants grow in the exact same conditions, they should grow to the same height.”

Note. Sixth-grade students are not expected to exhibit the highest levels of the explaining variability construct: model distribution, and model competition, because those levels are aligned with seventh-grade standards. Adapted from “An Examination of Variability: Using Construct Measurement to Develop an Interdisciplinary Assessment,*”* by F.C. Scott, 2024, (Publication No. 31336083). [Doctoral dissertation, Middle Tennessee State University]. ProQuest Dissertations and Theses Global.

Appendix 4-B

Instructional Materials for Weather Data Investigation

Google Slides Used for the Weather Data Investigation

Student Handouts

Lesson 2: What's the Temperature? Student Handout

April 22, 2024 9:45 am

TEMPERATURE at different weather stations (DEGREES FAHRENHEIT)
51.8
52.2
57.7
51.6
54.5
59.4
53.4
56.1
51.4
56.7
60.1
55.4
54.1
51.6
51.4
59.7
58.5
57.6
52.9

What was the temperature in our town at 9:45 am on April 22nd? Create a data display to provide evidence for your answer to this question.

Lesson 2 Claim-Evidence-Reasoning Student Handout

CLAIM: A statement you believe is true.

I think the temperature
was____

EVIDENCE: Data or factual information that supports your claim.
For example: The mean is…
My data display shows…

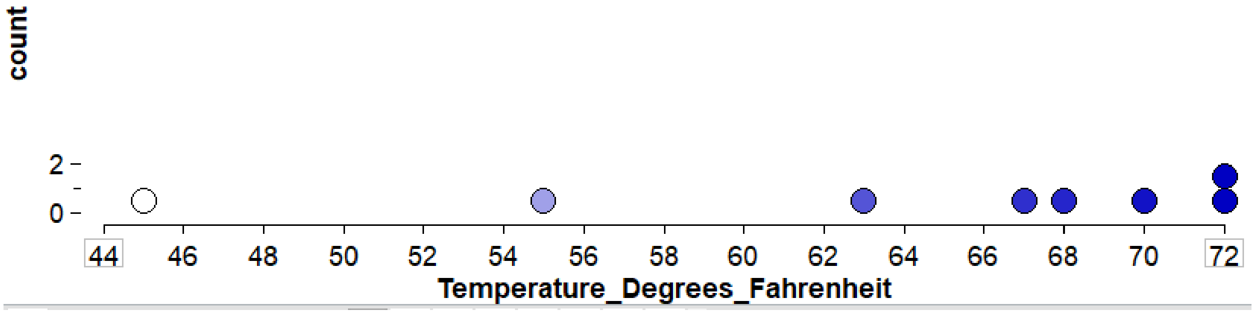
____

REASONING: Explaining how or why your evidence supports your claim.
For example: This evidence supports my claim because…
This evidence shows… because…

Lesson 3: What’s Typically the Warmest Part of the Day? Student Handout

These temperature data were collected every hour from 7:53 am until 2:53 pm on March 29th, a typical sunny day.

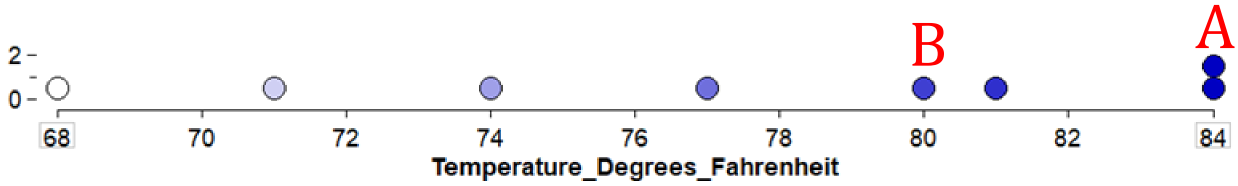
Label morning, noon, and afternoon on the data display.



What caused all this variability?

Draw your own model to explain why the warmest temperatures on a sunny day often occur in the afternoon. **Be sure to use the words radiation, conduction, and convection on your drawing.**

Lesson 3: Formative Assessment



2. Kia and Aubrey are talking about the temperatures at noon on warm, sunny days.

Aubrey thinks letter A should be labeled as noon because noon is often the warmest part of a warm, sunny day.

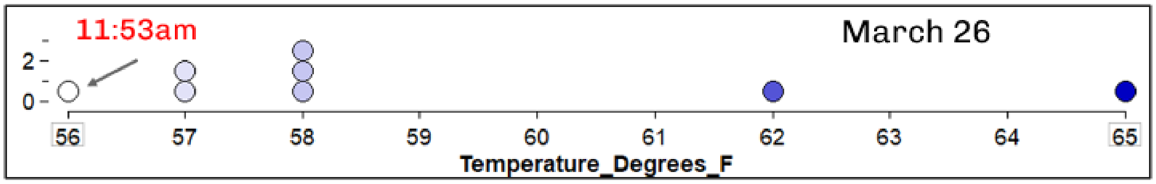
Kia thinks letter B should be labeled as noon because noon is often NOT the warmest part of a warm, sunny day.

Which student do you agree with? Explain why you agree using what you know about heat transfer and weather.

I agree with ______________________________.

I agree with her because ____

Lesson 4: What Other Factors Influence the Temperature? Student Handout



1. Why was the temperature at noon on March 26th the coolest temperature of the day?

Claim: I think ____

Evidence: The data shows that _________________________________

Reasoning: This evidence supports my claim because____________________

Lesson 5: In Our Town, What Factors Influence the Temperature? Student Handout

Based on what we've talked about that could explain the variability in the temperatures in our town (time of day, clouds, wind, which direction the wind comes from, precipitation, etc.), think of a question you want to investigate using this big data set.

My question is ____

____

____

Make a plan for your investigation.

What information will you need to answer this question?

____

____

____

Using CODAP, create a data display or several data displays that will help you answer your question.

Make a CLAIM about the answer to your question using your data display and what you know about the weather.

I think **because**

What EVIDENCE do you see in your data display that supports your claim?

My data display(s) shows

Explain your REASONING for how your data display(s) supports or does not support your claim.

Chapter 5 Conclusion

In this dissertation, I addressed two understudied areas in research about the sensemaking process: how teachers' instructional strategies support different steps in the sensemaking process and how the sensemaking process guides students to integrate disciplinary knowledge, everyday experiences, and their observations during integrated STEM activities. Through this work, I sought to understand how teachers' discourse moves and instructional tasks supported students' engagement in the sensemaking process and how integrated STEM activities, i.e., data investigations could be viewed from a sensemaking lens. Therefore, in chapter two, I empirically investigated how experienced teachers' discourse moves initiated, sustained, and stopped the different steps of the sensemaking process when students were making sense of data displays in mathematics and science classes. In chapter three, I argued that a sensemaking lens is necessary for designing, teaching, and studying integrated STEM activities, and I described my new conceptual framework for integrated STEM, the Sensemaking Integrated STEM framework. My design study in chapter four used this new framework and the Explaining Variability construct to design a sixth-grade weather data investigation. In this study, I empirically investigated how the instructional activities I designed to support students' sensemaking about local temperature data supported students to connect their ideas about weather phenomena and use mathematical concepts as the developed explanations for variability. In this final chapter of my dissertation, I summarize the important findings from each chapter and then "zoom out" to discuss connections across the three chapters.

Chapter Two: Experienced Mathematics and Science Teachers' Discourse Moves to Support Middle School Students' Engagement in the Sensemaking Process

In this study, I investigated how experienced middle grade mathematics and science teachers used teacher discourse moves to initiate, sustain, and stop the sensemaking process during whole class discussions. To do this, I first looked for places in the classroom discourse when students engaged in sensemaking talk, and then I described what kind of idea work the students were doing, e.g., making claims, making observations, explaining, or giving evidence. I characterized the teachers' discourse moves that occurred right before and during these episodes of student sensemaking talk, and then I characterized the teachers' discourse moves that ended these episodes. Finally, I used the student sensemaking framework (Odden & Russ, 208, 2019) to look for patterns in teachers' discourse move across the data corpus.

I found that these veteran teachers used discourse moves to guide students to verbalize their possible sensemaking knowledge resources, i.e., their shared classroom knowledge framework. Teachers then used students' observations or ideas to invite students to initiate the sensemaking process by highlighting a puzzle for students to figure out. The sensemaking process was sustained for students when teachers used discourse moves to ask them to develop explanations and to press them for gaps or inconsistencies in their explanations. Teachers' discourse moves supported a sensemaking process that was dynamic and non-linear in the classroom discourse: teachers' discourse moves guided students to engage in, exit, and re-engage in the process of sensemaking.

These findings suggest that using discourse moves to support the sensemaking process is a complex teaching practice, even for experienced teachers. Many of these teachers used discourse moves that supported certain steps of the process, but not others. For example, teachers used discourse moves to support students to share their ideas, observations, or experiences, but did not subsequently use discourse moves to support students to develop or critique their explanations.

One implication from this work is that the sensemaking process and the discourse moves I described that supported each step could be used as a framework for the professional development of in-service teachers and for training pre-service teachers. This framework could help teachers develop discourse moves to guide students to transition from one step of the sensemaking process to the next.

One of my findings that I am curious to study further is the function of what I characterized as teachers' focusing discourse. This code occurred when teachers used their discourse to highlight some aspect of the data, problem, or phenomenon so that students understood what another student was saying or what the teacher was saying. I suspect that this code was too coarse, and that teachers' focusing discourse functioned in ways that I did not capture in my analysis. For example, sometimes teachers used their discourse to focus students' attention on another student's idea, and at other times, they focused students' attention on some aspect of the data display. These discourse moves were both coded as focusing discourse. I also suspect that teachers' focusing discourse is particularly important when teaching an integrated STEM activity because relevant aspects of the data, problem, or phenomenon may be readily apparent to an expert, the teacher, but not to the students as novices. This discourse move requires further study to understand how it functions in supporting students' engagement in the sensemaking process and in integrated STEM activities.

Chapter Three: The Sensemaking Integrated STEM Framework: Addressing the "When" and "How" of Integrated STEM

This chapter described the potential problems of using frameworks that only describe the disciplinary ideas or skills students engage in during integrated STEM activities, and the development of my new conceptual framework for integrated STEM, the Sensemaking Integrated STEM framework. Instead of thinking about what each of the letters in STEM contributed to the integrated STEM activity, I explored the "integrated" part of the activity and how students made connections between the ideas and practices of different disciplines as they experienced the activity. I theorized that the sensemaking process (Odden & Russ, 2018, 2019) was the mechanism that helped students to make those connections among disciplinary ideas and practices as they collectively worked to explain a gap in their knowledge.

Furthermore, when students experience learning activities, they bring with them knowledge resources from their everyday experiences and their prior learning (diSessa, 1993; Kapon, 2017). Students bring with them knowledge resources in the moment of making sense of an aspect of an integrated STEM activity, but students should also coherently make progress on an integrated STEM problem by connecting the knowledge resources generated across sensemaking moments. They potentially bring with them prior knowledge resources from learning experiences that occurred months previously or in other classes, e.g., from mathematics, science, computer science etc., that could be used during the sensemaking process. The timing of students' knowledge resources, therefore, is important when designing integrated STEM activities (Tytler et al., 2021). In this conceptual paper, I emphasized the importance of considering students' thinking and their experiences during integrated STEM activities when researchers and curriculum designers develop these activities.

I elaborated further on my thinking about this framework in chapter four and I showed how I used it to design an integrated STEM activity, a science data investigation. This work added to the field of integrated STEM research by describing a new student-centered sensemaking framework so that researchers, designers, and practitioners can explore student thinking as they generate and connect knowledge resources when they make sense of STEM problems.

Chapter Four: Making Sense of Variability: A Middle School Weather Data Investigation

In this design study, I used my new Sensemaking Integrated STEM framework and the Explaining Variability construct to design a weather data investigation for sixth-grade students. I asked the following questions related to my initial design conjectures: (a) how does engaging in the sensemaking process support students to explain variability in local weather data, (b) how do students connect their knowledge resources as they make sense of variability in local weather data, and (c) how do students use epistemic tools from their mathematics class as they make sense of variability in local weather data. I then inductively analyzed students' discourse and artifacts to develop rich descriptions of how students responded to the instructional activities in my design.

I found that using strategically selected data sets that highlighted a puzzle or gap in students' knowledge about variability supported students to engage in the sensemaking process. As they engaged in sensemaking, students connected their observations of the data with their knowledge of weather phenomena as they developed explanations for variability. Certain instructional activities in my design worked better than others at providing opportunities for students to connect their knowledge resources as they engaged in the sensemaking process. For example, I found, as the instructor, it was sometimes challenging to support students to coordinate and connect ideas across the different activities, especially when it required students to connect ideas from data models to explanatory models. There is evidence that when students had sensemaking opportunities to reach for concepts from mathematics class in my design, they connected statistical ideas with generating their own knowledge claims in science class.

As the first iteration of my design, there are still revisions to be made and more work to be done to study how students respond to opportunities for micro-, meso-, and macro-level integration. This design study, however, showed how the new Sensemaking Integrated STEM framework could be used to design an integrated STEM activity, and illustrated how designing opportunities for students to experience micro-, meso-, and macro-level integration led students to explain variability in local temperature data using ideas about weather phenomena, their prior experiences, and ideas from their mathematics class.

Connections Across the Three Studies

Across these three studies, I found describing student sensemaking as a process with discrete and observable steps allowed for descriptions of the nuances in how students engaged in sensemaking. As a conceptual and analytical framework, it provided opportunities to describe the knowledge resources students used in their discourse prior to engaging in the sensemaking process and the connections they made in their discourse among those resources as they engaged in the sensemaking process. Moreover, it allowed me to study how teachers' discourse moves and the design of sensemaking tasks supported the individual steps of the sensemaking process. Using this framework across these three studies made student sensemaking and how to support it more tractable to study.

As a practitioner, my observations of the experienced teachers in chapter two and my experiences as the instructor in the design study in chapter four showed me that supporting students' sensemaking is a complex and challenging teaching practice. Other research describing sensemaking in mathematics and science teachers' practice supports this finding (e.g., Fitzgerald & Palincsar, 2019; Hagenah et al., 2018; Leatham et al., 2015; Schwarz et al., 2023). I found it personally challenging to support students' engagement in the sensemaking process by noticing and coordinating students' ideas in the moment of teaching. Often, I inadvertently stopped student sensemaking by explaining too quickly. To improve teachers' understanding and execution of this complex practice, it is helpful to deconstruct student sensemaking and the instructional strategies that support it into manageable steps (Stockero et al., 2022). I intend to use the student sensemaking framework (Odden & Russ, 2018, 2019) in my future work as a professional development tool with practitioners and pre-service teachers.

Conclusion

This dissertation has made several contributions to the science and mathematics education literature about the sensemaking process. My empirical study in chapter two is the first to report on how teachers used certain discourse moves to support or stop the different steps in the sensemaking process. The findings from this manuscript could be used as a framework to further study how teachers' discourse moves function during the sensemaking process. These findings could also be used in the future as a framework for teachers' professional development or training pre-service teachers.

I contributed to the integrated STEM literature by developing a new conceptual framework for integrated STEM that focused on the sensemaking process and how students connect their knowledge resources at different instructional timescales. I showed how this framework could be used to design an integrated STEM activity, a weather data investigation, and how students responded to the designed opportunities for sensemaking and integration. My findings suggest that the Sensemaking Integrative STEM framework and the Explaining Variability construct are productive lenses for designing science data investigations to support students to connect variability in data with the phenomena that produced it. These frameworks could be used in the future design of science data investigations.

Together, these three manuscripts provide insights into how teachers' discourse moves and the instructional tasks teachers use can support students' engagement in the sensemaking process. They show how the process of student sensemaking, with its discrete and observable steps in student discourse, provides a valuable lens through which to study effective instructional strategies.

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