Five years of collaborative inquiry in a high school professional learning community for improving science instruction

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Abstract

Five years of collaborative inquiry in a high school professional learning community for improving science instruction

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Few studies have examined how professional learning communities (PLCs) engage in collaborative inquiry over multiple years. This dissertation describes how a PLC with high school science teachers, district-based coaches, and university researchers conducted collective inquiries over five years to improve science instruction. The PLC was situated in a culturally and linguistically diverse school that experienced high teacher and administrator turnover. This study aimed to explore 1) how the PLC developed multiple lines of inquiry to support students' scientific modeling over the first four years and 2) how five participant teachers' collaboration and classroom teaching to support students' construction of evidence-based explanations co-evolved during the last year of this study. This study was conducted as part of a larger research-practice partnership project. I joined the project in the third year and participated in the focal

PLC as a participant observer. To explore how the PLC developed lines of inquiry over four years, I qualitatively analyzed video recordings of the participants' interactions on twelve job-embedded professional development (PD) days (about 96 hours) where the participants engaged in cycles of collective planning, teaching, and debriefing of lessons. I also analyzed artifacts and interview data. Data suggest that, despite the turnover, the participants developed three lines of inquiry to improve sets of instructional practices to support students' scientific modeling, specifically aimed at facilitating 1) students' epistemic work, 2) students' productive collaboration, and 3) students'—especially emergent bilinguals'— academic language learning. To explore how the teachers' collaboration and teaching co-evolved in the last year, I qualitatively analyzed the video/audio recordings of teachers' interactions on one job-embedded PD day and in eight after-school meetings (about 19 hours) as well as their classroom teaching (34 lessons). I also analyzed artifacts and interview data. Data suggest that the teachers' collaboration in the PLC and their work in classrooms co-evolved over time, as the teachers actively negotiated their goals and expectations about student learning, identified problems of practice, and developed and tested a suite of instructional practices for supporting students' construction of evidence-based explanations. This study suggests implications about how to study and support teachers' collective inquiry over time.

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DEDICATION

To my family and best friend

Introduction

Recent studies in science education have emphasized the importance of providing rich opportunities for students to engage in epistemic practices of science and make sense of the world as knowledge builders (e.g., Duschl, 2008; Lehrer & Schauble, 2006). Scientific modeling and the construction of evidence-based explanations have been suggested as core epistemic practices in science education that can help students become epistemic agents through constructing, justifying, and revising their own models and explanations of phenomena using evidence (Braaten & Windschitl, 2011; Lehrer & Schauble, 2006; McNeill & Krajcik, 2008; Schwarz et al., 2009; Windschitl, Thompson, & Braaten, 2008). Facilitating students' engagement in these epistemic practices requires sophisticated planning and teaching (Windschitl, Thompson, & Braaten, 2018). However, not much is known about how teachers can grow their practice to facilitate students' meaningful engagement in these practices.

With respect to ways for promoting teacher learning, previous studies in teacher education have suggested that teachers can learn effectively by engaging in collaborative inquiry in professional learning communities (PLCs) (Grossman, Wineburg, & Woolworth, 2001; Hord, 1997; Little, 2003). In productive PLCs, teachers can collectively identify and address local problems of practice, develop and test instructional practices based on student data, and construct practice-based knowledge about teaching and student learning (Bryk, Gomez, Grunow, & LeMahieu, 2015).

While many studies have emphasized the importance of continuity and sustainability in teacher learning, not much is known about how teachers' collaborative work could evolve over multiple years. Furthermore, while it is generally assumed that teachers' collaboration in communities can foster improvements in their teaching practices, this assumption is not yet strongly supported because little is known about how teachers' collaboration can co-evolve with their classroom teaching over time.

In this longitudinal case study, I explore how a PLC with high school science teachers, district-based coaches, and university researchers conducted collective inquiries over five years to improve science instruction. The PLC was situated in a culturally and linguistically diverse school that experienced high teacher and administrator turnover. To address the knowledge gaps described above, I asked the following two research questions:

1. How do participants of a PLC—high school science teachers, coaches, and researchers— develop and sustain lines of inquiry to support students' scientific modeling over four years? By a "line of inquiry," I mean that the PLC engaged in multiple cycles of small experiments to improve a set of instructional practices with specific goals to support student learning for a sustained period of time.
2. How do five high school science teachers' collaboration in a PLC and classroom teaching to support students' construction of evidence-based explanations co-evolve over time?

Summary of Study Design

This study was conducted as part of a larger research-practice partnership project in which the research group that I belong to (Ambitious Science Teaching research group at the University of Washington) partnered with a mid-sized urban public-school district in the Pacific Northwest during the years 2012-18. The focal PLC of this study—Sealth High School science PLC—joined the partnership in 2013. I joined the project in 2015 which was the third year of the focal PLC's participation in the project. During 2015-18, I participated in the focal PLC as a participant observer and collected data. The PLC was situated in a culturally and linguistically diverse school and had a high teacher turnover rate. Each year, a few teachers left the school and one to three teachers newly joined the school and the PLC.

There were two kinds of job-embedded professional development (PD) settings in this study that set the stage for the participants' collective inquiry: Studio and Data meeting. In a Studio, the participants—teachers, coaches, and researchers— gathered for a full school day to conduct inquiry to improve their teaching by collectively planning, implementing, and reflecting on focal lessons. The focal PLC had 2-5 Studios every year from the start of their participation in the project. Data meetings were regular after-school meetings (held every three weeks) in which the participants conducted collective inquiries on their teaching based on data from their classes. Data meetings were introduced to the focal PLC in 2015.

The data for this study were gathered during 2013-18. The first two years of data were gathered as part of the larger project. I collected the data for the last three years after I had joined the project and the focal PLC. The data for this study included the followings: video recordings of thirteen Studios during 2013-18 (about 104 hours), audio recordings of eight Data meetings during 2017-18 (about 11 hours), video recordings of teachers' classroom teaching during 2017-18 (34 lessons), artifacts and field notes from the PLC meetings and classroom observations, and audio recordings of interviews conducted with teachers.

Synopsis

This dissertation is composed of three stand-alone sections. The first two sections focus on the two research questions of this dissertation. The last section summarizes key practices that teachers can engage in to drive collaborative inquiry using student work in PLCs. The brief introduction of the three sections is as follows:

Section 1: Sustaining an inquiry group in a high school experiencing high teacher turnover: Four years of collaborative inquiry to support students' scientific modeling

This section focuses on the first research question about how the participants of the focal PLC—teachers, coaches, and researchers— developed and sustained lines of inquiry to support students' scientific modeling over the first four years of this study. For this section, I qualitatively analyzed video recordings of the participants' interactions in twelve Studios (about 96 hours) during 2013-17. I also analyzed artifacts from the days and interview data.

Section 2: Co-evolution of high school science teachers' collaborative inquiry and classroom teaching to support students' evidence-based explanations

This section focuses on the second research question about how five Sealth High School teachers' collaboration in the PLC and classroom teaching to support students' construction of evidence-based explanations co-evolved over time. For this section, I qualitatively analyzed the video/audio recordings of the teachers' interactions in one Studio and eight Data meetings (about 19 hours) as well as their classroom teaching (34 lessons). I also analyzed artifacts from the meetings and classrooms and interview data.

Section 3: Using student work to drive collaborative inquiry in professional learning communities

This section summarizes three key practices that teachers can engage in to learn from student work and promote collaborative inquiry and improvement in PLCs. I explain the key practices in detail with examples and suggest benchmarks for PLCs to evaluate if/how they are making improvements in their inquiry and teaching.

Section 1. Sustaining an inquiry group in a high school experiencing high teacher turnover: Four years of collaborative inquiry to support students' scientific modeling

Introduction

Scientific modeling has been suggested as a core reform-oriented practice in science education that can help students become epistemic agents, rather than receivers of knowledge, in their learning (Lehrer & Schauble, 2006; Schwarz et al., 2009; Windschitl et al., 2008). By engaging in knowledge building processes of modeling, students can represent their emerging and developing ideas through models and see diverse sets of ideas from their peers. They can collaboratively build explanations of natural phenomena and revise their explanations further based on what they observe and learn from class activities.

Facilitating students' engagement in epistemic practices, such as scientific modeling, requires sophisticated planning and teaching. As facilitators, teachers are asked to carefully plan for students' opportunities to participate in knowledge construction (Passmore, Stewart, & Cartier, 2009), support students' reasoning through productive and responsive classroom discourses (Louca, Zacharia, & Constantinou, 2011; Thompson et al., 2016), and build classroom cultures that can position diverse learners as producers of knowledge (Stroupe, 2014). However, not much is known about how teachers can be supported in working on these multiple aspects of teaching and improve their practice to facilitate students' meaningful engagement in scientific modeling.

Because there cannot be one best way to support students' learning across contexts, scholars have suggested that teachers can learn effectively by participating in PLCs and engaging in collective inquiry to improve teaching (Grossman et al., 2001; Hord, 1997; Little, 2003). In such communities, teachers can collaborate to identify problems of practice in their own contexts, develop and implement instructional practices to address those problems, and test and improve the practices based on what they see from their students (Bryk et al., 2015). Many studies on teacher communities have emphasized the importance of continuity and sustainability in teacher learning (e.g., Hord, 1997; Wei, Darling-Hammond, Andree, Richardson, & Orphanos, 2009). However, not much has been done to qualitatively understand how teachers' collaborative work could evolve over the years.

In this longitudinal case study, I explore how a PLC with high school science teachers, district-based coaches, and university researchers conducted collective inquiries over four years to improve instruction to support students' scientific modeling. The participants' inquiries took place on twelve PD days where they engaged in cycles of collective planning, teaching, and debriefing of lessons. For this paper, I focused especially on how the participants developed and engaged in multiple *lines of inquiry*; in which they developed, iterated on, and improved sets of focal instructional practices and tools with specific goals to support students' learning for a sustained period of time.

Theoretical Background

This study is grounded in a situative perspective on learning which posits that learning occurs through learners' participation in activities and interactions with other participants and with tools in a community (Greeno, 2006; Lave & Wenger, 1991). For understanding the PLC members' collective inquiries to support students' scientific modeling, I drew on three bodies of literature: 1) studies on scientific modeling in the classroom (e.g., Schwarz et al., 2009), 2) studies on teacher learning in PLCs (e.g., Hord, 1997), and 3) studies in the field of improvement science (e.g., Bryk et al., 2015). The first body of literature has argued for the importance of supporting students' engagement in scientific modeling, however, has not focused much on how teachers can grow their classroom practice to facilitate students' modeling. To understand teacher learning over time and in communities, I drew on the second and third bodies of literature about PLCs and improvement science. Below, I review these bodies of literature.

Scientific Modeling and Modeling-based Teaching

In this section, I review the literature on supporting student learning with and about scientific modeling and supporting teacher learning about modeling-based teaching—facilitation of students' engagement in and learning through scientific modeling.

Supporting student learning with and about scientific modeling. Engaging students in the practice of scientific modeling can support students in learning authentic and relevant content and about the knowledge building processes of science, especially when instruction 1) honors students' emerging ideas and capabilities and 2) encourages students to construct, use, evaluate, and revise models for understanding, explaining, and making predictions about natural phenomena based on evidence (Lehrer & Schauble, 2006; Schwarz et al., 2009; Windschitl et al., 2008). With such rich opportunities to engage in epistemic processes of modeling, students can become active producers and evaluators rather than passive receivers of knowledge (Lehrer & Schauble, 2006). They can make sense of puzzling phenomena in their own ways, make connections among scientific ideas to explain phenomena, generate and test predictions, and revise explanations through gathering and synthesizing evidence across learning activities (Schwarz et al., 2009; Windschitl et al., 2008). Furthermore, the literature suggests that when students work together to co-construct models, they can expand their understanding of the content, as they share and discuss multiple ideas, explanations, and predictions and critically analyze the adequacy of those using evidence (Passmore & Svoboda, 2012; Shim & Kim, 2018;

Windschitl et al., 2008). Recent research also suggests that such instruction can be more inclusive for students, especially emergent bilingual (EB)[1] learners, as students use multiple modalities to represent and discuss ideas with models (e.g., drawing, writing, building physical objects, and using computer simulations) (Lee, Llosa, Grapin, Haas, & Goggins, 2019).

Supporting teacher learning about modeling-based teaching. Previous research has suggested that teachers need to learn particular knowledge and skills in order to support students' learning with and about modeling. Some studies have identified components of teacher knowledge that are essential for guiding students' modeling, including teachers' understanding of the nature of models and modeling and the use of models in classrooms (Justi & Gilbert, 2002; Oh & Oh, 2011). Other studies have emphasized the importance of helping teachers learn to plan for students' opportunities to engage in modeling (Kenyon, Davis, & Hug, 2011; Passmore et al., 2009; Windschitl et al., 2018). Teachers can learn how to select puzzling scientific phenomena that are relevant to students' lives and plan to help students construct, evaluate, and revise models of the phenomena over time using evidence from various learning activities (Windschitl et al., 2018). Most of the previous studies on supporting teacher learning about modeling-based teaching have focused on teachers' knowledge about scientific modeling and modeling-based teaching and their lesson planning. Specifically, they have focused on supporting teachers— mostly preservice teachers— in 1) growing their understanding of scientific modeling through engaging in modeling for themselves (e.g., Crawford & Cullin, 2004; Windschitl & Thompson, 2006), 2) developing pedagogical content knowledge for modeling-based teaching by assessing students' models or thinking about effective instructional strategies (Kenyon et al., 2011; Nelson & Davis, 2012), and 3) planning lessons by incorporating core components of scientific

[1] I use the term "emergent bilingual" to focus on students' potential to develop bilingualism (Garcia, 2009). Terms such as "English language learner" can suggest not knowing English as a limitation of the student.

modeling into their lesson plans using resources such as educative curriculum materials or instructional frameworks (Kenyon et al., 2011; Schwarz, 2009; Schwarz & Gwekwerere, 2007; Windschitl & Thompson, 2006).

Meanwhile, other studies have focused on how teachers could improve their facilitation of students' scientific modeling in classrooms. Some studies have provided principles and examples for shaping productive epistemic discourses and guiding students' collaborative reasoning in modeling processes (Louca et al., 2011; Thompson et al., 2016). Working on the development of discourse practices also includes attention to the building epistemic cultures in classrooms that can support students' productive engagement in knowledge building (Jimenez-Aleixandre, Rodriguez, & Duschl, 2000; Shim & Kim, 2018; Stroupe, 2014). Jimenez-Aleixandre et al. (2000) explored how epistemic cultures and discourses could complement or hinder student learning by describing how students' participation in a scientific practice looked different when they engaged in discourses around following traditional routines of "doing school" versus making sense of the natural world through "doing science."

While some studies examine individual teachers' knowledge, skills, and practices, for this study, I took a socially-situated approach to understanding teachers' professional learning about modeling-based teaching. As part of a larger research-practice partnership project, participants of this study engaged in cycles of collective planning, implementing, and reflecting on lessons to improve instruction to facilitate students' modeling. This setting allowed me to study how the participants collaboratively worked on and reasoned about multiple aspects of supporting students' modeling, such as planning for students' opportunities to engage in modeling, facilitating epistemic discourses in classrooms, and encouraging diverse students' participation in modeling. Next, I describe the second body of literature that informed my understanding of teachers' collaborative learning in a PLC.

Learning Opportunities for Teachers in Productive PLCs

A PLC is a kind of teacher community where educators seek to support student learning and build a shared vision and responsibility through collaboratively investigating their instructional practice (e.g., Darling-Hammond & McLaughlin, 1995; Hord, 1997; Wei et al., 2009). Yet, not all PLCs promote teachers' meaningful collaboration or learning. In this section, I discuss four key features of effective PLCs and how they can provide productive opportunities for teacher learning. First, productive PLCs develop trusting relationships and collaborative cultures among participants so that they can share and discuss diverse perspectives about teaching and learning, take collective responsibility for student learning, and collaborate to improve their teaching by de-privatizing their practice and addressing dilemmas in it (Grossman et al., 2001; Hargreaves & Fullan, 2012; Little, 2003). Second, in productive PLCs, teachers work together as co-inquirers and producers of knowledge as they engage in experimentation on their work with students (e.g., Darling-Hammond & McLaughlin, 1995; Hord, 1997; Horn, 2010; Little, 2003). Through experimentation, teachers engage in collective reasoning and decision-making about their teaching practices and can generate context-dependent and practice-based knowledge about how to better support their students (Little, 2003; Putnam & Borko, 2000). Third, in productive PLCs, teachers base their inquiries and decision-making on student data as evidence of student learning (Kazemi & Franke, 2004; Little, 2003). Such artifacts often include students' drawn/written explanations or teachers' observations of students' participation in classroom discourse. By carefully examining student data together, teachers can grow their understanding of their students' thinking and discuss how to instructionally build on students' ideas (Kazemi & Franke, 2004). Finally, PLCs can build trust and engage in continuous inquiry when they are structurally and socially supported. Important structural supports include protected time and opportunities to work in close physical proximity. Additionally, social support from school administrators and other experts such as researchers or coaches are important for bringing diverse perspectives, experiences, and resources (Coburn & Penuel, 2016).

While previous studies have emphasized the importance of sustaining teacher learning over long periods of time (e.g., Hord, 1997), only a few studies have qualitatively examined teachers' collaboration for more than one year (e.g., Horn, 2010; Richmond & Manokore, 2011). The studies that examined teachers' collaborative learning over time did so by studying inner processes of teachers' collaboration in productive or unproductive PLCs (e.g., Horn, 2010; Little, 2003; Nelson, 2009; Richmond & Manokore, 2011). For example, Horn (2010) examined how a team of high school mathematics teachers used representations of teaching practice—teaching replays and teaching rehearsals— in their conversations and how the representations could promote the teachers' pedagogical reasoning about complex teaching situations. For another example, Nelson (2009) analyzed three PLCs in which secondary science and mathematics teachers collectively developed instructional plans and used these as artifacts to reflect on their teaching. This current study takes a similar approach to examine interactions and artifact use over time, yet adds to the extant literature on PLCs by providing an empirical investigation of teachers' collaborative inquiry over a 4-year period of time in a supported setting.

Building and Sustaining Lines of Inquiry in PLCs

To analyze teachers' collective inquiry over time, I drew on recent improvement science research (Bryk et al., 2015; Langley et al., 2009). Especially, I focused on lines of inquiry that the participants developed and pursued over time. By "a line of inquiry," I mean that the participants conducted multiple cycles of small experiments for a sustained period of time to improve a set of instructional practices and tools with specific goals to support students' learning. This is based on the proposal from the field of improvement science to use disciplined inquiry to drive improvement. Bryk et al. (2015) have suggested that communities can improve effectively through identifying sets of practices to work on based on the systemic analysis of problems and goals, conducting cycles of small experiments on the practices to develop working theories about what works, for whom, and under what conditions, and developing measures for assessing improvement. The goal is to help communities construct practice-based knowledge for local contexts rather than generalizable knowledge that is replicable regardless of context (Bryk et al., 2015).

A line of inquiry centers around one or a set of instructional practices as the unit of improvement. Thompson et al. (under review) examined how eight PLCs launched into improvement work around focal instructional practices. Some teams generated and tested new instructional practices, others adopted and adapted existing practices, and still, others integrated new practices into existing practices. Across PLCs they found that PLCs were more likely to continue working on improving instructional practices that 1) directly addressed identified team goals and recognizable problems of practice, 2) could be implemented on a regular basis in classrooms with associated routines and tools, 3) promoted students' active participation in knowledge construction, and 4) had measures for examining the effectiveness of changes PLCs made through experimentation in classrooms.

For this study, I focused on how a PLC engaged in multiple lines of inquiry over four years, thus addressing the question about what sustained inquiry looks like over time. My central research question was: How do participants of a PLC—high school science teachers, coaches, and researchers— develop and sustain lines of inquiry through designing, testing, and improving instructional practices to support students' scientific modeling over four years?

Methods

This is a qualitative case study (Yin, 2014) aimed at generating an in-depth understanding of how participants of a PLC conducted inquiries over four years in a PD setting. I closely analyzed the participants' conversations and classroom teaching on the PD days to explore how they developed and engaged in lines of inquiry. In what follows, first, I explain the research context and my roles in this research. Second, I introduce the focal PLC and participants in this study. Third, I explain the PD setting that set the stage for the participants' collaborative inquiry. Finally, I describe the sources of data and methods used in the data analysis of this study.

Research-Practice Partnership Context and My Roles

Research-practice partnership context. This study was conducted as part of a larger research-practice partnership (Coburn & Penuel, 2016) project in which the research group that I belong to (Ambitious Science Teaching research group, University of Washington) partnered with a mid-sized urban public-school district in the Pacific Northwest during the years 2012-2018. The partnership aimed to 1) help secondary science teachers develop their practice and knowledge for supporting diverse students' meaningful participation in knowledge building processes of science and 2) build capacity in schools and teacher communities for making sustainable changes in systems. All the secondary schools in the district—eight schools in total—participated in the partnership. At each school, all science teachers collaborated with district-based coaches and focal university researchers on PD days.

My roles. I joined the research-practice partnership project in September, 2015. I joined the focal PLC of this study in the same month as a participant observer (Merriam & Tisdell, 2009). For the academic year of 2015-2016, I was one of the two researcher participants in the PLC. For the year of 2016-2017, I was the only researcher participant in the PLC. During the years that I participated in the PLC, most of the PD activities were planned and facilitated by district-based coaches and teachers in the PLC. As a researcher participant, I sometimes joined their meetings for planning PD days and engaged in discussions to set directions for and plan specific PD activities. I participated in all the PD days during the years of 2015-2017 and engaged in discussions with my perspectives and resources as a science education researcher. During the same years, I consented newly joined participants to data collection and collected data from the PD days. I informed teachers and coaches about my role as a researcher.

The Focal PLC and Participants

The focal PLC. For this study, I purposefully selected one of the eight school-based PLCs—Sealth High School PLC— to explore how teachers collaboratively developed and pursued lines of inquiry to improve their instruction over multiple years in a supported setting. I selected this group because the PLC continuously focused on supporting students' scientific modeling over the four years and developed and engaged in clear lines of inquiry. The participants co-developed sets of instructional practices and tried to improve those by iterating on and conducting inquiries on them. Sealth science teachers joined the partnership and started to work as a PLC in November 2013. For this study, I focused on their collaboration during the years of 2013-2017.

School context. Sealth High School is located in a high-poverty urban area and has a diverse student population. According to the demographic data gathered in 2017, among a total of 970 students, 30% were officially classified as EB students. 41% of the students were classified as Latina/Latino, 19% were classified as African American, 18% were classified as Asian, 12% were classified as European American, and the remaining students were from other ethnic groups including American Indian. 73% of the students received free or reduced lunch (Office of Superintendent of Public Instruction (OSPI), 2017).

Based on Sealth students' low graduation rate (67.4% for the Class of 2016 while the average rate in the state was 79.1%) (OSPI, 2017), the prime mission of the school was to help all students graduate and get ready for college, career, and citizenship. For academic supports, the school-wide efforts were put on enhancing standards-based instruction, promoting formative assessments, and supporting student discourse in classrooms. Furthermore, with the diverse student population, a strong emphasis was put on differentiating instruction for students, especially for EBs.

Participants. Participants in this study included the total of eleven Sealth High School science teachers, three university science education researchers including me, two district-based science coaches, and one district-based EB coach. Each year, a subgroup of these participants, including five to six Sealth teachers, engaged in the PLC and participated in the PD. Sealth High School had a high teacher turnover rate. Each year, a few teachers left the school and one to three teachers newly joined the school and the PLC. **Table 1** shows the participants, the number of years the teachers had taught prior to joining the PLC, whether they earned EB certification through receiving additional training for teaching EBs, and the number of years they participated in the PLC.

Table 1. Participants of the study (Participants of Sealth High School PLC)

Role in the PLC	Participant	Teaching experience: More than 5 years when first joined the PLC	EB Certification	Years engaged in the PLC
Sealth High School science teacher	Teacher Emma	Yes	No	2013-2017
	Teacher Anika	No	Yes	2013-2017
	Teacher Julie	No	No	2013-2015
	Teacher Matt	Yes	No	2013-2015
	Teacher Adriana	Yes	Yes	2013-2015
	Teacher Lisa	No	Yes	2014-2017
	Teacher Mary	No	No	2015-2016
	Teacher Kelsey	Yes	No	2015-2016
	Teacher Tom	No	Yes	2016-2017
	Teacher Heidi	No	No	2016-2017
	Teacher Bill	No	No	2016-2017
University science education researcher	Researcher Janet			2013-2015
	Researcher Katja			2013-2016
	Researcher Sue			2015-2017
District-based science coach	Coach Rebecca			2013-2017
	Coach Jamie			2013-2015
District-based EB coach	Coach Lane			2013-2017

PD Setting for Teachers' Collaboration: Studios

To set the stage for the participants' collaborative inquiry, the Ambitious Science Teaching research group adapted and introduced a job-embedded PD model, called *Studio* model, which invited the participants to collectively engage in cycles of planning, teaching, and reflecting on lessons. Below I discuss the structure of the PD model, the roles of PLC members, and the nature of collaboration among PLC members at Sealth High School.

The *Studio* PD model. The *Studio* model was adapted from two PD models: 1) the *Mathematics Studio Program* developed by the Teacher Development Group (2010) in math education and 2) the *Lesson Study* PD model (Lewis, Perry, & Murata, 2006). Both models support teachers' collective inquiries in the context of real lessons, but the *Studio* model of the Ambitious Science Teaching research group differed by focusing on supporting teachers' pursuit of long-term improvement goals and inquiries on instructional practices rather than individual lessons. The *Studio* model functioned through job-embedded PD days, called “Studios.” In Studios, the participants of Sealth PLC gathered for full school days to conduct collective inquiries to improve their teaching and student learning. On those days, they collectively planned, implemented, and reflected on focal lessons to test some hypotheses about how certain designs or changes in their teaching could affect student learning by gathering and examining classroom data from the lessons. They taught the same lesson twice in a day, which allowed the opportunity to collectively test a classroom tool or strategy. For each Studio, a teacher became the host teacher of the day and led the focal lessons in their classroom. Through a series of Studios, the participants could develop, test, and improve instructional practices based on student data and build their practice-based knowledge about how to support students in their own context.

Over the four years of the study period, Sealth PLC members participated in twelve Studios. They continuously worked on supporting students’ scientific modeling throughout the study period. In each Studio, the members invited students to create or revise scientific models to explain a puzzling phenomenon. **Table 2** shows the dates and host teachers of the twelve Studios and the puzzling phenomena that the members asked students to explain in the Studios.

Table 2. Context of the job-embedded PD: Studios

Year	Studio	Date (Month-date-year)	Host teacher	Puzzling phenomenon for scientific modeling
Year 1 2013-14	1	11-06-2013	Anika	How can fireworks have different colors?
	2	12-05-2013	Emma	How can a seed grow in a man's lung and continue to grow after it gets taken out?
	3	03-25-2014	Matt	What happens during the life cycle of stars and how do black holes form?
	4	04-24-2014	Anika	Why is the climate in Seattle different than Spokane?
Year 2 2014-15	5	10-13-2014	Anika	How can we design a Rube Goldberg device?
	6	02-10-2015	Emma	Why are some people more likely to get breast cancer?
	7	05-04-2015	Matt & Anika	How is the universe changing and how do we know?
Year 3 2015-16	8	10-01-2015	Anika	Why do different balls bounce to different heights?
	9	03-03-2016	Lisa	Why did Ms. Strange die after drinking a lot of water?
Year 4 2016-17	10	09-27-2016	Emma	Why do some people get sick when drinking milk?
	11	11-21-2016	Anika	Why do we need to wear sunscreen?
	12	02-07-2017	Bill	Why is Tuvalu (and other islands) going underwater?

Roles of coaches and researchers. Typically, about five science teachers, one to two secondary science coaches, one EB coach, and one to two researchers participated in each Studio. Over the years three researchers, including me, participated in the focal PLC as participant observers. With the goal of supporting the sustainability of teacher learning and leadership in the PLC, we first supported district-based coaches in leading the Studios. Then in the fourth year, the coaches and I supported two teacher leaders from Sealth High School in leading their own collective inquiries.

During the first year, for each Studio, the researchers (Researcher Janet and Katja) and coaches met with the host teacher and other PLC members to draft a plan for the focal lessons. Then, they worked together to prepare guiding questions and activities for the Studio. In the

Studio, the host teacher and the coaches mostly led discussions while the researchers sometimes helped facilitate some parts of discussions. All of the participants engaged in the discussions using their own expertise, perspectives, and resources. The teachers grounded their ideas and suggestions on their experiences of teaching their own students. The coaches brought in their observations and experiences from classrooms and leading Studios across the district. The researchers actively brought in ideas and tools from their own research on effective science teaching and those from the fields of science education and improvement science. During the second and the third years of collaboration, the science coaches mainly facilitated the PLC inquiries with the host teachers using the routines set in the first year. The researchers, including me, kept engaging in discussions using their perspectives and resources but did not take active roles in facilitating the inquiries. Then, in the fourth year, as part of the project-wide efforts, two teachers—Teacher Emma and Anika— became teacher leaders in the PLC and started to facilitate the PLC inquiries. The project provided the teacher leaders with some additional PD opportunities to learn about how to facilitate teacher inquiry and share ideas and resources across the district. The coaches supported the teacher leaders in planning for Studios and facilitated some parts of discussions when they were asked to help. I kept participating in discussions as a participant observer using my own expertise and resources.

Culture of collaboration in the focal PLC. Sealth teachers started to work as a PLC for the first time through this project. They had sometimes shared lesson materials and ideas before, but their collaboration was limited to sharing materials among teachers who taught the same subjects. From the start of the project, the teachers were open to de-privatizing their practice and discussing it. I suspect that this is partly because the lessons were co-planned and co-implemented by all the PLC members in Studios. The teachers' participation in discussions varied, particularly at the start of each year as the PLC adjusted to having new participants. The coaches and researchers tried to encourage all the teachers to share their ideas and questions, sometimes through structured discussions. The teachers generally showed a higher level of participation when they talked about concrete strategies or tools for their focal lessons or when they shared their observations from the lessons. Their participation increased as they spent more time collaborating with one another in more Studios and took turns in hosting the Studios. Most of the teachers seemed comfortable raising questions or sharing opinions about what would work best for their students at the end of the first year. Each year, some teachers newly joined the PLC. They were less active than other teachers when they first joined the collaboration. However, as they spent more time with other teachers both inside and outside the PD setting for months, their participation increased. Most of the newly joined teachers seemed comfortable sharing their ideas after engaging in two or three Studios.

The district and school administrators were supportive of the research-practice partnership. Initially a grant supported coaches' time and teacher release time to participate in Studios, but eventually this was fully funded by the school district. Sealth High School administrators occasionally visited Studios to understand the content of the science teachers' professional learning and tried to align their expectations for science instruction with what was being discussed in Studios.

Data Sources

The primary data for this study were 1) the video recordings of Sealth PLC members' conversations and classroom teaching in the twelve Studios during the school years of 2013-2017, which included approximately 96 hours of videos, 2) descriptive and reflective field notes, and 3) artifacts from the meetings, including artifacts co-constructed by the PLC members during the meetings as well as student work from focal lessons. The first two years of data were gathered as part of the larger research project. I collected data for the last two years while participating in the focal PLC as a participant observer. I also conducted semi-structured interviews (Merriam & Tisdell, 2009) with two teachers, Teacher Emma and Anika, who remained at Sealth over the course of the study. The interviews were conducted at the end of the study period, February 2017. I asked the teachers to reconstruct a story of their learning and inquiry throughout the four years of Studios using pictures of artifacts from the Studios.

Data Analysis

To analyze Sealth PLC members' conversations in Studios, I first identified *episodes of pedagogical reasoning* (Horn, 2010) as units of analysis in their conversations. According to Horn's (2010) definition, an episode of pedagogical reasoning refers to a unit of conversation in which teachers address an issue in their teaching practice and exhibit their reasoning about the issue by elaborating reasons, explanations, or justifications. The video recordings and artifacts from the meetings were coupled in the analysis and chunked by the episodes of pedagogical reasoning. The boundaries of the units were decided based on topical shifts in the conversations. Then, in each episode of pedagogical reasoning, I coded 1) problems of practice or questions that the PLC members raised, 2) instructional practices and tools that they developed and/or discussed, 3) student data that they used, including student work as well as their observations of students' participation in activities or interactions, and 4) their pedagogical reasoning, including their suggestions and decisions as well as reasons, explanations, or justifications.

I also analyzed Sealth teachers' classroom teaching in Studios to understand how they implemented the instructional practices and tools that they discussed in the PLC conversations and how they collected student data from the focal lessons. In the analysis, I focused on talk, tasks, and tools that the teachers invited students to engage with in the lessons.

Based on the analysis of the PLC members' conversations and classroom teaching in Studios, I identified lines of inquiry that they developed and engaged in over the four years. I focused on how they developed, tested, and improved instructional practices and tools based on their pedagogical reasoning with student data. I first identified sets of instructional practices and tools that got implemented and discussed over multiple Studios and then qualitatively analyzed how the members reasoned about these practices and tools over time. This was based on the definition of a line of inquiry—a line consisted of cycles of experiments conducted to improve a set of instructional practices and tools for a sustained period of time with specific goals to support students' learning. The interview data and field notes were used to add information to the patterns found in the analysis of the video recordings and the artifacts from the Studios. Throughout the analysis, I shared and discussed my findings with Researcher Janet and Katja to check the validity of the findings based on our experiences as researcher participants in the PLC.

Limitations

There are some limitations in this study that are important to consider. I took a situated perspective on learning (Greeno, 2006; Lave & Wenger, 1991) and carefully examined teacher interactions happening inside the Studios while taking some contextual information into account. In this process, it is possible that I missed some contextual information or interactions happening outside the PD setting that might have affected the teachers' collective inquiries and helped to justify or reexamine the findings. I tried to address this issue by writing detailed field notes describing some contextual information I gained from the teachers or coaches in each Studio. I also tried to deepen my understanding of the context by regularly visiting the teachers' classrooms in between Studios, checking in with the district-based coaches on a regular basis, and having conversations with administrators at Sealth High School. Furthermore, I invited the two teachers who stayed in the PLC for the whole study period to share their reflection about how their inquiry evolved over time to learn from their perspectives. I now turn to the findings.

Findings

Over four years, the Sealth PLC members focused on supporting students' meaningful engagement in scientific modeling. While their overall goal remained the same, instruction became more complex as they developed and pursued three lines of inquiry. The first line of inquiry focused on supporting students' epistemic work—construction of scientific models and explanations. The second line of inquiry centered around promoting students' collaboration in scientific modeling. The third line of inquiry aimed to facilitate students'—especially EB students'— academic language learning through scientific modeling. For each line of inquiry, the members developed or adapted a set of focal instructional practices and tools and tried to improve them by iterating on and testing changes on them over multiple Studios. **Figure 1** lists the three lines of inquiry, names the focal practices worked on for each line of inquiry, and includes timeframes of the inquiry.

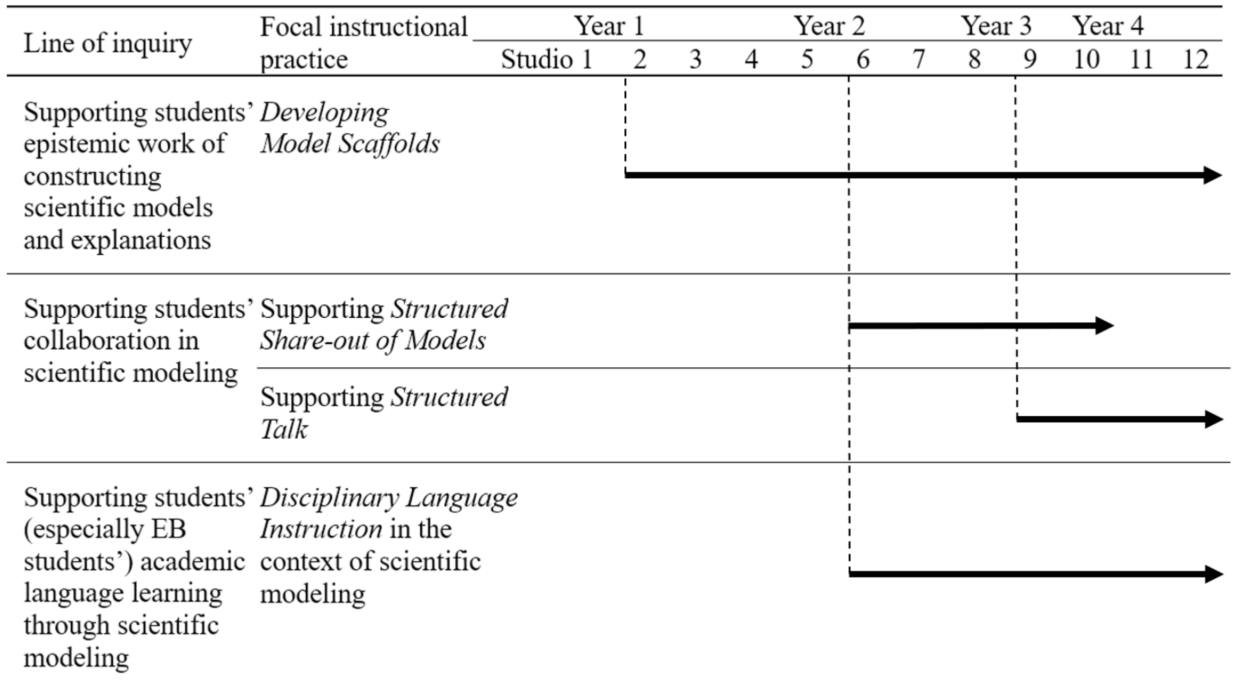


Figure 1. The three lines of inquiry that Sealth PLC members developed and the focal practices for each line, with the arrows showing when the members started to work on each practice and how long they inquired on the practices

In this section, I begin by describing how the PLC members set their inquiry goals at the outset of the project. Then, I explain how they launched and sustained the three lines of inquiry by working on the evolving sets of focal instructional practices and tools over multiple Studios.

Setting Inquiry Goals at the Start of Collaboration

At the start of their collaboration in Studio 1, the PLC members set their inquiry goals, which guided the development of their lines of inquiry. The Sealth High School teachers shared their areas of interest and problems of practice rooted in experiences from their own classrooms. Some teachers shared that they wanted to help students write explanations and essays because they had noticed that students often found it hard to start and continue writing and lacked confidence in writing. Other teachers referred to their school's focus on promoting student discourse and wondered about ways to encourage students' productive discussions. The teachers were also highly interested in supporting EB students' learning, based on the high EB population at Sealth (24% of students officially classified as EBs in Year 1). Two of the five teachers were teaching sheltered science classes for EBs at that time. Especially, the teachers said that they wanted to know more about how to better support EBs' reading, talking, and writing in science. While the teachers shared their areas of interest, Researcher Janet drafted the following goals on a whiteboard: 1) "scaffolding students' oral and written explanations," 2) "engaging students in robust student-to-student discourse," and 3) "improving instruction to support all students, especially EBs." Near the end of the discussion, the PLC members agreed to work on these three goals as a team. Researcher Janet then suggested that the team add a phrase, "evidence-based," to the first goal to define the kind of explanation that they would like their students to work on. With the addition, the first goal became "scaffolding students' evidence-based explanations, both oral and written."

Considering some of these goals, in Studio 1, the researcher and coach participants introduced scientific modeling to the team as a disciplinary practice that can help students' construction and expression of explanations. The PLC members worked on supporting students' scientific modeling on that day and then continued to collaborate on it in the following Studios. Their early efforts to facilitate students' modeling were mostly focused on their first articulated goal to support students' explanations. However, as they continued, they gradually incorporated their other goals into their efforts to support students' modeling. The integrated goals prompted the members to develop instructional practices to address the goals and eventually led them to develop lines of inquiry to improve the practices. In the following sections of the findings, I explain how the PLC members launched and developed their three lines of inquiry to support students' productive engagement and collaboration in scientific modeling.

The First Line of Inquiry to Support Students' Epistemic Work: Focusing on Developing Model Scaffolds and Examining Students' Scientific Models

The PLC's first line of inquiry focused on supporting students' epistemic work, specifically the construction and revision of scientific models about phenomena using evidence from class activities. The PLC members launched the inquiry early on in their collaboration, in their second Studio, by co-developing a focal practice, which I would call *Developing Model Scaffolds*. *Developing Model Scaffolds* was a collaborative planning and instructional practice in which teachers created, tested, and improved various model scaffolds—drawn or written scaffolds on model templates designed to help students construct and express their models of a natural phenomenon, typically on 11 x 17-inch pieces of paper. Their model scaffolds aimed to support specific aspects of students' explanations. **Figure 2** shows examples of model scaffolds on a model template that the PLC members developed for Studio 4. The model template includes a picture of the phenomenon students were studying—how landforms impact climate by comparing two cities on either side of a mountain range— and four forms of model scaffolds. The first two scaffolds—the explanation and evidence checklists— were important objects of inquiry that played a key role in promoting students' epistemic work. The PLC members explored how the scaffolds worked, for whom, and under what conditions by examining students' models and explanations in Studios.

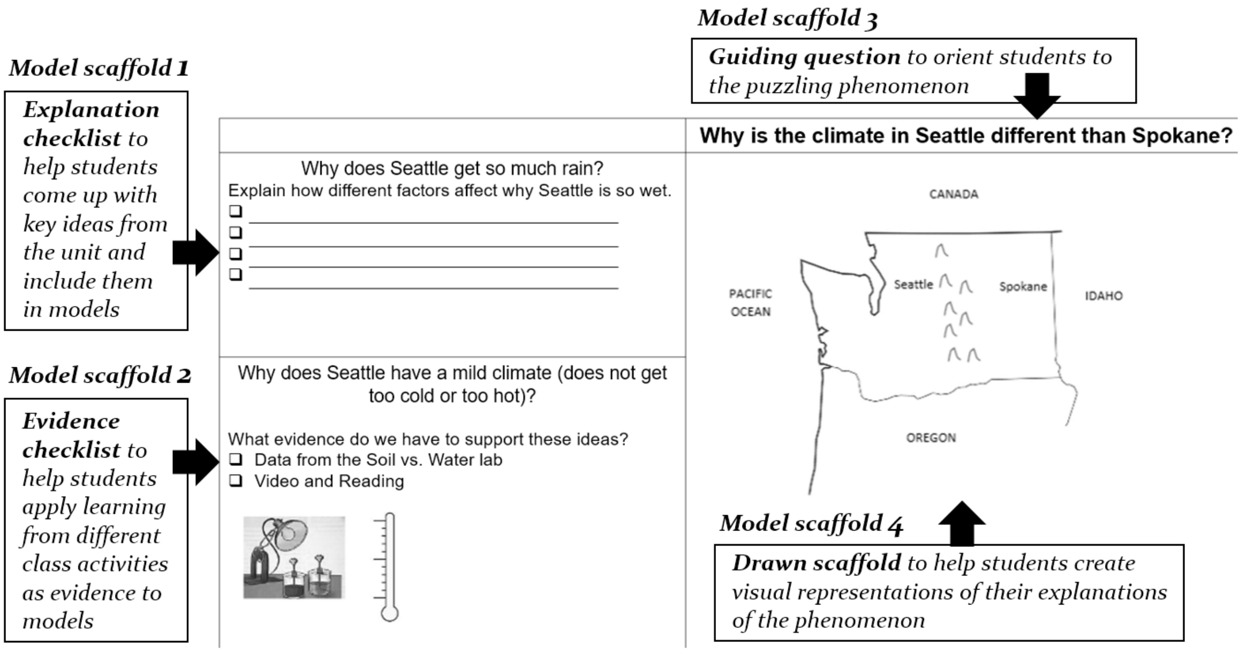
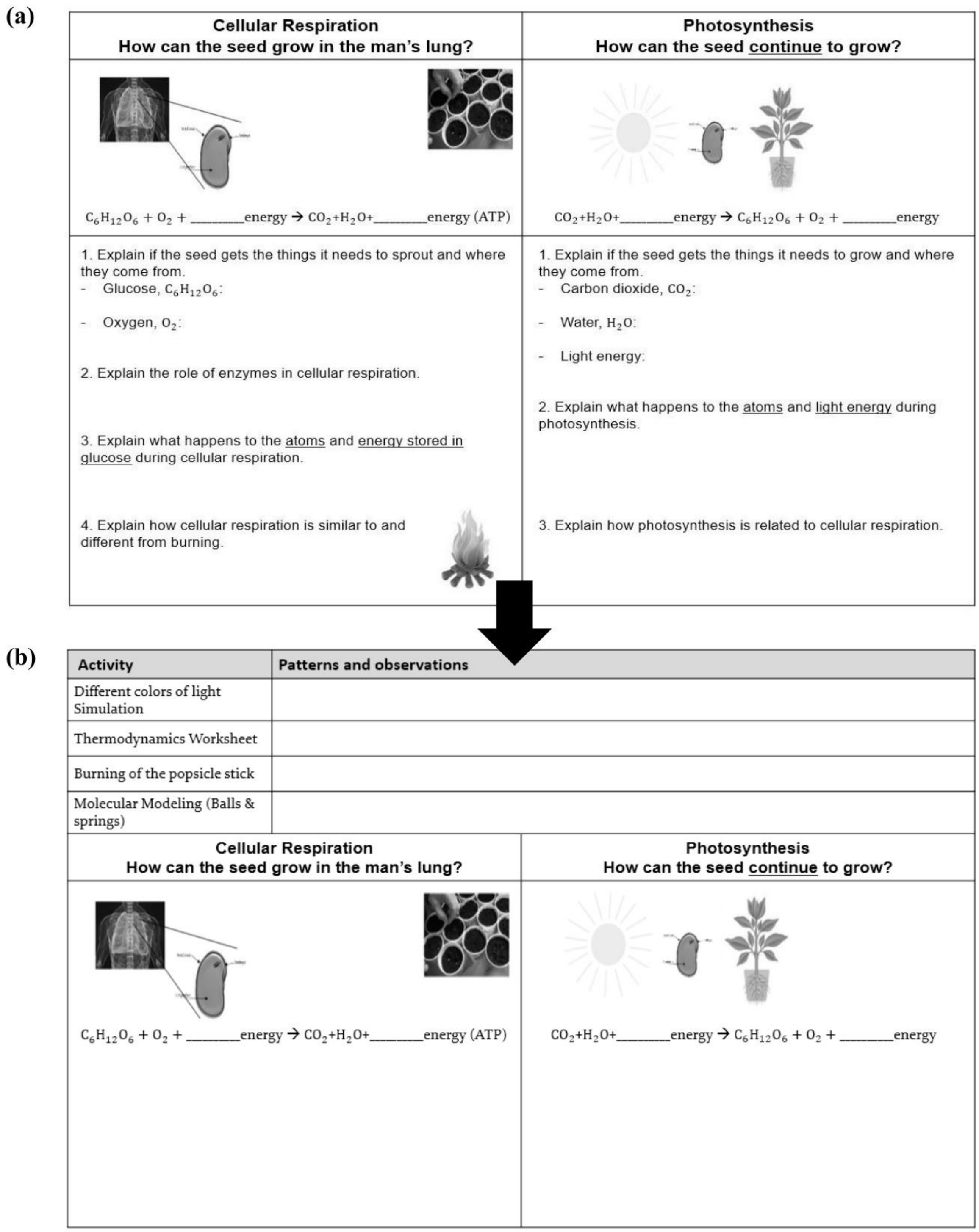


Figure 2. Examples of model scaffolds on a model template designed by the PLC members in Studio 4; Description of the model scaffolds annotated in italic

In what follows, I first describe how the PLC members began working on the practice of *Developing Model Scaffolds* and launched the line of inquiry in their second Studio. Then, I explain how this line of inquiry developed over four years of Studios to promote students' epistemic work of constructing evidence-based models and explanations.

Studio 2: Launching the line of inquiry to support students' epistemic work. In Studio 2, the PLC members collaborated on redesigning a specific classroom tool—a model template—drafted by two of them for use in their Studio lesson. Their collective efforts to revise the model template led them not only to make changes to the concrete tool but also to focus on how to promote specific aspects of students' epistemic engagement—especially, students' use of evidence and construction of their own explanations. They made direct and visible changes to the tool, which then supported the PLC in focusing on how these modifications supported or failed to support students in developing scientific explanations.

Modifying and testing model scaffolds. For Studio 2, the host teacher of the Studio, Teacher Emma, and Coach Jamie began the day by sharing a model template that they had drafted for the focal Studio lesson to help students construct scientific models at the end of an instructional unit about cellular respiration and photosynthesis (shown in **Figure 3(a)**). The unit was anchored around a puzzling phenomenon from a newspaper article in which a seed started to grow in a man's lung and continued to grow after it was taken out. During the planning session of the Studio, the PLC members identified some limitations in the model template and collectively revised it for the Studio lesson. They decided to 1) include an "evidence checklist" to support students' use of evidence and 2) delete the guiding prompts, which asked students to recall and reproduce discrete pieces of knowledge step by step. The revisions were made after the teachers and researchers started raising questions while reviewing the model template. The researcher and coach participants played key roles in shaping the questions by making explicit connections between the questions and the articulated goals of the PLC. The teachers actively engaged in suggesting and discussing ways to modify the template to address the questions. In what follows, I share some excerpts from these conversations.



(a)

Cellular Respiration How can the seed grow in the man's lung?	Photosynthesis How can the seed continue to grow?
$C_6H_{12}O_6 + O_2 +$ _______energy → CO_2+H_2O+_______energy (ATP)	CO_2+H_2O+_______energy → $C_6H_{12}O_6 + O_2 +$ _______energy
1. Explain if the seed gets the things it needs to sprout and where they come from. - Glucose, $C_6H_{12}O_6$: - Oxygen, O_2: 2. Explain the role of enzymes in cellular respiration. 3. Explain what happens to the atoms and energy stored in glucose during cellular respiration. 4. Explain how cellular respiration is similar to and different from burning.	1. Explain if the seed gets the things it needs to grow and where they come from. - Carbon dioxide, CO_2: - Water, H_2O: - Light energy: 2. Explain what happens to the atoms and light energy during photosynthesis. 3. Explain how photosynthesis is related to cellular respiration.

(b)

Activity	Patterns and observations
Different colors of light Simulation	
Thermodynamics Worksheet	
Burning of the popsicle stick	
Molecular Modeling (Balls & springs)	

Cellular Respiration How can the seed grow in the man's lung?	Photosynthesis How can the seed continue to grow?
$C_6H_{12}O_6 + O_2 +$ _______energy → CO_2+H_2O+_______energy (ATP)	CO_2+H_2O+_______energy → $C_6H_{12}O_6 + O_2 +$ _______energy

Figure 3. (a) The initial model template at the start of the planning session of Studio 2; (b) The revised model template with the model scaffold of the evidence checklist and more space for students to express their thinking

Developing the model scaffold of evidence checklist to support students' use of evidence in explanations. Early in the day as the PLC was reviewing their instructional plan and the model template tool, Teacher Julie posed a question about what resources students could use to get information when constructing their explanations. This prompted Researcher Janet to orient the members to one of their inquiry goals to support students' use of evidence in constructing explanations. The following excerpt shows part of the discussion:

Teacher Julie: One thing I wonder is how… How will students get the information they need and be able to compare burning fossil fuels with cellular respiration? Well, I see that it says, "explain how." But where do they get the information to answer that question?

Researcher Janet: This actually relates to a question I had. Because I went back and looked at one of our goals. You said that you are hoping to "scaffold students' evidence-based explanations" [*reading the goal*]. It makes me wonder, "How can we help them reference different kinds of activities in here and use them as evidence for this?" We can help them make connections to different kinds of activities that they have done.

Coach Rebecca: So, that's like summarizing what they did in the previous activities…

Teacher Adriana: Maybe, at the beginning of the day, you [*the host teacher, Emma*] can go over what they learned and chart out [*inaudible*] …

[*… the PLC members discuss other parts of the lesson for about twelve minutes …*]

Coach Rebecca: Just another thing to hold in our mind is… I heard Janet say something about using evidence. I don't think there is anything so far in the lesson plan that would help students access prior activities as evidence. So, that would be another possibility of an entry question.

Teacher Emma: We can do it as the checklist for the activities and the main idea. Then, they can include the activity that they just did on the colors of light and one of the main ideas that will come up is that plants need light to grow, specifically the blue light in sunlight. So, their do-now [*activity at the start of the lesson*] would be a… checklist of all the activities that they have done and the main idea that they got from that. *[Studio 2, Planning session, December 5th, 2013]*

Here, the PLC members started to actively brainstorm some practical ways, including charting and making a checklist of main ideas from class activities, to support students' epistemic work of using evidence in constructing explanations, based on Researcher Janet's suggestion to help students use what they had learned from class activities as evidence. Through this discussion, the members co-constructed a model scaffold—the evidence checklist— which included the list of activities that students had engaged in throughout the unit and space for students to summarize main ideas from each activity (featured at the top of the revised model template in **Figure 3(b)**). Throughout the day, the PLC members focused on students' use of evidence when teaching, examining student work, and discussing ways to build on students' thinking.

Deleting the guiding prompts and providing space for students to show their own thinking. The second major decision that the PLC members made was to delete the guiding prompts on the initial model template (featured in **Figure 3(a)**; e.g., "Explain where the materials that the seed needs to grow come from," and "Explain the role of enzymes in cellular respiration.") to encourage students' construction and expression of their own thinking about the phenomenon. The decision was made through a controversial discussion among the PLC members. Coach

Rebecca started the discussion by raising a concern that too many guiding prompts might hinder students from showing their ideas. Some teachers disagreed with the coach's implied suggestion to delete the guiding prompts by arguing that the questions could help students with initiating their modeling. The following excerpt shows how the discussion started with Rebecca's question:

Coach Rebecca: You [*Emma*] said you want them [*students*] to explain the process of cellular respiration on their own… I am curious about why you guys [*Emma and Coach Jamie*] decided to add so many questions versus have it more open.

Teacher Emma: Because I think we just wanted to give them space to write down their answers… not supposed to be just… all empty.

Coach Rebecca: I think… because modeling is showing your ideas and how they're connected and explaining something as a whole picture. And I'm not sure that breaking it down into these questions allows them to really show this as a model. It feels more like just a worksheet to me. I am just confused about if this will allow them to connect ideas.

Teacher Adriana: These questions can be used to help students understand what a model might look like. Because when you just give them a big open space, [*they could be like*] "What do I do with this? I don't know…" I would maybe be a little bit stuck. Not knowing where to start… *[Studio 2, Planning session, December 5th, 2013]*

In the discussion above, Coach Rebecca and the teachers—Teacher Emma and Adriana—engaged in argumentation with different opinions about the roles of the guiding prompts. Coach Rebecca claimed that the prompts might constrain students' modeling. She backed up her claim by reminding the members of one of their lesson goals to help students "explain the process of cellular respiration on their own" and explaining the purposes of the practice of scientific modeling. The teachers argued that the absence of prompts would confuse students about how to approach and start modeling. Here, the participants' arguments included some theoretical ideas about, for example, the nature and purposes of the epistemic practice of scientific modeling and the roles of scaffolding. However, the ideas were not only theoretical but also practical because they were contextualized in the discussion to decide concrete ways to revise the model template and better support students' learning. In this context, the participants openly discussed and weighed the pros and cons of different approaches through making some theoretical considerations explicit and taking them into account, rather than unconditionally following the opinions of "authority figures" who are regarded as being more knowledgeable about educational theories. Furthermore, the participants were flexible about their positions and put their efforts into finding ways to address the strengths of multiple approaches in practice rather than insisting on a certain approach and trying to defeat alternative approaches.

As the discussion went on, another teacher, Teacher Matt, who initially disagreed with the idea of deleting the guiding prompts, suggested that even if they took away the guiding prompts, they could still show students how to start modeling by demonstrating how to make connections among a few ideas to start explaining the phenomenon. This suggestion was to address the teachers' concern about not providing enough scaffolding for students to initiate modeling. The members liked this idea and by the end of the discussion, they agreed to 1) take away the guiding prompts to encourage students' construction and expression of their own models and 2) orally demonstrate to students during class how they could take one or two ideas from the evidence checklists and use them to explain the phenomenon. **Figure 3** shows how the model template evolved through the PLC members' discussion during the planning session of the Studio.

Discussing model scaffolds and next steps based on student data. The revised model template provided opportunities for the members to explore and support students' thinking throughout the day. In the debriefing session of the Studio, the members noticed substantial variations in students' models and focused on unpacking their explanations. They explored how students made connections among ideas and used what they learned from class activities to reason about the phenomenon. For example, the teachers noticed that a pair of students drew heat waves coming out from the seed undergoing cellular respiration. They found it interesting because the formula of cellular respiration they provided to students did not directly indicate the emission of heat in the process even though it is true that the process is exothermic. They examined the students' evidence checklist and found that the pair had written, "Cellular respiration and burning are similar because they give away energy," as their learning from their class activity of burning popsicle sticks.

This prompted the PLC members to be curious about and discuss how students made connections between evidence and explanations. For example, a teacher shared her noticing that the evidence checklist provided students a "jumping-off point":

Teacher Julie: Something that I noticed in the student work was… After looking back at their evidence from their past learning, they [*students*] were really able to start thinking about what might come next. It was a jumping-off point. For example, a student said, "Well, what makes the plant grow bigger?" and somebody said, "Glucose! Where does that [*idea*] go?" They weren't really sure, but it was clear at that point that they were moving beyond what they had written down [*in their evidence checklist*] and starting to really make some links between their past learning. *[Studio 2, Debriefing session, December 5th, 2013]*

Importantly, the teachers tried to understand how students reasoned about the phenomenon rather than focusing solely on their end products of models or judging the correctness of their ideas. This kind of data-driven discussion about the impact of model scaffolds and ways to improve those became an integral routine in *Developing Model Scaffolds* throughout the PLC's line of inquiry.

Based on what they noticed from students' models and participation in modeling, the PLC members also discussed future directions for instruction to support students' epistemic work further. One significant focus of the members' discussion was around supporting students in reasoning with ideas which they were uncertain about. For example, a teacher shared that a pair of students were not sure about how to incorporate an idea into their explanation. She said that it might have been good if she had asked them to write down uncertain ideas like that on a side of their model. Another teacher took up this idea and suggested that students could use sticky notes to record uncertain ideas and revisit those ideas over time. It is notable that the teachers came to encourage students' reasoning with uncertain ideas given that they started the day with a model template that provided step-by-step guidance to lead students to certain "desirable" answers (see Manz and Suarez (2018) for a further discussion about the importance of addressing uncertainty in science instruction). The teachers began to view modeling as a practice for students to reason through ideas rather than an assessment for them to just recall and reproduce what they know.

Furthermore, the evidence checklist prompted the teachers to focus on another epistemic aspect of modeling: revision of models over time. When the PLC members were modifying the Studio lesson for another class period on that day, the host teacher, Emma, said that the class had not done one of the activities listed in the evidence checklist yet. Then, another teacher suggested that students could first construct their models and then revisit and add to their models after engaging in the activity. Other PLC members agreed that it would be important for students to improve their models over time as they learn more things in class activities. This idea about revision became one of the important foci in their latter Studios and in their line of inquiry.

Summary of Studio 2. This Studio can be regarded as the launch point for this line of inquiry for the following reasons. First, the members developed the focal practice of *Developing Model Scaffolds* and tools, which they continued to work on in the following Studios, that helped them focus on and support specific aspects of students' epistemic work—for example, construction of explanations, use of evidence, reasoning with uncertain ideas, and revision of models. Second, they started to see diversity in students' thinking and put their efforts into unpacking and building on students' ideas and explanations. Finally, they began to expand their own views of scientific modeling by focusing on various epistemic aspects of the practice. In the next section, I explore how they continued the line of inquiry to support students' epistemic work in the following Studios.

Studios 3-12: The development of the line of inquiry to support students' epistemic work in subsequent Studios. As the PLC members continued to work on the practice of *Developing Model Scaffolds*, they developed two core foci in their efforts to support students' epistemic work: 1) promoting the depth of students' explanations and 2) supporting students' use of evidence and revision of models. Below, I explain how the members worked on these two foci by conducting cycles of experiments over multiple Studios to develop, test, and improve various model scaffolds, each aimed at supporting specific aspects of students' explanations.

Developing model scaffolds to promote the depth of students' explanations. One of the major model scaffolds that the PLC members worked on was the "explanation checklist," which was first developed in Studio 1 to provide students with prompts for ideas to think with. Even though the purpose of the model scaffold was to support students in constructing explanations, the initial explanation checklist designed and used in Studio 1 had some significant limitations in facilitating students' thinking. The checklist items asked students to recall and reproduce certain answers step by step and did not allow them to think in their own ways. For example, one checklist item was: "Use your Bohr models to write about the numbers of protons, neutrons, and electrons for each chemical." However, over time in the following Studios, the members improved their explanation checklist by inquiring on how to better support students' explanations with it. In Studios 3 and 4, with the aim of making the explanation checklist more open-ended and student-centered, the members designed blank checklists and led class discussions to help students come up with ideas to put into the checklists and use in their modeling. In the debriefing sessions, they focused on how students made connections among the ideas in the checklists and discussed how to support students' explanations further. With these efforts, the model scaffold of the explanation checklist evolved to include more open-ended prompts to promote students' thinking (e.g., "Why are some people more likely to get cancer?" in Studio 6) rather than directly asking for certain answers.

Another model scaffold that the PLC members developed was "rubrics" to help students reflect on the depth of their explanations. In Studio 3, the researcher participants introduced a rubric to the PLC. The rubric focused on examining how students made causal or relational connections among ideas and reasoned about unobservable processes or theoretical ideas. In each of the following Studios, the members adapted the rubric to make it specific for the unit and used it to examine students' explanations and explore how their instructional practices worked for students. More than just a tool for assessing student work, the rubrics came to be one of the model scaffolds, as the members decided to incorporate the adapted rubrics into their model templates to help students see how they could construct deeper explanations. For example, in Studio 5, the members provided rubric items as checklist items for students to reflect on the depth of their explanations. For another example, in Studio 12, the members developed a peer feedback protocol to help students give feedback to each other about the depth of their explanations using a rubric.

Developing model scaffolds to support students' use of evidence and revision of models. Over time the PLC focused on supporting students in revising scientific models throughout a unit of instruction, not just at the end. To this end, they developed scaffolds to support students in using evidence as the basis of model revision. For example, over the four years of Studios, they developed and tested multiple forms of evidence checklists. In Studios 6 and 8, the members developed graphic organizers to help students connect what they learned from activities as evidence to their explanations. For another example, the host teacher for Studio 9 asked students to construct initial models at the beginning of the focal unit and had the students record their learning from different class activities on sticky notes throughout the unit. Then, in Studio 9, the PLC members helped students revise their models using the evidence checklist and the sticky notes they created throughout the whole unit.

Over the four years. **Table 3** shows the kinds and purposes of the major model scaffolds that the PLC members developed to support students' epistemic work and how often and consistently the scaffolds were used over the four years of Studios. The model scaffolds, as highly visual objects for PLC inquiry, were continuously tested in different forms and mediated the PLC members' construction of practice-based knowledge about supporting students' construction, justification, and revision of models and explanations using evidence. This line of inquiry opened up opportunities for teachers to learn about the epistemic aspects of scientific modeling, how to support students' engagement in modeling, and how to attend to students' ideas and thinking.

Table 3. How often and consistently the PLC members worked on different kinds of model scaffolds over the twelve Studios for their first line of inquiry to support students' epistemic work (X: Studios in which they worked on each model scaffold)

Focus of inquiry	Tool: Model scaffold	Purpose	Year 1				Year 2			Year 3		Year 4		
			Studio 1	2	3	4	5	6	7	8	9	10	11	12
Promoting the depth of explanations	Explanation checklist	To provide prompts for ideas to include in explanations	X	X	X	X	X	X	X	X	X		X	
	Rubric	To help students reflect on the depth of explanations					X						X	X
	Zoom-in boxes	To help students reason about unobservable processes	X				X	X			X	X	X	
Supporting the use of evidence and revision	Evidence checklist	To help students gather and use evidence from class activities		X	X	X		X	X	X	X		X	X

The Second Line of Inquiry to Support Students' Collaboration in Scientific Modeling: Focusing on Helping Students Share and Discuss Ideas with Models

The PLC's first line of inquiry provided the members with rich opportunities to see diversity in students' models and reasoning, which led them to think about the potential of helping students learn from one another using models. Based on this thinking and their continuous focus on promoting student discourse in the classroom, the members developed a second line of inquiry focusing on supporting students' collaboration in scientific modeling, especially in discussing ideas with models and revising models based on discussions. In this line of inquiry, they collectively worked on supporting two focal classroom practices. The first practice, named

Structured Model Share-out, was developed by the PLC members in Year 2 to support students' sharing of ideas and learning from each other using models. The second practice, *Structured Talk*, was initially developed by another PLC in the district and shared with Sealth teachers in a district-wide teacher convening in Year 3. With the purpose of supporting students' discourses in modeling processes, Sealth PLC members adapted the practice by combining it with their other existing practices to support students' modeling and integrated it into their line of inquiry. **Table 4** shows how often and consistently the members worked on the two focal practices over the four years of Studios. Below, I explain how they collaborated on each practice and developed the line of inquiry to support students' collaborative work with models.

Table 4. How often and consistently the PLC members worked on the two focal classroom practices over the twelve Studios for their second line of inquiry to support students' collaboration in modeling (X: Studios in which they worked on each practice)

Line of inquiry	Focal classroom practice	Year 1				Year 2			Year 3		Year 4		
		Studio 1	2	3	4	5	6	7	8	9	10	11	12
Promoting students' collaboration in modeling	*Structured Model Share-out*						X	X	X	X	X		
	Structured Talk									X	X	X	X

Studios 6-10: Developing and improving the focal classroom practice of *Structured Model Share-out.* The first focal practice of this line of inquiry, *Structured Model Share-out*, was a classroom practice developed to support students in sharing and discussing models with classmates in structured ways. Coach Rebecca suggested to the PLC that they adapt a selecting and sequencing strategy described by Cartier, Smith, Stein, and Ross (2013) to help orchestrate productive discussions in classrooms. Based on this suggestion, in Studio 6, the PLC developed and tried out *Structured Model Share-out* as follows: In the focal lesson, each PLC member first

observed a group of students engaging in scientific modeling. Then, the members gathered in the middle of the classroom to briefly share their observations and select three models to be shared in a whole-class conversation. They also decided the order for the share-out so that students could build on ideas from one another. Next, the host teacher asked the three students who created the models to show and explain their ideas in front of the class using a visual presenter. After each student shared out, the teacher asked other students to rephrase what they heard and encouraged all students to revise their models based on shared ideas. The rephrasing part of the discussion was added with the purpose of helping EB students clearly hear their classmates' ideas.

From the Studio lesson, the PLC members identified two major problems of practice with respect to facilitating *Structured Model Share-out*. First, the members wondered how they could select and sequence students' models to be shared out effectively. They appreciated the range of ideas that students were able to share with the intentional selecting and sequencing, but they hoped to improve the practice to better support students in making connections among ideas and building on those ideas. Second, they noticed that most students just "copied and pasted" the ideas from each other without making sense of them. The members also found that students' rephrasing of ideas helped not only EBs but all students in clarifying what they heard. They wondered about ways to push the discussions further to help students reason about the ideas and use those as evidence in revising models.

In every Studio from Studio 6 to Studio 10, the members considered and tested various criteria to select and sequence students' models for the share-out and reflected on them. For example, they considered content represented in students' models and reasoned about how ideas in the models could be built on each other, focusing on promoting the depth of students' explanations in Studios 6, 7, and 10 and supporting students' use of evidence in Studios 8 and 9. For another example, they considered representational features of the models to help students see the range of ways to show ideas. They also tried out different formats of discussions such as partner talk or whole-class discussions and ways of scaffolding those discussions in Studios 6 through 8.

Studios 9-12: Adapting and improving the focal classroom practice of *Structured Talk.* As the members put their efforts into facilitating students' discussions, they identified another problem of practice: that it was challenging to engage many students, especially EBs, in meaningful discussions to reason through ideas. Based on this problem of practice, from Studio 9, the members started to incorporate *Structured Talk* into *Structured Model Share-out* with the purpose of promoting students' meaningful and equitable engagement in collaborative discussions with shared models. *Structured Talk* was a practice, initially developed by another PLC in the district based on ideas from Gibbons (2007), to support students'—especially EBs'—engagement in partner or small group discussions. In *Structured Talk*, students have protected turns and sentence starters to share and build on ideas and thinking. Knowing that they wanted to engage more EBs in discourses for scientific modeling, Sealth PLC members picked up this practice and majorly adapted it by combining it with other existing practices that they developed for supporting students' scientific modeling. The members started to work on *Structured Talk* in Studio 9 by integrating it into the small-group version of their practice of *Structured Model Share-out*. **Figure 4** shows the *Structured Talk* protocol used in the Studio lesson. In the lesson, students first worked in small groups to share and discuss pieces of evidence that they wrote on sticky notes and collaborated to use the evidence to support or revise their models. Here, the PLC members engaged students in *Structured Talk* by assigning roles and giving sentence starters to them with the purpose of promoting their collaboration in revising models using evidence. Then, the members used a similar discussion structure and the same sentence starters in the whole-class *Structured Model Share-out* to facilitate students' discussions. In the debriefing session of the Studio, the members reflected on how students participated in the discussions and how the protocol helped students, EBs in particular, with engaging in the collaborative work. In Studio 10, they kept working on this combined version of the two practices to help EB students discuss and revise models. In sum, in this line of inquiry, through iterating on and improving the focal practices of *Structured Model Share-out* and *Structured Talk*, the PLC members grew their practice-based knowledge about how to support students, EBs in particular, in collaborative epistemic work.

Structured Group Talk Protocol

- Person 1: Share your post-it.
- Person 2: "I think the main idea of the post-it is ___________________. Its effect on homeostasis/balance is _______________________________."
- Person 3: Explain where in the model the idea can be added.
- Person 4: Add it to the model.

[These roles rotate as each person shares their post-it!]

Figure 4. Structured Talk protocol used in Studio 9 to promote students'—especially EBs'—engagement in epistemic work of revising models using evidence

The Third Line of Inquiry to Support EBs' Academic Language Learning Through Scientific Modeling

Working in a school with about 25-30% of students officially classified as EBs, Sealth teachers had a high level of interest in supporting the EBs' science learning from the start of their collaboration. In particular, the two teachers who remained constant over the years, Emma and Anika, continuously encouraged the team to consider students' language learning based on their experiences of teaching EBs and learning English as a second language. From the early Studios, Sealth PLC members actively tried to build supports for EBs into their lessons and tested these supports by observing students' participation in class. Based on this common work, in Studio 6, the members identified a problem of practice in supporting the EBs' participation in scientific modeling. As a result, they developed a focal instructional practice, named *Disciplinary Language Instruction*, to work on the problem. Over time, the team iterated on the focal practice in Studios to support EBs' academic language learning through scientific modeling. Below, I describe the evolution of this practice over time.

Studios 1-6: Observing and supporting EBs' participation and learning in Studios. From the early Studios, the members had actively taken EBs into consideration when planning and debriefing Studio lessons. The members observed how specific EBs participated in scientific modeling and other class activities and tried to find ways to build on these observations. For example, in Studio 2, the members looked for ways to help the EBs write their ideas on the model template. The members reasoned that students' verbal sharing would help their writing and decided to have students first talk about their ideas with partners and then work on their models. Teacher Emma said, "Yeah, I think that [*talking before writing*] will really help them [*EBs*] practicing thought process and expressing that in words and sharing that with somebody. They all need that skill if they have to learn science in English." The members tried the strategy out and observed the EBs' participation in verbal sharing and modeling. After the lesson, they shared their observations and discussed ways to move forward. Some members thought that the strategy went well because they had observed some EBs writing down ideas from verbal sharing.

Other teachers disagreed, saying that some EBs felt more comfortable writing before talking and that students could be persuaded too easily by others if they had to talk before forming their own opinions. At the end of the discussion, the members agreed to keep testing the strategy of "talking before writing" in future Studios. For another example, in several Studios, the members noticed that scientific modeling could provide multiple entry points for EBs to process and share their ideas by inviting them to talk, draw, and write about their thinking. Furthermore, in many Studios, the members provided students with sentence frames to talk and write about their ideas during modeling.

Identifying a problem of practice in Studio 6. The PLC members' collective work to support EBs' learning led them to identify a problem of practice in Year 2: namely, that some EBs needed extra support in understanding some language structures and functions that are necessary for communicating ideas in science. This observation was made in Studio 6 in which the members tried to help students construct explanations of why some people are more likely to get breast cancer than others. In the Studio lesson, the members helped students identify the causes and effects of breast cancer from their reading and prior learning activities. Then, they asked the students to construct models to explain causal relationships in the phenomenon. In the debriefing session, when the members analyzed the students' models, Teacher Emma shared her noticing from students' writing that some students did not seem to understand the meaning of *cause* and *effect*. Teacher Anika added that she had spent a lot of time during the Studio lesson explaining what was meant by *cause* and *effect* to the four EBs that she had been observing.

The PLC members went on to discuss how they could better help EBs understand the language structures and functions necessary for discussing ideas in science, such as *cause and effect*. Coach Rebecca pointed out that two out of the four EBs that Teacher Anika observed were absent from the previous day's class in which Teacher Emma had taught the meaning of *cause* and *effect* more directly. The PLC members hypothesized that some direct instruction about language structures and functions could provide EBs with the tools for processing and communicating ideas in science and that this could facilitate the EBs' construction of scientific models and explanations. Based on this hypothesis, the members decided to incorporate some direct instruction about structures and functions of scientific language—language for communicating and reasoning with ideas in science— into their following Studios.

Studios 7-12: Developing and iterating on *Disciplinary Language Instruction*. In Studio 7, the members tried out the focal practice of *Disciplinary Language Instruction* that they had brainstormed in Studio 6. In the Studio lesson, students were asked to construct scientific models to predict how galaxies in the universe might be different in the future using evidence such as a graph showing Hubble's Law. Before the students worked on their models, the host teacher, Anika, explained the meaning of *cause* and *effect* using a poster that showed various forms of causal statements. She then encouraged students to practice generating causal statements about the phenomenon using given expressions. After the Studio lesson, the members examined the students'—especially the EBs'— models to see if they had written any causal statements with the given expressions. The members found that several students, including some EBs, had explained causal relations using the given expressions and decided to keep working on the practice of *Disciplinary Language Instruction* in the following Studios.

In every Studio from Studio 6, the PLC members collaborated on the focal practice of *Disciplinary Language Instruction* to support students' use of academic language in modeling. **Table 5** shows how consistently the PLC members worked on the practice over the four years. In Studios 8 and 10, they helped students learn expressions commonly used for comparing and contrasting ideas in science. Students practiced forming sentences using conjunctions such as *whereas*, *however*, and *in contrast*. In Studio 8, the members invited EBs to share how they would say the words, *compare* and *contrast*, in their native language. In Studios 11 and 12, the members had students learn how to share observations and support claims with evidence in science by using sentence frames. In sum, through iterating on and improving the focal practice of *Disciplinary Language Instruction* in multiple Studios, Sealth PLC members helped students—EBs in particular— grow their academic language skills to communicate and reason with ideas in scientific ways.

Table 5. How often and consistently the PLC members collaborated on the focal practice of Disciplinary Language Instruction to support students' academic language learning over the twelve Studios (X: Studios in which they worked on the practice)

Line of inquiry	Focal practice	Year 1				Year 2				Year 3		Year 4	
		Studio 1	2	3	4	5	6	7	8	9	10	11	12
Supporting EBs' academic language learning	*Disciplinary Language Instruction*						X	X	X	X	X	X	X

Discussion

In this study, I examined how participants of the focal PLC—high school science teachers, coaches, and researchers— developed and pursued lines of inquiry to improve their practice to support students' engagement in scientific modeling over four years. In this section, I discuss three features of Sealth High School teachers' professional learning that expand the extant literature on teacher learning in PLCs over time: 1) how the teachers addressed the complexity of teaching and improved multiple aspects of their modeling-based teaching through developing multiple lines of inquiry, 2) how they examined and used various kinds of student data to promote their lines of inquiry, and 3) how particular structures might have helped the PLC continuously improve practices over time despite high teacher turnover.

Addressing the Complexity of Teaching: Scientific Modeling as an Anchor for Developing Multiple Lines of Inquiry

While some studies have examined how teachers engage students in the epistemic processes of scientific modeling (generation, evaluation, use, and revision of models) (e.g., Louca et al., 2011; Thompson et al., 2016), the data from this study show that with time and opportunities to collaborate, teachers can address multiple dimensions of engaging students in knowledge construction. The PLC members began their collaborative work by developing instructional practices to support students' epistemic work of constructing scientific models. While working on the practices and associated tools, they recognized problems of practice and areas to work on based on their examination of students'—especially EB students'— participation and learning. They then turned to work on supporting additional dimensions such as supporting students' collaborative learning and addressing language learning.

Sealth teachers developed the three intertwined lines of inquiry through engaging in dynamic processes of identifying local problems of practice, developing sets of common practices and tools, and improving their work based on student data. Whereas other studies on modeling-based teaching have often focused on supporting teachers in planning lessons (Kenyon et al., 2011; Schwarz, 2009; Schwarz & Gwekwerere, 2007; Windschitl & Thompson, 2006), the teachers in this study worked on cycles of planning, implementing, and reflecting on lessons. These cycles opened up opportunities for the teachers to address the complexity of teaching through developing and testing concrete instructional practices and tools. The practices and tools incorporated distributed knowledge (Putnam & Borko, 2000) that the PLC members co-

constructed about what scientific modeling is and how they could support students' learning through scientific modeling. For example, the various kinds of model scaffolds that the members developed included knowledge about what makes good scientific explanations (e.g., justification using evidence) as well as concrete ways to support students' construction of models and explanations. For another example, the practice of *Disciplinary Language Instruction* reflected the members' noticing of EBs benefiting from explicit instructions about structures and functions of academic language and the potential of scientific modeling for helping EBs learn about and practice using academic language. By engaging in lines of inquiry to develop and improve these practices and tools, Sealth teachers could expand both their understanding and practice of supporting students' scientific modeling.

Sealth PLC members' expansive approaches to supporting students' modeling provided some insights about the potential affordances of modeling-based teaching. Whereas not many previous studies have focused on scientific models and modeling as ways for promoting diverse students' participation in classroom communities, Sealth teachers identified and worked on two major mechanisms by which they could support diverse students' learning through scientific modeling: 1) positioning students as sources of knowledge and promoting their collaboration using models and 2) supporting students' academic language learning through modeling.

Examining Student Work and Promoting Lines of Inquiry

Several types of student data became important to Sealth High School PLC members' collective inquiry and learning. This finding is aligned with what Kazemi and Franke (2004) found in their case study of teacher learning in a PLC: that discussions focusing on student work could help teachers shift the way they participate in pedagogical reasoning and decision-making in their collective work. The kinds of student data in this study included student work such as student models as well as the PLC members' observation of students' participation in class interactions and activities. I especially found three ways that student data could promote the lines of inquiry in the PLC. First, student data helped teachers identify specific problems of practice that they could work on. Second, student data led teachers to notice the versatility of scientific modeling for supporting multiple aspects of student learning. Finally, student data helped teachers test and improve their instructional practices and develop lines of inquiry over time. For example, Sealth teachers found that it was challenging to engage all students in meaningful discussions for reasoning through ideas. While engaging students in scientific modeling, they noticed that they could invite students to elaborate on their ideas by communicating their ideas and thinking with peers. Based on this noticing, the PLC members developed the focal practice of *Structured Model Share-out* to help students learn from each other using models. They also adapted and implemented the practice of *Structured Talk* to support diverse students' collaboration in constructing and revising models. Then, over multiple Studios, they tested and improved the practices by observing students'—especially EBs'— participation in activities and interactions and discussing ways to better support them. All of these processes did not happen linearly but were dynamically intertwined with one another. The improvement work kept pushing the participants to identify new problems of practice and develop practices and tools to address the emerging issues.

Structures and Driving Forces for Sustainable Inquiry

Importantly, this PLC was situated in a school that had a high teacher and administrator turnover. Only two teachers remained on staff while nine others came or left over the four years. Professional learning is often a challenge with such high rates of turnover (Hargreaves & Fullan, 2012). I speculate that holding some aspects of the professional learning context constant helped the team make progress on the development of inquiry and teaching. Over the years the research-practice partnership was constant such that researchers and district coaches interacting with the teachers regularly partnered and brought a similar perspective on supporting student learning and teacher learning. Also, participating in the partnership meant that each year the PLC had the same professional learning structure with Studios with the researchers and coaches. Furthermore, I think that the culture constructed and developed in the PLC as well as distributed knowledge held by the participants and by the co-constructed instructional practices and tools helped newcomers adjust to and engage in the lines of inquiry. For example, the two teachers who remained constant emphasized scientific modeling in their instruction and wanted to help newcomers learn similar practices. But rather than telling new teachers about their developing practices, they involved them in inquiry with the practices. Based on the findings from this study and some previous studies on teachers' collaborative learning (e.g., Thompson et al., under review), I conjecture that the continuous inquiry into improving modeling-based teaching coupled with the focus on developing easy-to-implement practices and tools helped give all members a reasonable foothold into the collaborative improvement work.

Conclusion and Implications

This four-year longitudinal study provides an empirical case of what sustainable collective inquiry could look like in a high-functioning PLC. Over the four years, Sealth PLC members continuously focused on supporting students' scientific modeling and co-developed sets of instructional practices around the focus based on their multidimensional goals and local context. Here, scientific modeling served as an anchor for their teaching and helped them reason about and improve multiple aspects of their teaching in a sustainable and manageable way.

This study suggests some implications for both educational researchers and practitioners about 1) the potential of modeling-based teaching for promoting both student learning and teacher learning and 2) how to understand and support teachers' collective learning and inquiries in PLCs. Regarding the first point, the findings suggest that modeling-based teaching could support multiple aspects of student learning—including students' collaborative engagement in knowledge building processes and EB students' language learning— as well as help teachers develop and reason about instructional practices that could serve multiple aims. While I did not collect evidence of student learning in this study, future research might consider how these affordances of modeling-based teaching bolster the evidence suggesting that scientific modeling can support all students' learning in general (e.g., Lehrer & Schauble, 2006) and support learning of students from underrepresented populations in particular (e.g., Brewe et al., 2010). Practically, teachers, coaches, and teacher educators could be informed about the various dimensions found in this study as a way to support teacher learning and inquiry over time. Regarding the second point, I used the concept of lines of inquiry to understand teachers' collective inquiries over a long period of time. I showed how a team of teachers developed and sustained intertwined lines of inquiry through engaging in cycles of planning, implementing, and reflecting on lessons in their own context and collectively working on concrete instructional practices and tools based on student data. For educational researchers, the findings from this study suggest that teachers' collaborative learning in PLCs could support teachers' localization of reform-oriented practices, such as scientific modeling, in their contexts and continuous problem solving for improving instruction. For teacher educators and coaches, this case could suggest some effective structures and resources to promote teachers' collaborative learning in PLCs.

Section 2. Co-evolution of high school science teachers' collaborative inquiry and classroom teaching to support students' evidence-based explanations

Introduction

Recent studies in teacher education have suggested the importance of promoting teachers' collaboration in PLCs (Grossman et al., 2001; Hord, 1997; Little, 2003). The studies have argued that in productive PLCs, teachers can take collective responsibility and work collaboratively to improve teaching and student learning in their local settings (Grossman et al., 2001; Hargreaves & Fullan, 2012; Kennedy, 2016). Based on these studies, there is a growing trend towards encouraging teachers' collaboration in school settings.

It is generally assumed that teachers' collaboration in PLCs can foster improvements in classroom teaching practices. However, this assumption is not yet strongly supported because even though a few studies have examined the impacts of teachers' participation in PLCs on their practices (e.g., Dunne, Nave, & Lewis, 2000; Kennedy, 2016; Louis & Marks, 1998), little is known about how teachers' collaborative learning in communities can *co-evolve* with their classroom teaching over time. It remains an open question about which processes in teacher collaborations connect with particular interactions in classroom teaching.

In this study, I explore how five high school science teachers' collaboration in a PLC, supported by a coach and a researcher, co-evolved with their classroom teaching over six months. Especially, I focus on how the teachers collaboratively worked on their goal to improve their teaching to support students' construction of evidence-based explanations. Constructing evidence-based explanations is one of the core epistemic practices in science through which students could generate *how* and *why* accounts of phenomena and learn how to support their claims with evidence (Braaten & Windschitl, 2011; McNeill & Krajcik, 2008; National Research Council, 2012). The teachers in this study made notable instructional shifts in their teaching by developing/adapting and using a suite of related instructional practices that supported students in constructing evidence-based explanations. I explore how the teachers' interactions in the PLC co-evolved with these instructional shifts in their teaching over the course of six months.

Theoretical Background

This study takes a situative perspective on learning (Greeno, 2006; Lave & Wenger, 1991) and builds on studies about teacher learning in PLCs (e.g., Hord, 1997) and studies in the field of improvement science (e.g., Bryk et al., 2015) discussed in the first study of this dissertation. In this current study, I focus on the connections between teachers' collective learning in PLCs and their classroom teaching. Regarding the content of teachers' collaboration and teaching, I focus on teachers' discussions and practices for supporting students' construction of evidence-based explanations. In what follows, I review what previous studies have found and suggested about 1) the connections between teachers' collaboration and classroom teaching and 2) supporting students' construction of evidence-based explanations in science classrooms.

Connections Between Teachers' Collective Learning in PLCs and Classroom Teaching

Previous empirical studies that have examined the connections between teachers' collective learning in communities and classroom teaching have mainly focused on examining whether teachers' participation in PLCs results in improvements in their knowledge for teaching or teaching practices (e.g., Dogan, Pringle, & Mesa, 2016; Dunne et al., 2000; Jones, Gardner, Robertson, & Robert, 2013; Louis & Marks, 1998; Nelson, 2009; Vescio, Ross, & Adams, 2008). Most of these studies have shown positive impacts of PLCs on teacher knowledge and practice. Regarding the impacts of PLCs on teacher knowledge, Dogan et al. (2016) reviewed fourteen recent studies on science teachers' professional learning in communities and concluded that PLCs could help teachers improve their pedagogical content knowledge and disciplinary content knowledge that might facilitate improvements in their teaching. Jones et al. (2013) asked 65 science teachers to self-assess their own understandings about teaching after participating in PLCs where they had tried to improve students' science standardized test scores by sharing ideas about teaching. The authors identified aspects of teacher understanding that got improved, which included the teachers' understandings of various assessment strategies, ways for planning lessons, and their curriculum materials. A few studies have focused on not only teacher knowledge but also some affective characteristics of teachers—e.g., self-efficacy, confidence, accountability, and creativity— that got improved as results of teachers' participation in PLCs and might mediate improvements in teachers' classroom practices (e.g., Jones et al., 2013; Richmond & Manokore, 2011). With respect to the impacts of PLCs on teachers' practices, Vescio et al. (2008) reviewed eleven previous empirical studies and concluded that well-developed PLCs could help teachers develop and implement more student-centered pedagogies. Louis and Marks (1998) conducted a quantitative investigation in 24 schools and found that PLCs with the core characteristics—shared sense of purpose, a collective focus on student learning, de-privatized practice, collaborative activity, and reflective dialogue— significantly contributed to higher levels of "authentic pedagogy" that emphasized higher order thinking, disciplined inquiry, and construction of meaning in classrooms. The authors examined teachers' classroom teaching through making classroom observations and conducting interviews with teachers. Nelson (2009) conducted a qualitative case study with three PLCs and found that teachers in two PLCs improved their practices by implementing activities and plans for supporting students' scientific writing that had been discussed in their PLC meetings. The author used the teachers' self-reported data for examining their classroom teaching practices. Some studies also focused on the impacts of PLCs on school cultures that could support teachers' classroom teaching (Louis & Marks, 1998; Vescio et al., 2008). From reviewing empirical studies, Vescio et al. (2008) suggested the following four features as key facets of school culture that could be improved by teachers' participation in learning communities and could positively affect their teaching: collaboration, a focus on student learning, teacher authority, and continuous teacher learning.

Co-evolution of teachers' collaboration and classroom teaching. While the majority of the earlier empirical studies have focused on examining the impacts of PLCs on teachers' classroom teaching, researchers taking sociocultural and/or situative approaches to studying teacher learning have pointed out the limitations of viewing teachers' learning in PD settings as unidirectionally influencing their classroom teaching (e.g., Kazemi & Franke, 2004; Kazemi & Hubbard, 2008). Studies on PLCs have emphasized that the purpose of encouraging teachers' participation in learning communities is not to disseminate generalizable knowledge of practice to individual teachers, but rather to help teachers collectively discuss and solve their local problems and become producers of knowledge for improving their practices (Little, 2003). In this sense, teachers' collaborative work in PLCs and their daily work in classrooms should mutually promote each other, and therefore teachers' classroom practices should not be regarded as mere "results" of their learning from the PLC settings. If researchers solely focused on the unidirectional influence of PLCs on teachers' teaching, they would miss opportunities to explore what travels back and forth and promotes teachers' learning and improvements across settings. To address this issue, Kazemi and Hubbard (2008) suggested to focus on the *co-evolution* of teachers' participation across the PD and classroom settings. The importance of continuity and sustainability of teacher learning in PLCs also provides a justification for focusing on the co-evolution, as the concept could help understand and explain how teachers' participation across settings evolve over time. Though, little empirical investigation has been done to understand how teachers' participation in PLCs and classroom teaching co-evolve over time.

A few studies have suggested some possible mechanisms for how teachers' collaboration in communities and their classroom teaching can co-evolve (e.g., Bryk et al., 2015; Grossman, Smagorinsky, & Valencia, 1999; Horn, 2010; Horn & Kane, 2015; Kazemi & Franke, 2004; Kazemi & Hubbard, 2008; Lewis, Perry, & Murata, 2006). In this literature review, I focus on three major mechanisms, suggested by previous studies, that could work either together or separately to promote the co-evolution of teachers' collaborative learning in PLCs and classroom teaching. The three mechanisms are as follows: 1) teachers using representations of teaching to collectively reason about and improve teaching practices, 2) teachers setting goals and expectations for collective work by analyzing problems of practice and classroom data, and 3) teachers conducting experimentation on instructional practices using classroom data and constructing working theories for improving teaching.

Teachers using representations of teaching to collectively reason about and improve teaching practices. Representations of teaching, including material representations—e.g., curriculum guides and instructional tools— and conversational representations—e.g., teaching replays and teaching rehearsals (Horn, 2010)—, help teachers collectively reason about and improve classroom practices (Horn & Kane, 2015). Some representations of teaching—especially instructional tools— can directly mediate teachers' interactions with one another and with students across boundaries of settings (Grossman et al., 1999). For example, in PLC meetings, teachers can co-construct instructional tools that can mediate the teachers' interactions with students in multiple classrooms. They can discuss assumptions about what counts as effective teaching while co-constructing the tools and brainstorming how to use the tools with students (Anagnostopoulos, Smith, & Basmadjian, 2007). Then, they can appropriate and use the tools in various ways to facilitate students' learning experiences across classrooms (Grossman et al., 1999) and bring their observations and experiences from classrooms back to PLC meetings to further discuss ways to improve the tools and promote students' learning. For another example, teachers can reconstruct or anticipate classroom interactions in PLC meetings through teaching replays or rehearsals and collectively reason on those to improve their interactions with students (Little, 2003; Horn, 2010). Student work also has been suggested as a core kind of representation of teaching that could cross boundaries of settings as well as serve various purposes in teachers' collaboration and classroom teaching (Kazemi & Franke, 2004; Kazemi & Hubbard, 2008). I discuss the roles of student work more specifically in the following two mechanisms. The interpretation and use of representations of teaching vary across contexts and depend on norms and expectations in social settings (Horn & Kane, 2015).

Teachers setting goals and expectations for collective work by analyzing problems of practice and classroom data. Studies have emphasized that it is important for teachers to develop shared vision and expectations about what counts as high-quality teaching and learning and therefore what is worth working on in a PLC (e.g., Hord, 1997). Specific goals based on concrete problems of practice help teachers concretize their vision, connect the vision with what is happening in their classrooms, and set directions for collective work to improve their teaching practices (Bryk et al., 2015). Teachers can identify problems of practice, specify their goals and expectations, and brainstorm and test instructional practices by analyzing and reasoning with classroom data centered around student work in PLCs (Bryk et al., 2015; Kazemi & Franke, 2004). Problems of practice do not automatically arise; rather, they are socially constructed by participants of a community through interactions (Coburn, 2006; Horn, 2007). Therefore, it is important to understand how teachers socially construct problems of practice and goals and expectations for their improvement based on classroom data, as these guide the teachers' efforts for improvement across settings.

Teachers conducting experimentation on instructional practices using classroom data and constructing working theories for improving teaching. For the co-evolution of teachers' collaboration in communities and their classroom practices, many studies have argued for the importance of teachers conducting collective inquiries on instructional practices and producing local knowledge for improvement (e.g., Cochran-Smith & Lytle, 1999; Darling-Hammond & McLaughlin, 1995; Little, 2003). Through engaging in collective inquiries, teachers can become active producers of knowledge by working together to tackle authentic problems of practice in their teaching, make collective judgments, and discuss and test instructional practices using classroom data. Regarding effective ways for conducting collective inquiries, improvement scientists have suggested to implement cycles of quick experiments to test how certain changes in instructional practices work or do not work for student learning in various contexts (Bryk et al., 2015; Langley et al., 2009). By testing instructional changes under multiple conditions, teachers can co-construct working theories about what works, for whom, and under what conditions for improving their teaching practices (Bryk et al., 2015). Bryk et al. (2015) suggested instructional practices, working theories of teaching and student learning, and practical measurements as three key components of a "learning loop for quality improvement (p. 90)."

Different studies have focused on different sets of mechanisms among these three mechanisms, mostly focusing on one or two. Therefore, the field lacks understanding of how these mechanisms can work together and promote the co-evolution of teachers' collaboration and teaching. In this study, I build on previous studies about all these three mechanisms to explore how a team of high school science teachers' collaboration and classroom teaching co-evolved over six months. Next, I review what earlier studies have suggested and found about supporting students' construction of evidence-based explanations in science education, as this was the major focus of the PLC.

Supporting Students' Construction of Evidence-based Explanations

Recent studies in science education and the current science standards movement have emphasized the importance of providing rich opportunities for students to engage in epistemic practices of science and make sense of the world as knowledge builders (e.g., Duschl, 2008; National Research Council, 2012; Schwarz, Passmore, & Reiser, 2017). The construction of evidence-based explanations of phenomena is a core epistemic practice in science, through which students can take active roles in knowledge building by generating *how* and *why* accounts of phenomena and justifying claims with evidence (e.g., Braaten & Windschitl, 2011; McNeill & Krajcik, 2008; National Research Council, 2012). Many studies have argued that students' participation in this core epistemic practice can promote their learning of not only scientific concepts but also epistemic norms about how knowledge is constructed and justified in science (e.g., Berland & Reiser, 2009; Braaten & Windschitl, 2011).

Evidence-based explanations. Evidence-based explanations are accounts for *how* and *why* phenomena, observed in the natural world, occurred. The two critical components of evidence-based explanations are 1) causal accounts including connections between observations (descriptions of what occurred in the macroscopic level) and underlying mechanisms or causes of phenomena and 2) justifications for knowledge claims in the explanations (Braaten & Windschitl, 2011; Kang, Thompson, & Windschitl, 2014; McNeill & Krajcik, 2008; Osborne & Patterson, 2011). Explanations should include coherent connections among these core components and should be internally consistent (Kang et al., 2014). Below, I elaborate on these two core components.

Causal accounts for how and why phenomena occurred. To construct a "good" scientific explanation of a phenomenon, students should describe observable relationships in the phenomenon and explain "the mechanisms that support cause and effect inferences about them" (National Research Council, 2012, p. 67). This characterization of scientific explanations asks students to move beyond describing an observable phenomenon in the macroscopic level. It asks students to find observable relationships, patterns, or processes in the phenomenon and reason about and articulate causal connections between those and underlying mechanisms that include unobservable and theoretical ideas (Braaten & Windschitl, 2011; McNeill, Berland, & Pelletier, 2017). A good scientific explanation provides a full causal story of how and why a phenomenon occurred by articulating complex webs of causation instead of listing a few simple cause-effect relationships (Braaten & Windschitl, 2011). Reasoning about and explaining complex webs of causation in a phenomenon help students deepen their understanding of the phenomenon and underlying ideas (Grotzer & Basca, 2003) as well as learn that there can be many acceptable models for explanations of a phenomenon (Braaten & Windschitl, 2011).

Justification using evidence. Ideas and knowledge claims in scientific explanations need to be justified with evidence and reasons (McNeill & Krajcik, 2008; Sandoval, 2003). Therefore, it is important for students to support their claims with relevant and sufficient evidence and reasons in their explanations (Kang et al., 2014; McNeill & Krajcik, 2008; Sandoval, 2003). Evidence refers to scientific data that support claims about phenomena. Evidence is not "discovered" from the natural world but is *constructed* by people in scientific communities through acts of reduction—selection of some aspects of phenomena to focus on— and amplification—making the phenomena of interest visible and subject to manipulation (Latour, 1987; Manz, 2016). Appropriateness and sufficiency have been suggested as the core criteria for judging the quality of the use of evidence in explanations (Kang et al., 2014; McNeill & Krajcik, 2008; Sandoval, 2003). Appropriateness refers to how relevant the data are to the claims that they support, and sufficiency refers to how sufficient and credible the data are for justifying the claims (Kang et al., 2014). Explanations should include not only relevant and sufficient evidence but also justifications for how the evidence supports target claims. Justifications should include appropriate and sufficient scientific principles to connect and defend the claims and evidence (McNeill & Krajcik, 2008).

Instructional supports for students' construction of evidence-based explanations. A number of previous studies have suggested effective instructional scaffolds and practices for supporting students' construction and writing of evidence-based explanations (e.g., Braaten & Windschitl, 2011; Kang et al., 2014; Manz & Renga, 2017; McNeill & Krajcik, 2008; Sandoval, 2003; Windschitl, Thompson, Braaten, & Stroupe, 2012). Some studies have primarily focused on supporting students in justifying claims with evidence and reasoning (Manz & Renga, 2017; McNeill & Krajcik, 2008; Sandoval, 2003), while other studies have focused on promoting both the depth of causal accounts and the use of evidence in students' explanations (Braaten & Windschitl, 2011; Kang et al., 2014; Windschitl et al., 2012).

In regard to supporting students' justification in constructing explanations, McNeill and Krajcik (2008) suggested to make the components of scientific arguments (claims, evidence, and reasoning) explicit to students so that students could understand what a good scientific argument looks like and how to write a well-supported argument. Manz and Renga examined how teachers guided students' evidence construction in classroom communities through helping students attend to and reason about noticings, public attributes, data collections, experimental variables and evidence, experimental claims, and facts (Manz, 2016; Manz & Renga, 2017).

For promoting both the depth of causal accounts and the use of evidence in students' explanations, Windschitl and his colleagues (2012) proposed an instructional framework, named *Ambitious Science Teaching* framework, including a core set of instructional practices and tools for supporting students' construction of scientific explanations of phenomena. The framework invites students to construct their initial explanations of a puzzling phenomenon at the start of an instructional unit and revise those explanations using evidence from various class activities throughout the unit. The framework pushes students to move beyond justifying a single claim with evidence. It asks students to make coherent connections among multiple claims and supporting evidence to build well-supported causal accounts for how and why a phenomenon occurred. Some other studies have suggested or examined various scaffolds that teachers could use to support students' construction of explanations with causal accounts and justifications (Braaten & Windschitl, 2011; Kang et al., 2014).

While a number of studies have focused on effective instructional tools and practices for supporting students' construction of explanations and how teachers take up those specific tools and practices in classrooms, little is known about how teachers develop their own sets of practices/tools or inquire on their practices over time to support students' construction of evidence-based explanations. This study explores how a team of teachers conducted their own inquiry to improve their teaching to support students' construction and writing of explanations.

To summarize, this study aims to answer the following research question: How do five high school science teachers' collaboration in a PLC and classroom teaching to support students' construction of evidence-based explanations co-evolve over time?

Methods

In this study, I used a qualitative case study approach (Yin, 2014) to generate an in-depth description and analysis of how a team of science teachers' collaboration and classroom teaching co-evolved over time. This study was conducted with the same focal PLC, Sealth High School science PLC, as the first study of this dissertation after the study period of the first study. For this study, I closely analyzed five Sealth teachers' interactions in the PLC meetings and classroom teaching over six months. In this section, I first introduce the research context and participants of this study. Then, I describe two PD structures—Studio and Data meeting— that set the stage for the teachers' collaboration. Finally, I explain how I collected and analyzed data for this study.

Research Context and Participants

Research-practice partnership context. This study was conducted with Sealth High School PLC in the school year of 2017-18, which was the fifth year of the PLC's participation in the research-practice partnership with the Ambitious Science Teaching research group at the University of Washington, described in the first study of this dissertation. In other words, this study focused on Sealth High School teachers' collaboration and classroom teaching after the four years of teachers' collaboration examined in the first study. There were some changes in the members, which I would explain more in the Participants section.

In this fifth year of the research-practice partnership, the university researchers and district-based coaches intentionally took minimal roles in the PLC meetings. During this year, Sealth High School PLC had one focal university science education researcher—me, Researcher Sue—and one district-based science coach—Coach Nancy. The researcher and the coach participated in the PLC meetings as participants with their expertise, but they did not take any leadership roles in the meetings. The meetings were led by the teacher leader of the team, Teacher Anika, who had been the leader since 2016. Researcher Sue and Coach Nancy sometimes met with Anika after PLC meetings to help her debrief and plan for upcoming meetings.

Participants and school context. The focal PLC—Sealth High School PLC— was purposefully selected for this study because of the following reasons. First, the administrators of Sealth High School asked teachers to have regular after-school department meetings every three weeks, which set the stage for the participant teachers' collective inquiry on teaching. Second, the team had participated in the research-practice partnership for more than four years since 2013 and developed a collaborative culture in the community. The culture allowed the teachers to safely de-privatize their teaching practices, address dilemmas in their teaching, and discuss various viewpoints about learning and teaching. Third, the teachers continuously focused on a team goal to support students' construction of evidence-based explanations over the course of the study period—six months. Finally, I had collaborated with this team since 2015 as a researcher participant and built relationships with the teachers as well as grown both insider and outsider perspectives to understand the dynamics in this community.

The context of Sealth High School, including student demographic information and the school-level foci, was described in the first study of this dissertation. During the school year of 2017-18, the school administrators especially focused on helping teachers engage in collective inquiries on instructional practices. The administrators asked teachers in each department to have regular after-school meetings every three weeks and pursue year-long goals for improvement through conducting inquiries on common instructional strategies. These after-school meetings became the major setting for the participant teachers' collaboration in this study. The administrators came to two of the after-school meetings of the science PLC throughout the school year to understand science teachers' goals and approaches for improvement.

Sealth High School science PLC had five Sealth science teachers, Researcher Sue, and Coach Nancy as participants during the school year of 2017-18. **Table 6** shows some information about the five participant teachers: when they joined the PLC, how many years they had been teaching, whether they received additional training for teaching EB students and earned the EB certification, and the subjects and grade levels that they taught during 2017-18. Katie newly joined the PLC at the start of the school year. Four among the five teachers—Anika, Emma, Lisa, and Katie— taught the same subject, biology. Further, because the school was going through a reorganization of the school curricula, all the four teachers were asked to teach the same or similar units throughout the year. Tom was the only teacher who taught chemistry. The last column of **Table 6** shows the contexts of the focal classes that I visited to make classroom observations for this study. Each class had 15-20 students, with 20%-31% of students officially classified as EB students. All the focal classes were mixed-ability classes.

Table 6. Participant teachers of the study (Sealth High School PLC during 2017-18) and the contexts of the focal classes for classroom observation

Teacher	Year of joining the PLC	Teaching experience	EB Certification	Subject, Grade level	Focal class context
Anika (Leader)	2013	5 years	Yes	Biology, 9^{th} grade	16 students; mixed-ability; 5 official EB students
Emma	2013	12 years	No	Biology, 10^{th} grade	18 students; mixed-ability; 5 official EB students
Lisa	2014	7 years	Yes	Biology, 10^{th} & 11^{th} grades	20 students; mixed-grade (mostly 10^{th} grade and a few 11^{th} grade students); mixed-ability; 6 official EB students
Tom	2016	2 years	Yes	Chemistry, 10^{th}-12^{th} grades	15 students; mixed-grade (8 11^{th} grade, 3 10^{th} grade, and 4 12^{th} grade students); mixed-ability; 3 official EB students
Katie	2017	20 years	Yes	Biology, 9^{th} grade	18 students; mixed-ability; 4 official EB students

My roles in the PLC. During the study period, I participated in all the PLC meetings of this focal PLC as a *participant as observer* (Gold, 1958). As a researcher participant, I engaged in discussions using my perspectives and resources as a science education researcher. I sometimes had meetings with Anika and Coach Nancy to help Anika plan for upcoming PLC meetings. When I made observations in the teachers' classrooms, I took the stance of the *observer as participant* (Gold, 1958) and primarily focused on gathering data. I consented all the teachers to data collection and collected data from the PLC meetings and their classrooms. I informed the teachers and the coach about my role as a researcher.

Settings for Collaboration: PD Structures of Studio and Data Meeting

There were two kinds of PD settings for the teachers' collaboration in this study: Studio and Data meeting. I introduced the structure and theoretical grounds of the PD model of *Studio* in the first study of this dissertation. The focal PLC had one Studio—job-embedded PD day— over the period of this study. On the Studio day, the participants of the PLC gathered for a full school day to conduct collective inquiry to improve teaching and student learning. Lisa was the host teacher of the Studio. In the Studio, the participants first collectively planned and implemented a focal lesson to support students' construction of explanations. Then, they debriefed the lesson and revised the lesson to teach it again in another period. By teaching the revised lesson, the participants had a chance to test some hypotheses about how certain changes in their teaching could affect student learning by gathering and examining classroom data.

Data meeting was another PD structure that was in play on a more regular basis. In the research-practice partnership project, the Ambitious Science Teaching research group introduced "Data meetings" to the school district and participant teachers in 2015. Data meetings were regular after-school meetings for teachers to conduct collective inquiries on their teaching based on data from their classes. In the school year of 2015-16, university researchers from the research group guided teachers' inquiries in the Data meetings of school-based PLCs. In 2016-17, in each PLC, one or two teachers became teacher leaders of the PLC and led the Data meetings. Anika and Emma were the leaders of Sealth High School PLC. The project held some district-wide PD meetings for the teacher leaders to learn about how to lead teachers' inquiry and share insights across PLCs. Finally, in the school year of 2017-18, which was the year this study was conducted, the teacher leaders almost solely led the Data meetings in each school-based PLC with some help from researchers and coaches. The project did not hold any district-level PD meetings across schools during this year. Anika became the sole leader of Sealth High School PLC and led the Data meetings. Sealth PLC used the time allocated for their department meetings—75-minute after-school meetings held every three weeks— for their Data meetings. In the Data meetings, the participants set year-long goals for improvement and tried to pursue the goals through conducting collective inquiries on teaching using data from their classes. **Table 7** shows the dates and main content of the PLC meetings—one Studio and eight Data meetings—of Sealth High School PLC during the study period, from September 2017 to February 2018.

Table 7. PLC meetings of Sealth High School science PLC during the study period

PLC meeting	Date (Month-Date-Year)	Main content of discussions
Data meeting 1	09-21-2017	Setting the team goal
Data meeting 2	10-05-2017	Developing a team rubric to assess students' written explanations
Data meeting 3	10-26-2017	Discussing how to promote students' formative work; Examining students' written explanations
Studio	11-09-2017	Co-planning and co-teaching focal lessons; Identifying problems of practice; Testing instructional supports for promoting students' use of evidence
Data meeting 4	11-09-2017	Brainstorming instructional practices for supporting students' use of evidence
Data meeting 5	12-07-2017	Making a consensus about what to expect in students' evidence-based explanations; Deciding a focal instructional practice
Data meeting 6	01-11-2018	Sharing insights from implementing common instructional practices and tools
Data meeting 7	01-25-2018	Examining student work; Identifying new problems of practice; Continuing to negotiate expectations
Data meeting 8	02-15-2018	Examining student work; Identifying new problems of practice; Continuing to negotiate expectations

Data Collection

Data from the PLC meetings. I participated in all the PLC meetings of Sealth PLC during the study period—from September 2017 to February 2018— and collected data as a *participant as observer* (Gold, 1958). The data from the PLC meetings included the followings: the video recordings of Sealth PLC members' interactions and teaching in the Studio—approximately 8 hours of videos—, audio recordings of the members' conversations in the eight Data meetings—approximately 11 hours of audio recordings—, descriptive and reflective field notes that I wrote during and after each PLC meeting, and artifacts from the PLC meetings—including pictures of posters made by the teachers as well as student work that the teachers brought to the meetings. The audio recordings of the Data meetings were fully transcribed for analysis. Parts of the video recordings of the Studio were transcribed for analysis as well.

Classroom data. I made classroom observations in the five teachers' classrooms as an *observer as participant* (Gold, 1958) during October 2017 and February 2018. At the beginning of the school year, after the team set the goal to support students' writing of scientific explanations, I asked the teachers to invite me to their classes when students worked on the construction or revision of scientific models or explanations of phenomena. As the teachers' collective inquiry proceeded, the teachers came up with some instructional practices and tools for supporting students' construction of evidence-based explanations. I asked the teachers to invite me to their classes when they implemented the practices and tools in their teaching as well. I set focal classes for observation with the teachers, and the focal classes were Anika's 6th period class, Emma's 4th period class, Lisa's 3rd period class, Tom's 5th period class, and Katie's 2nd period class. The classes were selected because those classes were taught before the teachers' planning periods or lunch break so that I could ask the teachers some debriefing questions about the lessons after the observations. The contexts of the focal classes are described in **Table 6**. In total, I observed 34 lessons during October 2017 and February 2018 (6 lessons of Anika, 8 lessons of Emma, 7 lessons of Lisa, 6 lessons of Tom, and 7 lessons of Katie). Each lesson lasted for either 50 or 85 minutes. I collected the following kinds of data from each lesson I observed: video-recordings of the teachers' interactions with students, video-recordings of students' interactions with one another in small groups, artifacts from the lessons including pictures of student work and lesson materials, descriptive and reflective field notes of observations that I wrote, and audio-recordings of short interviews that I conducted with the teachers after each observation. In the short interviews, I asked the teachers to reflect on their lesson goals, how their lessons went, how students participated, and what they learned from the lessons. In classrooms, I used a video camera to capture classroom interactions among the teachers and students. I set the camera at the back of the classrooms to capture whole-class interactions and occasionally moved to small groups with the camera when the teachers interacted with small groups or when students worked in small groups. I introduced myself to students as a university science education researcher trying to learn about good science teaching from the classes. My interactions with students were minimal. I sometimes asked students a few clarification questions about their work. I took pictures of lesson materials and students' work during the lessons. When students constructed scientific models or explanations, I took pictures of all the students' work after the lessons.

Interview data. I conducted semi-structured interviews (Merriam & Tisdell, 2009) with the teachers individually at the end of the school year in May and June 2018. Each interview took about one hour. I asked the teachers to reflect on their work towards their goals in the PLC and in their classrooms throughout the year. I asked them to share critical moments in the PLC meetings and in their classrooms that promoted their learning. I also asked them if the PLC meetings were helpful for their teaching and why. Pictures of artifacts from the meetings were provided to the teachers to help their reflection. Finally, I asked them to reflect on their use of specific instructional practices and tools that they had discussed in the PLC meetings. All the interviews were audio-recorded and transcribed for analysis.

Data Analysis

I analyzed the teachers' interactions in the PLC meetings and their classroom teaching during the study period. For analyzing the teachers' interactions in the PLC meetings, I first identified *episodes of pedagogical reasoning* (Horn, 2010) as units of analysis in their discussions. In each episode of pedagogical reasoning, the teachers reasoned about an issue in their teaching practice by making their reasons, explanations, or justifications explicit (Horn, 2010). For the data from the Studio, the video recordings and artifacts from the day were coupled in the analysis and chunked by the episodes of pedagogical reasoning. For the data from the eight Data meetings, the transcripts of the teachers' conversations and artifacts from the meetings were coupled and chunked by the episodes of pedagogical reasoning. In each episode of pedagogical reasoning, I first identified the following two kinds of conceptual resources (Horn & Kane, 2015) in the teachers' discussions: 1) problems of practice or questions raised by the teachers or other participants in the PLC [code: *problems of practice/questions*] and 2) representations of teaching (Horn & Kane, 2015)—e.g., instructional tools, student work, and conversational representations such as teaching rehearsals (Horn, 2010)— [code: *representations of teaching*]. Then, I coded the content of the teachers' discussions with the following codes: 1) discussions of goals and expectations about student learning and teaching—e.g., discussions of what to expect in students' evidence-based explanations— [code: *goals and expectations*], 2) discussions of instructional practices [code: *practice*], 3) discussions of data including student work [code: *data*], and 4) discussions of working theories (Bryk et al., 2015) about student learning and teaching [code: *working theory*]. With the coded data, I qualitatively characterized the teachers' interactions in each episode of pedagogical reasoning.

For the analysis of the teachers' classroom teaching, the video recordings and artifacts from each lesson were coupled. From the classroom data, I first identified instructional practices and tools that the teachers implemented for supporting students' construction of evidence-based explanations. Examples of the instructional practices and tools are described in **Table 8** in the Findings section. Then, I qualitatively analyzed and characterized classroom interactions that happened while the instructional practices and tools were being implemented. The classroom interactions were divided into episodes for the analysis. The boundaries of the episodes were decided based on topical shifts in conversations or shifts in the kinds of tasks that students engaged in.

After coding and characterizing the teachers' interactions in the PLC meetings and the classroom interactions in their focal classes, I created data displays to juxtapose the analyzed episodes along the timeline of the study period. Then, I qualitatively analyzed how the interactions in the two settings—the PLC and the teachers' classrooms— co-evolved over time by exploring connections across the settings. While the observational data (video or audio recordings and artifacts) were prioritized in the data analysis, the interview data and field notes added information to the patterns identified from the observational data.

Limitations

This study has some limitations that are important to take into account. First, I took a situated perspective on learning (Greeno, 2006; Lave & Wenger, 1991) and examined the five teachers' interactions with one another and with students in the PLC meetings and in their classrooms. There might have been some contextual factors or interactions outside these settings that affected the teachers' collaboration and classroom teaching, which could help justify or reexamine the findings of this study. I tried to deepen my understanding of contextual influences by actively communicating with the teachers, coaches, and sometimes administrators to ask for their perspectives about what was happening both inside and outside the settings of this study to address this issue. Second, because my visits to the teachers' classrooms were by invitation, there could be some gaps in my understanding of the observed patterns or trends in the teachers' teaching. To address this issue, I checked in with the teachers regularly about what activities they did in each instructional unit, how the activities were connected, and how students participated in those activities. I also asked students to show their work from previous activities and briefly share what they had been learning when I visited the focal classes. Now I move on to explain the findings of this study.

Findings

The teachers in this study focused on supporting students' construction of evidence-based explanations and consistently worked on it over six months across the settings—in the PLC and in their classrooms. During this time, I observed a clear shift in the teachers' classroom teaching, especially in how they supported students' writing of evidence-based explanations. I found that the shift was closely connected to their collaborative work in the PLC: specifically, their noticing of students needing assistance in using evidence (data), their negotiation of what to expect in students' evidence-based explanations (goals and expectations), and their discussions of instructional practices for supporting students' use of evidence in writing explanations (practice). In this section, I first briefly describe the shift that I observed in the teachers' classroom teaching. Then, I explain key features of the teachers' collaboration in the PLC and classroom teaching before and after the shift. I call the phase before the shift, which was from September to December 2017, as "Phase 1" and the phase after the shift, which was from January to February 2018, as "Phase 2."

Overview of the Shift in the Teachers' Classroom Teaching

Notably, most of the teachers increased the amount and kinds of instructional supports for scaffolding students' construction of evidence-based explanations in their third instructional unit which they taught during Phase 2, compared to the first and the second units which they taught during Phase 1. I identified five kinds of instructional supports that the teachers used to promote students' evidence-based explanations. **Table 8** describes the five instructional supports.

Table 8. Five kinds of instructional supports that the teachers used in their teaching to support students' use of evidence in writing explanations

Instructional Support (Symbol)	Description
Ambitious Science Teaching Unit Framework (AST Framework; ◉)	An instructional framework designed to help students construct and revise scientific models and explanations of a puzzling phenomenon throughout an instructional unit based on evidence gathered from class activities
Explicit conversation about what evidence is (▲)	Teacher-led classroom conversation about what evidence is and the importance of using evidence in constructing scientific claims and explanations
Summary Table (▤)	A tool to help students summarize their learning from class activities and connect it to their explanations of puzzling phenomena
Rubric with criteria about the use of evidence in explanations (▨)	Rubric to help students reflect on the use of evidence in their or others' written explanations
Writing scaffolds (▦)	Sentence frames or text structures for scaffolding students' writing of evidence-based explanations

While the other instructional supports were used to explicitly encourage and promote students' use of evidence in writing explanations, the *Ambitious Science Teaching Unit Framework* (*AST Framework*; based on principles suggested by Windschitl et al. (2012)) set the stage for the other supports by inviting students to construct and revise scientific models and explanations of a puzzling phenomenon throughout an instructional unit. Sealth High School teachers adopted this framework from their several years of partnership with the Ambitious Science Teaching research group at the University of Washington. While the framework has various features for positioning students as knowledge builders, in this paper, I focus on its potential to help students use their learning from different class activities as evidence for constructing and revising explanations.

Table 9 shows sets of these supports that the five teachers used in their instructional units during the two phases. Phase 1 and Phase 2 had distinct classroom trends, with Phase 2 having most of the teachers trying out and experimenting various kinds of supports for scaffolding students' writing of evidence-based explanations. In Phase 1, while Lisa and Tom made some individual efforts in their classrooms, most of the teachers (Emma, Katie, and Anika) did not provide explicit supports for students' use of evidence when students worked on their models or explanations. All the five teachers grounded their teaching on the AST Framework which encouraged students to revise their explanations based on their learning from class activities. However, Emma, Katie, and Anika focused mostly on the depth of students' explanations and did not explicitly prompt students to cite or use evidence in their writing.

Table 9. Sets of instructional supports that the five teaches used for scaffolding students' writing of evidence-based explanations across three instructional units during Phase 1 and Phase 2 (◉: AST Framework, ▲: Explicit conversation about what evidence is, ▤: Summary Table, ▨: Rubric with criteria about the use of evidence, ▦: Writing scaffolds)

Teacher	Phase 1		Phase 2
	1st Instructional Unit Oct – Mid Nov 2017	2nd Instructional Unit Mid Nov – Mid Dec 2017	3rd Instructional Unit Jan – Mid Feb 2018
Emma	◉ ▦ (3 lessons observed)	◉ (1 lesson observed)	◉ ▲ ▤ ▦ ▨ (4 lessons observed)
Katie	◉ (2 lessons observed)	◉ (2 lessons observed)	◉ ▲ ▤ ▦ ▨ (3 lessons observed)
Anika	◉ (2 lessons observed)	◉ (1 lesson observed)	◉ ▲ ▤ ▦ (3 lessons observed)
Lisa	◉ ▲ ▤ ▦ (2 lessons observed)	◉ (1 lesson observed)	◉ ▲ ▤ ▦ (4 lessons observed)
Tom	◉ ▲ ▤ ▦ ▨ (2 lessons observed)	◉ ▲ ▤ ▦ ▨ (2 lessons observed)	▨ (2 lessons observed)

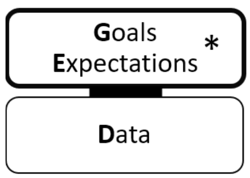
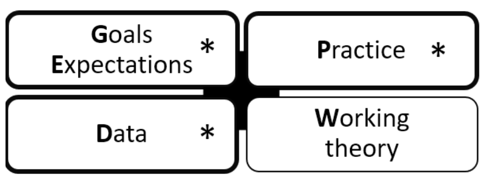
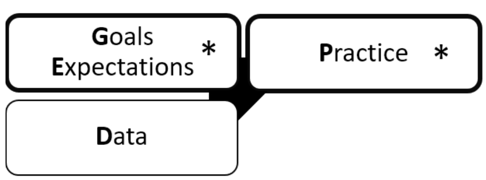
Meanwhile, in Phase 2, most of the teachers increased the amount and kinds of their instructional supports for promoting students' use of evidence in writing. Four among the five teachers (Emma, Katie, Anika, and Lisa) had explicit conversations with their students about what evidence is and why it is important to use evidence in scientific explanations. They tried out multiple ways to co-construct and use the tool of *Summary Table* (see **Table 8** for description) with their students to help students use what they learned from class activities as evidence in constructing explanations. Furthermore, the teachers provided students with writing scaffolds such as sentence frames and text structures to help their writing of evidence-based explanations. Emma and Katie used a rubric including criteria about the use of evidence in explanations, originally developed by all the five teachers in a PLC meeting for assessing students' explanations, to help students reflect on their explanations as well as give peer feedback to each other. On the other hand, one teacher, Tom, showed an exceptional shift in his teaching, as he moved from Phase 1 to Phase 2. He dropped many of the supports that he tried in his earlier instructional units. In what follows, I explain key features of the teachers' collaboration in the PLC meetings and classroom teaching during the two phases, focusing on both the general trends observed as well as variations in individual teachers' teaching.

Phase 1: Co-constructing and Negotiating Expectations About Students' Evidence-based Explanations and Brainstorming Instructional Supports

The shift in the teachers' classroom teaching described above occurred after the teachers had discussed and agreed on how to start what they called as "cycles of inquiry" in the fifth Data meeting. Before they got to that point, during Phase 1, they had spent significant amount of time co-constructing and negotiating their goals and expectations about supporting students' evidence-based explanations and brainstorming instructional supports for scaffolding students' use of evidence. The teachers' discussions were grounded on their noticing of students needing assistance in writing evidence-based explanations.

It was not until the Studio, in which the teachers had a chance to collectively plan and teach lessons, that the teachers started to discuss instructional ways for supporting students' writing of evidence-based explanation. Before the Studio, the teachers mostly focused on setting their goals and expectations for improving students' written explanations. The Studio provided opportunities for the teachers to identify problems of practice and specify their focus based on common classroom data, which led them to discuss concrete ways for supporting students' use of evidence in writing explanations. **Table 10** shows how the teachers' discussions in the PLC meetings looked different before, during, and after the Studio. In what follows, I first explain the teachers' collaboration before the Studio, in the first three Data meetings, where they started to discuss goals and expectations for improving students' written explanations. Then, I explain how the teachers specified their focus based on classroom data and discussed their expectations and instructional ways for supporting students' use of evidence in the Studio and in the following Data meetings. Finally, I describe the teachers' classroom teaching during Phase 1, which did not show notable changes during the whole phase.

Table 10. Characteristics of the teachers' discussions about supporting students' evidence-based explanations in the PLC meetings during Phase 1

PLC meetings (Months)	Discourse components (major components emphasized with *)	Main content
Data meetings 1, 2, & 3 (Sep-Oct 2017)		Setting goals and expectations for improving students' written explanations (goals and expectations) based on general noticing from students' work (data)
Studio (Nov 2017)		Identifying problems of practice and recognizing gaps in expectations based on common classroom data (practice, goals and expectations, data); actively discussing specific ways for supporting students' use of evidence (practice); drawing conclusions from a pedagogical experiment (working theory)
Data meetings 4 & 5 (Nov-Dec 2017)		Actively discussing and negotiating expectations (goals and expectations) and brainstorming instructional practices (practice) for supporting students' writing of evidence-based explanations based on noticing from the Studio (data)

Data meetings 1-3: Starting to discuss expectations about students' written explanations by setting the team goal and developing an assessment tool. The teachers spent most of the PLC meeting time discussing their expectations about students' written explanations (goals and expectations) before the Studio, in their first three after-school Data meetings. The teachers sometimes backed up their points with what they had generally noticed from students' work (data) but did not yet move on to discuss instructional ways for supporting students' construction of explanations (lacking discussions about practice). In the first Data meeting, the teachers collectively set their goal to support students' writing of scientific explanations (goals and expectations) based on their noticing of students struggling with scientific writing (data). Regarding the noticing, Emma said, "The greatest need that I have is my frustration with students' written work because it's seldom at their grade level [*Data meeting 1, September 21st, 2017*]." Anika said, "They [*students*] seem to struggle with writing quite a bit and I don't know how to support them with writing. Writing in science is a little different than writing in language arts and I feel like I need to support them better with how to write in science." The teachers tried to specify their goal in response to their administrators' request to submit a measurable team goal. At the end of the meeting, the teachers articulated their goal as "75% of students in science classes on the Sealth campus will be able to show one step of growth in their ability to construct a written explanation by April 2018."

While setting the team goal, the teachers agreed on the necessity to develop a team rubric reflecting their expectations about students' written explanations (goals and expectations) for assessing both students' work and the team's progress towards the goal. The teachers collectively developed the team rubric in the second Data meeting, focusing on two dimensions of scientific explanations: the depth of explanations and the use of evidence (goals and expectations). They decided on these two dimensions by reviewing the rubrics that they had used in former PD days to assess students' models and explanations in previous years. In this paper, I focus on the teachers' efforts towards promoting students' *use of evidence* in writing explanations because it is the dimension that the teachers mostly focused on in their PLC meetings. **Figure 5** shows part of the team rubric including the criteria for assessing students' use of evidence in written explanations. As shown in the figure, while the rubric had the potential to address some important aspects of evidence-based explanations, such as connections between evidence and claims/hypotheses and the use of counterevidence, it lacked clear expectations about what the teachers meant by "evidence." The teachers did not explicitly discuss the meaning of "evidence" while constructing the rubric, either.

Criteria	*BEGINNING*	*APPROACHING*	*MEETING*	*EXCEEDING*
Use of evidence	Identifies evidence with little connection to claim/hypothesis	Explains how and why **one** piece of evidence is related to a claim/hypothesis	Explains how and why **multiple** pieces of evidence is related to a claim/hypothesis	Identifies a counter-claim and explains how at least one piece of evidence can be used to refute it

Figure 5. Part of the team rubric that the teachers developed in the second Data meeting to assess students' use of evidence in written explanations

For testing the team rubric and solidifying expectations (goals and expectations), in the third Data meeting, the teachers brought their students' drawn and written explanations (data) and individually examined those using the team rubric. While examining the data (data), the teachers raised a few questions about the criteria on the team rubric (goals and expectations). Regarding the criteria about students' use of evidence, Katie asked a question about what they meant by "evidence," which led the teachers to have a brief conversation about it:

Katie: So, what do we consider as evidence? What are we counting as evidence (*goals and expectations*)?

Researcher Sue: That's a good question. That's why I put some question marks here [*showing the rubric that she was marking on while examining some of the teachers' classroom data*]. Because I was not sure what was provided to them, what they discussed before… so, I didn't know the context enough to say what's evidence and not for them (*goals and expectations*).

Katie: So, do we want them to reference the "egg lab" and the "onion lab" as evidence on the model? Or them to say that the… it's going from high concentration to low concentration of water? Does that count as evidence (*goals and expectations*)?

Anika: I would want them to reference it somehow. Like, um, "I know this because we saw in the lab that they got bigger," or "I know this because I saw it in the picture (*goals and expectations*)." Like, for mine, it was mostly like, "I saw it in the picture," or they just drew the picture on there (*data*). [*Data meeting 3, October 26th, 2017*]

This brief conversation was the only discussion that the teachers had about students' use of evidence on that day. In the conversation, the teachers briefly discussed their expectations about students' evidence-based explanations, such as whether they wanted to see the sources of evidence in students' explanations (goals and expectations), considering what they were seeing from students' work (data). However, they did not move on to discuss instructional supports based on the expectations (lacking discussions about practice), as they did not recognize specific problems of practice about students' use of evidence at that point.

The Studio: Actively discussing instructional ways for promoting students' use of evidence based on problems identified from common classroom data. The Studio set the stage for the teachers to actively discuss instructional ways for supporting students' use of evidence in writing explanations (practice) which had not been their focus in the previous after-school Data meetings. In the Studio, the teachers identified specific problems to address based on common classroom data: that 1) students were rarely using evidence in their writing (data) and 2) the teachers themselves did not have a consensus about what they meant by "evidence" (goals and expectations). The teachers' noticing of these problems led them to discuss their expectations about students' evidence-based explanations (goals and expectations) and brainstorm concrete ways for promoting students' use of evidence (practice).

Identifying problems from classroom data. The teachers had not paid particular attention to students' use of evidence until they identified some problems about it in their focal lesson of the Studio. In their first focal lesson of the day, the teachers asked students to write explanations about the relationships between the amount/type/speed of exercise and variables including breathing rate, pulse rate, and the amount of oxygen and carbon dioxide going in and out of bodies. The teachers provided students with a sheet of paper with several pieces of scientific information, including experimental data from the class' science labs, and encouraged students to use the information as evidence when constructing explanations. The teachers also used the team rubric that they had developed in the second Data meeting as an instructional tool in this lesson. They invited students to use the rubric to reflect on their explanations as well as give feedback to peers' explanations. After the first focal lesson, the teachers used the team rubric to collectively assess students' explanations (data). This was when the teachers identified two specific problems regarding students' use of evidence in explanations. First, the teachers noticed that most of the students' written explanations (9 out of 12 examined explanations) did not include any information from the given worksheet, which could potentially work as evidence, or any other kinds of evidence (data), even though the students had been explicitly asked to use evidence in their writing and reflect on it using the given rubric during the lesson. When examining the student work, the teachers wrote down what they noticed on a chart paper. A teacher wrote, "Students are much better at getting to a depth of explanation than they are at using/calling out the evidence that got them there [*Studio, November 9th, 2017*]." Another teacher commented, "Is it taught that way? Or is it from their past experience?" Second, the teachers realized that it was not clear for both the students as well as the teachers themselves what "evidence" meant (goals and expectations). For example, a teacher wrote, "How can it be really clear to students what "evidence" means?" Another teacher wrote, "It's confusing for us [*underlined by the teacher*] to think about what counts as evidence vs. depth of explanation!"

Brainstorming and testing instructional ways for supporting students' use of evidence while raising questions about expectations. The teachers' noticing of the problems led them to seek for instructional ways to promote students' use of evidence (practice) when they tried to revise the lesson plan for the second focal lesson. In the discussion, the teachers kept raising questions about what they meant by "evidence" and what they would expect in students' evidence-based explanations (goals and expectations). The conversation below shows part of the discussion:

Anika: We could prompt for a specific piece of evidence (*practice*)… but I think they [*students*] also need help with understanding what exactly is evidence (*goals and expectations, practice*).

Tom: Yeah, I'm trying to figure out how to make that clearer for students and us (*goals and expectations, practice*).

Lisa (the host teacher): I would ditto the piece about clearly defining what evidence is, what we want students to put (*goals and expectations*). I'm wondering if there's something that we need to do as a class to define what evidence is… not something that I want to spend a lot of time on, but to kind of have an agreement on that or some suggestions at least on what evidence is (*goals and expectations, practice*).

Katie: Could you possibly have, on your manipulated and responding variable list, could you have a table next to it saying "evidence for …" to connect the two (*practice*)?

Lisa: So, on that graphic organizer, have them list out evidence before they write their explanations (*practice*)? [*Studio, November 9th, 2017*]

Here, the teachers were raising questions about how to make the meaning of "evidence" clearer for both students and the teachers themselves (goals and expectations) and discussing specific ways for promoting students' use of evidence in the second focal lesson (practice). The following excerpt shows another example of how the teachers questioned what they meant by "evidence" and what they would expect in students' evidence-based explanations (goals and expectations):

Anika: So, one of the pieces of evidence is the picture of the circulatory system, is that right? So, if I… like, what's like a student response we want? Like, using that picture as evidence… what would that sound like (*goals and expectations*)?

Lisa: So, I think, usually, when people use that image with some relation to, um, heart rate or maybe O_2 or CO_2… I would want students to say something like, "Our heart will beat faster because we need extra oxygen and energy in our cells when we're doing exercise. When our heart beats faster, it's pumping more blood to our cells and delivering more oxygen and energy (*goals and expectations*)."

Anika: But even… I'm sorry about pulling us back, but even what you were saying, the summative explanation of what's happening… it didn't sound like evidence. But maybe I just don't understand evidence (*goals and expectations*). But I also know we can't spend much time on this, because I know we need to tweak the lesson. So, I'm… I don't know. [*Studio, November 9th, 2017*]

Like in this conversation, while raising and discussing questions, some of the teachers, including Anika, recognized that they were not on the same page about what they would expect in students' evidence-based explanations (goals and expectations). However, because of the time limit for preparing the second lesson, the teachers moved on to discuss specific instructional ways for promoting students' use of evidence in the focal lesson (practice). They did not spend much time reconciling their expectations on this day, but their recognition of the misalignments played a key role and elicited deeper discussions in the following Data meetings.

From the discussion, the teachers came up with five small instructional changes that they would apply to the second focal lesson to support students' use of evidence in constructing explanations (practice). The changes included labeling the pieces of scientific information on the worksheet as "evidence" and asking students to circle specific pieces of evidence that could support their explanations and use those in their writing. The teachers implemented these changes in the second lesson and compared classroom data—students' written explanations—gathered from the two focal lessons. From the pedagogical experiment, the teachers concluded that specific prompts for using evidence seemed to increase the number of students who used some pieces of given information as evidence in their written explanations, based on the data that

7 out of 13 students used evidence in the second focal lesson while 3 out of 12 students did so in the first lesson (practice, data, and working theory).

Data meetings after the Studio: Making a consensus about expectations about students' evidence-based explanations and actively discussing instructional practices. While the Studio set the stage for the teachers to specify their focus and start to discuss their expectations and instructional supports for promoting students' use of evidence, there were several limitations in the teachers' discussions on that day. The teachers had limited time—about an hour— for tweaking the lesson plan in between the two focal lessons, and this made them primarily focus on finding concrete instructional ways that could work for the specific lesson. Even though some of the teachers noticed misalignments in their expectations about students' evidence-based explanations, they did not explicitly discuss those or try to reach a consensus due to the time limit. The teachers also did not have many chances to think about which parts of their instruction could be applied to other lessons beyond the focal lessons of the Studio.

The teachers' discussions in the following two Data meetings played a key role in bringing the shift in their classroom teaching. In the meetings, the teachers 1) negotiated and made a consensus about their expectations about students' evidence-based explanations (goals and expectations) and 2) brainstormed and discussed instructional practices for supporting students' writing of evidence-based explanations across instructional units (practice). Based on these discussions, the teachers decided on a focal instructional tool—Summary Table— to collectively conduct cycles of inquiry in their classrooms, and this boosted the shift in their classroom instruction which I would explain more in the "Phase 2" section of the findings. Here, I focus on how the teachers made a consensus about their expectations and discussed instructional practices for promoting students' use of evidence in the last two Data meetings of Phase 1.

Making a consensus about what to expect in students' evidence-based explanations. Building on the questions raised in the Studio, in the last Data meeting of Phase 1, the teachers negotiated and reached a consensus about their expectations about students' evidence-based explanations (goals and expectations). After the Studio, the teacher leader, Anika, and Researcher Sue briefly discussed where to go next and both agreed that the team would need some kind of consensus about what they would expect in students' evidence-based explanations. Based on this need, at the start of the fifth Data meeting, Researcher Sue raised questions about what the team meant by "evidence" and what the use of evidence would look like in students' written explanations. Starting from these questions, the teachers spent most of the meeting time, more than 40 minutes, discussing and making a consensus about their expectations.

The teachers' consensus included three major agreements on what to expect in students' evidence-based explanations. First, the teachers agreed that students would need to explicitly include the sources and content of evidence in their explanations. The following excerpt shows part of the teachers' discussion about this first point:

Tom: I have a question. Do they [*students*] have to say like, "I saw in the video that this happens," or just by saying it… the fact that we know that they got their information from this place, is that evidence? Or do we want them to explicitly say like, "This is the evidence for what I am saying and here's where I found it." Because I think when we tried to classify evidence last time [*in the Studio*], I would have said something like that was evidence, but I don't think that everyone was saying that (*goals and expectations*).

Lisa: I think referencing their evidence is an important skill for them to develop for many different courses they would take. In their writing of conclusion, they need to explain how they got their data. I mean, it depends on the context, too, but I think that there should be times within a unit that they reference the sources they get evidence from (*goals and expectations*).

Katie: Um, referencing where they got the evidence… Like, on a test, they would have to say, "I know the egg shrinks because of the osmosis," and to get the credit, they would have to say that they saw it in the egg lab or in the cell lab or whatever… they can't just say the thing shrinks (*goals and expectations*)? Ok.

Lisa: Um, so, I was looking at an essay that one of my students was writing today and it was talking about the process of digestion. And she was making statements like, "In our time cards, you know, from Time 0 to Time 1, I saw that these things happened." So, I feel like a statement like that would kind of get at referencing where your ideas come from (*data, goals and expectations*). [*Data meeting 5, December 7th, 2017*]

Like in the conversation above, the teachers made it explicit that they would want students to include not only the content but also the sources of evidence in their explanations. Second, the teachers agreed to ask students to articulate clear connections between their evidence and specific parts of their unit-level models or explanations supported by the evidence. This second point was aligned with the AST Framework (see **Table 8** for description), which all the five teachers had been using in their instruction, that asked students to develop models and explanations of a puzzling phenomenon throughout an instructional unit. Finally, the teachers agreed on the kinds of evidence that they would like to see in students' explanations. The teachers said that students could use their personal experiences and initial observations as evidence for their initial explanations of a phenomenon at the beginning of a unit, add specific observations or data from class activities as evidence to support a few parts of their explanations in the middle of the unit, and use claims and conclusions from activities across the unit as evidence for their revised explanations at the end of the unit. This final point about the kinds of evidence was also closely connected to the principles and structures of the AST Framework.

Discussing instructional practices for supporting students' writing of evidence-based explanations and setting a focal practice for conducting cycles of inquiry. While the teachers focused on making specific instructional changes in the context of their focal lessons in the Studio, in the following two Data meetings, they discussed more general instructional practices that could be implemented across instructional units to promote students' use of evidence (practice). The discussions were prompted by the teachers' noticing of students needing assistance in using evidence (data from the Studio) and their administrators' request to conduct "cycles of inquiry" in the Data meetings. The discussion below shows how the teacher leader, Anika, introduced the administrators' request about the cycles of inquiry and how the teachers suggested to focus on promoting students' use of evidence as a specific area to work on:

Anika: So, we have our year-long goal. And then for each cycle [*of inquiry*], all of us try doing the same strategy for that period of time, and we compare results across different classrooms for the same strategy. And within that cycle, we also gather evidence from text and research. So, we all practice the same strategy at the same time, and then once we've finished that cycle, then we start to ask, "What's a different strategy that we want to try out?" And then trying out that one as a department at the same time and doing multiple cycles throughout the school year… like that. So, that's where our administration is coming from. Ok, so, do we have anything that we want to try for our first cycle?

Tom: Um, I don't know what, but something around evidence. In Lisa's class [*in the Studio*], the [*students'*] depth of explanation was pretty strong for initial and final [*explanations*], but evidence was still kind of lacking (*data*). So, I need better ways to scaffold that, I think.

Anika: I am also curious about the Summary Table thing. Like, the use of a Summary Table as sources of evidence (*practice*)? [*Data meeting 4, November 9th, 2017*]

Based on Anika's explanation of the concept of cycles of inquiry, the teachers started to suggest and discuss concrete instructional practices to try out as a team with their specified goal of promoting students' use of evidence in writing explanations (goals and expectations, practice). Examples of the practices that the teachers suggested were as follows: using the tool of Summary Table (which the teachers had gotten from their multiple years of partnership with the Ambitious Science Teaching research group at the University of Washington; see **Table 8** for description of the tool) to help students apply their learning from class activities to their explanations, helping students use the team rubric (developed by the teachers in the second Data meeting) to assess the use of evidence in explanations, engaging students in providing and receiving peer feedback about their use of evidence in writing, using sentence frames to scaffold students' writing of evidence-based explanations, helping students create and use "evidence checklists" to reflect on their use of evidence, and providing students with exemplars of evidence-based explanations to help them set their expectations about the meaning of "evidence" and how to use it in writing.

In the fifth Data meeting, after reaching the consensus about what to expect in students' evidence-based explanations, the teachers voted on the focal instructional practice that they would like to conduct cycles of inquiry on as a team in their classrooms (practice). The one that got the most votes was the practice of using the Summary Table to help students apply their learning from class activities as evidence to their unit-level explanations. All the teachers, except Katie who joined the team at the start of the school year, had known about the tool of Summary Table from their collaboration with the Ambitious Science Teaching research group in the previous years. Tom and Lisa were using the tool in their classroom teaching as well. To be on the same page about the tool, the teachers read a two-page guide about the tool which Anika had received from the Ambitious Science Teaching research group a few years ago. After reading, all the teachers agreed to try out the tool in their classroom teaching and went on to discuss what their Summary Table would look like. In what follows, I explain how the teachers' classroom teaching looked before this fifth Data meeting during Phase 1. Then, I move on to describe their classroom teaching and collaboration in the PLC after this Data meeting, during Phase 2 where they conducted cycles of inquiry to promote students' use of evidence in writing explanations.

Classroom teaching during Phase 1: Only a few teachers individually trying out some strategies for supporting students' use of evidence. As shown in **Table 9** and described in the first section of the findings, during Phase 1, most of the teachers (Emma, Katie, and Anika) did not pay particular attention to or provide explicit supports for promoting students' use of evidence in their classroom teaching. This trend was analyzed from both the classroom observations made during this period and the interviews conducted with the teachers at the end of the school year to get the teachers' perspectives about their teaching and collaboration throughout the year. During Phase 1, even though the teachers set the team goal to support students' writing of explanations early in the year and recognized the need to promote students' use of evidence in the Studio, the goals by themselves did not seem to be enough for bringing significant shifts in the three teachers' teaching practices. The teachers also had an opportunity to brainstorm and test specific instructional scaffolds for promoting students' use of evidence in the focal lessons of the Studio, but those scaffolds were not observed outside the context of the focal lessons in the teachers' classrooms.

While the three teachers did not explicitly focus on promoting students' use of evidence in their teaching, the other two teachers, Tom and Lisa, made some individual efforts in their classrooms to support students' use of evidence during Phase 1. Both teachers' efforts were prompted by the team goal to support students' writing of evidence-based explanations set early in the school year. However, the two teachers showed notably different approaches to supporting students' use of evidence in their teaching. The biggest difference was that while Lisa focused on students' use of evidence within a class activity, Tom focused on supporting students' construction of evidence-based explanations throughout an instructional unit. Lisa engaged students in writing conclusions for a science lab using data from the lab as evidence. She provided students with a writing template including spaces for writing claims, evidence, and reasoning constituting the conclusions (▦ in **Table 8** and **Table 9**) and introduced "evidence" as data supporting specific claims in the conclusions (▲). Lisa used the Summary Table (▤) in her teaching, but she mostly used the tool for reviewing class activities rather than for scaffolding students' use of evidence. On the other hand, Tom asked students to use multiple kinds of evidence, including conclusions from various class activities, to support their unit-level explanations of a puzzling phenomenon throughout an instructional unit. He used various instructional supports at multiple points in a unit. He used the Summary Table (▤) as a major tool to help students use their learning from class activities as evidence in their explanations. He used the team rubric developed in the second Data meeting as an instructional tool and asked students to self-assess their own explanations using the rubric (▨). He emphasized the importance of supporting claims in an explanation with evidence (▲) and provided some sentence frames that students could use to write evidence-based claims in their explanations (▦).

Because Tom was the only teacher who taught chemistry while all the other teachers taught the same instructional units in biology, Tom's instructional supports had less chance to travel across the boundaries of classrooms. The other four teachers often co-planned their units and shared ideas and materials for lessons. This way, Emma got the writing scaffolds that Lisa had used for supporting students' writing of conclusions for a science lab and used the scaffolds in her teaching (▦). However, Tom's instructional supports for scaffolding students' use of evidence were not observed in other teachers' classrooms during Phase 1. Now, I move on to Phase 2 where the teachers actively conducted inquiries on common instructional practices and tools both in their classrooms and in the PLC.

Phase 2: Conducting Inquiries on Common Instructional Practices and Tools for Supporting Students' Use of Evidence Across Settings

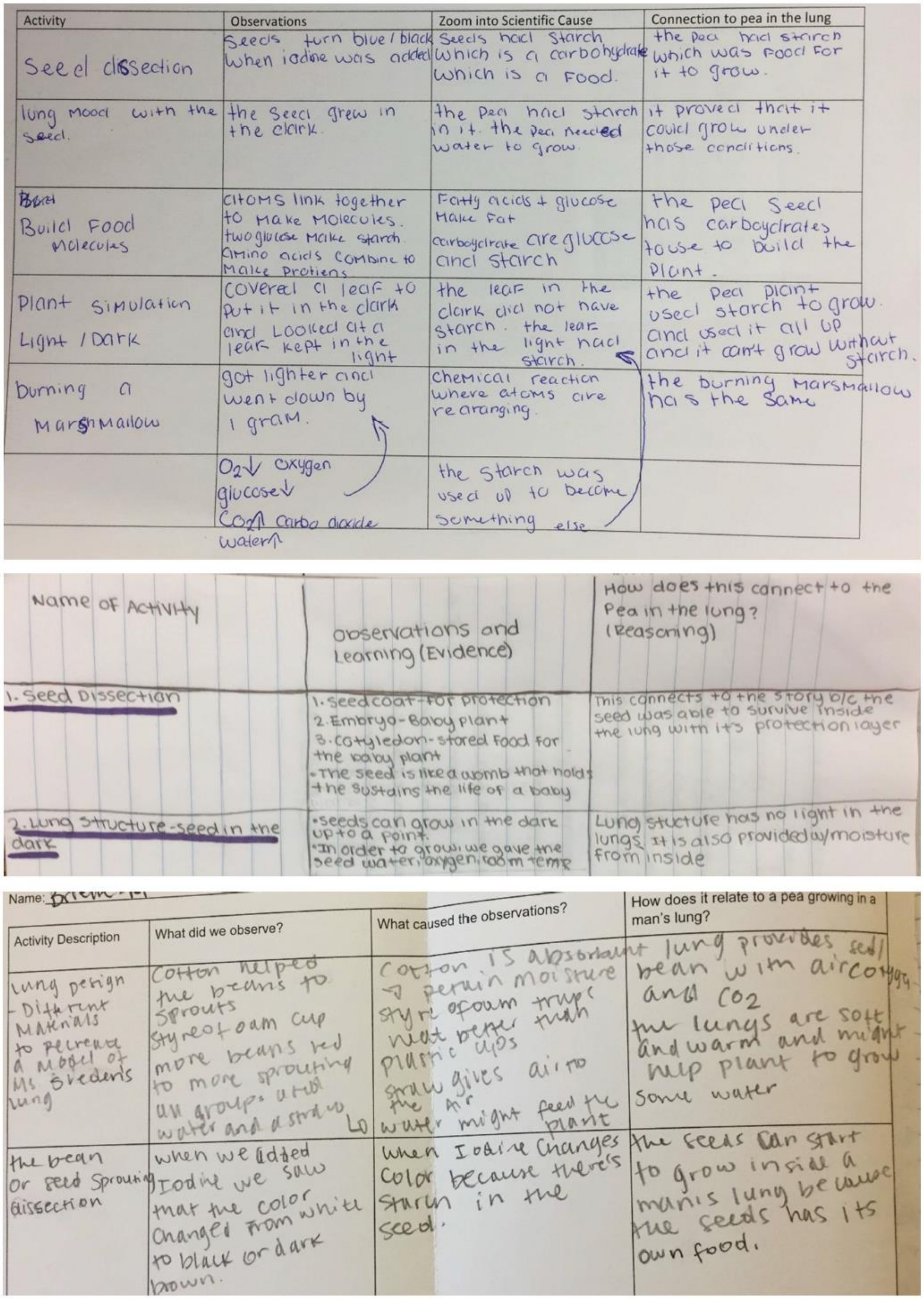
The shift toward including multiple instructional practices in the teachers' classroom teaching, which became the criterion for distinguishing between and characterizing Phase 1 and Phase 2, occurred after the fifth Data meeting where the teachers made a consensus about their expectations about students' evidence-based explanations and discussed how to conduct cycles of inquiry for promoting students' use of evidence. In Phase 2, all the teachers, except Tom, used sets of instructional supports, including the Summary Table (▤), for supporting students' writing of evidence-based explanations in their classroom teaching. In the PLC meetings, the teachers conducted inquiries on their common instructional practices and tools by sharing their insights and learning from classroom teaching, collectively analyzing student work, continuing to negotiate their expectations about students' explanations, and identifying new problems of practice to address (practice, data, working theory, and goals and expectations). In what follows, I first describe how the teachers provided sets of instructional supports for scaffolding students' use of evidence in their classrooms during Phase 2. Then, I explain how the teachers' collaboration in the PLC meetings looked during the same period.

Classroom teaching during Phase 2: Most of the teachers testing various instructional supports for scaffolding students' use of evidence. As shown in **Table 9**, while only two teachers made explicit efforts to promote students' use of evidence in their classrooms in Phase 1, in Phase 2, all the teachers, except one teacher, Tom, used various supports in their teaching to scaffold students' writing of evidence-based explanations. Below, I first explain what was commonly observed across the four teachers' classrooms (all the teachers' classrooms except Tom's). Then, I explain variations observed in the teachers' teaching, including the exceptional shift observed in Tom's case.

Common instructional supports observed across the classrooms. The four teachers' (Emma, Katie, Anika, and Lisa) approaches to supporting students' use of evidence in Phase 2 were aligned with one another. All the four teachers used the AST Framework (◉ in **Table 8** and **Table 9**) that set the stage for other kinds of instructional supports in their teaching. With the AST Framework, the teachers provided the following three instructional supports in common for scaffolding students' writing of evidence-based explanations: explicit conversations about evidence (▲), the Summary Table (▤), and sentence frames (▦).

Regarding the first support, the four teachers explicitly communicated with students about the meaning of and the importance of using "evidence" (▲), based on the consensus that they had made in the fifth Data meeting about what to expect in students' evidence-based explanations. All the four teachers emphasized the importance of using evidence to support claims in explanations. They asked students to articulate the sources and content of evidence and make clear connections between specific claims and evidence in writing. For example, here is how Emma shared her expectations about evidence with her students in a class: “In your explanations, I will also be looking for evidence that supports your thinking. In our science class, our evidence would be what we’ve learned from the activities that we’ve done. So, for example, you said something like that a pea can grow inside the man’s lungs [*the puzzling phenomenon of the unit*] because the seed has glucose, right? Ok, so, that’s your claim. How do you know that? How do you know that the seed has glucose? I want you to tell me how you know by citing activities you did in class. “I know this because I saw this thing happening in this experiment that we did,” “I know this because we read about this thing.” That’s what scientists do, right? They say something like the moon is round or the earth is round. How do they know? They have to cite evidence [*Emma’s 4th period class, January 8th, 2018*].”

The second common support that the four teachers used in class was the Summary Table (▤) which they had decided as their focal instructional tool for conducting cycles of inquiry in the fifth Data meeting. The teachers introduced the Summary Table to students with an explicit emphasis on evidence. They asked students to use the tool to review their learning from class activities and use the learning as evidence for supporting claims in their explanations. The teachers had students include the following components, which had been discussed and agreed upon among the teachers in the fifth Data meeting, in their Summary Tables: names/descriptions of class activities, observations made from the activities, learning from the activities including the causes of what had been observed, and how the observations and learning could be connected to their explanations of the puzzling phenomenon of the unit. **Figure 6** shows examples of Summary Tables filled out by students in three different classes: Katie’s, Emma’s, and Lisa’s.



(a)

Activity	Observations	Zoom into Scientific Cause	Connection to pea in the lung
Seed dissection	Seeds turn blue / black when iodine was added	Seeds had starch which is a carbohydrate which is a food.	the pea had starch which was food for it to grow.
lung mood with the seed.	the seed grew in the dark.	the pea had starch in it. the pea needed water to grow.	it proved that it could grow under those conditions.
Build Food Molecules	atoms link together to make molecules. two glucose make starch. Amino acids combine to make protiens	Fatty acids + glucose make fat carboydrate are glucose and starch	the pea seed has carboydrates to use to build the plant.
Plant simulation Light / Dark	covered a leaf to put it in the dark and looked at a leaf kept in the light	the leaf in the dark did not have starch. the leaf in the light had starch.	the pea plant used starch to grow. and used it all up and it can't grow without starch.
burning a marshmallow	got lighter and went down by 1 gram.	chemical reaction where atoms are rearanging.	the burning marshmallow has the same
	O_2↓ oxygen glucose↓ CO_2↑ carbo dioxide water↑	the starch was used up to become something else	

(b)

Name of Activity	observations and Learning (Evidence)	How does this connect to the Pea in the lung? (Reasoning)
1. Seed Dissection	1. seed coat - for protection 2. Embryo - Baby plant 3. cotyledon - stored food for the baby plant - The seed is like a womb that holds the sustains the life of a baby	This connects to the story b/c the seed was able to survive inside the lung with it's protection layer
2. Lung structure - seed in the dark	• seeds can grow in the dark up to a point • In order to grow, we gave the seed water, oxygen, room temp	Lung stucture has no light in the lungs. It is also provided w/moisture from inside

(c)

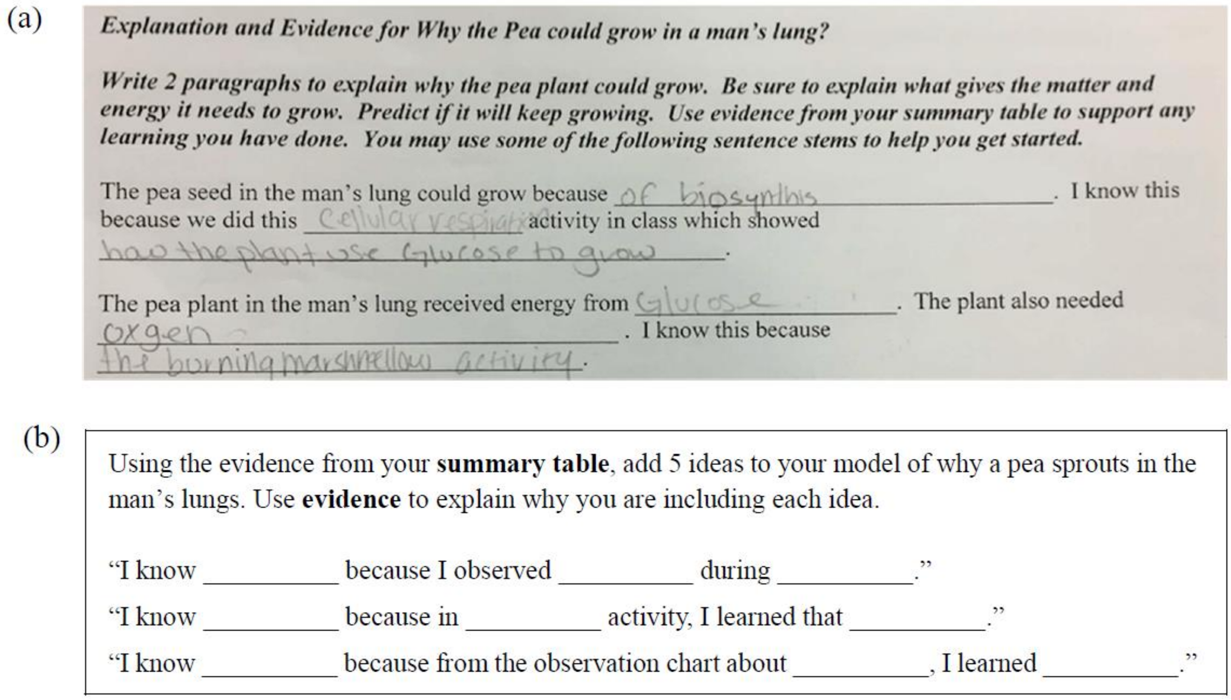
Name: [illegible]

Activity Description	What did we observe?	What caused the observations?	How does it relate to a pea growing in a man's lung?
lung design - Different Materials to recreate a model of Ms Sveden's lung	Cotton helped the beans to sprouts styreofoam cup more beans red to more sprouting all groups used water and a straw	Cotton is absorbant → retain moisture styrofoam traps heat better than plastic cups straw gives air to the air water might feed the plant	lung provides seed/bean with air oxygen and CO_2 the lungs are soft and warm and might help plant to grow some water
the bean or seed sprouting dissection	when we added Iodine we saw that the color changed from white to black or dark brown.	when Iodine changes color because there's starch in the seed.	the seeds can start to grow inside a man's lung because the seeds has its own food.

Figure 6. Students' Summary Tables from the classes of (a) Katie (Jan 18th, 2018), (b) Emma (Jan 15th, 2018), and (c) Lisa (Jan 15th, 2018)

The purposes and components of the Summary Table tool were introduced similarly to students in the teachers' classes, however, the ways that the teachers co-constructed Summary Tables with their students varied across the classrooms. As the teachers agreed to conduct cycles of inquiry on the tool, they intentionally tried various ways to help students work on and use the tool for learning. For example, Lisa notably diversified the ways she used the tool with her students in Phase 2, compared to how she did so in Phase 1. In Phase 1, Lisa led whole-class discussions to talk about what had been learned from class activities and then summarized the learning on her Summary Table while students copied down what she wrote on their own tables. In contrast, in Phase 2, Lisa invited students to have discussions in partners or in small groups and fill out the Summary Tables in their own ways. For another example, Emma had her students work in small groups and had each group make a poster about one row of the Summary Table. Each group's poster included observations and learning from one class activity as well as how the observations and learning could be connected to the puzzling phenomenon of the unit. The students shared their posters and had discussions about those to think across multiple activities. The teachers could test multiple ways of having students work on their Summary Tables because they revisited the same tool after every one or two class activities. The teachers then helped students use their Summary Tables for revising their models and explanations.

The third kind of instructional support that the teachers used in common was sentence frames (▦) for scaffolding students' writing of evidence-based statements. The teachers brainstormed a version of a sentence frame in the fifth Data meeting based on their consensus about what to expect in students' evidence-based explanations. The sentence frame was as follows: "I know this because in ___ activity, we had data around ___ which shows ___ and can support ___ part of my explanation." The teachers used revised versions of this sentence frame in their classes to support students' use of evidence in writing explanations. **Figure 7** shows some examples of the sentence frames used in Katie's and Lisa's classes.


(a)

Explanation and Evidence for Why the Pea could grow in a man's lung?

Write 2 paragraphs to explain why the pea plant could grow. Be sure to explain what gives the matter and energy it needs to grow. Predict if it will keep growing. Use evidence from your summary table to support any learning you have done. You may use some of the following sentence stems to help you get started.

The pea seed in the man's lung could grow because of biosynthis. I know this because we did this Cellular respiration activity in class which showed how the plant use Glucose to grow.

The pea plant in the man's lung received energy from Glucose. The plant also needed oxgen. I know this because the burning marshmellow activity.

(b)

Using the evidence from your **summary table**, add 5 ideas to your model of why a pea sprouts in the man's lungs. Use **evidence** to explain why you are including each idea.

"I know __________ because I observed __________ during __________."

"I know __________ because in __________ activity, I learned that __________."

"I know __________ because from the observation chart about __________, I learned __________."

Figure 7. Sentence frames for scaffolding students' writing of evidence-based explanations provided and used in the classes of (a) Katie (Jan 31st, 2018) and (b) Lisa (Jan 24th, 2018; Lisa's sentence frames were projected on the screen during the class)

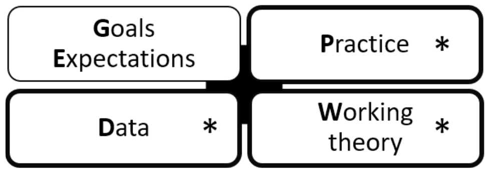
Variations across the classrooms. Not only common features but also some variations were observed in the teachers' classroom teaching during Phase 2. One variation was that Emma and Katie included the writing of evidence-based explanations as part of both summative and formative assessments in their classes, while the other teachers mostly treated it as a formative assessment only. For summative assessments, teachers needed to explicitly communicate their expectations for students' work and grading. To share their expectations as well as to guide students' writing, both Emma and Katie used the team rubric, developed in their second Data meeting for assessing students' written explanations, in their teaching. The teachers provided students with modified versions of the team rubric including criteria about the use of evidence and depth of explanations (▨) and asked students to use the rubrics to reflect on and revise their explanations. The rubrics helped students see what makes good scientific explanations and self-assess and revise their explanations. Emma also had students assess peers' explanations and exchange feedback about ways to improve the explanations using the rubrics. Meanwhile, the other three teachers—Lisa, Anika, and Tom— did not use rubrics including expectations about students' use of evidence in their teaching during the same period.

Another variation observed in the teachers' teaching was the exceptional shift observed in Tom's classes. In Phase 2, Tom dropped most of the instructional supports that he had tried in Phase 1 for supporting students' writing of evidence-based explanations. This was in contrast with the other four teachers' cases where they notably increased the amount and kinds of instructional supports for promoting students' use of evidence. Tom said in the interview that it had been hard for him to try out practices for supporting students' use of evidence in the second semester, which lasted from January until the end of the school year, because "there was not much space for authentic use of evidence in the unit [*Interview with Tom, May 31st, 2018*]." Tom had been asked to try out a pilot curriculum for a chemistry unit, which was about trends in the periodic table of the elements, that would be adopted by the school district in the following year. He implemented the curriculum during his second semester, but he "struggled a lot with that unit [*Interview with Tom, May 31st, 2018*]," as he said in the interview. According to Tom's description, the unit was not aligned with the AST Framework (◉ in **Table 8** and **Table 9**) because the activities in the unit were rigidly prescribed and did not build on each other. Tom said that he could not come up with an anchoring puzzling phenomenon for the unit or support students' revision of explanations over time because he could not change the order or content of the activities to help students pursue their own questions or explore ideas for a sustained period of time. Because the Sealth teachers' discussions of what evidence is and how to support students' use of evidence were closely connected to the structures and principles of the AST Framework, especially around supporting students' construction and revision of models and explanations of a puzzling phenomenon throughout a unit, Tom found it hard to apply what the team had been discussing in the meetings to his classroom teaching during Phase 2. Furthermore, because he was the only teacher teaching chemistry in the team, it was hard for him to discuss concrete ways to improve his unit with the other teachers. As he recognized the unit as an exceptional one, he did not bring up his issues around the unit in the PLC meetings, either.

In sum, in Phase 2, the teachers notably increased the amount and kinds of instructional supports for scaffolding students' use of evidence in their classroom teaching, except for Tom who dropped the supports with the AST Framework. Now, I move on to describe key characteristics of the teachers' collaboration in the PLC meeting during the same period.

Data meetings during Phase 2: Sharing insights and co-analyzing student work to improve practice while identifying new problems of practice. In the PLC meetings during Phase 2, the teachers' collaboration showed different characteristics than Phase 1. While the teachers mostly focused on negotiating their expectations and brainstorming instructional practices in Phase 1, in Phase 2, they tested the instructional supports, co-analyzed student work, discussed their learning and identified new problems of practice while continuing to negotiate some expectations about students' use of evidence (practice, data, theory, and goals and expectations). **Table 11** shows the characteristics of the teachers' discussions during Phase 2.

Table 11. Characteristics of the teachers’ discussions about supporting students’ evidence-based explanations in the PLC meetings during Phase 2

PLC meetings (Months)	Discourse components (major components emphasized with *)	Main content
Data meetings 6, 7, & 8 (Jan-Feb 2018)		Testing instructional supports and identifying new problems of practice (practice) by co-analyzing student work (data); accumulating insights and learning from pedagogical experiments (working theory); continuing to negotiate expectations (goals and expectations)

In the Data meetings during Phase 2, the teachers shared insights and learning from implementing and testing instructional practices and tools for supporting students’ use of evidence in their classrooms. For example, in Data meeting 6, the teacher leader, Anika, asked the teachers to share their answers to the following questions: “How did you facilitate the Summary Table activity? How did it go? What went well? What did not go well? What questions do you want to ask the group about facilitating the Summary Table activity? If you had to do the Summary Table activity again, what would you change? And what would you keep the same and why? [*Anika, Data meeting 6, January 11th, 2018*]” The teachers had some private think time to reflect on their own practices and then shared their reflection. They discussed diverse ways that they had tried to help students work on their Summary Tables. For example, Anika said that she had invited her students to work in small groups to draw and write down their learning from class activities on whiteboards and discuss how they could connect the learning to their explanations of the puzzling phenomenon. Lisa shared that she had tried four different ways, including some whole-class activities and small-group activities, to facilitate students’ work with Summary Tables. The teachers discussed pros and cons of having students work in small groups versus as a whole class for co-constructing Summary Tables. This discussion prompted some teachers to try out new ways to facilitate students' work with the Summary Table tool in their following lessons. In another discussion in Data meeting 7, the teachers shared and discussed some examples of sentence frames that they had used in their classes for supporting students' writing of evidence-based explanations.

The teachers also actively raised and discussed questions and problems of practice about supporting students' use of evidence that they had identified from their classroom teaching. For example, in Data meeting 6, when the teachers discussed how they had been using the Summary Table tool with their students, Emma asked a question about how to better support students in connecting their learning from class activities to their unit-level explanations of puzzling phenomena. Lisa said that she had asked her students to write down a specific claim about the focal puzzling phenomenon after each activity and then support the claim with specific data, observations, or learning from the activity. The teachers went on to discuss some sentence frames that could help students connect their learning to their unit-level explanations.

Furthermore, in the Data meetings during Phase 2, the teachers collectively analyzed student work—students' written explanations— from their classes using the common assessment tool—the team rubric that they had developed in the second Data meeting. The purpose of the analysis was to examine whether their instructional practices helped students use evidence and construct deeper explanations. When preparing for Data meetings 7 and 8, Anika asked one or two teachers to bring their student work to each Data meeting. Katie brought her students' written explanations to Data meeting 7 and Tom and Lisa brought their students' explanations to Data meeting 8. In the meetings, each teacher who brought their student work shared the contexts of their units and lessons and then all the teachers examined the student work together using the team rubric. This co-analysis of student work helped the teachers see trends in student work as well as learn from each other about ways to scaffold students' writing of explanations with concrete student examples. While analyzing student work, the teachers also identified new problems of practice to work on. For example, in Data meeting 8, the teachers recognized that while many students attempted to cite evidence by describing their learning from class activities using a sentence frame provided ("I know this because __, in __ activity, I learned about __."), only a few students made substantial connections between the evidence and their claims by explaining how the evidence supported the claims. Based on this problem of practice identified, the teachers went on to discuss some concrete practices to help students justify their claims with evidence by making stronger connections between those two. Examples of the discussed practices were revising sentence frames to emphasize the connections between evidence and claims and having students analyze some exemplar student explanations including strong justifications.

The teachers' discussions about what to expect in students' evidence-based explanations (goals and expectations) continued while they co-analyzed student data and discussed instructional practices in Phase 2. For example, in Data meeting 6, Katie said that it had been still confusing for her to distinguish the two criteria in their team rubric—depth of explanations and use of evidence— when she had tried to assess students' explanations with the rubric. While raising the issue, she shared some of her students' written explanations with the team. The other teachers examined the student work that Katie brought and shared what they saw as evidence in the students' explanations to address Katie's question as well as to see if they were on the same page. For another example, in Data meeting 8, Anika raised a question about what the team meant by "counterclaim" in the team rubric and how students' explanations would look if students refuted a counterclaim with evidence in their explanations. Tom said that the teachers could provide students with lists of misconceptions and ask them to refute one of those misconceptions using evidence from class activities. He said that the misconceptions could be examples of counterclaims that students could refute. The teachers liked this idea and went on to discuss if they could add another column to the Summary Table to help students refute counterclaims throughout an instructional unit.

To summarize, in Phase 2, the teachers implemented and tested sets of instructional supports for scaffolding students' writing of evidence-based explanations in their classrooms. In the Data meetings, the teachers conducted inquiries on their instructional practices and tools by sharing their insights and learning from classroom teaching, collectively analyzing student work, identifying new problems of practice to address, and continuing to negotiate their expectations about students' explanations (practice, data, working theory, and goals and expectations).

Discussion

The teachers' collaboration in the PLC meetings and their work in classrooms co-evolved and promoted their learning in both settings over the six months. In this section, I discuss what fostered the co-evolution of the teachers' collaboration and teaching and how the co-evolution supported the teachers' professional learning about facilitating students' construction of evidence-based explanations. I especially focus on 1) the co-evolution mechanisms observed in the findings, 2) PD structures that supported the co-evolution and teacher inquiry, and 3) teacher learning about supporting students' evidence-based explanations fostered by the co-evolution.

Mechanisms for the Co-evolution of Teachers' Collaboration and Teaching

From reviewing earlier studies in teacher education, I found three possible mechanisms for the co-evolution of teachers' collaborative learning in PLCs and classroom teaching, which I reviewed in the Theoretical Background section of this study. The three mechanisms were as follows: 1) teachers using representations of teaching to collectively reason about and improve teaching practices, 2) teachers setting goals and expectations for collective work by analyzing problems of practice and classroom data, and 3) teachers conducting experimentation on instructional practices using classroom data and constructing working theories for improving teaching (Bryk et al., 2015; Grossman et al., 1999; Horn & Kane, 2015; Kazemi & Franke, 2004; Kazemi & Hubbard, 2008). Because most of the previous studies have focused on one or two mechanisms among these three, the field lacks understanding of how these mechanisms work together and promote the co-evolution of teachers' collaboration and teaching.

In the focal case of this study, I found that all these three co-evolution mechanisms worked together in an interconnected and complementary way and contributed to Sealth teachers' improvements across settings, both in the PLC and in their classrooms. Diverse representations of teaching— including a collectively developed assessment tool, student work, and instructional tools— crossed boundaries of settings and helped the teachers identify a specific problem of practice to work on, which was that they needed to better support students' use of evidence in constructing explanations, and conduct collective inquiries on common instructional practices and tools. The representations of teaching were not given to the teachers by outside "experts." Rather, the teachers actively developed and used various representations of teaching in their collective inquiry to improve their teaching. Furthermore, while many studies suggested the goal setting as a prior step for teachers' collective inquiry and experimentation on instructional practices (e.g., Bryk et al., 2015), the teachers in this study kept negotiating their goals and expectations about supporting student learning while collectively inquiring on their practices and tools across settings. In other words, the processes of goal setting and collective inquiry on practices were dynamically intertwined in the teachers' collaboration and teaching.

PD Structures Supporting the Co-evolution and Teacher Inquiry

Different job-embedded PD structures for teachers' professional learning—Studio and Data meeting— had different affordances that worked in a complementary way for promoting the co-evolution of Sealth teachers' collaboration and teaching. Structurally, Data meetings were regular after-school meetings that invited teachers to discuss how to collectively improve based on data from their classes while the Studio was a whole-day PD that asked teachers to collectively plan, teach, and reflect on focal lessons. Before the Studio, the Data meetings set the stage for the teachers to set their year-long goal and start to discuss their expectations about students' learning. Then, the Studio provided opportunities for the teachers to identify concrete problems of practice and specify their focus based on common classroom data and start to brainstorm and test instructional ways for supporting students' learning. The Data meetings after the Studio provided unique opportunities that the Studio did not. While the teachers' efforts in the Studio were mostly focused on the focal lessons that they needed to co-plan and co-teach on that day, in the following Data meetings, the teachers spent a substantial amount of time negotiating their expectations about students' learning and discussing some broader instructional practices that could be implemented across instructional units. This led the teachers to collectively shift their classroom teaching by implementing and testing common instructional practices and working towards their collective goal. In the meetings, the teachers discussed ways to improve the practices while identifying new problems of practice to work on based on classroom data.

These findings provide some empirical evidence and implications that add to what previous studies have suggested about the importance of designing PD opportunities that closely reflect teachers' practices in classrooms (Borko, 2004; Kazemi & Hubbard, 2008; Lewis et al., 2006). Specifically, the findings from this study add that 1) there are multiple forms of effective PD structures that have unique affordances for promoting teachers' classroom teaching and 2) it is important to make sure that PD activities build on each other and provide cohesive and continuous opportunities for teachers to expand their learning and improve teaching over time.

The Co-evolution Promoting Teacher Learning about Supporting Students' Construction of Evidence-based Explanations

While earlier studies on supporting students' construction of explanations mostly focused on suggesting effective instructional tools and practices and examining how teachers took up those specific tools and practices in classrooms (e.g., McNeill & Krajcik, 2008), the findings of this study show how a group of teachers actively developed, used, and conducted inquiries on their own set of practices and tools for supporting students' construction of evidence-based explanations. The teachers did not simply choose to adopt or test an instructional practice. Instead, through their collaboration and work in classrooms, the teachers 1) collectively decided to focus on a specific aspect of students' explanations—students' use of evidence— based on problems of practice identified from their teaching, 2) discussed and negotiated their expectations about evidence and students' evidence-based explanations, and 3) developed and tested a suite of instructional practices and tools for scaffolding students' use of evidence in constructing explanations. With these efforts, the teachers made a notable instructional shift across classrooms by implementing and testing their own set of instructional supports including a range of practices and tools (e.g., the use of unit-level tools, writing scaffolds, and assessment tools as well as having conversations about the nature of evidence with students). Through developing and testing these instructional supports, the teachers constructed their own practice-based knowledge about how to support students' construction of evidence-based explanations over time. Sealth teachers' approaches to supporting students' construction of explanations were closely connected to the AST Framework (Windschitl et al., 2012; Windschitl et al., 2018) which they had gotten from their years of partnership with the Ambitious Science Teaching research group at the University of Washington. With the framework, the teachers sought ways to support students in constructing and justifying unit-level explanations of phenomena with various kinds of evidence from class activities. Meanwhile, because the teachers recognized that their supports were closely linked to the framework, a teacher found it hard to apply what the team had been discussing and developing to his teaching when he recognized his unit as "misaligned" with the Ambitious Science Teaching framework.

Conclusion and Implications

The team of high school science teachers in this study collectively improved their teaching practices to support students' construction of evidence-based explanations through their collaboration in the PLC. The teachers' collaboration and classroom teaching co-evolved over the course of six months, and the co-evolution was promoted by the three intertwined mechanisms discussed in the Theoretical Background and Discussion sections of this study. The teachers actively negotiated their goals and expectations about student learning, identified problems of practice, and developed and tested a suite of instructional practices and tools for supporting students' construction of evidence-based explanations, using various representations of teaching throughout their collaboration.

This study was conducted after four years of research-practice partnership between the school district that this team belonged to and the Ambitious Science Teaching research group at the University of Washington. From that point, this study provides some implications about both the power of long-term partnerships as well as efforts necessary for building structures and capacity for initiating and sustaining teacher-driven inquiry. Based on the culture of inquiry built from their long-term collaboration, the teachers in this study shaped and led their collective inquiry as active professional agents and made notable aligned shifts in their instruction. The infrastructures (e.g., PD structures of Studio and Data meeting), human resources (e.g., the teacher leader), resources for inquiry and instruction (e.g., the Summary Table tool, rubrics from previous PD meetings, documented history of the team's inquiry), and stances and habits of inquiry (e.g., collective work on common problems of practice, experimentation on instructional practices based on student data) that had been established from the long-term partnership facilitated the teachers' pedagogical inquiry for addressing their own problems of practice. This study not only implies that supporting teacher learning and inquiry requires time and efforts, but also suggests some concrete implications about the kinds of supports that could promote teacher learning effectively by providing a case of productive and sustainable teacher inquiry in a PLC that built on a long-term research-practice partnership.

This study provides some implications for both educational researchers and practitioners. The mechanisms for the co-evolution of teachers' collective inquiry and classroom teaching observed in this study can help educational researchers deepen their understanding of teacher learning across settings. Future research can consider exploring how these and other mechanisms can work across contexts and promote not only teacher learning but also student learning in classrooms. This study also suggests some effective PD structures for supporting teacher learning and inquiry that educational researchers and practitioners can use and explore. For science education researchers and practitioners, the findings of this study suggest that teachers might benefit from getting some support in deepening their understanding of scientific evidence and evidence-based explanations. Sealth teachers spent a significant amount of time negotiating their sense about what evidence is and what to expect in students' evidence-based explanations. Their consensus about these boosted their discussions and implementation of concrete instructional practices for supporting students' use of evidence. The teachers could construct their own practice-based knowledge by working on problems of practice and testing a set of instructional supports in their classrooms. These findings can provide some insights about how to support teachers' learning and inquiry on facilitating students' productive engagement in scientific practices.

Section 3. Using student work to drive collaborative inquiry in professional learning communities

Introduction

In professional learning communities (PLCs), student work can serve as signposts, guides, and data for teachers' collective inquiry (see Kazemi & Franke (2004) for more information about how student work can foster teachers' collective inquiry). However, bringing student work to PLC meetings does not guarantee productive collaboration in PLCs. So, how can a group of teachers effectively use student work to improve their inquiry and teaching? This paper summarizes three key practices that teachers can use in PLCs to learn from student work and promote collaborative inquiry and improvement. Here, "student work" includes not only the end products that students create but also how students engage in knowledge-building activities in classrooms. (See Darling-Hammond & McLaughlin (1995), Hargreaves & Fullan (2012), Horn (2010), and Little (2003) for more information about effective ways to foster collaborative inquiry in PLCs.)

In this paper, I explain the three key practices in detail with examples and suggest benchmarks for PLCs to evaluate if/how they are making improvements in their inquiry and teaching. The three practices are 1) setting team goals and expectations about high-quality student work, 2) identifying problems to work on by analyzing student work, and 3) trying out and testing new strategies in classrooms by examining student work. **Figure 8** shows relationships among these three practices and the central role student work plays. Research shows that teams do not engage in these practices in a specific order. Rather, they can start from any practice and go back and forth among practices to promote collaborative inquiry.

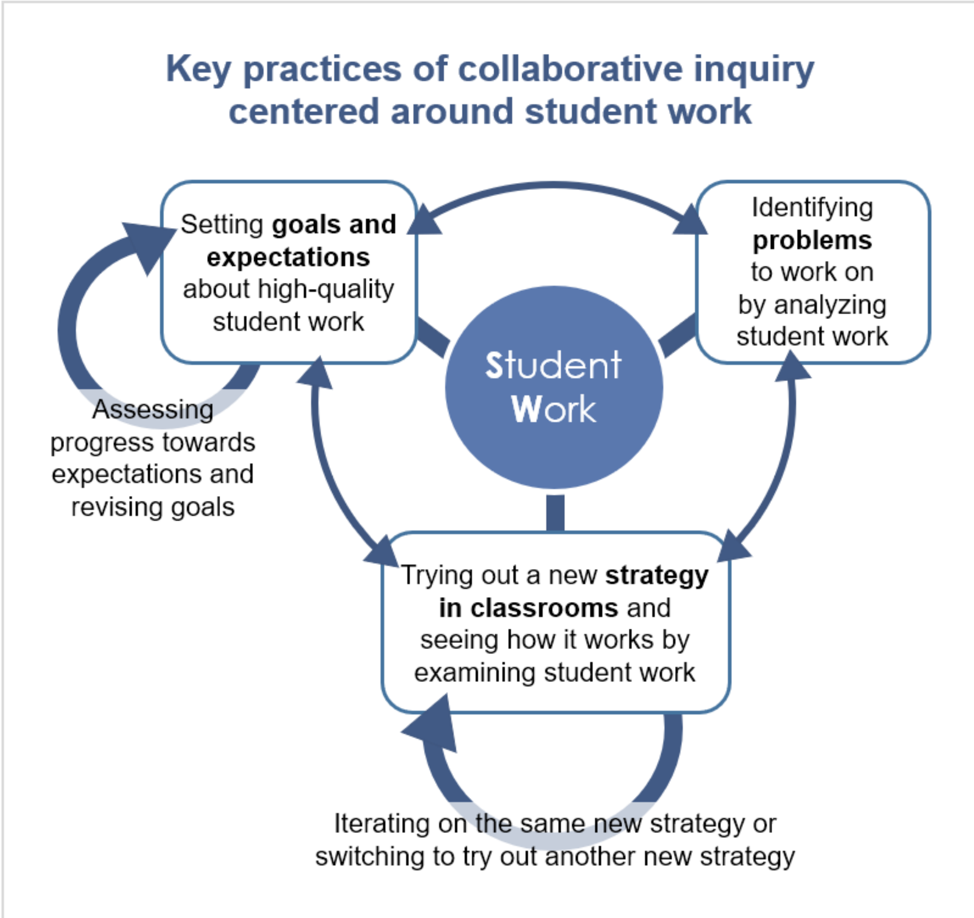


Figure 8. Key practices of collaborative inquiry centered around student work

In what follows, I explain these three key practices using examples from a highly collaborative PLC—Sealth PLC. Sealth PLC consisted of five high school science teachers that had collaborated for several years. In this study, I focus on how the teachers tried to improve their teaching to support students' writing of scientific explanations through engaging in these key practices over the course of a school year.

Setting Team Goals and Expectations about High-quality Student Work: "What Do We Want to See in Students' Work?"

To set the direction for collaborative inquiry and assess the progression, it is important for PLCs to set measurable team goals for improving teaching and constantly revisit and revise the goals over time (helpful questions to ask: "What is our goal for improving student work? How can we measure our progress?"; Bryk et al., 2015). While setting and revising their goals, teachers can discuss what they currently see from their students' work as well as their expectations about what high-quality student work would look like ("What do we want to see in students' work? What would students' productive participation in knowledge building look like?"). Learning goals in academic standards—e.g., *Common Core State Standards*, *Next Generation Science Standards*— and relevant articles can be useful for setting expectations about high-quality student work ("How would specific learning goals in academic standards look in students' work? What would student work that meets or exceeds standards look like?"). Teachers can develop common assessments or rubrics for assessing student work to specify their expectations and evaluate their progression over time. Now let's see how Sealth PLC members engaged in this key practice of setting goals and expectations.

How Sealth PLC Members Set and Revised Goals and Expectations about Supporting Students' Writing of Explanations

At the beginning of the school year, the five science teachers in Sealth PLC gathered and discussed what they wanted to work on as a team throughout the year based on what they were seeing from students' work in classrooms. Many of the teachers shared that their students were struggling with writing. To address this issue, the team decided to collaborate on supporting students' writing of scientific explanations. In response to their administrators' request to submit a measurable team goal, the teachers wrote their goal as "75% of students in science classes will be able to show one step of growth in their ability to construct a written explanation by the end of the school year." Soon, the teachers agreed on the necessity to develop a team rubric to assess both students' explanations as well as the team's progress towards the goal. While developing the rubric, the teachers actively discussed what they hoped to see in students' written scientific explanations. They collectively unpacked learning goals in the *Next Generation Science Standards* (NGSS Lead States, 2013) and read a book chapter about how to support students' construction of scientific explanations (McNeill et al., 2017). From their reading, the teachers identified two dimensions of explanations that their students could improve on: depth of explanation and use of evidence. The teachers then discussed how students' explanations would look in the "beginning," "approaching," "meeting," and "exceeding" levels for each dimension (examples of questions asked: "How would the depth of students' explanations look different in the "meeting" versus "exceeding" level? How do we want students to use evidence in writing? What would that look like in students' explanations?"). **Figure 9** shows the team rubric that the teachers constructed based on the discussion.

Criteria	*BEGINNING*	*APPROACHING*	*MEETING*	*EXCEEDING*
Depth of explanation	"What" Explanation ● Describes observations ● Gives definitions and facts ● Identifies different variables and components in the system	"How" Explanation ● Describes a single cause and effect relationship ● Identifies causes and effects (correlation) ● "If/When... then…" ● "If/When... then... because… (with observables)"	● "How does the cause *cause* the effect? How does the manipulated variable cause the responding variable to change?" (causation) ● "If/When ... then… because… (with scientific reasoning)" ● Includes unobservables or theoretical ideas	*Meeting +* ● Connects multiple unobservables to explain reasoning
Use of evidence	Identifies evidence with little connection to claim/hypothesis	Explains how and why **one** piece of evidence is related to a claim/hypothesis	Explains how and why **multiple** pieces of evidence is related to a claim/hypothesis	Identifies a counter-claim and explains how at least one piece of evidence can be used to refute it

Figure 9. The team rubric that Sealth PLC developed to assess students' written scientific explanations

The teachers used the team rubric throughout the year to assess both students' explanations and the team's progress over time. In doing so, the teachers constantly revisited and revised their goals and expectations about supporting student work. For example, while assessing students' explanations with the rubric, the teachers found that they had different opinions about what they would regard as "evidence" in students' explanations. This noticing pushed the teachers to have discussions to make a consensus about what they meant by evidence and what they would expect in students' evidence-based explanations. For another example, the teachers found that students needed more support in using evidence than in other parts of constructing explanations. This finding prompted the teachers to revise their goal to focus more on supporting students' use of evidence in writing explanations. It is important to note that this key practice of setting goals and expectations was not a one-off event for the team. Rather, the team constantly engaged in this key practice to negotiate and adjust their goals and expectations over time.

In sum, **Table 12** shows examples of questions and tools that teachers can use to engage in this key practice of setting goals and expectations about high-quality student work.

Table 12. Questions and tools for facilitating the key practice of setting goals and expectations

Key practice	Questions for driving inquiry	Tools and resources for inquiry
Setting team goals and expectations about high-quality student work	• What do we want to see in students' work? • What would students' productive participation in knowledge building look like? • What is our goal for improving student work? How can we measure our progress? • How would *(learning goals in academic standards)* look in students' work? What would student work that meets or exceeds standards look like?	• Academic standards (e.g., *Common Core State Standards*, *Next Generation Science Standards*) • Articles • Rubrics constructed by PLC members for assessing student work, reflecting expectations about high-quality work • Common assessments

Identifying Problems to Work on by Analyzing Student Work: "What Do We Need to Work on to Improve Student Work?"

Pathways for PLC inquiry cannot be prescribed because there cannot be one best way to improve teaching. Teaching should be responsive to students' and communities' needs. Then, how can PLCs drive their inquiry to build on their own students' needs? One effective way to do this is to identify problems to work on by analyzing student work (see Horn & Little (2010) for more information about how identifying problems of practice can foster teachers' collective inquiry). Teachers can identify problems and areas to focus on by analyzing what they see from their students' work and participation in class activities (helpful questions to ask: "What do we see in students' work? What do we see from students' participation in knowledge-building activities in class? What areas do students need the most support in? What do we need to work on to improve student work?”). Teachers can share what they find as challenging in their teaching and find common difficulties to address together (“What problems of practice do we have in teaching?”). Let’s move on to see how Sealth PLC members identified problems to address over time by using various tools.

How Sealth PLC Members Identified Problems to Work on by Examining Student Work

Throughout the school year, Sealth PLC members used multiple kinds of tools to analyze student work as well as students’ participation in class activities. From the analysis, the teachers could identify problems to address and drive their inquiry together. The main tool that the teachers regularly used in the PLC meetings was the team rubric which they had collectively developed early in the year for assessing students’ written explanations (**Figure 9**). With their team goal to improve students’ written explanations, the teachers regularly brought students’ written explanations from classrooms and examined the explanations together using the rubric. This regular activity helped the teachers monitor their progress and identify a series of problems to work on. At first, the teachers generally noticed that their students were struggling with writing (problem 1). By examining students’ written explanations with the team rubric, the teachers found that they needed to support students in using evidence especially because most students were rarely using evidence in their explanations (problem 2). The teachers came up with several strategies that they could try together in their classrooms to promote students’ use of evidence. After trying out some of the strategies, the teachers examined students’ explanations again. They found that the strategies helped students include more evidence in their explanations, but only a few students were making clear connections between evidence and claims in their explanations (problem 3). The teachers went on to discuss additional strategies to support students in making connections between claims and evidence. Here, the team rubric constantly helped the teachers ground their inquiry on the analysis of students' explanations.

Figure 10 shows examples of some other tools that Sealth teachers used to gather information about student work. **Figure 10(a)** shows an observation tool that the teachers developed and used in their classrooms to record how pairs of students engaged in discussions to share explanations. **Figure 10(b)** shows an exit ticket that the teachers developed to understand students' perceptions about their participation in class activities. The teachers used these tools to gather information about how students engaged in class activities and identify areas to focus on to better support students' participation in activities and learning.

(a) Observation tool

Observation Tool
When a pair of students share their explanations

- Do the students build on each other's ideas?
- Do the students make connections among ideas? How?
- General notes about what the students are talking about

(b) Student exit ticket

Exit Ticket **Period:____** **Name: ________________**

Put an X on the line that indicates how much you agree with the following statement:

In class today, we helped each other improve our science ideas.

1: Not at all 2 3 4: A lot

I felt I best learned science ideas today when we ________________________

because ________________________________.

Figure 10. Examples of tools that Sealth PLC members developed and used to collect information about students' engagement in class activities

To summarize, **Table 13** shows examples of questions and tools that teachers can use to engage in this key practice of identifying problems to work on by analyzing student work.

Table 13. Questions and tools for facilitating the key practice of identifying problems

Key practice	Questions for driving inquiry	Tools and resources for inquiry
Identifying problems to work on by analyzing student work	• What do we see in students' work? • What do we see from students' participation in knowledge building work in class? • What areas do students need the most support in? How can we provide this support? • What do we need to work on to improve student work? • What problems of practice do we have in teaching?	• Assessment tools for identifying trends in students' work (e.g., a rubric for assessing student work) • Observation sheets for recording observations from classrooms

Trying Out and Testing New Strategies in Classrooms by Examining Student Work: "What Works? For Whom? Under What Conditions?"

Teachers can improve teaching together by trying out and testing new strategies in classrooms and collectively reflecting on those using student work. In this process, three questions can help teachers move forward effectively: "What works? For whom? Under what conditions? (Bryk et al., 2015)" Based on initial goals and problems identified, teachers can first brainstorm strategies and tools that they can try together in their classrooms to address the problems and proceed toward their goals. They can try out one or a set of strategies/tools in their classrooms and see how those work by examining student work. Then, they can either make changes to the strategies and try those again or move on to try and test other strategies to improve teaching. Let's see how Sealth PLC members used and tested common tools and strategies in their inquiry.

How Sealth PLC Members Tested Common Tools and Strategies Using Student Work

From analyzing students' written explanations using the team rubric (**Figure 9**), Sealth teachers found that students were rarely using evidence in their explanations. To address this problem, the teachers actively brainstormed ways to promote students' use of evidence in their teaching. They read a book chapter about how to scaffold students' construction of evidence-based explanations (Windschitl et al., 2018) and found a useful tool, called *Summary Table*, designed to help students summarize their learning from class activities and use that as evidence in their writing. To find out what works well for their students, the teachers tried various ways to use this tool with their students in their classrooms.

Regarding how to help students review their learning with the Summary Table tool. The teachers tried a variety of ways to help students review their learning from class activities using the *Summary Table* tool. For example, one teacher asked students to work in small groups to fill out their *Summary Tables* together while another teacher had students use the tool individually to review their learning. In a PLC meeting, the teachers shared what strategies worked well and what did not go well with the tool. From the discussion, the teachers concluded that students with different learning styles seemed to benefit from different ways of working on the *Summary Table* ("The discussions were really rich in some small groups. Students seemed to be learning a lot from the discussions." "But some students just stop thinking when they are put into groups." "Some students prefer to write before talking.") and therefore it would be important to provide multiple ways for students to work on the tool. This discussion prompted some of the teachers to try new ways to engage students with the *Summary Table* tool in their following lessons.

Regarding how to support students' use of evidence in writing explanations. The teachers asked students to use what they had written in their *Summary Tables* as evidence in writing explanations. Over several PLC meetings, the teachers examined students' explanations to see if there were any changes in how students used evidence in their explanations. The teachers found that even though the *Summary Table* tool helped students include potential evidence—their learning from class activities— in their explanations, most students did not make clear connections between the potential evidence and claims in their explanations. The teachers brainstormed ways to address this issue and came up with two strategies to try together in their classrooms: using sentence frames to help students make connections between claims and evidence and helping students give peer feedback to one another about their use of evidence. Like what they did with the *Summary Table* tool, the teachers tried various ways to work on these strategies in their classrooms and reflected on how those strategies went by analyzing student work in PLC meetings. Through engaging in cycles of trying out and testing common tools and strategies, the teachers could build a set of their own conclusions about what works, for whom, and under what conditions.

To summarize, **Table 14** shows examples of questions and tools that teachers can use to engage in this key practice of testing new strategies by examining student work.

Table 14. Questions and tools for facilitating the key practice of testing new strategies

Key practice	Questions for driving inquiry	Tools and resources for inquiry
Trying out and testing new strategies in classrooms by examining student work	• What are strategies/tools that we can try together in classrooms? • What strategies/tools worked well? How and why? What did not work well? What do we want to change about the strategies/tools? What questions do we have? • For whom did the strategies work well? How did the strategies support the learning of specific groups of students (e.g., Emergent Bilingual students)? • Under what conditions did the strategies work well? • What can be our next step?	• Articles introducing effective classroom tools/strategies • Assessment tools for identifying trends in students' work (e.g., a rubric for assessing student work) • Observation sheets for recording observations from classrooms • Reflection tools

Summary

Teachers can use tips and tools suggested in this paper to engage in the three key practices of collaborative inquiry: 1) setting and revising team goals and expectations about high-quality student work, 2) identifying problems to work on by analyzing student work, and 3) trying out and testing new strategies in classrooms by examining student work. Like Sealth teachers did, teachers can go back and forth among practices to build and promote their own lines of inquiry.

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Publications

Papers (Peer-reviewed)

1. **Shim, S.-Y.**, & Kim, H.-B. (2018). Framing negotiation: Dynamics of epistemological and positional framing in small groups during scientific modeling. *Science Education, 102*(1), 128-

152.

2. **Shim, S.-Y.,** Thompson, J., Richards, J., & Vaa, K. (2018). Agree/Disagree T-charts: Supporting young students in scientific argumentation and modeling. *Science and Children, 56*(1), 39-47.

3. **Shim, S.-Y.**, & Kim, H.-B. (2014). Pre-service teachers' scaffolding of students' explanations in an inquiry-based biology classroom: Focusing on their learning approach styles and orientations to teaching science. *Biology Education, 42*(1), 95-114.

4. Kang, E., Kim, C.-J., Choe, S.-U., Noh, T., Yoo, J., **Shim, S.-Y.**, & Kim, H.-B. (2014). Exploring Korean 4th graders' career aspirations in science with a focus on science identity. *Journal of the Korean Association for Science Education, 34*(7), 613-624.

Presentations

1. **Shim, S.-Y.**, & Thompson, J. (2018, April). A 4-year story of improvement work in a high school science professional learning community with Studio model. Oral presentation at the annual meeting of the American Educational Research Association (AERA), New York City, NY, USA.

2. Richards, J., Thompson, J., Kazemi, E., Lomax, K., Fox, A., **Shim, S.-Y.**, Dobie, T., Anderson, E., Sherin, M., Sherin, B., & Teske, P. (2018, April). Designing practice-based learning labs for K-2 teachers: Initial lessons learned. Poster presentation at the annual meeting of the American Educational Research Association (AERA), New York City, NY, USA.

3. **Shim, S.-Y.**, Fowler, K., Thompson, J., Richards, J., & Zaccagnino, C. (2018, March). K-2 teachers' noticing and pedagogical reasoning about young students' engagement in model-

based inquiry. Oral presentation at the annual meeting of the National Association for Research in Science Teaching (NARST), Atlanta, GA, USA.

4. **Shim, S.-Y.**, & Thompson, J. (2018, March). Development in high school teachers' pedagogical frames about scientific modeling in a professional learning community. Poster presentation at the annual meeting of the National Association for Research in Science Teaching (NARST), Atlanta, GA, USA.

5. Fox, L. A., Lomax, K., & **Shim, S.-Y.** (2017, August). Mathematical and scientific modeling with young learners. Oral presentation at the annual meeting of the Starting Strong P-3rd Grade Institute, Spokane, WA, USA.

6. **Shim, S.-Y.**, & Thompson, J. (2017, April). Teachers' evolving pedagogical frames for scientific modeling: Three-year longitudinal study in a professional learning community. Oral presentation at the annual meeting of the American Educational Research Association (AERA), San Antonio, TX, USA.

7. Richards, J., Fox, L. A., **Shim, S.-Y.**, Anderson, E., Dobie, T., Sherin, B., Lee, J., Thompson, J., Kazemi, E., Lomax, K., & Sherin, M. G. (2017, April). Exploring K-2 teacher learning about modeling in practice-based online courses. Oral presentation at the annual meeting of the American Educational Research Association (AERA), San Antonio, TX, USA.

8. **Shim, S.-Y.**, & Kim, H.-B. (2016, April). Dynamics of students' epistemological and positional framing during small group modeling. Oral presentation at the annual meeting of the National Association for Research in Science Teaching (NARST), Baltimore, MD, USA.

9. **Shim, S.-Y.**, & Kang, E., & Kim, H.-B. (2015, September). Shift in students' epistemological

framing and network of epistemological resources during small group modeling. Poster presentation at the annual meeting of the European Science Education Research Association (ESERA), Helsinki, Finland.

10. **Shim, S.-Y.,** Kang, E., & Kim, H.-B. (2015, February). Framing shift: Focusing on small group students' social interaction and co-construction of scientific models. Oral presentation at the annual meeting of the Korean Association for Science Education, Busan, South Korea.

11. **Shim, S.-Y.**, Kang, E., & Kim, H.-B. (2014, December). Shift in small group students' epistemological framing during the social construction of scientific models. Oral presentation at the annual Asian Regional Conference of the International History, Philosophy and Science Teaching (IHPST) Group, Taipei, Taiwan.

12. **Shim, S.-Y.**, Lee, Y., & Martin, S. (2013, December). Integrating autobiographical writing and sociocultural theory to promote reflection on science teaching and learning in teacher education. Poster presentation at the annual SNU (Seoul National University) - HU (Hokkaido University) - NTNU (National Taiwan Normal University) Joint Symposium, Seoul, South Korea.

13. **Shim, S.-Y.**, & Kim, H.-B. (2013, August). Characteristics of classroom discourse of four pre-service teachers in their inquiry-based biology classroom: focusing on their learning approach styles. Poster presentation at the annual meeting of the Korean Association of Biological Sciences, Seoul, South Korea.

Research Experiences

09/2018-06/2019, **Research Assistant (RA)** in Project: "New approaches to support the clinical experience of novice teachers" (Funded by National Science Foundation; Research organizations: University of Washington, University of Santa Barbara; PIs: Karin Lohwasser, Mark Windschitl, & Jennifer Doherty)

06/2016-06/2018, **RA** in Project: “Learning labs: Using videos, exemplary STEM instruction and online teacher collaboration to enhance K-2 mathematics and science practice and classroom discourse” (Funded by National Science Foundation; Research organizations: University of Washington, Northwestern University, Teaching Channel; PIs: Jessica Thompson, Elham Kazemi, Meriam Sherin, Bruce Sherin, & Paul Teske)

09/2015-06/2017, **RA** in Project: “Building capacity for the Next Generation Science Standards through Networked Improvement Communities” (Funded by National Science Foundation; Research organization: University of Washington; PI: Jessica Thompson)

09/2013-08/2015, **RA** in Project: “Developing and theorizing ‘Strategies for co-construction of scientific models’ adapted to Korean science classroom context through expansive cyclic research” (Funded by the National Research Foundation of Korea; Research organization: Seoul National University; PI: Chan-Jong Kim)

01/2014-08/2015, **RA** in Project: “Building small group norms and developing small group argumentation through cogenerative dialogue in science inquiry class” (Funded by the National Research Foundation of Korea; Research organization: Seoul National University; PI: Heui-Baik Kim)

09/2013-08/2014, **RA** in Project: “Adolescents’ formal and informal education community activities and developmental process of interest, concern, engagement, and aspirations about STEAM” (Funded by the National Research Foundation of Korea; Research organization: Seoul National University; PI: Chan-Jong Kim)

Work Experiences

09/2015-06/2019, **RA** (Research Assistant) in three research projects (Science Education, Curriculum and Instruction, University of Washington)

01/2016-03/2016 & 01/2019-03/2019, **TA** (Teaching Assistant) of a course named "Teaching and learning in science for elementary pre-service teachers" (University of Washington, Seattle, USA)

09/2013-08/2015, **TA** (Teaching Assistant) and **RA** (Research Assistant) of Department of Science Education in Seoul National University (Seoul, South Korea)

04/2013-08/2015, **TA** (Teaching Assistant) of "Educational Program for Science-gifted Students in Gwanak-gu" (Seoul, South Korea)

03/2011-12/2014, **TA** (Teaching Assistant) of Korean Biology Olympiad (Seoul, South Korea)

01/2012-06/2012, **Science intern teacher** at a 8^{th} grade physic classroom in Glasgow Middle School (Fairfax County Public Schools, Virginia, USA) -Internship sponsored by Korean Ministry of Education, Science and Technology

08/2010-02/2011, **Intern** at SNU (Seoul National University) Institution of Molecular Biology and Genetics (Seoul, South Korea)

Awards, Scholarship, and Fellowship

Outstanding Paper Award (2014, The Korean Society of Biology Education)

Graduate fellowship (2015-2016, Tuition waiver for international students, Washington State; 1^{st}, 2^{nd} semester/2014, Korea Student Aid Foundation)

Graduation from college with honors (*Summa cum laude*, 3.96/4.3)

1st prize in the "1st Essay Contest for Seeking Ways to Promote Youths' Interest in Science and Technology" organized by The Korean Federation of Science and Technology Societies (2011)

Scholarship for outstanding college students (2nd semester/2009, Korea Student Aid Foundation; 1st, 2nd semester/2011, Bumeun foundation)

Teaching Certification

Korean Instructional II Certificate in Biology (7-12)

Leadership / Community Service Activities

05/16/2018, **Facilitator**, Co-facilitated "Global K-12 Education workshop", College of Education, University of Washington

10/2017-02/2017, Student representative on the STEM Research Assistant Professor search committee, College of Education, University of Washington

09/2017-06/2019, **Mentor**, Mentored a peer doctoral student at the University of Washington

01/2011-01/2012, **President**, Biological Experiment & Education Student Club

03/2013-08/2013, **Mentor**, Peer-mentored two international students at Seoul National University

09/2012-08/2013, **Tutor**, Seoul National University Children's Hospital