ABSTRACT

Title of Dissertation: CREATING OPPORTUNITIES FOR EPISTEMIC AGENCY IN THE LEARNING OF SCIENTIFIC DISCIPLINES

By: Christine Hirst Bernhardt, Doctor of Philosophy, 2024

Dissertation directed by: Dr. Andrew Elby, Department of Teaching, Learning, Policy and Leadership

This dissertation consists of three studies exploring factors affecting whether, when and how students engage in sensemaking in science disciplines, and the epistemological components of instruction that impact their engagement. Each study is grounded in science education reform efforts, including the Next Generation Science Standards (NGSS), which call upon educators to engage students in science practices to learn science through sensemaking and necessitate a reorientation to position learners to "shape the knowledge building work in their classroom community (Miller et al., 2018, p. 1058; NRC, 2012). In other words, students must now act with *epistemic agency* to figure out more than they learn about (Krist et al., 2019).

Study 1 addresses a gap in astronomy education research literature. Astronomy education is largely centered on undergraduates and is minimally researched in pre-college settings. I conducted a qualitative study with thematic analysis of surveys (N = 68) and 10 interviews with select participants to discover methods of teaching and learning astronomy internationally, as a follow on to the quantitative curricular study by Salimpour et al. (2021). I was looking for examples of astronomy as a gateway for further STEM learning in classrooms and community, and as a bridge to equity, as well as examples and takeaways. While the interview participants provided notable examples of programs which disrupt representation gaps in astronomy fields and promote STEM connections amongst historically underserved populations, I did not find easily replicable examples for US teachers to use astronomy as a "gateway" science; I found other nations wrestling with similar issues of deprioritized science instruction, lack of resources and poor access to teacher professional learning opportunities. Therefore, I turned to a deeper understanding of epistemologies of teaching and learning in studies 2 and 3.

Papers 2 and 3 investigate the role of epistemological *framing*, or how people make sense of a particular situation, through speech and behaviors, from past experience (Elby & Hammer, 2010; Goffman, 1974; Hammer et al., 2004). Students may frame learning science as *doing school* for completion of worksheets and production of "correct" answers for a grade, or they may frame learning science as *doing science* when they consider "correct" as considering available evidence and weighing it against predicted outcomes to make sense of phenomena or developing disciplinary knowledge through the process of sensemaking (Hutchinson & Hammer, 2010; Miller et al., 2018). In papers 2 and 3, I explored how teachers used framing *moves* or *bids* through explicit or implicit signals such as means of instruction, tone, or body language to sustain, shift or redirect students' approaches to learning activities (Berland & Hammer, 2012). In paper 2, I investigated the impact of two teachers varied framing moves while using similar curricular materials through secondary video analysis. I used codes for cognitive authority and epistemological stance to segment each teacher's dialogue while introducing the activities, or their" public talk," which established and sustained classroom norms for participation and engagement. I also analyzed dialogue between each teacher and small student groups, as seen from a teacher-worn GoPro camera. I found that one teacher mostly framed the lesson as students *doing science* and established a culture of collaboration. I found that the other teacher mostly framed the lesson as *doing school* and established a culture of compliance. However, these findings were nuanced and context dependent.

In paper 3, I investigated, through a single case study, how a veteran teacher acknowledged, addressed and adapted her work within the same curriculum from paper 2 to address a mismatch between the epistemic agency afforded by the materials and students' "typical" epistemic agency enacted in that classroom. I engaged in a collaborative planning interview and observation cycle with the teacher, Amy, over five observations and eight interviews. While I intended to better understand and characterize Amy's framing moves and how those moves positioned students to act with epistemic agency, I determined that, what I thought were purely her framing moves were also reinforcing embedded commitments (for *relationships* and *community*). These commitments were baked into all of her framing moves for sensemaking. I also saw over multiple days that students did not take up her framing bids; after revisiting the data, including a lesson not using the curricular materials, I saw students in her class and school, by structural design, always had some form of epistemic agency, and that the curricular materials suppressed some of the form of epistemic agency to which they were accustomed. By contrast, when Amy modified the lesson to grant students their "typical" epistemic agency, the lesson went well, with students engaging excitedly in scientific argumentation. Therefore, this study demonstrated that the construct of epistemic agency is not monolithic, that the *form* of epistemic agency matters. Students recognize when there is a mismatch between the epistemic agency invited by curriculum and that which they are accustomed to, which influences their engagement and participation. Amy demonstrated the pedagogical moves and strategies to realign this mismatch.

These studies are significant in that many teachers use highly structured materials to assist with NGSS implementation, yet the manner in which teachers approach these materials determine the objectives they establish, and the framing moves they enact, which are likely taken up by students (EdReports, 2022). Paper 3 specifically demonstrates the ability of expert, veteran teachers to understand and act upon knowledge of their students. This knowledge should be leveraged and supported through professional development and curriculum. Paper 1 is also significant because the NGSS embeds and interconnects Earth and Space Science into every grade band in every content area, thus elevating a previously ignored subject matter. Many teachers globally, as Paper 1 demonstrated, are unprepared to integrate this content with efficacy and authenticity. Therefore, we must consider, honor and respect the insight, experience and professionalism of teachers, and work holistically in that space to better understand what they already do well, instead of trying to consistently reshape or re-direct. Perhaps instead of teaching about practices and disciplinary engagement from a deficit stance, professional development should center teachers as professionals to improvise, to experience and to adapt materials as only professionals can. Each of the studies presented in this dissertation describes teachers (or teacher educators in Paper 1) with expert knowledge of their classroom or disciplinary cultures as they relate to engagement, and suggest that we must trust teachers, as professionals, to do just that.

CREATING OPPORTUNITIES FOR EPISTEMIC AGENCY IN THE LEARNING OF SCIENTIFIC DISCIPLINES

by

Christine Hirst Bernhardt

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2024

Advisory Committee:
Professor Andrew Elby, Chair
Doug Lombardi, Ph.D., Member
Andrew M. Brantlinger, Ph.D., Member
Daniel M. Levin, Ph.D., Member
Timothy Spuck, Ed.D., Member

Preface

This dissertation consists of three papers. As I discuss in my introduction, the first may seem unrelated to the to the other two, yet through this work I dove into the realms of cognition and learning. And through this work, I stretched myself. I had to embody each of these principals. It was hard.

"I am not so smart, I just stayed with the problem longer"

Albert Einstein

Dedication

This dissertation is dedicated to my amazing chair, Dr. Elby, who patiently helped me transition from teacher to researcher. Thank you for your mentorship, your guidance, and for the opportunity to continue learning. This dissertation is also dedicated to my amazing boys and husband, who were so patient through my writing. To my husband who supported me through all of this. To the Albert Einstein Fellowship, for giving me a seat at the table, as a teacher. And to my students, my kidlets, you forever inspire me and remind me that teaching goes beyond a lesson or a classroom. You were my best teachers.

Acknowledgements

Dr. Janelle Bailey was my co-author on my first paper, which is now in publication. You will note the use of British English, which Word notes as misspellings. Dr. Andy Elby will be my co-author on paper 3 for publication this Fall, as well a submission to NARST 2025.

Table of Contents

ABSTRACT 1

PREFACE II

DEDICATION III

ACKNOWLEDGEMENTS IV

TABLE OF CONTENTS V

LIST OF FIGURES XIV

CHAPTER 1: INTRODUCTION 1

MY NARRATIVE 3

ABSTRACT: SPACE FOR ALL 11

CHAPTER 2: SPACE FOR ALL: A MULTINATIONAL STUDY ON THE STATUS OF ASTRONOMY EDUCATION 12

INTRODUCTION 12

BACKGROUND 13

Astronomy in the Curriculum 13

Astronomy and Early Science Learning 14

Diversity in STEM and Astronomy 16

Academic Prioritisation Problem 17

Disrupting Colonial Views of Earth and Space Science 19

Astronomy as a Gateway 19

Methods 20

Research Design 20

Recruitment 21

Participants 21

Language Acknowledgment 22

Data Collection 23

Interviews 24

Data Analysis 25

Interviews 28

Researchers' Positions 29

Results 29

Survey 29

Interview Results 33

Cross Case Analysis 33

RQ 1: How is astronomy used internationally to promote STEM in community and school? 34

RQ 2: What lessons can be learned from international astronomy education efforts? 36

RQ 3: How do international astronomy education efforts attend to equity and diversity? 46

Summary 48

Limitations 48

Discussion 49

Implications for Practice 50

Implications for Research 52

Conclusion 53

Ethics Statement 54

References 56

CHAPTER 3: A TALE OF TWO CLASSROOMS: VARIED FRAMING MOVES AND IMPLICATIONS FOR STUDENTS' EPISTEMIC AGENCY WITH STRUCTURED SCIENCE MATERIALS 62

Introduction 62

Background and Literature Review 64

NGSS: The Latest Science Reform 64

Epistemological Framing 66

Epistemic Agency 74

Framing Moves While Using Structured Materials 78

Examining Epistemological Framing with Video Analysis 80

Rationale For Study 81

Methods 82

Research Design 82

Curricular Materials 83

Data Sources 84

Case Selection 84

Data Flow 86

Analysis 92

My positionality and perspective: 96

Findings 96

RQ 1: How did two teachers frame the same MEL-based lesson? 97

For School or For Science 103

Questioning Strategies 105

Pronouns and Positioning 106

Group Work 109

Summary: Differences between Melissa's and Coral's small-group interactions 116

RQ 2: What are the impacts on students' epistemic agency? 117

SUMMARY 120

DISCUSSION 122

FRAMING MOVES AND CLASSROOM CULTURES 122

POWER STRUCTURES AND STUDENTS' EPISTEMIC AGENCY 124

SIGNIFICANCE 127

SUPPORTING TEACHERS 128

NEXT STEPS 131

ALTERNATIVE EXPLANATIONS 132

CONCLUSION 133

REFERENCES 134

CHAPTER 4: RECOGNIZED AND REALIGNED: A VETERAN TEACHER'S MOVES TO REALIGN FAMILIAR FORMS OF EPISTEMIC AGENCY WHILE USING NGSS INSPIRED MATERIALS 145

INTRODUCTION 145

LITERATURE REVIEW 149

NGSS REFORM: STUDENTS AS SCIENTISTS 149

FRAMING THE GAME 152

STUDENT IDEAS IN SENSEMAKING 160

SUPPORTING STUDENTS AS EPISTEMIC AGENTS 161

Epistemic Agency with Structured Curriculum 170

Study Aims 174

Methods 175

Study Design Overview 175

Materials 176

Case Study Participant 179

Study Setting 180

Data Sources 181

Analysis 188

Revised Analysis: Allowing the Data to Speak 194

Our revised research question: 198

Discussion 199

Professional Science or Science Class? 199

Epistemic agency… to do what? 201

Mismatched Epistemic Agency 203

Greater epistemic agency does not always mean less structure. 204

Trusting Students 207

Framing Moves are Important…but Insufficient 208

Teachers Recognize Established Classroom Cultures 211

Implications 213

Limitations, Alternative Explanations and Next steps 218

CONCLUSION 219

REFERENCES 222

APPENDIX 240

A. CODING FOR PAPER 2 240

B. VIGNETTE FOR PAPER 3..241

QUESTIONS.. 241

TEACHER 1: MS. LUMEN.. 241

TEACHER 2: MS. LIGHTBULB.. 243

C. JOINT DISPLAYS FOR ANALYSIS 246

D. INTERVIEW PROTOCOL, PAPER 3 250

INTERVIEW 1 250

FROM VIGNETTE.. 250

FOR MEL:.. 250

CHAPTER 5: RESEARCH SYNTHESIS AND NEXT STEPS..251

INTRODUCTION 251

OPERATIONALIZING AUTHENTIC SCIENCE: SCIENCE PRACTICES..251

STUDY SNAPSHOTS 254

STUDY CONTRIBUTIONS TO RESEARCH AND PRACTICE..256

Paper 1: Space for All 256

Paper 2: A Tale of Two Classrooms 260

Paper 3: Recognized and Realigned 262

Personal Meaning and Meta Reflection 266

The Journey 266

Synthesis. 267

Relational Teaching and Language 268

Digital Natives 270

Professional Development 271

Next Steps 273

Looking for Differing Forms of Epistemic Agency 273

Other Means of Observing Epistemic Agency 273

Supporting teachers 274

Epistemic Agency and Astronomy 276

References 276

This Table of Contents is automatically generated by MS Word, linked to the Heading formats used within the Chapter text.

List of Figures

Figure 1 IAU Membership by Gender 17

Figure 2 Country of Respondents 22

Figure 3 Years Involved with Astronomy Education 22

Figure 4 Two questions used to sort responses. 24

Figure 5 Location of Interview Participants 25

Figure 6 Diagram of coding passes 26

Figure 7 Self-ranking of familiarity with national education systems 30

Figure 8 Grades astronomy is taught 31

Figure 9 Role of respondents 31

Figure 10 Identifiers for interview participants 33

Figure 11 Codes, descriptions and examples 87

Figure 12 Codes for cognitive authority 89

Figure 13 Codebook 92

Figure 14 Sample of Segmented Table 94

Figure 15 Histogram of categorical codes for each teacher 98

Figure 16 Segmented dialogue 102

Figure 17 Summary of research questions 120

Chapter 1: Introduction

Teaching science has never been more stressful and complicated; a recent nationally representative survey found the compounded impacts of COVID-19 and political polarization has dramatically influenced stress and decisions to leave the profession (Woo et al., 2022). I set my three dissertation papers amid this context to demonstrate the capacities of a) space content in communities and classrooms in paper 1 and b) the role of teachers' epistemological framing which impacts students epistemic agency in paper 2, and c) the significance of teacher's established cultures and classroom epistemic agency when using prescriptive materials in paper 3. While the three papers may seem drastically different, they represent my academic and professional Journey from a practitioner to a researcher.

In my first paper, I sought to highlight international examples and exemplars to inform teaching of astronomy in American classrooms. This multiple case study was a follow-on qualitative study from a colleague's quantitative study exploring international curriculum documents. I used thematic analysis to provide dynamic examples from ten countries. My initial intention was to create a scalable model for U.S. classrooms following the infusion of Earth and space content within the NGSS framework. As my academic journey continued, I realized in order to address widespread lack of teachers' proficiency in Earth and space, I had to first divert my attention towards cognition- specifically epistemologies of teaching and learning.

Papers 2 and 3 result from this step away from disciplinary content and towards epistemologies of teaching and learning. My goal beyond my doctorate is to merge these two fields to connect the epistemic opportunities within Earth and Space content to support authentic and agentic science learning. In contrast to most epistemological literature focused on students, I chose to focus on teachers' epistemologies and epistemic impacts on students. Papers 2 and 3 are situated within the teaching context of using highly structured materials and how these materials are a) framed by teachers and b) taken up by students. In each, I was looking for places that students acted with epistemic agency and engaged in sensemaking.

In paper 2, I deeply analyzed secondary video data from two teachers using very similar lessons. The materials, student work and strategies should have been nearly identical, yet students displayed nearly opposite observable behaviors. In this paper, I make the case that variation in the two teachers *framing* resulted in differing outcomes and elevated or amplified opportunities for students to act with epistemic agency. Paper 3 is a single case study with a veteran teacher to explore how she acknowledged, adapted and mitigated mismatched epistemic agency while using prescriptive materials. Paper 3 aims to unify literature on framing and epistemic agency, while moving the field beyond a singular or monolithic construct of what epistemic agency is and what it is for.

My Narrative

My inclusion of these three articles and the pursuit of my doctorate are deeply personal decisions rooted in experiences of Science Education. I include this narrative to contextualize my positionality. My decision to enter teaching non-traditionally, and in response to the teachers I did not have. My career as an educator, and now a researcher stem from my experiences as a learner and an attempt to see my students first, and teach them second. My passion for Earth and Space education served as a mediator to foster learning for at risk students, and ultimately to launch many scientific careers.

Many years ago, my dream of being an astronomer was thwarted when I I didn't see any girls in science or even astronomy as a job, other than astronauts. I didn't exactly want to go to space. I just wanted to learn about it.in Montessori, I could dive into any content I wanted. When I switched to “traditional” public school, I quickly learned that I wasn’t “good” at science. When my parents divorced and I changed high schools halfway through my freshman year, I learned I wasn't good at school at all and actively quit trying. I knew I wanted to pursue higher education but High School became enslavement to a system that didn't include me. My mom was gay and we were extremely poor. I enrolled in the first accredited charter school, graduated a year early with straight A’s and enrolled in community college by 16. I transferred as far away as I could get with in-state tuition as a Native American studies and Music major.

From late elementary through my second year in college, I focused on music. I sang in many award-winning jazz groups and dreamed of "making it" as a professional musician. I intentionally postponed taking science until the last possible minute and opted for geology as an easier route than traditional science courses. I had taken Biology in high school and, to put it lightly, the teacher and I did not see eye to eye. I spent many days sitting in the hall or ditching. Biology seemed so disconnected, and I did not understand or care how a cell was structured, split or mutated. I regularly escaped to the mountains to backpack or camp, and biology failed provide context for the landscapes I loved. But geology explained the world. Suddenly, I understood why Northern California differed from Southern, why the river flowed where it did and why I lived in Earthquake Country. I marveled at the humility of Earth sciences. Whereas other sciences seek to replicate and manipulate, geology passively observes, wonders, questions and admits the limits of knowing. The science wasn't "set" but actively sought to learn, which made me feel like I could belong. I took every science class I could, often 5 at a time, including biology. After I took chemistry, biology made much more sense. A couple years later, in my third trimester of pregnancy while fat and bored, I took a fast track physics course over 3 weeks. I set the curve.

I did not, however, leave with a degree in geology. I had missed the cohort window of courses (every two years), so all of my coursework was for the sake of learning, not a degree. When I graduated, I knew that there were so many kids that could be scientists if someone told them they could instead of discouraging them, like I was. I also knew that I didn't necessarily need to pursue a field in The Sciences, but that my role was something different. I didn't yet know I would be a teacher, but I knew I was a hippie, I lived in a truck, and I wanted to be outside; so I taught Outdoor School. This was the perfect pairing of outdoor adventure and geologic learning. I had the privilege to take inner city kids from Los Angeles all over the mountains. Most had never been hiking, or in the snow, or even walked in dirt. At the end of my second year I realized that I loved the relationships I formed with the students and it made me really sad to see them leave every week. Like a Looney Tunes anvil, it hit me: I was a teacher. Laughably, every job I ever held was either teaching, coaching or mentoring. Teaching Earth science in a classroom was my destiny.

I had no idea until I entered the classroom that Earth science was the most deprioritized science; there was no AP class, there was no IB, there was no advanced. There wasn't even a high school textbook. When I began at West Ranch High school, the school was still relatively new and had not yet graduated a class. The Earth science classes did not have a credentialed teacher but rotated between out of field teachers or with long-term substitutes. Earth science was where they shoved students who needed a couple credits to graduate and were not deemed to be successful in the trifecta of traditional Sciences. Regularly, 60% of my students had IEPs, were at least 3 grade levels behind, and barely spoke English. I loved it. No one saw these kids or gave them an opportunity. In California, English Language Learners and students who failed the exit exam were forced into test prep courses instead of electives. Most of my students had their days filled with academic courses and test prep courses related to those academic courses. I was determined that in my class they would be successful and because of my class they would graduate.

I remember a faculty meeting in which we were to write down the name or names of teachers that inspired us to become teachers. Others filled pages with tear jerking prose about their inspiration. I had one sticky note that said “no one.” While teaching, I lived in a migrant farm worker community, was a single mom and lived on food stamps. I related much more to my students in those communities than my fellow teachers in suburbia. I worked tirelessly to make my course lab-based and to move away from the low-level worksheet-based perception of Earth science. I spent the entire first month doing science literacy labs with relatable topics: determining which bubble gum was best by measuring bubbles; determining variations in size of peanuts, using tag based games from my years of teaching outdoor school for concept review, and my infamous hot salsa lab: I made the hottest of hot salsa and students had to design an experiment to determine if hot salsa made them sweat, while measuring their change in temperature. How hot? I had to wear double latex gloves and goggles to handle it. It was legendary. One year a student asked me, a month in, when we were going to start doing science. He thought science had to involve a book and memorizing worksheets. We had never opened the book.

My class was focused first on reaching students, and second on teaching science. I knew that the second could not exist without the first. I saw myself as their advocate when no one else could or would. I nearly changed to counseling, but in my third-year teaching, I entered a Master's in Science Education program and knew that I would pursue my doctorate. My thesis focused on the use of personal, relational interventions on at-risk students in science. I was the first to do a thesis in lieu of action research.

Around the same time, I was asked if I could teach astronomy, my first love. It was also not a lab class or Advanced or AP and was mostly taken by my earth science students who wanted my class again. Again, I worked tirelessly to make the class hands-on which is very difficult with astronomical scales of time and, well, space. I was up most nights past midnight scouring University web pages for lab activities but realized that very few materials existed to facilitate deep learning in astronomy. I knew I had to make them. I enrolled in community college astronomy classes in the evenings to learn more and was accepted to a master's program. I brought content directly from my classes to my students. During the fall of 2014, the first year I was able to make the course a year-long, I was sharing what I had learned about Cosmic dust accumulation at the edge of the atmosphere. One of my students asked if we could potentially retrieve it if we had something like a high-altitude balloon. I responded that I had no idea but let's try. Hence, my high-altitude balloon program began.

While I thought that I had made learning about the students, it wasn't until I began the process of shifting all authority to students during the high-altitude balloon project that I really saw what I had lacked: trust. I had to trust them, even if I knew they would fail. I had to let them fail. But I saw that even in failure was deep learning-sometimes more so than when experiments or launches went perfectly (which they didn't'). I could endlessly share the dozens of amazing experiments, research, videos, papers and presentations that came from this- but those can all be found on the internet. Many of those students went on to pursue science degrees, and a group of girls that I mentored started an astronomy mentoring club. The project spurred amazing outcomes. The project also completely changed my perspective of teaching and the function of school science.

In subsequent years I transformed my class to entirely center on student experiments. I had the opportunity to entirely shape the course and wrote grants for equipment. I was less space focused and more about opportunities for students to drive learning within it. I tried sharing with my fellow teachers, my admin and district. Although they knew the value and saw the media attention, "science for all" dominated their objective. Suddenly only NGSS courses, of which I developed as a content specialist, were allowed. Nearly all elective courses, including mine, were eliminated in favor of this unified approach. We developed materials designed to elicit student thinking, but we really directed it. Our hands on, phenomena driven, and award-winning district material was predominately worksheets. I knew there was more to science. I spoke out and was silenced. My walls became tired of my pleas for what I knew learning should be-that students could really drive the process. When I asked if I could lead a PD on ballooning for the many teachers interested, I was asked "what NGSS standards does that cover?" My response of "all of them" was not received.

When I entered my doctoral program during 2020, I thought that I would have the place to develop astronomy curriculum and professional development for teachers. Instead, what I realized was the *epistemic agency* was the researchy term that described exactly what I saw with my students. I was also teaching during the pandemic, and I'm now married to a science teacher so I'm not immune to the present state of Education and the complexity of pressures that teachers face. The last thing teachers need is one more thing, one more standard, one more practice, one more PD. One more is too much. I want my work to be additive for teachers and the profession. For me, focusing on framing is just that; this minor shift in approach can be applied anywhere to achieve highly desirable outcomes. The connection between framing, noticing and epistemic agency just makes sense. Earth and space sciences uniquely foster these learning opportunities (with a closed book). I am committed to investigating science education as a means to itself, not to address future economies. A STEM workforce who has excelled in school but never actively engaged in science is a frightening prospect. Science education must respond to the question-"to what ends?"

Thank you for the opportunity to dive into my journey. This was a valuable exercise to evaluate my current work in connection to my past in light of my new research lens.

If you ever want to try some really hot salsa, yo soy tu chica.

Abstract: Space for All

Existing research in astronomy education is largely centred on undergraduates. We conducted this qualitative study to explore examples of astronomy education internationally, providing context to the quantitative study by Salimpour et al. (2021). Our methods included an online survey (N = 68) and 10 interviews with select participants to discover the methods of learning and teaching astronomy in K12. We used thematic analysis to contrast international astronomy education efforts in formal and informal education settings. Interview participants provided examples of programs which disrupt representation gaps in astronomy fields and promote STEM connections amongst historically underserved populations. The present study will inform future studies and collaborations between educators, astronomers, and informal spaces, and provide examples of astronomy integrations in coursework and community. This, along with the ongoing work of Salimpour and Fitzgerald, can provide multinational curricular and pedagogical examples of leveraging astronomy as a “gateway science” and inform interdisciplinary/transdisciplinary approaches to teaching science.

Chapter 2: Space for All: A Multinational Study on the Status of Astronomy Education

Introduction

Astronomy is one of the oldest sciences with well-established cultural and social significance (Hall, 2013; Impey, 2021; Salimpour & Fitzgerald, 2022). Celestial phenomena continue to fascinate young learners, yet few students have access to astronomy education. When effectively implemented, astronomy topics seamlessly integrate into existing coursework, facilitating connections across seemingly disparate disciplines and harnessing students' inherent curiosity. As a "gateway science," astronomy fosters abundant opportunities to engage with science practices. This is particularly vital as we emerge from a global pandemic and adapt classroom and workplace environments for Digital Natives. The world may not need an influx of astronomers, but it does need scientifically literate global citizens.

Salimpour and colleagues (2021) conducted the most extensive study to date on astronomy education, systematically quantifying the occurrence and frequency of astronomy in 52 national curricula from 37 Organisation for Economic and Cooperative Development (OECD) member countries [plus China and South Africa]. The authors located astronomy in 100% of surveyed national curricula beyond elementary school, yet generally housed within other subjects (Salimpour et al., 2021). Additional research is necessary to integrate existing pedagogies, practices, professional development, and curriculum to better reflect the interdisciplinary and dynamic nature of the field (Salimpour et al., 2021). The present study is a first attempt at addressing this charge in primary and secondary learning environments around the world.

Background

Astronomy in the Curriculum

Astronomy is well suited for integration within other STEM courses and can support transdisciplinary learning in humanities, arts, and civics (Salimpour et al., 2021). Yet, Pasachoff and Percy (2005) describe the presence of astronomy in curriculum as dependent upon the belief structures of national curriculum developers. Salimpour et al. (2021) found optional or elective courses in astronomy present in only 17% of national curriculum surveyed, but embedded and integrated astronomy to be quite common. While 100% of curricula had astronomy at some level beyond elementary school, only 27% (14 curricula) had astronomy topics in all grade levels. In general, lower grades had a higher inclusion of astronomy content. Forty curricula (77%) included astronomy in Grades 1 and 4 and 44 (87%) in Grade 6; this number drops to 28 curricula (54%) in Grade 7. The elementary presentation of topics in these curricula was generally homogenous and focused on positionality of celestial objects. Content was generally descriptive rather than conceptual, and focused on recall rather than interpretation or inquiry, which appeared in only 6% of curricula. Curricular statements contained numerous errors, such as referencing stars instead of galaxies, demonstrating a lack of familiarity of astronomical concepts and applications within the educational community. Not only were there missed opportunities for integrating technology and complex topics such as telescopes and cosmology, which are both explicit within the same physics curricula, but the authors did not find telescopes in any inquiry-based curricula (Salimpour et al., 2021).

Astronomy and Early Science Learning

Astronomy content can be leveraged to encourage young children's participation in science and STEM. Children are natural scientists; they learn from and with the natural world (National Academies of Sciences, Engineering, and Medicine [NASEM], 2021b). Students enter the classroom having made observations and having drawn conclusions about real world phenomena. While science and astronomy are clearly indicated in global curricula, many students do not have access to science education until middle grades. A recent study identified quality science learning in early education as a fundamental need; researchers found that only 17% of students in American classrooms receive science daily before Grade 3, and only 27% in Grades 4-6 (NASEM, 2021b). Students who do not receive quality science education early are set up for challenges in later classes. In the US, a persistent opportunity gap separates science learning in poor, under-resourced schools from those in affluent neighbourhoods; the COVID-19 pandemic also exposed huge gaps in access to technology (NASEM, 2021a). Early exposure to the processes and practices of astronomy can encourage equitable participation and engagement, which can significantly influence STEM identity formation in girls and underrepresented populations (Kang et al., 2019; Kim et al., 2018; Maltese & Tai, 2010).

Astronomy can enhance opportunities for engagement with science practices beyond a specific domain. While its relevance to physics and maths are obvious, learning astronomy also requires art, history, communication, and literacy. The importance of space (and Earth) sciences at younger ages is underscored by their robust inclusion within the US *Next Generation Science Standard*s, which also suggest that exposure to STEM activities can build an inclusive environment for marginalised students who might not see the relevance of science to their lives (NGSS Lead States, 2013).[1] Astronomy can provide opportunities for students to "do science" as they puzzle over complex questions instead of validating theories and performing lockstep school tasks (NRC, 2007; Nicol et al., 2019; Rodriguez, 2017). Embedded astronomy can unify content while providing opportunities to explore the evidential sources of knowledge, connecting students to their collective present, past, and future.

---

[1] Forty-four states have adopted frameworks based upon NGSS. States such as California have even renamed physics courses to "physics in the Universe," which includes robust astronomy sequences.

Diversity in STEM and Astronomy

In the US, astronomy encompasses the lowest representation of women and Persons of Colour in any STEM field; furthermore, women account for around 15% of global astronomers (Cesarsky & Walker, 2010). The gender gap is reflected in global membership in the International Astronomical Union (IAU; Figure 1): women make up 21% of membership, although the youngest age bracket (25-30) disrupts this trend with 47% enrolment (Cesarsky & Walker, 2010; IAU, n.d.). In the US, the number of minority students pursuing physics degrees has increased, yet fewer than 100 total PhDs have been granted to African American women (Chen, 2017). The number of minority students receiving PhDs in Astronomy hovers between 1%-5% (NRC, 2013; Porter & Ivie, 2019).

country	no. of members	% of total in IAU	% of women members from country
Argentina	134	1.3	35.8
Ukraine	188	1.9	27.1
Italy	568	5.6	24.7
Bulgaria	57	0.6	24.6
France	700	6.9	24.3
Portugal	43	0.4	23.3
Brazil	172	1.7	22.7
Hungary	48	0.5	20.8
Ireland	44	0.4	20.5
Austria	49	0.5	18.4
Spain	303	3.0	17.8
Mexico	111	1.1	17.1
Russian Fed.	368	3.6	17.1
Finland	67	0.7	16.4
Greece	108	1.1	15.7
Chile	90	0.9	15.6
Belgium	117	1.2	15.4
China (Nanjing)	409	4.0	15.4
Australia	262	2.6	15.3
South Africa	71	0.7	14.1
Sweden	111	1.1	13.5
Poland	149	1.5	13.4
Canada	245	2.4	12.2
USA	2594	25.5	12.1
Czech Rep.	92	0.9	12.0
UK	524	5.2	11.6
Netherlands	208	2.1	11.5
Egypt	56	0.6	10.7
Korea	109	1.1	10.1
Denmark	63	0.6	9.5
Germany	532	5.2	9.4
Switzerland	76	0.8	9.2
Israel	75	0.7	8.0
China (Taipei)	51	0.5	7.8
India	222	2.2	7.7
Japan	598	5.9	5.5

From http://www.iau.org/administration/membership/individual/distribution

Figure 1 IAU Membership by Gender

Academic Prioritisation Problem

Unequal demographics in the field--whether gender, ethnicity, religion, language, or other identity--are an external indicator of an academic prioritisation problem within the sciences. In most English-speaking nations, Earth and space sciences are poorly represented in favour of other scientific fields (Dodick & Orion, 2003; Orion, 2017; Orion, 2019). In the United States, there is no advanced placement course or test. Most states did not accept Earth- and space-related courses for university acceptance until very recently, if at all. One of the largest university systems in the United States with 10 campuses and over 250,000 students excludes Earth or space coursework from science entrance requirements (Regents of the University of California, n.d.). Globally, qualified teachers of Earth and space sciences are scarce prior to university coursework, and secondary courses generally serve as a low-level graduation requirement (Lewis & Lu, 2017; Orion, 2017). By the time students reach university the moment to select a STEM field has likely passed (Lewis & Lu, 2017; Maltese & Tai, 2010). Exposure to early science learning and access to electives such as Earth science and astronomy correlate to demographics and access (NASEM, 2021a), which in turn reproduce global gaps in representation (Cesarsky & Walker, 2010; Porter & Ivie, 2019). Astronomy exposure in the middle years can shift students' focus and perspective (Salimpour et al., 2021). Primary environments are critical for the formation of a STEM identity, particularly amongst girls and students of underrepresented groups (Kim & Sinatra, 2018). Restricting astronomy (and Earth science) education to university settings is an injustice that furthers the representation gap of women and underrepresented communities in global STEM economies.

Disrupting Colonial Views of Earth and Space Science

Curricular representations can inform representations of who can do science and perceptions of inclusion. Astronomy provides “untapped cultural capital” to address diversity within science (Salimpour & Fitzgerald, 2022, p. 2). Recent research by Salimpour and Fitzgerald (2022) has provided a foundation to decolonize astronomy through multiple worldviews, yet current curricula continue to present a singular “way of knowing.” Of the 52 curricula studied by Salimpour et al. (2021), only three included indigenous or non-colonial references; only one mentioned “women” in general; and two named specific women. Minimal mention of women and First Peoples communicates subtle forms of exclusion against girls and underrepresented populations, perpetuating the representation gap and colonial representations of the scientific process.

Astronomy as a Gateway

A holistic approach is required to disrupt the trend of academic deprioritization and underrepresentation (Orion, 2019). Instead of approaching science subjects as individual silos, space can provide a broad background for scientific and cultural competency, mathematical and language literacy, and global communication. Standalone astronomy courses may be rare, but many national curricula integrate astronomical topics into other coursework; this approach can be leveraged to further science study and careers.

This study was guided by the following research questions:

1. How is astronomy used internationally to promote STEM (science, technology, engineering, and mathematics) in community and school?
2. What lessons can be learned from international examples of astronomy education, and what challenges do they face?
3. How do international astronomy education efforts attend to equity and diversity?

Methods

Research Design

This study used a primarily qualitative design, using both a survey and semi-structured interviews to provide examples of astronomy education beyond published curricular documents. Qualitative methodology was chosen to provide a narrative lens and personal voice of formal and informal educators. The use of a survey allowed us to collect data from participants in various settings (university, secondary, professional) and roles (astronomers, professors, teacher educators, teachers) to corroborate the findings of the Salimpour et al. (2021) curricular study. The survey also allowed us to determine countries with sufficient astronomy content and expertise to allow for follow-up interviews, which contextualised quantitative data from this and previous studies.

Recruitment

We recruited participants through the National Astronomy Education Coordinators (NAEC) with the IAU and social media pages targeting teachers of astronomy. Members were encouraged to respond and share with their networks.

Participants

Survey participants (n = 68) were either professional astronomers, university instructors, formal or informal educators, or any combination, including from 23 non-US countries (Figure 2). The US was oversampled in the survey (n = 22) due to recruitment within American education-based social media pages. Although we initially solicited US participation, we wanted to elevate and amplify the voices of those who may have been excluded in previous astronomy education studies and chose not to include US participants in interviews. We decided to include a wide variety of examples in the data and to highlight rich examples of informal and formal astronomy. Nearly a third (30%) of participants had been involved in astronomy education efforts for over 20 years (Figure 3).

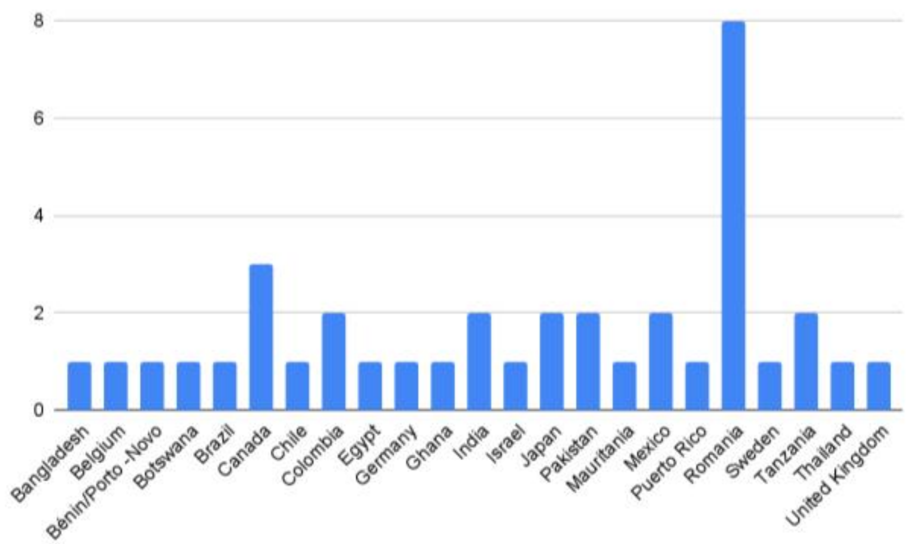


Figure 2 Country of Respondents

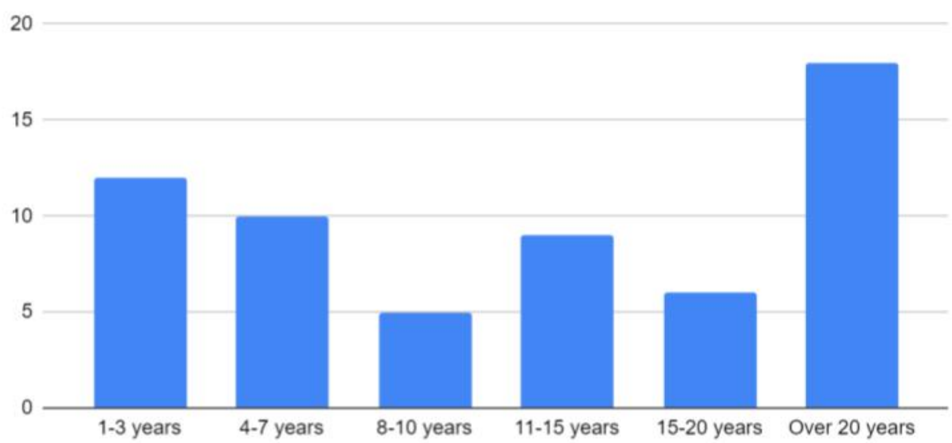


Figure 3 Years Involved with Astronomy Education

Language Acknowledgment

English is not a universal language or "first" language; English was a second (or third) language for each selected interview participant. The Romanian interview required the use of a translator. We sought Romanian participation (reflected in the frequency of Romanian survey responses) due to recent research (Ficuț-Vicaș, 2018) investigating the need and desire for astronomy in Romanian curricula. While the researchers intended for the study to be inclusive, we recognize that our limited proficiency in languages other than English may have unintentionally excluded qualified individuals from contributing to the study.

Data Collection

Sixty-eight participants completed an online survey which was analysed, coded, and used to purposefully select 10 participants for semi-structured interviews. Each of these data sources is described below.

Survey.

Participants completed an online survey starting with research consent forms and national and professional identifiers. Questions included, among others, a self-ranking item of knowledge about their national education standards and an open-ended item about placement of astronomy in the curriculum. Participants also provided a lesson description to demonstrate their ability to intentionally integrate specific subject matter with appropriate teaching strategies to facilitate deep learning. Figure 4 shows two of the survey items used in the consideration of interview participants.

Self ranking question
How familiar are you with efforts in your country to bring astronomy to students who would not otherwise have it?" (1=no knowledge, 5=highly knowledgeable)
Open ended question
Imagine a typical astronomy lesson from one of the grade bands in the previous question. Please describe the grade band and what this lesson or activity may look like. What would students do? What would students learn? How would they be assessed, if at all?:

Figure 4 Two questions used to sort responses.

Interviews

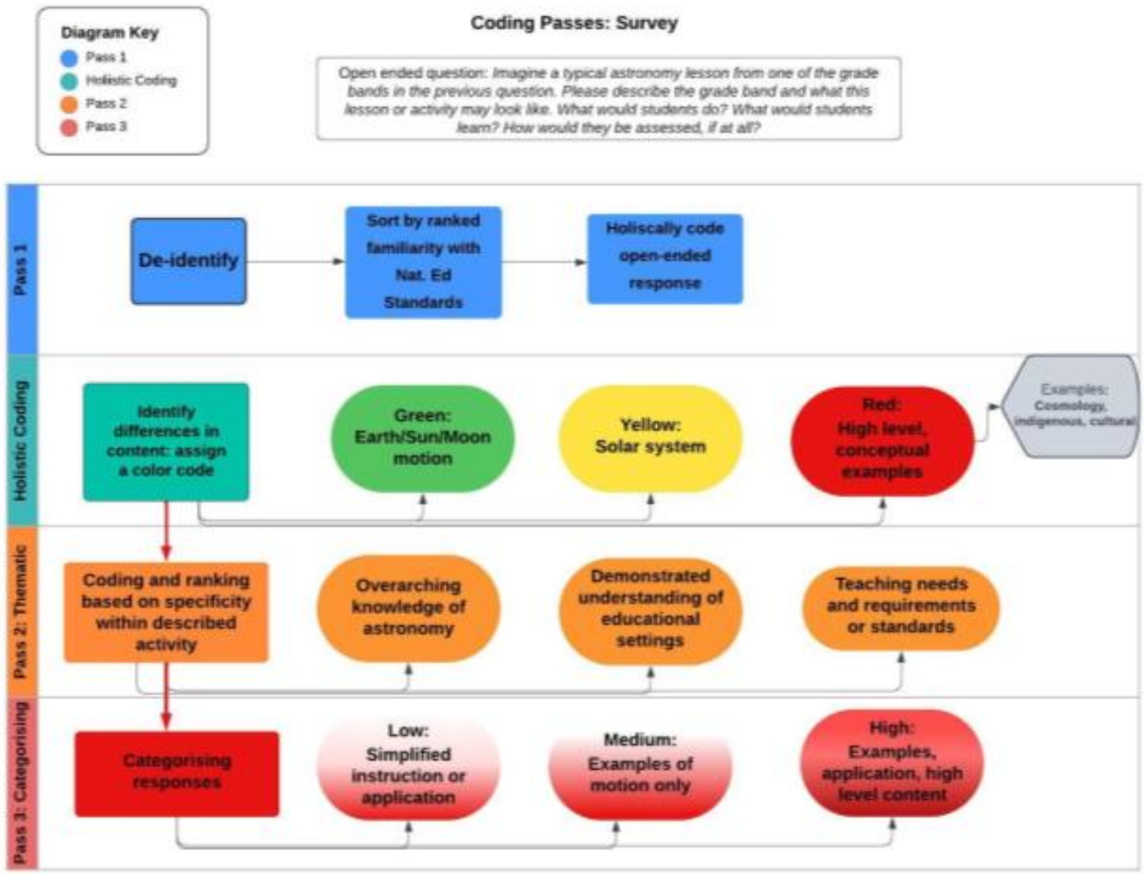
Ten participants were selected for semi-structured video interviews (Figure 5). Participants were asked to discuss the relationship between their national education systems and astronomy, national contexts of astronomy and education, opportunities and barriers to integrating astronomy, teacher education and professional development, and the presence or influence of a space program. These general themes formed the foundation for cross case analysis. The semi-structured nature of interviews allowed for additional probing, such as explanations of specific components of respondents' work and their motivations to study space.

Note: Figure created in Google maps by the first author.

Figure 5 Location of Interview Participants

Data Analysis

Survey responses were sorted and coded (Figure 4) in three passes, which allowed us to select interview participants. We describe each method below and provide a graphical representation of the process in Figure 6.



Note: created by the first author in LucidCharts

Figure 6 Diagram of coding passes

Survey.

During our first coding pass we sorted responses based on familiarity with national education standards (i.e., the closed question in Figure 4). Next de-identified responses to the open-ended question were holistically coded (Huberman & Saldaña, 2019; Saldaña, 2021) based on demonstrated content knowledge and instructional design. Holistic coding allowed the data to drive our process. We noted whether examples of lessons and assessments were provided in the question, however we acknowledge that this required a high level of fluency in English and so a lack of inclusion in the written response may not be indicative of a lack of knowledge in this area. We used colour codes to characterise differences in referenced content: terms related to the Earth/Sun/Moon system or motions were coded in green, solar system coded in yellow, and higher level or deep conceptual examples coded red. Higher level examples included cosmology or any relation to indigenous or cultural astronomy. This method did not hold for all responses, so a thematic framework (Huberman & Saldaña, 2019) was used for the second pass.

The second pass ranked respondents thematically based upon specificity within their described student activity, demonstrated astronomy knowledge, and active learning (non-lecture based) practice (Lombardi et al., 2021). Coding included identifying themes of overarching astronomy knowledge, demonstrated understanding of educational settings, teaching needs and requirements, standards, and any other information from their response.

The third pass was categorically coded in a spreadsheet. Categories "*high*," "*medium*," and "*low*" were assigned with colour codes to components of open-ended responses based on demonstration of content knowledge and instructional design. For example, "*high*" codes included lesson activities with specific examples, application of content, and/or content beyond celestial motion (e.g., Kepler's laws, astrobiology, cultural astronomy); "*medium*" included motion related examples; and "*low*" included simplified level of instruction or application. Codes and notes from the second pass were included, and new coding emerged in this stage. Responses with a significant degree of "*high*" level categorical codes or other interesting factors, such as *mandatory astronomy in the curriculum*, were numerically ranked and sorted. Finally, we compared all rankings to identify which participants would be interviewed and to balance country selections.

Interviews

Interview data analysis was informed by the work of Miles et al. (2019). Following each interview, detailed analytic memos were composed and stored in a password protected folder. Interviews were transcribed using Otter.ai and manually corrected. Holistic coding was used to generate comparative themes from transcripts used in cross case analysis. Thematic arrays and comparison tables were created to characterise and compare themes across countries and to aggregate situated characteristics. Emergent themes included education systems (including curriculum and assessment), teachers and teaching, benefits and barriers to teaching astronomy in formal settings, and national astronomy programs. Each interview participant also shared local examples.

Researchers’ Positions

The authors are white, English speaking American women. Both have experience in K-12 and university teaching of astronomy. Both authors have extensive experience with US education standards and teacher training and professional development. The first author is a NAEC that provided access to participants in similar roles through an online communication system. Nine of ten interviewees were non-white, English as a second (or third or fourth) language. One interviewee (Romania) required an interpreter.

Results

Survey

Survey results indicated most respondents were moderately to very familiar with their respective education systems (Figure 6). Over 80% selected “3” or above on a scale where 1 = no knowledge, 5 = highly knowledgeable (n = 68; M = 3.63, SD = 1.22).

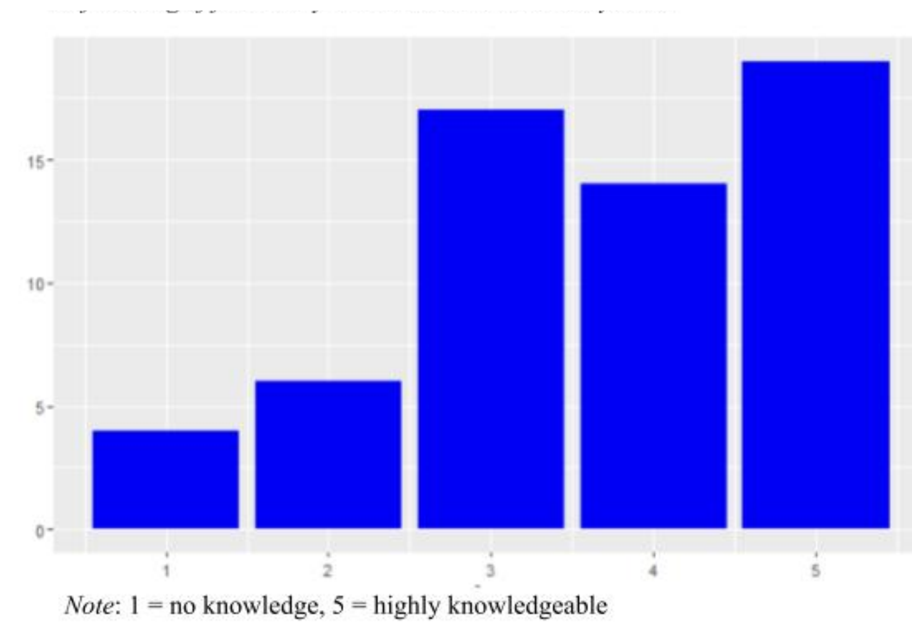
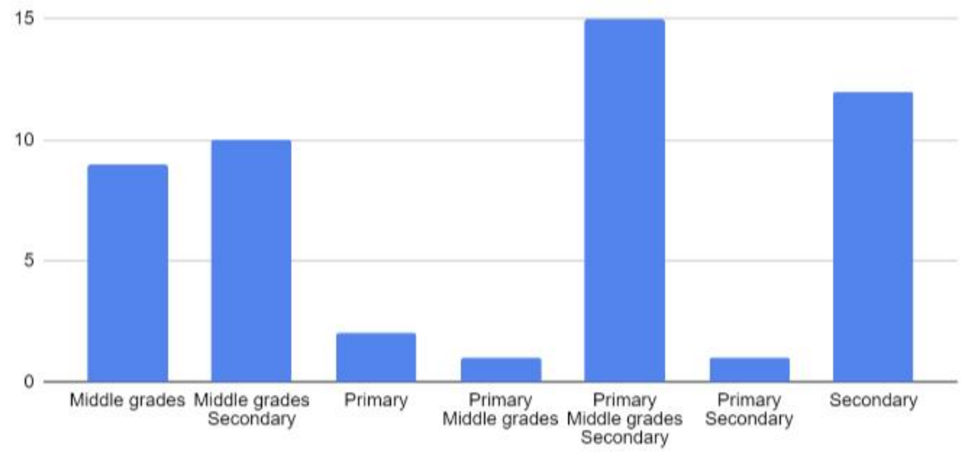


Figure 7 Self-ranking of familiarity with national education systems

Figure 7 shows the distribution of the grade levels at which astronomy is taught in respondents' countries. Over half of participants indicated this occurs at the university level (*n = 34*). This was neither surprising nor the focus of the present study; therefore, these responses were omitted from Figure 7 to allow us to focus on primary and secondary learning. Participants confirmed the Salimpour et al. (2021) study indicating that astronomy content appears across multiple grades in their country.



Note: participants could select all that apply.

Figure 8 Grades astronomy is taught

Amongst participants, 70% were educators in primary or secondary grades, however many respondents served within overlapping formal and informal capacities (such as university professor and professional astronomer). Secondary teachers defined the largest respondent population (Figure 8).

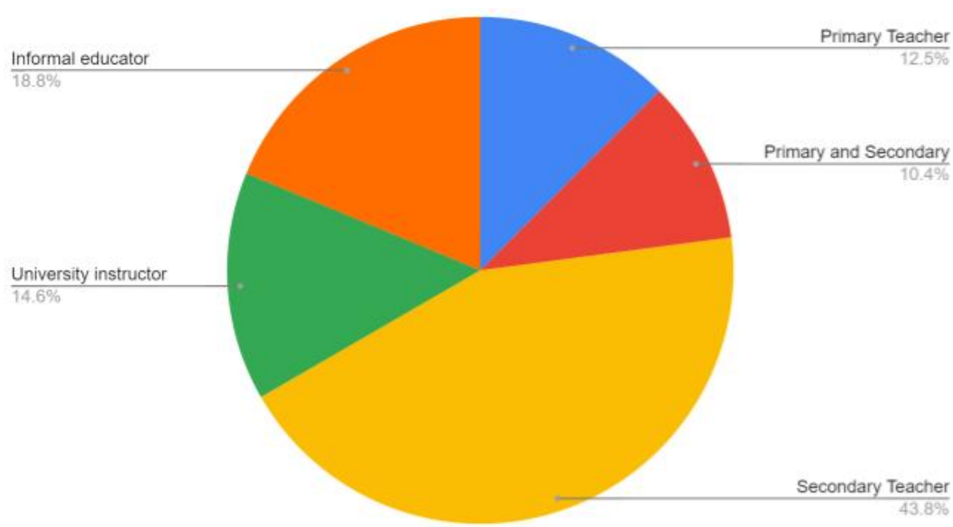


Figure 9 Role of respondents

Open Ended Survey Responses.

Results of the coding process revealed great variation in responses; most participants did not answer all components of a given question, particularly regarding assessment. Some copied academic standards, while others described specific activities. Some respondents generalised based on age-assumed expectations (such as low-level recall), not professional experience; some presumed school outcomes (such as testing), while others provided individual perspective and examples. Nearly all responses included reference to Earth/Sun motion, and many included moon phases, motion, and observable features (craters, tides, diurnal motion). Two mentioned cultural or indigenous references to astronomy while no respondents mentioned women. Assessment was cited 12 times, and formative assessment once. The second coding pass revealed eight non-US responses that demonstrated deep understanding of student knowledge and grade-appropriate activities, content knowledge, understanding of education systems, astronomical intersections of standards, and teacher needs. These examples also provided specific lessons or learning processes that incorporated astronomy.

Interview Results

Cross Case Analysis

In the following sections, we revisit the research questions and provide examples from interview data to answer them. We cannot overstate that data represents individual settings and contributions and may not fully reflect national educational settings or practices. The following identifiers (Figure 10) were used to identify participants and their associated countries as we addressed the research questions while de-identifying them personally. In general, we used the first initial of the country when referring to the participant and the full country name otherwise. Six of the interview participants were National Astronomy Education Coordinators.

Country	Role	Identifier
Mexico	Secondary teacher, space program director	M
Romania	Past educator, math and astronomy education government official	R
Japan	Teacher educator, former professional astronomer	J
Nigeria	Space agency employee, outreach coordinator	N
Thailand	Professional astronomer, outreach coordinator	T
Pakistan	Non-profit founder, informal education leader, local celebrity	P
Brazil	Planetarium director and teacher educator	B
Belgium (Flanders)	Observatory director, professor, teacher educator	BF
Canada (Quebec)	Director-National astronomy education program	Q
Colombia	Planetarium director, outreach and teacher education coordinator	C

Figure 10 Identifiers for interview participants

RQ 1: How is astronomy used internationally to promote STEM in community and school?

Participants from numerous countries cited the role of public stargazing events and the use of telescopes to inspire STEM in communities and schools. In multiple instances, these events also attended to equity (see also RQ 3). In Nigeria, Astronomers Without Borders (AWB) acquired telescopes from abroad (they are not sold anywhere in the country) for use in public events. Volunteers—most of whom are women—placed telescopes in malls and shopping centres for public observation; this is, for many, the only time they will see a telescope. In Mexico, M and their students acquired telescopes through a university partnership, which they then set up in rural communities on weekends for public viewing. M noted that telescopes address a critical need in these rural communities that lack facilities or opportunities for young people to engage with each other in a productive way. Japan's numerous observatories and planetariums host popular star parties, attended by over 8 million people annually. T's program (Thailand) loans hundreds of telescopes to students and teachers for individual projects and observations. During the pandemic lockdown of 2020, Q initiated a virtual "look up" campaign to unite family members separated by the pandemic through synchronous sky observations. P uses art and theatre in public spaces to engage the public with issues of light pollution in Karachi, Pakistan. Through this local phenomena, P highlights awareness of the interconnections between astronomy and society. He creates art pieces and costumes to represent changes to biodiversity, a parallel symptom of light pollution.

One emergent theme, which is consistent with the literature, was the use of astronomy to engage with the nature of science and STEM. In Mexico, M stated that space topics incentivized opportunities to learn, engaging some students who were otherwise unexcited about school. M's program has gained national recognition, prestige, and respect. Access to the astronomy program is coveted and competitive: "space is the prize" for students who work hard. M uses space as the medium to promote social mobility and job opportunities in STEM through monthly workforce development programs in a region of high poverty and few education opportunities. Students are treated to [free] high-end meals in expensive restaurants during the events and hear from experts in various fields. Recently, students learned about careers in animation. M prompts students to "think about the skills you need to be your parents' boss." In Brazil, B takes a portable planetarium to every school in the state in order to assess the age of science interest loss. P created a program to teach business and marketing skills through the lens of space. One rural student in P's program learned about constellations in order to create and sell star charts.

RQ 2: What lessons can be learned from international astronomy education efforts?

Informal Education.

Informal education played a surprising role in astronomy education efforts; we expected to find examples from classrooms, however the interview data revealed the importance of informal learning in sustaining engagement with astronomy. In Japan (as in many of the countries we investigated), most astronomy education occurs outside the classroom. Over 350 observatories, planetariums, and science centres are attended by over 8 million people annually. Every region of Japan has at least a moderate sized observatory, and large, 1-m public telescopes are not uncommon. Star parties and public lectures are well attended. Programs focus on engaging and interest capturing current topics in space, JAXA, the Japanese Space Agency, has also greatly increased their public presence through education and outreach. In Nigeria, AWB and the Nigerian Space Agency collectively and collaboratively address gaps in formal and informal education. The Nigerian Space Agency brings students on site for lectures and field trips, while AWB travels to schools. AWB also works outside of the school calendar. Many volunteers (and the AWB director) work with both organisations. In Quebec, amateur and professional astronomers collaborate to offer stargazing opportunities for the public. Similar networks of amateur astronomers exist in Pakistan, Canada, and Japan. In Pakistan, informal and community-based initiatives have sparked enough interest to prompt the creation of teacher and student materials. High national interest has led to informal astronomy programs in Colombia as well; the first computer-powered planetarium in Latin America sits in the former site of a crime-ridden neighbourhood in urban Colombia, and offers opportunities for schools and teachers to learn astronomy. The sprawling park complex now includes botanical gardens and a library focused on scientific literacy and social connections to science. In Belgium, the only opportunities to learn about astronomy are likely to be informal due to strict curricular requirements in formal education that exclude astronomy and discourage modification.

Astronomy and Curriculum.

In most countries in our study, descriptive astronomy topics of motion and the solar system were minimally embedded in younger grades, while some advanced topics may emerge in secondary physics courses or through projects. Some countries (Japan, Romania, Pakistan) integrated astronomy into units within other course work, but participants noted that many teachers skip these sections. Astronomy is loosely embedded into grades 3-6 and somewhat into the Japanese curriculum of high school Earth science; as in the US and elsewhere, most students opt to take “higher” courses. The Canadian curriculum includes a robust suite of astronomy across every grade band, although implementation varies by province. First Nations astronomy appears in multiple provinces and grades; this differs slightly from the findings of Salimpour et al. (2021), which looked only at Quebec. Innovative and engaging topics include space exploration, economic development, and sustainability. In Canada and other nations, including astronomy in curricula yet excluding it from exams allows teachers to skip or minimise if they lack time or proficiency. Approximately 20 years ago, Romania removed astronomy from their curricula, although (as in many countries) physics coursework could include astronomy. Physics was later reduced from 3-4 hours per week to 1-2, thus reducing content to minimum standards and eliminating any remainder of astronomy. However, recent National support and research favours future inclusion. R created an astronomy curriculum for the first three primary grades focused on women in space, which was nationally adopted in 2022. Upper grades and a teachers' manual are in development.

Thailand is the only represented nation that mandates an entire year (in high school) of astronomy, which has both the positive impact of widespread exposure and negative impact of forced learning. The rapid inclusion of astronomy as a standalone class was not coupled with supportive educator preparation, leading to an unrealistic ideal of the field and disillusionment amongst students. T's research institution has dedicated a substantial component of their budget to outreach and teacher education in order to address the gaps imposed by reform. Thailand presents an interesting paradox: Is requiring astronomy a benefit or a barrier to curiosity, engagement, and continued learning?

While only two participants addressed astronomy explicitly in their standards (Canada and Thailand), participants cited curricular flexibility or widespread use of projects to increase opportunities for astronomy study. Countries with mandated and scripted curricula left little room for variation. In Belgium, teachers who deviate from the adopted curriculum can be audited to ensure they address standards and fired for repeated violations. Conversely, teachers in Mexico have much more freedom to address curriculum needs and are encouraged to participate in high profile activities that increase the visibility of the school. M and his students have appeared on television numerous times, which administrators perceive favourably. Many participants also cited curricular differences between public and private schools. In Pakistan, teachers in private schools are exempt from the confines of the provincial curriculum, which could allow for greater inclusion of astronomy.

Astronomy was used in multiple instances of national and international projects and contests. Many of the interviewees organised regional or national events for Astronomy Olympiad, international observing events, International Space Week, and eclipse viewing. Colombia has a national Astronomy Olympiad team, which C cited as igniting his passion for astronomy. Thai students can earn scholarships through Olympiad, as well as address the national graduation project requirement (astronomical observations can also fulfil this goal). T and colleagues mentor student clubs and individual projects with their outreach. In Mexico, which is amidst curricular reform, teachers are encouraged to use projects to foster extracurricular learning. While rare, some Japanese students use astronomy for research projects, and JAXA supports student competitions to build small satellites.

National Contexts of Education.

Participants perceived the varying contexts, settings, and dynamics of education and the teaching profession in each country to influence astronomy use in classrooms. Some nations, such as Japan and Nigeria, included teachers in curricular decisions while others, such as Thailand, imposed decisions upon them. In Mexico, principals make curricular decisions. In Japan, curricular practice and pedagogy are standardised and uniform; this is not seen as de-professionalizing, but as a benefit in that high quality is expected everywhere, regardless of location or region. Japanese teachers can modify curricula, but have little time to do so. In Canada, education is differentially mandated by the Minister of Education in each of 10 provinces. Some provinces recently revised curricula while others have not changed in 30 years. This gap in reform and implementation was perceived as a hindrance to including newer topics in astronomy, such as exoplanets. The variation between strictly adhering to or deviating from curriculum is limited by the size and “person power” of individual provinces.

Some participants, such as T, cited the role of national exams in driving curricular decisions. Thai students’ curricular tracks are also determined by testing. The Canadian curriculum contains a commendable quantity of astronomy, including exploration and First Nations, yet fails to be included any in exams. Unsurprisingly, there is little incentive to comply with teaching the astronomy content that is present in the curriculum.

Reform.

Every interview participant cited national education reform efforts as a contributing factor to including or excluding astronomy in curriculum. Reform was cited as additional stress to overburdened teachers. In Mexico, a “new model” of education emphasises social emotional learning and is more topic based than integrated. In Japan, teachers are now required to teach English at an earlier age and to incorporate new pedagogical elements. In some nations, teachers contributed to reform efforts and materials: Japan, for example, revises their educational standards and curriculum about every 10 years with teacher input. Pakistan heavily involves teachers in national committees and curriculum boards. Other nations impose decisions in hierarchical fashion: Thailand failed to include any teacher insight or support prior to requiring a standalone astronomy class.

National Space Programs.

The presence of a national space program, professional astronomers, or mobility within space science fields was perceived by participants as influencing national prestige and engagement with astronomy. Belgium, for example, lacks a space program and has had only two citizens in space. There is little excitement for space exploration or national connection to the global space industry, and universities do not offer astronomy until graduate school. Contrarily, astronomy is of high national interest and “social capital” in Japan. Informal astronomy education efforts and popularisation of the Japanese space program in the media were attributed to thriving interest in space fields. JAXA has emerged in recent years as a prominent figure in the global space economy and is a household name. The space agency provides many outreach opportunities through school site visits, student contests, and teacher training. The Nigerian Space Agency brings 1000 students per week to their site during the school year. In 2009, they wrote astronomy curricula, although this unfortunately fell prey to political bureaucracy and has not been implemented. T's national astronomical science program has the largest social media presence of any group in the country; they are synonymous with space. This program allocates 20% of their budget to outreach and education efforts, loans hundreds of telescopes to schools, and assists in clubs and national contests. The Canadian Space Agency (CSA) has scaled back a once-robust outreach program, yet notably includes First Nations astronomy activities on their website. Mexico has a new space program with minimal outreach and presence amongst the Mexican population. The Mexican space program, according to their website, is focused on communications whereas Japanese and Canadian programs explicitly focus on exploration.

The presence of a space program also seemed to contribute to the growth potential of the profession. Many Japanese universities have astronomy degree programs and introductory coursework. In Canada, there are more individual astronomy PhDs than jobs; over half of graduates do not work for CSA, however Q assumed that the agency was growing. Thailand has a newer space agency and workforce. The presence of astronomy in Thai schools allows students to consider this as a viable career, however the nation lacks job opportunities to match the interest. When T's program began, there were only a handful of astronomers in the country. Thailand has only one university degree program, and now a few dozen astronomers; this greatly limits collaborations between professional astronomers and educators, or coordinated events. Columbia lacks any PhD program in astronomy; astronomers are either self-taught or travel abroad for advanced study.

University Partnerships.

In various cases, university partnerships played an important role in connecting students and communities to STEM. University partnerships seemed to represent larger, collaborative programs. In Brazil, a partnership with a university established an astronomy research program to assess the loss of interest in science through visits to every school in the state and to design interventions based on the findings. In Mexico, a university telescope loan program provides training and mentorship for students to build the borrowed telescopes. Students, with parents as notetakers, travel to the university to learn the science and engineering behind telescopes from university students and professors. For many, this is their first time leaving their communities and their first exposure to a university setting. Thus, astronomy is "opening their eyes to the world" and occupational opportunities outside of their community. In Japan, Brazil, Pakistan, Belgium and Thailand, universities or research centres provide training for teachers in astronomy. In each, however, participation and recruitment were consistent barriers, particularly in the wake of the pandemic.

Educator Professional Learning.

Teacher professional learning programs were discussed in many interviews. The Romanian Ministry of Education and the IAU Office of Astronomy Education have recently implemented professional development for teachers in multiple regions throughout the country and begun developing astronomy curricular material for early grades. In Mexico, teachers travel to M's school site for up to a week to learn how to implement similar astronomy programs and projects; 500-600 teachers have brought telescopes to their classrooms and communities over the life of this program. T's program plays a vital role in equipping teachers with the astronomical skills to teach the national curriculum. They offer five large annual training sessions at multiple locations. A university in Pakistan has an astronomy program for teachers and provides space-integrated STEM curriculum materials.

Common Barriers.

Each interview participant expressed frustration at the minimal teacher training opportunities in astronomy and lack of prioritisation for space-based curriculum topics. Textbook language emerged as a significant barrier in two countries: In Mexico, middle school level astronomy textbooks are not available in Spanish. Similarly, in Quebec, space-related materials are only available in English, whereas French is spoken in schools. Q recently created the first astronomy outreach and curricular material for French speakers in the nation.

Funding was a significant barrier to astronomy education. In Mexico and Nigeria, education is free but materials are not. Ironically, the prohibitive cost associated with robotics programs and local availability of the university telescope loan originally led M to include astronomy topics. N and AWB provide free curricular resources to schools in Nigeria and travel directly to communities to eliminate transportation costs.

Teacher burden, stress, and time commitments were also cited as common barriers. In Japan, which has high respect (and pay) for teachers, increased teacher stress is perceived as a national problem. Teachers in Japan have additional responsibilities to community and local education authorities. Attendance at professional development and participation in astronomy clubs at planetariums rapidly declined in recent years, resulting in the elimination of many such programs. A decreasing population in Japan has also led to smaller schools with increased class sizes, adding to the cumulative weight upon teachers. Teachers in Japan are highly trained; time was perceived as a greater barrier than teacher confidence, as in other countries.

RQ 3: How do international astronomy education efforts attend to equity and diversity?

Several programs demonstrated innovative integrations of astronomy and equity. Telescope loan programs provide access and opportunities to poor classrooms and remote communities in Mexico and Thailand. Astronomy was a catalyst for social mobility in Mexico and Pakistan. M founded a space-based workforce development program with mentorship and university exposure. P created a program to integrate tools of astronomy technology with professional trades, incorporating robotic telescopes to teach business and entrepreneurship. P's non-profit also uses community art and theatre to demonstrate the role of light pollution as a symptom of social problems.

Inclusive activities occurred in several instances. Popular planetarium shows in Japan centre collective human futures in space. Brazil uses astronomy to investigate the age at which science interest declines and will design space-based curricular tools to address their findings. Curricular documents in several Canadian provinces include First Nations perspectives on celestial motion, sustainability, and interconnectedness as early as kindergarten. Interestingly, in rural and largely First Nation Nunavut, curricular documents lack any reference to First Nations perspectives yet students should be introduced to the problems of space travel in grade 6.

AWB (in Nigeria) uses astronomy to actively disrupt gender stratification and to showcase women in STEM fields. Female volunteers spotlight possibilities for girls and opportunities to pursue STEM fields at public and school-based space events. They provide girls with feminine products so they may avoid missing school during their menstrual cycles, and support girls taking national high school graduation exams and university entrance exams; the cost of each easily exceeds a month's income. AWB and N fundraise to provide financial support to families so that their school-aged children can attend summer camp, instead of working, so families do not lose income.

JAXA is also seen as disrupting gender roles in a "society of men" and employs more women than most other STEM sectors. R uses astronomy to address the persistent gender gap in the Romanian workforce. Nationally, curriculum failed to connect students to careers, but R uses content centred on women in space as a lever to simultaneously change the curriculum, demonstrate to the Ministry of Education the importance of astronomy, and promote domestic career growth.

For M, exposing his students to space content and careers is an act of equity. He fears that his country will be left out of the growing global space economy if young people lack access to learn about space. He has appealed to his Ministry of Education to include astronomy and aerospace content because "space is a human right." His community is located near famous Mayan pyramids and other sites of deep cultural and astronomical significance. Multigenerational stories connecting Earth and sky speak to the cultural connection to astronomy; “we are natural astronomers—astronomy is in our blood.”

Summary

Overall interview coding results indicated that countries represented by interview participants favoured informal, self-directed astronomy learning over mandated and formal curricula. Thailand, which mandated a year of astronomy, cited low levels of student interest and an “unfair representation of the field,” whereas countries with national space agencies, planetariums, and informal learning opportunities maintained public interest, demonstrated career potential, and promoted the “social capital” of astronomy (Japan, interview). Some nations lacked professional astronomers or university programs, limiting professional growth opportunities. Partnerships, collaborations, and outreach emerged as important ingredients to learning astronomy.

Limitations

Case studies from interviews were included in this analysis, however broad generalisations are beyond the scope of this study. Case studies represent individual perspectives and experiences that may not reflect large scale practices across classrooms, communities, or nations. Descriptions provided by participants in the present study may be generalizations; it is unknown (and beyond the scope of this study) the extent curricular implementation aligns with these perceptions. Further, curricular references may reflect adopted standards that could differ from implemented practice. We also acknowledge the language limitations that may have prevented the input of very qualified individuals.

This study is not an effort to minimise or qualify educational efforts in any nation, but an attempt to create a collaborative space to learn from and with each other to increase access to astronomy education. This study incorporates the words, thoughts, and experiences of individual representatives of select nations. Their opinions, perspectives, and voices carry this work. This may not be entirely representative of education systems within their country, and we acknowledge that individual interviews pose significant limitations to national extrapolations. However, each interviewee provided rich context for cross cultural learning through local examples, lessons learned, and descriptions of outreach efforts. As nations revise and reform education efforts, particularly related to STEM, astronomy offers unique opportunities.

Discussion

School systems have frequently focused on curriculum, test preparation, and disciplinary control rather than engaging in quality learning experiences (Brown et al., 2019). Emerging from a global pandemic presents a golden opportunity to invigorate learning with relevant topics of interest that leverage multiple facets of STEM thinking and learning. This study provides examples of leveraging astronomy as a gateway to STEM and corridor to equity to equip the next generation of global citizens.

The multidisciplinary nature of astronomy can reframe science as a practice, with students meaningfully connecting core ideas and concepts (NRC, 2007) to inform who can do science and whose knowledge is counted (Ko & Krist, 2019). We see this attempt at expanding the range of who can do science in the efforts of N and AWB, M, P, R, and B, for example. Programmatic efforts such as by P, M, T, and C positioned students as scientists through the lens of astronomy, while B's efforts used astronomy as an indicator of greater issues in science education. Embedded astronomy content has the capacity to highlight shifts from science as a singular endeavour to that of collaborative and global society, thus reflecting a more accurate depiction of the field (Salimpour et al., 2021). Efforts such as those by P, Q and M highlight the transdisciplinary and collaborative nature of astronomy.

Implications for Practice

Astronomy education in the 21st century should focus less on the common basic descriptors found in curricular documents and include items of relevance and interest within the field (Pasachoff, 2001). A recent study in Romania (Ficuț-Vicaș, 2018) indicated strong parental and educator support for returning astronomy topics to the curriculum. Space travel, exploration, economies, and commercialization represent legitimate and engaging topics for students, while highlighting the intersecting roles of art, history, technology, media, and government relations within

STEM. Astrobiology and various free plants in space projects[2] provide the ability to conduct analog experiments and participate in citizen science. Many free robotic telescope programs[3] allow students to conduct high quality observations from any location. Free software[4] is available for image analysis and data reduction, including asteroid detection and solar observations.

This study illustrates the need to include informal learning and partnerships in teaching astronomy. Pompea and Russo (2020) demonstrate a number of ways that astronomers can engage with education, including informal education and community engagement strategies and the outcomes that may emerge from these settings. Informal and community learning can provide critical opportunities for STEM identity development, particularly amongst women and underrepresented populations (Fields, 2009). Events such as star parties allow familial and community connection

---

[2] Grow Beyond Earth; Space Chili Grow a Pepper Challenge; Tomatosphere (available in the US and Canada)

[3] NASA Microobservatory; Stellarium; WorldWideTelescope; SLOOH is low cost

[4] NASA Asteroid Data Hunter (Topcoder); NASA FITS Image Viewer; American Association of Variable Star Observers; Solar and Heliophysics Observatory (SOHO)

through shared identity negotiation (Wenger, 2011). Diversity, equity, and inclusion cannot be separated from the context of astronomy education. Cultural connections to astronomy are well documented in literature, yet elusive in curriculum (Salimpour & Fitzgerald, 2022). Material quality and content must be updated to reflect multiple worldviews and demographics of students, instead of propelling an antiquated view of who can do science.

Implications for Research

Future research should investigate characteristics and impacts of these programs on student learning and teacher self-efficacy, as well as integration with national curricula. Research should also focus on the role of partnerships with informal learning centres, universities, and astronomers. Community-driven programs, such as within Pakistan and Nigeria, should be studied to determine their effectiveness and contributions to STEM, as well as their scalability. The Brazilian program, which includes robust evaluation, provides a unique model for replication. Studies on informal astronomy learning, particularly in countries with no inclusion of astronomy within the curriculum (such as Japan and Belgium), could focus on the drivers and moments of identification within STEM fields amongst professionals, particularly women and those from underrepresented populations.

Salimpour et al.'s (2021) study demonstrated, and this study supports, the need for research on professional development and curricular needs of integrated astronomy to ensure rich astronomical sequences permeate classrooms. Every participant confirmed this need and expressed frustration at the lack of astronomy preparation for teachers in their country. Coordinated national and international efforts from organisations such as the IAU and space agencies should focus on establishing common topics, best practices, and activities to integrate robust astronomy instruction. Programming should focus on conceptual understanding and application, moving beyond surficial, descriptive topics. Astronomers and educators should have equal footing within this planning. Professional learning for teachers should be free and globally available online with opportunities for professional learning communities and onsite continued learning. The *Big Ideas in Astronomy* (Retrê et al., 2020) could serve as a foundation, while the current study provides several examples of partnerships with informal learning centres, universities, and astronomers to support teachers. Networks such as NASA Solar System Ambassadors, Nigeria's (and others') Astronomers Without Borders, and Mexico's university partnership could be scaled to meet the needs of individual regions.

Conclusion

Knowledge of the Earth-space system is vital for society's future; humanity is increasingly dependent upon space-based technologies for climate modelling, communications, information systems, and defence. As we return to the Moon and explore possibilities of life off planet, we must also consider opening space to those previously excluded from the field; equitable access and exposure to learning of space science is a critical act of justice and inclusion that must be addressed within the astronomical and education communities.

Curricular reform efforts present an opportunity to weave space content into existing coursework. Students who are exposed to robust learning sequences, including space sciences, at earlier ages are also more likely to choose these careers and college tracks. We have the collective potential to drastically disrupt and diversify the representation and perspective of this field by providing astronomy coursework to every student, beginning in elementary school. Graduate student recruitment and adult workforce training programs fail to encompass the magnitude of this opportunity, or to adequately address the root of inequities in STEM fields (Maltese & Tai, 2010). Embracing astronomy in the greater context of primary and secondary education requires the involvement of all stakeholders—from educators to industry, state and federal governments, and universities. Astronomy provides an untapped potential to incorporate non-western views of knowing and inclusion in STEM (Salimpour & Fitzgerald, 2022) and to leverage astronomy as a transdisciplinary and transformative process, practice, and content area for the good of the global community. The present study provides examples of communities and individuals doing just that.

Ethics Statement

This study was carried out under the education research program at University of California, Santa Barbara (IRB# 61-22-0025). All procedures performed in this study were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all survey and interview participants involved in this study. This research was not supported by grant funding from any entity or institution. The first author holds a similar role to some participants as the national chair of an international committee on astronomy education.

References

Cesarsky, C., & Walker, H. (2010). Head count: Statistics about women in astronomy. *Astronomy & Geophysics*, *51*(2), 2.33–2.36. https://doi.org/10.1111/j.1468-4004.2010.51233.x

Chen, S. (2017, April). How African-American women succeed in physics. *APS News, 26*(4). http://www.aps.org/publications/apsnews/201704/women.cfm

Dodick, J., & Orion, N. (2003). Geology as an historical science: Its perception within science and the education System. *Science & Education*, *12*(2), 197–211. https://doi.org/10.1023/A:1023096001250

Ficuț-Vicaș, D. (2018). The role of astronomy in Romanian education. *Romanian Review of Geographical Education, VII(*2)*,* 36–48. https://doi.org/10.23741/RRGE220183

Fields, D. A. (2009). What do students gain from a week at science camp? Youth perceptions and the design of an immersive, research-oriented astronomy camp. *International Journal of Science Education, 31*(2), 151-171. https://doi.org/10.1080/09500690701648291

Impey, C. (2012). Astronomy in the United States: Workforce development and public engagement. In A. Heck (Ed.), *Organizations, people and strategies in astronomy I (OPSA I)* (pp. 77–91). Venngeist.

International Astronomical Union. (n.d.). *Geographical and gender distribution of individual and junior members*. Retrieved November 11, 2022, from https://www.iau.org/administration/membership/individual/distribution/

Kang, H.,, Calabrese Barton, A., Tan, E.,, Simpkins, S., Rhee, H., & Turner, C. (2019). How do middle school girls of color develop STEM identities? Middle school girls' participation in science activities and identification with STEM careers. *Science Education*, *103*(2), 418–439. http://dx.doi.org./10.1002/sce.21492

Kim, A. Y., Sinatra, G. M., & Seyranian, V. (2018). Developing a STEM identity among young women: A social identity perspective. *Review of Educational Research*, *88*(4), 589–625. http://dx.doi.org.proxy.library.ucsb.edu:2048/10.3102/0034654318779957

Ko, M.-L. M., & Krist, C. (2019). Opening up curricula to redistribute epistemic agency: A framework for supporting science teaching. *Science Education*, *103*(4), 979–1010. https://doi.org/10.1002/sce.21511

Krumenaker, L. E. (2009). The modern U.S. high school astronomy course, its status and makeup, and the effects of No Child Left Behind. *Astronomy Education Review, 8*(1), 010107. https://doi.org/10.3847/AER2009052

Lewis, E., & Lu, J. (2017). A case of fragmented high school Earth and space science education in the Great Plains: Tracing teacher certification policy to students' access. *Journal of Geoscience Education*, *65*(3), 304–321. https://doi.org/10.5408/17-253.1

Lombardi, D., Shipley, T. F., Astronomy Team (Bailey, J. M., Bretones, P. S., Prather, E. E.), Biology Team (Ballen, C. J., Knight, J. K., Smith, M. K.), Chemistry Team (Stowe, R. L., Cooper, M. M.), Engineering Team (Prince, M., Geography Team (Atit, K., Utall, D. H.), Geoscience Team (LaDue, N. D., McNeal, P. M., Ryker, K., St. John, K., van der Hoeven Kraft, K. J.), & Physics Team (Doktor, J. L. (2021). The curious construct of active learning. *Psychological Science for the Public Interest*, *22*(1), 8–43. https://doi.org/10.1177/1529100620973974

Maltese, A. V., & Tai, R. H. (2010). Eyeballs in the fridge: Sources of early interest in science. *International Journal of Science Education*, *32*(5), 669–685. https://doi.org/10.1080/09500690902792385

Miles, M. B., Huberman, A. M., & Saldaña, J. (2019). *Qualitative data analysis: A methods sourcebook* (4th ed.). SAGE.

National Academies of Sciences, Engineering, and Medicine. (2021a). *Call to action for science education: Building opportunity for the future*. The National Academies Press. https://doi.org/10.17226/26152

National Academies of Sciences, Engineering, and Medicine. (2021b). *Science and engineering in preschool through elementary grades: The brilliance of children and the strengths of educators*. The National Academies Press. https://doi.org/10.17226/26215

National Research Council. (2007.) *Taking science to school: Learning and teaching science in grades K-8.* The National Academies Press. https://doi.org/10.17226/11625

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. The National Academies Press. http://www.nextgenscience.org/

Orion, N. (2001). Geology as an Historical Science: Its Perception within Science and the Education System. *Science & Education*. Retrieved June 9, 2021, from https://www.academia.edu/19880134/Geology_as_an_Historical_Science_Its_Perception_within_Science_and_the_Education_System

Orion, N. (2017). The relevance of earth science for informed citizenship: Its potential and fulfillment. In *Contextualizing Teaching to Improve Learning: The Case of Science and Geography* (pp. 41–56).

Orion, N. (2019). The future challenge of Earth science education research. *Disciplinary and Interdisciplinary Science Education Research*, *1*(1), 3. https://doi.org/10.1186/s43031-019-0003-z

Pasachoff, J. M. (2001). What should students learn? *The Physics Teacher*, *39*, 381–382. https://doi.org/10.1119/1.1407137

Percy, J. R. (1998). Astronomy education: An international perspective. *International Astronomical Union Colloquium*, *162*, 2–6. https://doi.org/10.1017/S025292110011468X

Pompea, S. M., & Russo, P. (2020). Astronomers engaging with the education ecosystem: A best-evidence synthesis. *Annual Review of Astronomy and Astrophysics, 58*(1), 313-361. https://doi.org/10.1146/annurev-astro-032620-021943

Porter, A. M., & Ivie, R. (2019). *Women in physics and astronomy, 2019.* American Institute of Physics. https://www.aip.org/statistics/reports/women-physics-and-astronomy-2019

Regents of the University of California. (n.d.). *Subject requirement (A-G).* Retrieved November 11, 2022, from https://admission.universityofcalifornia.edu/admission-requirements/freshman-requirements/subject-requirement-a-g.html

Retrê, J., Russo, P., Lee, H., Penteado, E., Salimpour, S., Fitzgerald, M. T., Ramchandani, J., Pössel, M., Scorza, C., Christensen, L. L., Arends, E., Pompea, S. M., & Schrier, W. (2020). *Big ideas in astronomy: A proposed definition of astronomy literacy.* IAU Office of Astronomy for Education. https://astro4edu.org/media/bigideas_images/BigIdeas_v2.0.pdf

Saldaña, J. (2021). The coding manual for qualitative researchers (4th ed.). Sage.

Salimpour, S., Bartlett, S., Fitzgerald, M. T., McKinnon, D. H., Cutts, K. R., James, C. R., Miller, S., Danaia, L., Hollow, R. P., Cabezon, S., Faye, M., Tomita, A., Max, C., de Korte, M., Baudouin, C., Birkenbauma, D., Kallery, M., Anjos, S., Wu, Q., … Ortiz-Gil, A. (2021). The gateway science: A review of astronomy in the

OECD school curricula, including China and South Africa. *Research in Science Education, 51*(4), 975–996. https://doi.org/10.1007/s11165-020-09922-0

Salimpour, S., Fitzgerald, M.T. Astronomy and Culture. *Sci & Educ* **33**, 405–426 (2024). *https://doi-org.proxy-um.researchport.umd.edu/10.1007/s11191-022-00389-1*

Wenger, M. C. (2011). *Free-choice family learning experiences at informal astronomy observing events* (Publication No. 3488307) [Doctoral dissertation, The University of Arizona]. ProQuest Dissertations & Theses (PQDT).

Chapter 3: A Tale of Two Classrooms: Varied Framing Moves and Implications for Students' Epistemic Agency with Structured Science Materials

Introduction

Students may "do a science lesson" but never actually "do science." Hutchinson and Hammer (2010) described science classes where "students use sanctioned methods to produce answers, which then serve as a sort of currency to be exchanged for a grade" (p.508). School may include accumulation of facts designed to be completed with accuracy, efficiency and without depth or relevance to daily life (Pope, 2001). Successful students in science are (or should be) those who can frame their experience around sensemaking rather than rote answer (re)production (Lemke, 1990; Hammer et.al., 2005). Understanding science requires a conceptual understanding of phenomena as a scientist; science courses should be a means to this end (Hutchinson and Hammer, 2010).

Recent science education reform efforts call upon educators to engage students in scientific practices as a means for them to learn science through sensemaking about phenomena (NRC, 2012). Whereas "traditional" science courses promote passive transmission of content, students in classrooms aligned to the Next Generation Science Standards, or NGSS engage in science practices (Hutchinson & Hammer, 2010; Miller et. al., 2018; NRC, 2012; Stroupe, 2014). Students must now have "epistemic agency," which is the opportunity to " shape the knowledge building work in their classroom community" (Miller et al., 2018, p. 1058). Framing school science as opportunities to construct valued knowledge and learn through sensemaking offers opportunities and obstacles for teaching. This instructional reorientation towards student-driven learning may conflict with mounting pressures, such as pacing and evaluation, which reduce those opportunities. It may not always be feasible to allow students to determine the learning trajectory or for their ideas to guide instruction, which some researchers have argued is increasingly difficult given the abundance of pre-packaged and structured curricula (Miller, et al, 2018).

Teachers' epistemological framing moves may shift or nudge students from engaging with tasks of school (e.g., just "doing the lesson") towards engaging with practices of science. Epistemological framing, in the classroom sense, describes an individual's interpretation of "what's going on here" as it relates to knowledge or learning (Berland & Hammer, 2012; Elby & Hammer, 2010). Teachers can frame school science for compliance with established structures of accuracy and procedural tasks or for engagement in science practices and sensemaking driven by students (Hutchinson & Hammer, 2010). This is particularly important when using structured instructional materials, which may direct a teacher's focus and attention (Coffey & Edwards, 2016). The present study seeks to better understand the nuance of how teachers' epistemological framings (and resulting bids for students' framings) affect the ways students engage with structured NGSS-aligned science activities. The following questions guided this study: 1) How do two teachers frame the same learning experience, and 2) What are the impacts of the teacher's framing upon students' epistemic agency?

Background and Literature Review

NGSS: The Latest Science Reform

This study is anchored within the context of the Next Generation Science Standards (NGSS), which have been adopted by 44 states*[5] (NRC, 2012). The NGSS framework (NRC, 2012) recast instructional and epistemological practices to deemphasize facts, to provide depth over breadth, and to foster "engaging opportunities to experience how science is actually done" (*A Framework for K-12 Science Education*, 2012, p. 1). The NGSS reorient instruction towards participation in science practices, which center the role of students to shape the knowledge and practices of the community (A Framework for K-12 Science Education, 2012; Stroup, 2014; Miller et al., 2018). This shift will require new interactions for teachers, students, and systems (Ko & Krist, 2019). Participation in science practices is dependent upon students' intellectual involvement through talk and interaction (Berland et al, 2016). NGSS ideally requires teachers to shift the locus of learning to students, to position them as *doers of science* instead of just *doers of school*.

[5] 26 have adopted NGSS in its entirety, while others have adopted components or adaptations of the standards. Only 6 states have shown little to no modification since the adoption of NGSS.

The Standards are not a silver bullet reaffirming our place in the global STEM workforce or ensuring the US has a competitive edge. The Standards are not a curriculum or pedagogical method, but suggested goals for knowledge across three dimensions (Schellinger et al., 2022). The Standards are not required, and not every state has taken up the charge. Connected and integrated learning throughout K-12, as suggested in the Framework, necessitate an overhaul of our antiquated “factory model” of education; looping teachers with students, common planning time and increased preparation time would help the US align more closely other industrialized nations who have successfully connected learning across grades (NRC, 2012; Darling-Hammond, 2022).

However well intentioned, the coupling of science practices with science content (SEP and DCI) may present an inauthentic, externally derived and often prescriptive view of science (Miller et al, 2018). Many teachers rely on structured or prescriptive materials to assist in the transition towards NGSS instruction. Miller et.al. (2018) argued that teachers can influence students' ability to construct knowledge and enact appropriate science practices, instead of replacing one canonically correct idea with a correct practice. This study is situated within that tension; through video analysis of two teachers using similar structured materials, I will explore how students’ uptake of science practices is influenced by how the teacher frames the classroom activity.

Epistemological Framing

Epistemological framing concerns how people make sense of what is going on in a particular situation, and likely drives many school interactions (Goffman, 1974; Hammer et al., 2004). Framing in this sense is the cognitive means by which a student answers the tacit question “what are we doing here?” (Goffman, 1974). Science educators generally refer to framing to describe how people-students or teachers-use speech and behaviors to generalize or make sense of situations from past experience (Hutchinson & Hammer, 2010; Elby & Hammer, 2010; Russ & Luna, 2013; Richards et al., 2020). Framing of new situations–be it a classroom activity or a restaurant visit-require activation and consideration of past patterns (schema), which then shift to accommodate new situations (Berland & Hammer, 2012). In classrooms, epistemological framing is how members consider the relationship of teaching and learning upon knowledge construction, which helps to determine their participation and engagement (Berland & Hammer, 2012; Russ & Luna, 2013).

Framing, as a theoretical construct, can integrate what the teacher *brings* to the classroom with the interactions *within* the classroom (Luna, 2018). Framing is constructed and distributed by individuals in a community, which determine knowledge at play during various times (Russ & Luna, 2013). Framing is sensitive to the flux of classroom interactions, which are likely established by the teacher, and embedded into classroom cultures (Carlone et al., 2021; Richards et al., 2020).

Framing *bids* or framing *moves* have to do with the verbal and behavioral cues sent to reinforce or shift people's approaches to an activity. Teachers use framing moves to harness engagement in different types of instructional activities (i.e. lecture, collaborative discussion, design, sensemaking) while ensuring students enact the appropriate epistemological practices to match the activity. Teachers may notice certain student signals while engaging in an activity, such as simply filling out a worksheet with minimal discussion, and may use productive framing moves to shift or nudge their manner of engagement towards a different approach, such as comparing and discussing their preliminary answers. Teachers can deploy-and students take up-framing bids to reproduce knowledge, to follow directions and report results for the teacher's evaluation, *or* to make sense of phenomena and wrestle with uncertainty (Hutchinson & Hammer, 2010; Manz & Suárez, 2018; Schellinger et al., 2022).

Of course, different students may respond to the teacher's framing moves in different ways, and the teacher's own framing of the classroom activity can shift during the lesson (Levin et al., 2009; Russ, 2018). Still, it's worth looking for patterns connecting teacher's framing moves to students' enactment (or not) of epistemic agency.

Teachers' Framing.

Teachers' framing can explain variation between teachers enactment of the same science curriculum (Pinnow & Zangori, 2024). Teachers framing of learning activities drives what they notice and attend to, which helps to establish classroom cultures and norms of participation, engagement and expected contribution (Carlone et. al., 2021; Richards et al., 2020; Russ & Luna, 2013; Russ, 2018). Several studies describe the role of teachers framing to support students' scientific knowledge construction: In their study of pre-service teachers, Kawasaki and Sandoval (2019) determined that teachers' framing of science activities could invite or shut down students' participation and engagement. Framing moves are particularly important when teaching students who, for various reasons, have come to expect learning in school to consist of *transmitted knowledge* from teacher to student. With this in mind, an attentive educator may frame activities and include instructional scaffolds to activate diverse sources of knowledge. Carlone et. al. (2021) demonstrated that teachers could frame student contributions as valuable to classroom sensemaking, which pushed back against deficit-based narratives of marginalized elementary schools [and students]. Similarly, Miller et. al. (2018) described the role of teachers' framing to establish codes of conduct defining whose voice and knowledge is valued.

Students' Framing: Doing School vs Doing Science.

While teachers' framing establishes their *expectations* for how students approach learning activities, the students' framing of the classroom activity informs their *enacted* engagement (Hutchinson & Hammer, 2010; Russ & Luna, 2013). Many studies describe students' framing of science activities as *doing school* (or a *science* *lesson*) or *doing science* (Berland et al., 2020; Berland & Hammer, 2012; Duschl, 2000; Hutchinson & Hammer, 2010; Pope, 2001; Russ & Luna, 2013; Russ, 2018). In "traditional" science courses, the production of correct answers may be emphasized more than activities which foster sensemaking and more closely mirror professional science (Hutchinson & Hammer, 2010). Teachers in such classes determine and disseminate "correct" information and determine sources of knowledge (Lemke, 1990; Hutchinson & Hammer, 2010). Students in such classes see their role to receive and reproduce information from the teacher and seek value and achievement through matching their information to received information (Hutchinson & Hammer, 2010). The production of a correct *product* over understanding of *process* contrasts with the real-world practice, providing little insight into the field of science. Students *doing school* may attend more to following procedures than on *doing science* and developing disciplinary knowledge or sensemaking. Conversely, when students are *doing science* they determine what is "correct" by considering available evidence and collaborating with peers, and weighing it against predicted outcomes to make sense of phenomena (Hutchinson & Hammer, 2010; Miller et al., 2018).

Student and teacher framing of the same activities may be at odds with one another; Schellinger et. al. (2022) coded student work as *doing of school* or *doing of* *science* [6]while engaged in integrated engineering/science activities. When students were *doing school*, they completed a worksheet and responded with rote answers; when students were *doing science*, they explored and manipulated materials to iteratively and collectively develop questions. In this particular study, a teacher conceptualized student work enforced by a worksheet to create a diagram and moved students towards completion of the task and away from their moments of productively framing the underlying scientific phenomena at play. Students held productive discussions, but the teacher encouraged them to focus less on their thought processes and more on completing the worksheet. In another instance, students framed their work as *doing science* when they persistently worked through a problem through tinkering and were allowed to wrestle with uncertainty. The authors' determined that a teachers' ability to attend and respond to students' interests, which may manifest through "productive divergences" or student directed tangential discourse, were important to leverage students' framing towards doing science (Schellinger et al., 2022, p. 53). However, without adequate time, it is understandable that teachers may shut down productive divergence in discussion in favor of collecting work before the bell or grading deadline. These instances highlight the inherent tensions teachers face in framing experiences for science, while navigating the realities of school.

[6] And doing engineering, however this is outside of the present scope of study.

Students learn common classroom norms at an early age, such as the value of acceptable answers over understanding (Lemke, 1990), and this affects how they might frame a new activity. Hutchinson and Hammer (2010) described science courses in which "students use sanctioned methods to produce answers, which then serve as a sort of currency to be exchanged for a grade" (p. 508). Other researchers (Brousseau, 1997; Herbst & Kirkpatrick, 1999) describe this tactic as a "didactical contract." This contract between students and teachers may value the culture and values of educators and the education community over that of students, which can further separate many students from science and STEM (Hutchison & Hammer, 2010; Miller et al., 2018; Kawasaki & Sandoval, 2019). Achievement (or accuracy on assessments) separates schools, districts, states and university acceptance. High achievement is highly rewarded, while low achievement has been met by negative and sometimes punitive measures. Over time, the process of producing and being rewarded with the right answer embeds into students' classroom interpretation and contributes to their frames of learning, often to unproductive ends. Based on past experience, it is easy to understand why a student would repeat the same behavior in science which has served them well in other courses, and may adopt an inaccurate view of their own ability when they are not met with the same result.

Framing Moves for Science and Sensemaking.

Teachers can use framing bids to shift or cue students towards sensemaking and science practices and away from engaging in compliance-based procedural tasks

(Hutchinson & Hammer, 2010; Schwarz et al., 2021). Hutchinson and Hammer (2010) described an instructor (the first author) shifting how a class engaged with an activity through metacognitive messages-tone of voice, language and emphasizing everyday language-which promoted their productive (re)framing of the classroom activity. The authors described several instances of students' productive sensemaking of mass and buoyancy, emphasizing the role of their everyday language to construct meaning. They noted student's use of "thicker", "heavier", "lighter" to describe terms associated with density. The instructor used the term "weight" instead of "mass" to incorporate a more commonplace term as they constructed meaning, and to indicate attention towards students' framing of phenomena above canonical correctness. (Weight differs from mass, and canonically, mass is the quantity involved in defining density.)

Similarly, Rosenberg et al., (2006) and Elby and Hammer (2010) both analyzed activity from a middle school rock cycle lesson to illustrate cueing of productive epistemological frames. Initially, students relied upon a worksheet, using unfamiliar words to create a list of ordered steps of the rock cycle. Rosenberg et al.(2006) characterized this framing as *copy and paste*, in which students located and collected relevant pieces of information without incorporating their own ideas or language. Following the teachers' intervention and bid to "use what you know" students shifted their frame to *causal storytelling* to use their own words to describe mechanisms of change within rocks and the Earth. In the process, students also shifted from using the worksheets as the source of knowledge to using the worksheets as a reference point within their knowledge building. Both sets of authors used this episode to demonstrate shifting or nudging student epistemological frames from "transmissionist" to "constructivist;" I describe this as shifting students from engaging with *doing school* towards *doing science* by framing towards sensemaking.

Several studies describe how teachers can support students' sensemaking through explicit or tacit framing moves. Schwarz et al., (2021) examined how elementary teachers either expanded, maintained or closed down student sensemaking during classroom discussions. The authors determined that leveraging common resources or experiences was critical to expanding sensemaking opportunities, yet teachers should carefully consider systematic sensemaking practices anchored in students' funds of knowledge to afford such opportunities to *all* students. Teachers could encourage building upon others' ideas, and creating space to hear additional student contributions. Alternately, they found that teachers shut down students' sensemaking when they dismiss, correct or ignore student contributions.

Productive framing moves for science and sensemaking position students to grapple with uncertainty and to puzzle over phenomena (Hutchinson & Hammer, 2010). Ford (2008) described science students with a "grasp of practice" when, during an experiment they focused on achieving meaningful (to them!) results to understand phenomena, rather than when they focused on following instructions with discrete steps and controlled variables, without considering underlying phenomena. A student who frames science in this way may recognize that knowledge can come from anywhere. They may see their role to assess and contrast this knowledge with their reasoning and experience, which closely resembles the practice of science, and echoes the learning goals defined by the National Research Council (2007; 2010) and National Academies of Science (2007; 2013; 2021) which underlie the Next Generation Science Standards Framework (2013). Teachers could incorporate student generated models and collaborative discussions in which students understand and act upon their role to actively construct knowledge through sensemaking, not to reproduce knowledge presented to them (Schellinger et al., 2022).

Epistemic Agency

Traditional school systems position teachers and other sources of authority (text, curricula) as the sole epistemic agent to determine and value ideas and knowledge (Carlone et al., 2021; Krist, 2024). Alternately, Stroupe (2014) described students in NGSS-aligned classrooms as epistemic agents to shape and contribute to the classroom communities' knowledge construction (Damsa et al., 2010; Miller et al., 2018). NGSS classrooms center student ideas as valuable, in the public plane, for students to negotiate "what counted" as science ideas and to shape the knowledge community. In such classrooms, students act with authority to determine information as "right" or "wrong," which redistributes cognitive authority. Over time, this redistribution or retention of cognitive authority places science learning as "public" for all members of the community to hold each other accountable vs. “private” for individual accountability to the teacher (and text).

Many scholars describe epistemic agency as the authority to take, act upon or evaluate knowledge (Carlone et al., 2021; Damsa et al., 2010; Kawasaki & Sandoval, 2019; Ko & Krist, 2019; Miller et al., 2018: Stroup, 2014). NGSS-aligned instruction, by definition, must provide opportunities for students to act with epistemic agency to participate in knowledge construction work (Stroupe, 2014). Acting with epistemic agency can be identified through 1) Interaction between individuals through coconstruction of shared knowledge 2) Positioning (students’ positioning of themselves or being positioned) to formulate whose knowledge is valued, and 3) to assess whose knowledge “counts” as valued (Damsa et al, 2010; Stroupe, 2014; Miller et al., 2018; Carlone et al., 2021). Early studies indicated that when students are granted greater epistemic agency, both teachers and students were more likely to incorporate authentic science practices (Minstrell, 1982; Warren & Roseberry, 1995).

Classrooms which promote students’ epistemic agency value diversity in language, background, culture and experience to establish rich knowledge building landscapes (Bang et al, 2012; Miller et al., 2018; Sezen-Barrie et al., 2020; Stroupe, 2014). Fostering epistemic agency in science may look like opening dialogic space for or pursuing student ideas, interest and values to drive the entire learning trajectory, to allow choice within assignments, or promoting diverse ideas within discussions (Stroup, 2014; Kawasaki & Sandoval, 2019; Ko & Krist, 2019; Berland et al., 2020; Haverly et al., 2020; Sezen-Barrie et al., 2020; Krist et al, 2023). Through this lens, teachers simultaneously support students' sensemaking while valuing their ideas and voices which foster opportunities for epistemic agency (Miller et. al., 2018). Ko and Krist (2019) investigated the three diverse cases of teachers' "opening up" their curriculum (in this case NGSS-exemplar curriculum) to redistribute epistemic agency through a framework designed to embrace the tensions between adhering to curricular goals and creating space for students epistemic agency. The authors described a teacher opening up methods of investigation for students' ideas, a teacher-led demonstration which was opened up to include alternate explanations, and a teacher who opened explanatory goals through student-interest driven discussion. In order to open up such space for students' epistemic agency, the authors determined that teachers should be open to "adapting their pacing, intended coverage, and/or amount of time spent" to allow for a range of student responses which emerge as a result of opening up space (p. 1003).

Teachers can foster students' epistemic agency by eliciting ideas and allowing those ideas to shape discussion or to guide instruction (Bang et al, 2012; Carlone et al., 2021; Ko & Krist, 2019; Stroupe et al., 2018). Students enacting epistemic agency may take up roles typically afforded by authority figures, such as critiquing ideas of peers or scientists (González-Howard & McNeill, 2020), choosing experimental elements such as procedures, data collection or research questions (Cherbow &

McNeill, 2022; Ko & Krist, 2019; Miller et al., 2018); they may propose alternative solutions or choose their method of demonstrating understanding (Ko & Krist, 2019; Krist et al., 2023; Zimmerman & Weible, 2018), or they may determine sources of information (Miller et. al., 2018; Stroupe, 2014). In science classrooms that foster students' epistemic agency, the teacher's absolute authority over knowledge is minimized in favor of students' autonomy (Carlone et al., 2021).

Framing Moves for Fostering Students' Epistemic Agency.

Teachers framing moves can support or inhibit opportunities for students' epistemic agency. Kawasaki and Sandoval's (2019) case study found that teacher framing had a direct impact on students' epistemic agency. They cited a teacher who made connections for students, removing their ability to act as epistemic agents and ultimately decreasing participation by "taking back" cognitive authority. Alternatively, when the teacher framed activities around an anchor phenomenon and opened up students' roles to include decision making, their participation resembled that of a true scientific community. Kawasaki and Sandoval (2019) and Sezen-Barrie et al (2020) described new teachers who struggled with students' puzzlement and "filled the gaps," which discouraged participation and removed opportunities for epistemic agency. Comfort with students' discomfort and uncertainty in science may characterize essential components of teachers' work. Manz and Suarez (2013) traced strategies to help teachers negotiate and develop a nuanced view of students' authentic science work with phenomena. All of the teachers in the study believed in the value of students' wrestling with the "messiness" of uncertainty. Through professional development, the teachers shifted from models or explanations to simplify concepts for students to see the value of stepping back for students to make their own choices. I cast this work as framing for sensemaking as teachers step back and invite students to step in.

Framing Moves While Using Structured Materials

Framing is particularly important when using prescriptive materials, which can prioritize procedures over practices, and uphold traditional hierarchies of knowledge (Carlone et al., 2019). Teachers' perception of a task's difficulty can inform how they frame activities for students, which determines their response; if substantive talk is not encouraged, an expectation is set that substantive engagement is not required or appropriate (Russ & Luna, 2013). If canonical science is prioritized, teachers tend to retain accountability for knowledge dissemination. Instructional materials may direct a teacher's focus, which may in turn send epistemic messages to students reinforcing institutional hierarchies of knowledge and remove opportunities for epistemic agency (Coffey & Edwards, 2016; Sikorski & Hammer, 2017; Schafer et al., 2023). When teachers prioritize understanding of the science process-whether using structured materials or not- they can share power amongst students and pursue their ideas to co-construct knowledge (Stroup, 2014; Miller et al., 2018; Sezen-Barrie et al., 2020; Carlone et al., 2021).

Teachers may inauthentically frame activities towards students' knowledge construction which can remove opportunities for epistemic agency. Ko and Krist (2019) described several examples of teachers' "opening-up" space within constraints of NGSS exemplar curricula to redistribute cognitive authority to students and foster opportunities for their epistemic agency. One of the teachers used a demonstration to differentiate between two substances, yet instead of conducting this herself, the teacher invited students into the process of determining ways to investigate differences, such as which data to collect and how they could use that to support their claims. Students took up the teachers' bid to construct explanations, however this productive knowledge work stopped immediately when they saw their "ideas" as concepts on a worksheet, concluding that the "ideas" were predetermined and not really the results of the students' collective work. One student felt "tricked" and disengaged in the remaining investigation when she no longer felt the ideas were her own. I am not discouraging teachers from using NGSS exemplar materials; on the contrary-these are vetted materials aimed at assisting teachers and students towards NGSS aligned instruction. As Ko and Krist (2019) remind us, teachers must ensure students' ideas are valued and consequential to learning, even if activities are planned or scripted. The point here is that, when using structured materials that guide students along certain learning trajectories, the teacher faces tough tensions and choices about how to foster students' epistemic agency within those constraints.

Examining Epistemological Framing with Video Analysis

Research examining teachers' framing and framing moves has successfully leveraged video analysis, providing in situ, non-interrupted examination, which is imperative for accurate examination of teacher practices within established classroom cultures. Russ and Luna (2013) inferred a teacher's framing based on what the teacher noticed, which they captured with video technology. They determined that the teacher framed for students' to construct *disciplinary knowledge* during class discussions but for centering *procedural knowledge* during lab activities. Either of these framings then helps drive what the teacher notices and responds to in student talk, when then reinforces the framing—a feedback loop. Other studies (Krist et. al., 2023; Sherin, 2011) use teachers' "tagging" of video moments; while a body camera (e.g., a GoPro) records the teacher's classroom interactions, the teacher presses a button or the like to tag segments of video as fitting some criterion such as noticing student thinking or moments of student sensemaking. While these studies provide insight into teachers' noticing, I argue that the disruptions and influence over instructional decisions required in "tagging" moments might influence how they're framing the classroom activity, leading to results that could differ from those of more naturalistic studies. In this study, I will therefore use video analysis that includes teachers' point-of-view footage but without teacher selected moments. This provides an uninterrupted, holistic picture of teachers' framing bids and how these bids are taken up by students. Further analysis of these moments allowed me to infer opportunities for students' epistemic agency.

Rationale For Study

This study was motivated by the need for teachers and researchers to understand and collectively work within the complexities of allowing students to drive instruction, particularly when using prescriptive curricula. I refer to *prescriptive* curricula synonymously with *well-designed structured* curricula which includes specific learning targets supporting complex forms of learning (Ball & Cohen, 1996; Ko & Krist, 2019). By prescriptive, I mean materials which predetermines what sources of knowledge students begin with and how they are supposed to build on that knowledge to reach and represent their conclusions. NGSS-aligned materials include embedded engagement with science practices and activities to generate explanations of phenomena. The present study is particularly timely given the increased emphasis among the science education research community to create space for student driven learning which may conflict with mounting curricular constraints and pressures, particularly emerging from a global pandemic, which reduce these opportunities. This study is grounded in the work of Ko and Krist (2019) and Krist et. al. (2023) who investigated the moment-to-moment epistemic considerations which guide teachers' practice. The authors affirm the role of well-designed curricular materials which can support teachers' to "create space" for students' science ideas and questions, which can redistribute epistemic agency. I am not the first to compare variation between two teachers' enactment of the same lesson; Enyedy and Goldberg (2004) investigated participation frameworks established through interaction. The authors examined relationships, roles and responsibilities of participants in learning communities, and the impacts upon students' understanding of science. I apply and extend this work in my analysis and characterization of teachers framing bids and their classroom cultures.

Methods

The following section will identify my methods to categorize and classify varied framing moves and to infer how these moves were taken up and acted upon by students. However, there was not a singular method or best fit. Framing, as a holistic construct, cannot be adequately captured using singular methods, therefore a combination of methodologies were deployed and compared, as described below.

Research Design

The present study used qualitative methods with elements drawn from phenomenology to characterize variation between two expert science teachers framing of classroom activity in the context of helping student use instructional scaffolds, Model-Evidence Link (MEL) diagrams (Knaack, 1984).[7] The data consists of classroom video previously collected as part of a broader project, as described

---

[7] See Lombardi et al., 2018, Governor et al., 2021 and Lombardi et al., 2022

below. A qualitative approach was the most appropriate method to characterize classroom events as they transpired within the classroom. I used elements of phenomenology to allow my method and analysis to take shape alongside my observations of the classroom videos, and to be open to new ideas while setting aside my experiences as an educator (Knaack, 1984). I used descriptive coding, analytic memos and multiple observations of the video recorded teacher-student group interaction to examine the fine-grained substance of each exchange and to infer teachers' framing.

Curricular Materials

The teachers in this study used MEL scaffolds, which were designed to NGSS and state science standards. Lombardi et al. (2013, 2018) developed Model-Evidence-Link (MEL) activities as a mechanism to facilitate students' learning about controversial socioscientific issues. MEL activities use an instructional scaffold to facilitate students' evaluation of scientific and unscientific models and their connection to lines of evidence through use of a diagrammatic framework. Students must determine the plausibility of each model and connect them to plausible lines of evidence based on the strength of the connection. In the original MEL activity, students are given two models and four lines of evidence. In the baMEL (build-a-MEL) scaffold, students select two models to pursue from three, and select four lines of evidence from eight. Each line of evidence is supported by a one-page evidence text to guide students' decision making. Prior studies evaluated students' discourse and agency (Lombardi, et al., 2022). This is the first to focus on the teacher. Both classes in the present study were using the baMEL, however the teachers in the study were using different topics (Fracking and Fossil Evidence).

Data Sources

The present study used secondary video analysis of in-person classroom instructions during the 2019-2020 school year, which was collected as part of a larger study. The larger study included a DataBrary of video and audio data from MEL participating classrooms in the Northeast and Southeast of the United States (Nez et al., 2019). I reviewed many teachers' data files within the DataBrary to select only those which had both fixed camera footage (typically from the back of the classroom) and teacher-worn GoPro footage for more than one class period for use in this study. All data files had audio. Separate audio data was collected at each student table and was used only to validate transcripts.

Case Selection

I selected two veteran science teachers for this analysis. Coral [8]taught middle school in the Northeast of the United States and used the Fossils baMEL. Melissa taught high school in the Southeast of the United States class, and used the Fracking baMEL. The teachers demonstrated a range of differences in their classrooms while

[8] All names are pseudonyms to protect the identity of the participants.

guiding students to complete similar tasks. Initially, to inform future professional development for teachers, I was looking for teachers that taught the lessons similarly, or that had practices worth emulating to foster epistemic agency while using MEL materials. I spent many hours viewing video in the data corpus. I was looking for clean and clear enactments of the MEL activities. Initially, I selected Melissa as an exemplary MEL teacher. I initially overlooked Coral based on my first impressions of her class as rowdy and chaotic. For example, students were seen standing next to or sitting on tables as they discussed the activities. They moved freely and loudly. They interrupted her and engaged in continuous discussions. I was intrigued by the stark differences between Coral's class and Melissa's in terms of student behavior and teacher talk. Coral stood in the corner of the room, which I initially interpreted as docile, while Melissa stood at the front, which I interpreted as authoritative. I was drawn to Melissa's class for the order and quiet. Students were seen sitting quietly at their seats throughout the class and never spoke out of turn (or much at all). As I repeatedly watched each class, however, I realized that-while I was looking for evidence of epistemic agency-I saw the impact of each teacher's framing upon students' epistemic agency. As I discuss in later chapters, what I first understood to be chaos, I later determined was evidence of the culture of learning which supported and trusted students' autonomy, while the quiet and orderly class was actually exhibiting evidence of expected compliance. Only through immersion in the data was I able to tease out the nuance between cases.

Data Flow

I took notes from the whole class (fixed camera) video and the teacher-worn GoPro. I selected one clip from small group interaction, observed with the teacher-worn GoPro, for intensified sampling. I repeatedly watched the videos, taking additional notes, noting interactions, explicit and implicit messages, and student responses. Then, I manually transcribed both the whole class video and my selected GoPro video of the teachers' interactions with small groups of students. I recorded these episodes of interaction in a spreadsheet. I used the GoPros audio stream to validate my transcription based on the separate audio recorded data.

After I manually transcribed each, I added additional notes on my impressions, what students said, and who held cognitive authority in each instance. I flagged spoken and unspoken events in the transcript, which I used to generate first-cycle inductive codes. For example, I coded engagement by assessing students' body language. In one class, a group of boys huddled around a table, sat on the table or leaned on it. The teacher never corrected their spatial positions and postures, which seemed a necessary component of their engagement. They were allowed to be comfortable. In another instance, a student put his head down and dramatically displayed his boredom. Each instance allowed me to infer whether students were engaged with the task. While I observed and noted students' engagement in my open coding cycles, I used this to infer the uptake and response to the teachers' framing moves.

After a few more cycles of open coding, I extracted examples (Figure 1) from the videos indicating framing moves for *school and* aligned with procedures or procedural tasks*,* or *science* and practices of sensemaking to infer teachers' framing moves (Elby, 2005; Russ, 2014; Saldaña, 2016).

Code	**Description**	**Examples from Videos**
School	Framing moves which center procedural tasks for completion, position answers as right or wrong, and position teachers as transmitting knowledge and assessing answers.	"A's you are first, make sure name date and period are on there, you are going to read the description of each model and rank your plausibility."
Sensemaking	Framing moves which center student ideas in sensemaking, position knowledge as coming from anywhere and students as assessing answers.	"Today your goal is to get a look at everything and to start making decisions on what you want to look into more, so you are not really going to be filling out the worksheet."

Figure 11 Codes, descriptions and examples

I attempted to complete my analysis using coding alone. I immediately noticed differences in each teacher's epistemological framing -towards *school* or towards *science*. However, each teacher in my analysis also had distinct codes to characterize their interactions or instruction: for example, Melissa consistently used *IRE*-Initiation-Response-Evaluation to initiate talk and discussion, which naturally limits student contributions to short responses evaluated as correct or incorrect by the teacher, while Coral used *redirecting* moves to shift student behavior and sometimes used *validating* at times when she also framed for sensemaking (Schwartz et al., 2021). I expected that both teachers would sometimes use *Procedural* talk, which I separated from the code of *School*. I added these new codes to my codebook and attempted to apply these codes to each class to explain their variability.

I created a histogram to contrast the two teachers (see Findings). While my coding scheme aligned with existing literature and was somewhat insightful, it did not fully capture a holistic sense of how the two classes differed and how those differences affected student engagement or epistemic agency. The code frequencies only described aspects of the teacher, which was unbefitting for moment-to-moment analysis and narrowed my focus to framing without connection to student uptake. This method also excluded teacher noticing patterns which are connected to and support teachers' framing (Russ & Luna, 2013). In other words, coding alone allowed me to *locate* the teachers' varied framing moves, but this method did not allow for inference or connection to students' epistemic agency. Therefore, I had to adapt my method to search for and better understand this nuance.

I attempted to replicate a method used by Kawasaki and Sandoval (2019) to locate cognitive authority over knowledge and interpret students' epistemic agency. In their study, the authors developed a rating system of -1,0 or +1 for each days' activity *framing*, *version of practice* and *epistemic agency*. In instances in which the lesson favored students' sensemaking and they acted with epistemic agency, each rating would be a +1. When the teacher was uncomfortable with students' uncertainty or in which her framed moves prompted task completion, elements would be a -1. While this practice was well aligned with characterizing an entire lesson, this method was unbefitting for moment-to-moment analysis, particularly in a lesson which required a large degree of procedural talk, and which necessitated a prolonged introduction. However, drawing from Kawasaki and Sandoval (2019), I incorporated elements for *cognitive authority* into my codebook. Specifically, I developed criteria (Figure 2) to determine who held cognitive authority over tasks (*T_authority; S_authority*) based on work by Stroup (2014), Kawasaki and Sandoval (2019), and Miller et. al. (2018). I expanded my coding scheme to include specifics of where cognitive authority was located and how it was transferred, which allowed me to identify opportunities for students' epistemic agency while using MEL materials. I did not intend for these codes to be used in isolation, but in coordination with my previous codes, which allowed me to characterize segments of dialogue, described below.

Cognitive Authority	**Description**	**Example**
Teacher holds cognitive authority Code: T_authority	• Determined means and structure of tasks • Decided and dictated how to make decisions • Dictated structure and procedure for students • Determined and assessed valued knowledge	"You need to state what you have chosen and state why to your group mates so that everyone can understand"
Student holds cognitive authority Code: S_authority	• Decided means and structure of tasks • Decided how to make decisions • Individuals or groups determined structure and procedures • Determined and assessed valued knowledge	"So you just have to decide if you want to stick with it and keep working with it tomorrow, or if you want to dump it. This is a keep or dump moment, not a final decision. You have to read the articles a little further before you do that."

Figure 12 Codes for cognitive authority

Here, I wish to clarify that the MEL is a structured activity that largely predetermines the topic students will discuss, the information sources they will draw from (with some choice, in the baMEL), and the knowledge product they will create, the MEL diagram. When I code for or otherwise analyze students' sensemaking and epistemic agency, this applies to sensemaking, and epistemic agency as afforded by the materials; students can individually and collaboratively decide what counts as convincing arguments about whether an how the pieces of evidence support or don't support each given model. So, in some senses, the MEL materials held cognitive authority, while in other senses the materials invited students to assume cognitive authority—and this study focuses on how the teacher's framing moves affected students' uptake of cognitive authority. I also wish to clarify that I do not fault structured materials like the MEL; as a teacher, I understand and appreciate the impact of powerful learning materials such as the MEL upon students' engagement with science practices and appreciate how such materials can help teachers meet their school's or school district's expectations about what material the teachers should cover.

To be transparent and honest to the reader, I acknowledge that I added codes much later in the writing process based on use of pronouns from Enyedy and Goldberg (2004). While my initial analysis centered on evidence and constructs that resonated with my personal experiences as a teacher, such as the importance of tone and the existence of schoolish vs. scientific framings and enactments of lessons, I found that Enyedy and Goldberg (2004) aligned with my methodological convictions. Therefore, I was compelled to revise my codebook and analysis based on this work.

My final codebook with collapsed categories as subcodes and codes as themes is presented below in Figure 3.

Code	Sub codes	Description	Example
Epistemological framing: *School*	Completion Directives IRE	Teacher frames activities for the purposes of correct, completion or compliance over engagement with science. May use directive instruction to get students to do something. May ask close-ended questions with binary answers.	Decide which two to focus on, make sure they are recorded on your paper, and make sure you've share what you chosen, which you've chosen and why
Epistemological framing: *Science/Sensemaking*	Web of learning Collective tasks	Teachers' framing supports students' engagement with science practices, such as collaboration, arguing or evaluating evidence. Tasks are framed around a "web" of activities Use of inclusive pronouns implies membership in classroom community.	Today your goal is to get a look at everything and to start making decisions on what you want to look into more, so you are not really going to be filling out the worksheet.
T_authority	Transferring authority	Teacher defines terms, finishes sentences, directs scope of ideas. May begin to transfer or lend some authority to students to limited extent.	Keep in mind you have all categories open to you and that sometimes, we use falsifiability, right? to support, so something that is falsifiable actually ends up supporting something else so keep that in mind as you are looking through your evidence.

S_authority	Students decide With students	Teacher frames learning and action within the activity as student driven and collaborative	And if you like number 1, you can choose it as a group. But your job is to try to narrow it down to 4. You can worry about the models later, you can do the models now, but you should be making the decision as a group not independently.
Validating	Positive Valuing	Teacher affirms student ideas or thinking in a positive manner	You can do the arrows together, but you don't have too. You can discuss it, and I think that's a great idea.
Procedural	Task management Isolated tasks	Teacher attends to menial tasks within the activity such as where to put items.	Make sure you have an A a B and a C. Does everyone have an A a B and a C?

Figure 13 Codebook

Analysis

My initial coding scheme only provided a partial picture of each class, and I still did not have a clear understanding of why they were so different. Therefore, I went back to the data with an open mind.

Segmenting Dialogue of Teachers' Introductions.

I segmented the introductory teachers' talk within the transcript to view each class at a finer grain size and to extrapolate varied opportunities for epistemic agency within each class. By introductory, I mean how the teachers introduced and discussed the activities at the beginning of the class, prior to students beginning the activities in groups or individually. The introductions given by each teacher were "public talk," making ideas and information accessible to all members of the classroom community from a privileged role of authority, allowing me to examine established and sustained classroom norms (Enyedy & Goldberg, 2004). My segments were: *Introducing the Topic*, *Introducing the Task,* and *Introducing Plausibility*. I determined these particular segments because they were a necessary component of each lesson, and we might expect them to play out similarly given that the teachers had received the same professional development regime; they both participated in a 3-day summer program to work through the MEL materials as "students" and to engage in other activities, to familiarize themselves with the processes and practices embedded in the materials. I was particularly interested in how the teacher framed instructional elements as either an act of *science* with expected engagement in science practices to make sense of phenomena or an act of *school* with procedural talk or isolated talks focused on how to engage with or complete the task (Elby & Hammer, 2001; Pope, 2001; Stroupe, 2014; Miller et al., 2018; Kawasaki & Sandoval, 2019; Ko & Krist, 2019). Multiple overlapping codes prompted me to further separate and characterize the identifiers of *epistemic agency* to see the relationship between their observational codes related to framing moves and implications or enactments of those framing moves. I arranged the table with codes surrounding each line of associated dialogue for each teacher, with rationale in the far column (Figure 4).

Introducing topic				
Teacher	**Framing Codes**	**Dialogic Example**	**Epistemic agency**	**Rationale**

	Science purpose Collective tasks Web of Learning With students	Today and tomorrow we are going to be learning about fossils. Right now you have 3 different possible models. Later on you are going to choose 2 that you want to work with, but right now you have to look at all 3. So let's go through them one at a time.	Transferring S_authority	Positions students as capable of choosing for purpose of science, partners with students to learn. Introduces topic in context and supports through background

Figure 14 Sample of Segmented Table

My column for framing codes also incorporated two instances of what the teacher noticed or attended too (underlined), yet only for purposes of inferring framing based on Russ and Luna (2013). In each case, this had to do with the target of the teachers' attention. For example, in the example above the teacher set up the purpose of the activity as one of science (science purpose). A thorough analysis of teachers' noticing, and attention are related, but outside the scope of this work.

In the second line of dialog, the teacher uses the first-person plural pronoun in "let's" implying she is with students as a member of their community, not holding an asymmetrical or hierarchical position over them. This method allowed me to isolate the role of each teacher's framing bids with the materials and to infer the impacts on students uptake of the framing bids as observed in student behaviors. Students in both classes completed the same tasks, used the same materials, and constructed models having the same structure at the conclusion of the activity, as guided by the MEL (both teachers used the baMEL activity, but used different topics). Thus, by segmenting the dialogue, I could better discern moment-to-moment variation within teachers' framing of the materials and activity, and how their respective framing created or suppressed opportunities for students to act with epistemic agency while using the materials.

Small Group Dialogue.

A body of research (Elby, 2010; Gupta & Elby, Elby & Hammer, 2010; Hammer, 1996; 2011; Louca et al., 2004; Rosenberg et al., 2006; Russ & Luna, 2013) used portions of classroom dialogue to interpret and infer epistemological framing. However, this is most often applied to *students'* framing and approach to learning, not teachers' framing and approach to teaching. Therefore, I incorporated this methodology (line-by-line analysis of classroom interactions) to provide evidence of *teachers'* epistemic framing and impacts upon *students'* frames and resultant epistemic agency, I selected a clip from the teacher worn GoPro for intensified sampling from the DataBrary (Nez et al, 2019). I sought clips which included student-student and/or student-teacher dialogue. Teachers' interactions with small groups were generally 3-5 minutes. I tried to select longer clips (closer to 5 minutes) which included common classroom instances of the teacher approaching a group to check for understanding or to redirect and refocus their task.

Because the teacher was circulating the room during the activity, student-student intra-group conversations were only captured if the teacher paused to observe before or after she interacted with them.

My positionality and perspective:

I acknowledge the potential of insider bias; I taught high school science and STEM on the West Coast of the United States for 15 years prior to entering academia. As such, I see classroom interactions through my teacher lens before I put on my researcher hat. I was amidst my doctoral program while I was working on this research. My own epistemology and research skills expanded while I worked on this, which shifted my lens of research. As discussed above, my initial reaction to the two teachers in the videos changed with my theoretical perspective. I understand and relate to the need for students to comply with structures, procedures and pacing, but also appreciate opportunities to push against those confines. As a teacher, I have also had days where I just could not, for varying reasons, go “off script.” The tensions between the realities of teaching and the perspective of educational researchers, and my new role navigating the gaps between the two, propelled me to explore this varied terrain. This also prompted me to present the same videos I used in analysis to a group of teachers to explore their perspectives, which I presented at NARST 2024.

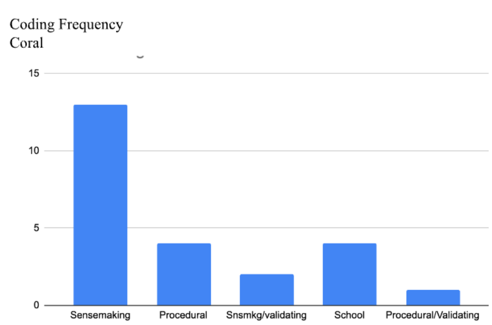
Findings

In the following section, I describe the findings of each method. I separate this section into research questions and supporting data to provide evidence of the similarities between each classroom to emphasize subtle nuance. There was significant overlap between each question, such that I hope I clearly convey the relationships between framing moves for science and sensemaking vs. school and completion, and associated opportunities for students to act with epistemic agency.

RQ 1: How did two teachers frame the same MEL-based lesson?

The similarities between each teacher allowed me to create a histogram from the codebook (Figure 5) to compare the frequency of each teacher's framing moves. I expected and observed procedural and task-oriented framing moves for both teachers. Coral had a greater variety of codes, including *sensemaking*, while Melissa had more codes for *school*. I observed each teacher use specific codes 1-3 times throughout the lesson that were not applicable to the other: Melissa used *IRE* or *Directive* methods of interaction, while Coral paired *Validating* with both *Sensemaking* and *Procedural* focus in redirecting student behavior or shifting their engagement.

As discussed in the previous section, coding was insufficient to connect or infer the implications of each teacher's framing moves upon a student's epistemic agency, or to capture more holistically the differences between the two enactments of a MEL lesson. I now provide a finer-grained analysis of the various segments of the teachers' talk.



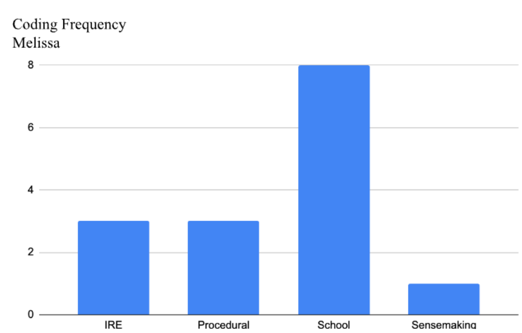


Figure 15 Histogram of categorical codes for each teacher

Framing Variation While Introducing the Activity.

Both teachers established their instructional objectives for learning through explicit and implicit messages during their introductions of the MEL activity (Figure 6). I segmented each teachers' dialogue based on similar elements of their introduction to draw holistic inference of their goals (Enyedy & Goldberg, 2004). I assessed each teachers' word choice, questioning strategies, tone and orientation to characterize and infer messages sent to students, which may have established expectations for and influenced their engagement and participation.

Each teacher began the MEL lesson by introducing the activity; Coral explicitly focused on the topical nature of students' investigation (fossils), while Melissa explicitly focused on physical materials and tasks. Both teachers introduced students' tasks, but with subtle variation; Melissa introduced individual elements of activities such as "*the worksheet with the arrows,"* while Coral introduced tasks by emphasizing the processes students were expected to take up, such as "*doing your analysis,*" or "*as you are making decisions.*"

In general, Coral focused on *processes* students were expected to take up, such as decision making and analysis. She focused less on following procedures, and more on continuity and connection to prior learning (coded as *web of learning*). Generally, Melissa emphasized students' *practices* of argumentation regarding the knowledge work of justifying placement of their arrows as they determined which lines of evidence were plausible. Both teachers also promoted sensemaking, but in slightly different ways; Coral posed sensemaking questions regarding their general knowledge work, while engaged with the MEL materials, while Melissa posed sensemaking questions connected to students' application of plausibility (the focus of the MEL activities). While both teachers facilitated students' progression through the activities, Coral generally promoted collaborative work, while Melissa promoted completion of activities. I inferred that in Coral's class, students acted upon messages to discuss and determine plausible evidence collectively, while students in Melissa's class acted upon messages to determine plausible evidence privately.

Both teachers placed students into groups to work through materials; in Coral's class, students formed separate "expert" groups to read through one evidence text before returning to their original groups, while in Melissa's class students read all evidence text in their groups. Both teachers retained and shifted cognitive authority, but at different points in their introduction; Coral read through each of the models and evidence to the class, while Melissa directed task management.

Introducing topic				
Teacher	**Framing Codes**	**Diologic Example**	**Epistemic agency**	**Rationale**
Coral	Science purpose *Collective tasks* *Web of learning* *With students*	*Today and tomorrow we are going to be learning about fossils and how valid they are or not in determining the history of the Earth.* *Right now you have 3 different possible models. Later on you are going to choose 2 that you want to work with, but right now you have to look at all 3.* *So let's go through them one at a time.*	S_authority	Positions students as capable of choosing for purpose of science, partners with students to learn. Introduces topic in context and supports through background. Connects their activity to the larger activity purpose. Uses inclusive pronouns.
Melissa	Procedural *Isolated tasks* Sensemaking IRE School Sensemaking *Web of learning*	*Check that you have 4 blue cards and 8 red cards.* *Remember it was all on paper for you and now they have cards.* *What do you notice that is different about this one?* *How many models do you have this time? Last time?* *Last time we sorted the info for you and we decided which were important enough for you to focus on.* *In the end you are still going to end up with 2 models and 4 evidences. but you are the ones now who get to decide which ones you want to focus on. Okay? we gave you hints last time about how to focus on different pieces of evidence, but I'm not going to really give you hints this time.*	T_authority *Transfers authority* T_authority S_authority	No topic introduction-straight to task management and separating tasks. IRE-low level, closed ended questions Affirms class culture Transfers authority over tasks but affirms her authority-"we gave you…not going too"

Introducing Task				
Teacher	**Codes**	**Example**	**Epistemic agency**	**Rationale**
Coral	Procedural *Students decide* *Web of learning* Science/sensemaking *Web of learning*	*Right now you have 8 pieces of evidence that you're going to look through as a group, your lab group. You have 8 you have to look at.* *But today we are going to narrow it down to 4 and you are going to dump 4 that you don't find very interesting, or that are not what you want to use as evidence. Also of the 3 models, you are going to dump 1.* *Today your goal is to get a look at everything and to start making decisions on what you want to look into more, so you are not really going to be filling out the worksheet.*	T_authority S_authority	Focus on practice, with choice driving their task. Does not direct the process. Connects their activity to the larger activity purpose. Shifts away from focus on materials or completion towards sensemaking.
Melissa	Sensemaking *Isolated tasks* *IRE*	*You need to look through there and decide what you find compelling.* *I don't want to guide you alot on this. You need to look through there and decide what is helpful.* *You guys are in a pair or trio-does that mean that you all have to choose to investigate the same two models? not at all, one of you can choose a and b, the next can...whatever. However, should you be discussing your choices as a group? Yes.*	S_authority T_authority *Private ideas*	Helpful for task completion. Teacher guides the process, maintains position of power by affirming her role as a potential guide. . IRE; Purposeless talk

Introducing Plausibility				
Teacher	**Codes**	**Example**	**Epistemic agency**	**Rationale**
Coral	Science purpose *Web of learning*	*You are going to determine the plausibility-or how likely each one is to be true. 1 being very implausible or impossible and 10 being highly plausible- and you are pretty sure it is true.* (reads one of the models with word *interpret).*	T_authority	Provides purpose to their work and grounds it in the larger activity.
	Sensemaking	*Do you know what interpret means? Can you think of it? Go ahead Ian.* (student responds)	*Public ideas*	Ideas for public use.
	Validating	*Good, right! So you are looking at information and making an inference of what it means.*	S_authority	
	Positive Sensemaking/*Validating*	*Great! Any other examples? Any other ideas? That was a great way of putting it.*		Elicits student ideas instead of giving them definitions.
	Web of learning	*Let's say you are just starting to learn English and someone is talking to you and you can't really understand everything they are saying, and you have to interpret what they are saying from the information you have.so here it is again; when people interpret fossils, they are really just the remains of something that used to be alive and it's not an exact copy of that thing. and they have to interpret the pieces they have..*		Provides example for students' to connect to their lives and experiences.
Melissa	Procedural School *Isolated tasks* *Directive* *Isolated tasks* *IRE* Procedural	*So the first thing we are going to do is rank the plausibility of each model. (teacher manages mismatched materials amongst the group).* *Make sure you have an A a B and a C. Does everyone have an A a B and a C? Here A's you are first, make sure name date and period are on there.* *You are going to read the description of each model and rank your plausibility.* *Do you guys remember what plausibility means? What did we decide that means? How what? (whispers) this is where you talk. How likely or....what was the other word we used, one that started with P...plausible also sounds like possible. Okay? and we talked about if it was a realistic possibility..... Okay?* *Does everyone have one? remember name, date, teacher, make sure we have all of those.*	T_authority	Focus on task and procedural management not their thinking. Task focussed and disconnected. Teacher does not wait for student responses or ask open ended questions. She answers herself. Maintains low level focus. Maintained focus on tasks.

Beginning the Activity				
Teacher	**Codes**	**Diologic Example**	**Epistemic agency**	**Rationale**
Coral	Sensemaking *Web of learning*	*Today your goal is to get a look at everything and to start making decisions on what you want to look into more, so you are not really going to be filling out the worksheet.*	S_authority	Shifting students away from focusing on completion. Positive focus of redirection.
	Directive *Valuing*	*Please don't open up the cards. We are not doing that yet..I'm glad you're excited though.*	T_authority	
	Web of learning	*You're going to be reading 3 articles assigned to your group... This is a close reading exercise to help you focus. Then you go back to your group and act as the expert."*	S_authority Collective learning	Positioning/framing students as experts. Gives purpose and connection to larger activity.
Melissa	Procedural *Directive* School	*Does everyone have one? remember name, date, teacher, make sure we have all of those. (students working silently).* *Raise your hand if you are still working on your plausibility ranking worksheet. You have about 1 more minute.*	T_authority *Private ideas*	Objective is completion in a given time. IRE.
		You guys can set your plausibility ranking aside for a second and I want you to look at the arrows worksheet. actually you can put them all together I'll grab them. That way you guys have lots of room to maneuver. *If you need to look at yours again at the end to rerank or if that informs your reranking ...I can get that to you ...we can look at them again in the end.*	T_authority	Task/procedure management
	Isolated tasks *Directive* Procedural	*Go ahead and fill in your name date teacher period please on your arrow sheet. Thank you for your help with our record keeping.*		Refers to worksheet by the task not process or practice.
	Procedural *Isolated tasks*	*So as you can see on your arrows you guys are going to choose 2 models and then you are going to choose 4 evidence of the 8 to focus on.and I don't even want to say to go with those models, but choose 4 of the 8 .*	T_authority	Micromanages their work. Minimizes the need for their intellectual investment.
	Directive	*There absolutely should be conversation going on.*		Talk for the purpose of fulfilling lesson expectations, what "should" happen..
	Procedural *Isolated tasks*	*Once you have chosen your models, you need to state what you have chosen and state why to your group mates so that everyone can understand what everyone's thoughts are.*		Directs each aspect of the process.

Figure 16 Segmented dialogue

Only by segmenting the dialogue based on similarities was I able to see subtle variation and nuance. For example, while Coral held cognitive authority as she read through models to the class, her classroom dynamics and other framing moves seemed to invite students into discussion and may have sent messages to encourage participation. Melissa told students they should be talking and discussing with their groups, yet she may have sent messages that may not have encouraged or promoted collaboration.

For School or For Science

I inferred each teachers general framing moves as oriented *for school* or *for science* aligned to the literature and my established codebook (Hutchinson & Hammer, 2010; Miller et al., 2018; Richards et al., 2020; Russ, 2018; Schwarz et al., 2021; Stroup, 2014). I inferred framing moves oriented towards *school* when the teacher attended to tasks and procedures, and set-up students' tasks around completion and compliance. I used framing for *science* and *sensemaking* when the teacher attended to students' knowledge construction practices, and established students' tasks around collaboration.

Melissa, generally, used more framing moves for school: for example, she used *directives* to focus students' action and attention on completing a specific element or worksheet, such as "*Make sure you have an A a B and a C. Does everyone have an A a B and a C?* And *"A's you are first, make sure- name, date and period are on there. You are going to read the description of each model and rank your plausibility."* These statements may have sent messages to students that they were expected to participate by following instructions. By isolating procedural tasks, such as "*name, date, period*" Melissa may have sent subtle, implicit messages to students which minimized their required engagement, and conflicted with her explicit messages to make decisions (Enyedy & Goldberg, 2004). Although Melissa stated students would make decisions, her continued focus on instructions and completing worksheets removed the value of students' enacted decision making while engaged in the activities:

> *"you guys have one more minute…you guys can set your plausibility ranking aside for a second and I want you to look at the arrows worksheet.. Go ahead and fill in your **name, date, teacher, period**, please, on your **arrow sheet**…So as you can see **on your arrows** you guys are going to choose 2 models and then you are going to choose 4 evidence of the 8 to focus on .and I don't even want to say to go with those models, but choose 4 of the 8…Once you have chosen your models, you need to state what you have chosen and state why to your group mates so that everyone can understand what everyone's thoughts are."*

In the text above, Melissa used self-perpetuating frames which emphasized and reinforced goals of completion (Russ & Luna, 2013). While she used sensemaking frames which emphasized elements of the activities ("*state what you have chosen, and why")* this may have sent messages to students that completion of those elements within the worksheet was more important than the intellectual work undertaken as a product of each element. Melissa's class seemed to take up these messages and work individually. On three separate occasions throughout class, she reminds students to talk:

> *1. There absolutely should be conversation going on.*
>
> *2. …And make sure you are talking so there is something to hear on the voice recorders (laughs)*
>
> *3. However, should you be discussing your choices as a group? (answers) Absolutely you should be discussion with your group.*

Coral, in general, used framing moves for science and sensemaking. She asked questions which prompted deeper thinking, such as "*what made you not choose some of them*?" When she used behavioral redirecting moves, she did so in a validating way which honored the students' actions as contributing, not distracting, from the community (*"Please don't open up the cards we are not doing that yet.,.I'm* *glad you're excited though*”). She framed students' work as collective, and their task as driven by their knowledge. She did not read instructions to students, but oriented students’ tasks around what they determined to be “*interesting*” in order to *“make decisions*.” In this way, she may have sent messages to students that their ideas were valuable and vital to their knowledge work. Students seemed to take up and act upon this messaging as they read to each other, discussed their ideas and openly expressed puzzlement:

> *“I feel like C is the one supporting fossils and then A and B are not supporting fossils, but I don't understand why it's supporting, or not. So C definitely.”*

Questioning Strategies

The MEL materials task students to determine the plausibility of socio scientific or scientific arguments based on evidence. During the introduction, both teachers posed questions to help students better understand the term plausibility yet did so in different ways: Coral introduced the term by focusing on the word *interpret* and to situate the term *plausibility* into a sentence for context. She provided examples and a scenario to help students understand the term *interpret*, which they could apply to infer *plausibility*. She used affirming language and re-voiced their explanations which valued their contributions for the collective. In this way, she framed for community knowledge within the larger construct of the activity.

Coral: You are going to determine the <u>plausibility</u> or how likely each one is to be true-10 being highly <u>plausible</u> and you are pretty sure it is true (and opposite). Do you know what interpret means? What does it mean? Ian? Good, right! So you are looking at information and making an inference of what it means. Any other ideas? That was a great way of putting it. Let's say you are just starting to learn English and someone is talking to you and you can't really understand everything they are saying, and you have to <u>interpret</u>

	what they are saying from the information you have. So here it is again; when people <u>interpret</u> fossils, they are really just the remains of something that used to be alive and it's not an exact copy of that thing. and they have to interpret the pieces they have...
Student:	(Gives inaudible response).
Coral:	That's a really interesting note-it's saying-you are saying-we cannot make ANY conclusions about past environments, so very black and white statements-(another student says something) -right-oh good point. So Chris is saying he would choose a middle number because he thinks ANY is too strong of a statement.

Melissa posed questions about the meaning of plausibility by invoking causal connections to the word *possible*. Melissa generally closed ended questioning approaches, such as IRE (Initiate-Respond-Evaluate) scripts. This questioning strategy may have sent messages to students regarding their expected participation (Enyedy & Goldberg, 2004). Student responses were generally hushed, minimal or one-word responses, which she revoiced:

Melissa:	What did we decide that means? How, what? (whispers) this is where you talk. How likely or....what was the other word we used, one that started with P...*plausible* also sounds like *possible*.
Students:	(Quiet, no response).
Melissa:	Okay? and we talked about if it was a realistic possibility.....

Pronouns and Positioning

I noticed that both teachers used pronouns to establish, reinforce and sustain classroom expectations for activities, so I selected small portions of dialogue for each teacher and included a brief pronoun analysis as it related to framing moves. Pronouns can be indicative of the rights, responsibilities and relationships between members of classroom communities, and how those members are commonly positioned (Enyedy & Goldberg, 2004; Erickson, 1982). Enyedy and Goldberg (2004) identified inclusive pronouns (we, us), which establish a feeling of unity, and exclusive pronouns (you, I), which point to specific, individual activities that separate the speaker and hearer. I expected this analysis to inform connections between established student expectations for participation and observed participation. In the introduction segment below, I noted Melissa's use of dichotomous, exclusive language, while Coral used inclusive, unifying language:

Melissa: Check_that **you** have 4 blue cards and 8 red cards.

Coral: Today and tomorrow, **we** are going to be learning about fossils.

While there appeared connection between pronoun use and student participation in some cases, this method, as in other singular methods, was not indicative of the expected engagement or participation. In the excerpts below, each teacher demonstrated nuanced variation between their pronoun use and their explicit instruction; for example, both teachers began with inclusive pronouns, and both concluded with exclusive pronouns separating themselves as the authority ("*you are going to…*"). The manner in which each applied pronouns within their framing moves may offer some clues into differences in student uptake: Coral gave very brief instructions, emphasizing students' choice within the greater context of the activities ("*what you find interesting*"). Melissa used more inclusive pronouns, however she provided more detailed instructions, which may have isolated tasks or minimized expectations for participation ("*remember, name, date, period*").

Coral: So **let's** go through them one at a time. You have 8 you have to look at. But today **we** are going to narrow it down to 4 and **you** are going to dump 4 that you don't find very interesting, or that are not what you want to use as evidence. Also of the 3 models, **you** are going to dump 1.

Melissa: So the first thing **we** are going to do is rank the plausibility of each model. Make sure you have an A a B and a C. Does everyone have an A a B and a C? Here A's- you are first, make sure name, date and period are on there. **You** are going to read the description of each model and rank your plausibility. Do you guys remember what plausibility means? What did **we** decide that means? How, what? (whispers) this is where **you** talk. How likely or....what was the other word **we** used, one that started with P...plausible also sounds like possible. Okay? And **we** talked about if it was a realistic possibility..... Okay? Does everyone have one? remember name, date, teacher, make sure **we** have all of those.

While similar, the subtle differences in framing moves, while accompanying pronoun use, may have sent messages to students which conflicted with the descriptions of Enyedy and Goldberg (2004); for example, Melissa used more inclusive pronouns, yet her framing moves may have isolated tasks, and informed or influenced students' participation leading to a "diminished understanding of the nature of scientific activity that sees science as a collection of isolated facts and procedures with little relevance to their own lives" Enyedy & Goldberg, 2004, p.918). Coral used more exclusive pronouns, yet her framing moves may have sent messages that students were capable of scientific work by not emphasizing individual elements. Thus, pronoun usage was an insufficient singular method to describe differences in students' participation.

However, there were several examples which demonstrate the correlation between teachers' pronoun use and framing moves, which align the messages sent to and taken up by students. In the following example of *directing the task*, Coral positively shifts a corrective and potentially negative situation by using an inclusive pronoun. In this way, she includes herself into the community instead of isolating a behavior. She then provides purpose to their activity, while emphasizing their role as experts, instead of directing the task. Melissa redirected students' attention towards materials and procedures with exclusive pronouns. Her instruction separated their tasks of explanation and choice, which may have reduced the ability to connect and apply such constructs towards students' greater intellectual work.

Coral:	Please don't open up the cards. **We** are not doing that yet..I'm glad you're excited though. You're going to be reading 3 articles assigned to your group... This is a close reading exercise to help you focus. Then you go back to your group and act as the expert."
Melissa:	Does everyone have one? Remember name, date, teacher, make sure we have all of those. **You** need to state what **you** have chosen and state why to your group mates so that everyone can understand.

Group Work

So far, I have analyzed the framing moves embedded in the teachers' talk during the whole-class segments at the beginning of class, before students began the activity. Next, I analyze the framing moves embedded in the teachers' interactions with the small groups of students as they worked through the MEL activity. In both classrooms, students worked through the MEL activities in small groups after the teachers' initial instruction. Both teachers' interactions with student groups tended towards task management as expected, and both teachers moved students through the activities, but with different emphasis: Coral emphasized knowledge construction amidst their MEL tasks, while Melissa emphasized the task itself in order to construct knowledge. Below I provide examples of each teachers' small group interactions.

Coral's Group Interactions: Redirecting.

In the following example, Coral approached a group of four students. This example was chosen because it represents a common exchange between students and Coral during this class-that of *redirecting* and *refocusing*. This example demonstrated her framing moves to shift students towards sensemaking from a focus on task completion or *doing school*. In this instance, Coral stood back and observed the students interacting for about a minute before she interjected.

> Coral: So, which one are you talking about now? Because I think you might have rushed to make a decision.

After observing and nudging them to slow down instead of quickly completing the task, she clarifies the task.

> Coral: It's easier if you all have the same then you can discuss. So, don't just pick the ones you read. I was just breaking up the reading, so you are now experts in each one. So you are helping each other to make a decision on which 4 you want to analyze further to support or reject the models. So, what I'd like-who was in the group that had number 1? Jorge? Ok so read the white card that has 1 on it, and explain the different evidences that have a 1. And if you like number 1, you can choose it as a group. But your job is to try to narrow it down to 4. You can worry about the models later, you can do the models now, but you should be making the decision as a group not independently. You're helping each other make a decision on which 4 you want to analyze further.

Coral provided context and purpose ("*so you are now the experts in each one*") and emphasized their role as a learning community ("*you are helping each other make a decision*"). She emphasized their collective knowledge work and minimized the procedural tasks, reminding students that their task was to "*make a decision*" and they could "*worry about the models later.*" In this way, she framed the activity as drawing on the group's collective and public knowledge construction, which can allow student ideas to shape knowledge spaces. While she did remind the group about working collaboratively, this was framed as "*helping each other*" not for purposes of completing a worksheet.

The students' response (below) is worth considering: the group immediately began reading together, with one student taking the lead and another correcting a mispronounced word (a moment later a second student corrected another word) in a manner accepted by all group members, without isolating individual behaviors or shortcomings. The group dynamic appeared natural and routine. Conversations around science and the MEL topics began immediately and were deeply connected to active and collaborative knowledge construction—and Coral then supports what they are doing as working toward a "keep or dump moment, not a final decision" about what models to focus on.

Student 2:	(reading out loud) fossils are pre.. pre..
Student 3:	Preserved
Student 1:	(Continues reading)
Student 2:	I feel like that supports-not strongly supports-but supports model C.
Student 4:	It seems like it doesn't give any information on….
Student 1:	I feel like it just says trilobites, but it doesn't say how it fits (talks inaudibly, looking at his paper)
Coral:	So, you just have to decide if you want to stick with it and keep working with it tomorrow, or if you want to dump it. This is a keep or dump moment, not a final decision. You have to read the articles a little further before you do that.
Coral:	(to whole class) I just want to remind you that you are only making decisions on what you want to keep or what you want to dump. You don't need to make any final decisions. The ones you keep you will read more fully.

In the next example, Coral was comfortable with students' puzzlement, allowing students to freely discuss, without finishing or correcting their thoughts.

Students naturally brought in prior learning, which is reflective of their alignment with Coral's framing moves to position MEL activities as continuous and connected to whatever funds or other stores of knowledge students bring to the table (Enyedy & Goldberg, 2004). Students talked to each other directly, not through the teacher. Coral affirmed and revoiced their decisions with a summary, while moving them forward in their process. Coral responded directly to the substance of students' discussion in order to move them towards the goals of the activity. Although she directed how they proceed, she does so in a way which affirmed their contributions to the process and to each other. In this way, she made their work public and knowledge construction visible and valuable, which (among other things) reinforces collaborative knowledge construction as the expected activity in this class session (Stroupe, 2014).

Student 1:	I feel like C is the one supporting fossils and then A and B are not supporting fossils, but I don't understand why it's supporting or not. So C definitely.
Student 2:	I think it's B.
Student 1:	Do you want to do A or B? I feel like we read something ...want to decide that after we choose the evidence?
Coral:	<u>That might be a wise choice</u> so you want to choose C and then decide between A and B? Ok, I can see why you would feel that way. Alright so Jorge is going to tell you about evidence 1, then all the way through until you make your choices about which you will keep.

However, this excerpt does allow for a nuanced view of framing moves with prescriptive materials: Coral framed the group's work around a specific practice-*obtaining and evaluating information for decision making*-but not for deeper thinking. She cut off student conversation when they discussed disciplinary content and responded to and redirected the procedural nature of their task (Code:*reset)*. In this way, she relocated the locus of authority back to her. Thus, although this interaction was framed in a manner which positioned students to act with epistemic agency, compliance with the structure of the task concluded the event. Here, the goals of the activity-to make a decision-are explicit. I cannot understate the need to consider the simultaneously competing tensions that may inhibit opportunities for teachers to deviate from the structure of activities.

Melissa's Group Interaction: Assessing Ideas and Driving Toward *Plausibility*.

Melissa channeled her group interactions towards understanding, applying and evaluating the *plausibility* of each line of evidence, which perfectly aligned with the curricular goals of the materials. Melissa focused her questioning to groups around similar questions related to the concept and definition of plausibility, and their choices of models. She used questioning strategies to spur additional thinking and connection related to plausibility: "*does one being more implausible make another more plausible"* However*,* once students responded, Melissa was not observed prompting further discussion about their models or responding to disciplinary talk. Here is a typical example:

Melissa:	So, what did you guys choose?
Student:	B and C. Because we decided that model A was the least plausible
Melissa:	Ok. So...why...does least plausible to you equal 'don't want to study,' or 'don't want to review or investigate?'
Student:	We just thought it would be better if we investigated the solutions for the problems.
Melissa.	So plausible solutions vs improbable solutions. Okay. um .does one being implausible make another more plausible sometimes?
Student:	yea it could. because if something is really implausible the solution for it might be harder to reach or an unsustainable goal.
Melissa:	okay. I'm not trying to change your mind, just having a conversation. getting your thoughts. Keep in mind you have all categories open to you and that sometimes, we use falsifiability, right? to support, so something

that is falsifiable actually ends up supporting. So something else so keep that in mind as you are looking through your evidence.

Melissa: You guys can go ahead and record which models you decide on and then start figuring out what evidence you would like to use. Don't forget you need to review the evidence text with each evidence card.

In this example, Melissa (like Coral) directs students to make decisions about which models to explore, with emphasis on the meaning and implications of “plausibility” and “falsifiability” (key concepts in the MEL learning goals) but not on students’ reasoning about the models, e.g., why they found model A “least plausible.” This example highlights Melissa’s attunement with the instructional goals of the MEL and her pedagogical alignment towards those goals. Melissa used similar framing moves in group interactions to direct conversation and discussion towards application of plausibility with interspersed procedural reminders, ensuring completion within the confines of the class period. Notably, Melissa anticipated common misunderstandings and questions by filling gaps for students (falsifiability, reminders about reading evidence text), which both demonstrate a deep understanding of her students; while this may be perceived as simplifying instruction amongst education researchers, this is a common and productive practice particularly in high school classes (such as Melissa’s) in which student talk may be difficult to elicit. However, doing so may have sent the message that completing the task in a particular way was the point of the activity, a perhaps-unintended framing move.

In one interaction, Melissa initially took a different tack and engaged students in discussion of their disciplinary ideas about the models:

Melissa: So what did you guys decide?

Student:	B and C.
Melissa:	How come?
Student:	Because there are signs of stuff like the water ..with engineering being able to not necessarily fix it long term with the water supply going down but its giving us alternatives. I’m not sure if I'm saying this right but I'm pretty sure fresh water including glacier water only makes up 2% of all water.
Melissa:	Okay so what I hear you say is based on your background knowledge you feel like that is a compelling model.
Student:	Yea and that's already been predicted as well as food shortages as population increases and everything resource wise is going to drop dramatically.
Melissa:	So, not to change your minds, but to throw a wrench in what you are saying, does something have to be already done in order to be studied?
Student:	(pauses….) no.
Melissa:	Okay! …..walks away.

Melissa initially revoiced the student’s idea, which cast their ideas as valuable and positioned their group learning as collective (“what did *you guys* decide”). She then validated the students’ reasoning as stemming from the students’ background knowledge. However, in her next turn of talk, Melissa’s question redirected the focus back to how to choose their models. She did so with a close-ended question; the student offers, and Melissa accepts a one-word answer, “no,” prompting Melissa to close the discussion by affirming the answer (“Okay!”) and leaving. After this, the students’ conversation stopped. The data may not reveal Melissa’s thought process in-the-moment, but she may be facing the well-documented tensions teachers face between emphasizing task completion (which in this case could support sensemaking later in the lesson) and fostering students' epistemic agency (Ko and Krist, 2019; Miller et al., 2018; Stroupe. 2014).

Summary: Differences between Melissa's and Coral's small-group interactions

While there is subtle and nuanced difference in each teacher's delivery of the the MEL lesson, the additive sum of subtle differences over the academic year may have resulted in the extreme differences in participation observed during the MEL lessons. In other words, small differences in framing moves-- observed pronoun use, small group interaction and questioning strategies--may add up over time and result in large differences in student participation. These subtle messages and cues are picked up by students who sustain and reinforce the established classroom culture defining norms of participation and engagement (Carlone et. al., 2021; Russ, 2018).

Some of these nuanced differences, such as pausing to listen and respond to group discussions or to guide group discussions with questions, may have sent differing messages regarding the teachers' instructional goals. Based on this subtlety, I inferred that Melissa's instructional goals were to understand the anchor principal of *plausibility*. Melissa focused on the task structure of activity elements (e.g."arrow worksheet" or "pre/post survey") which may have sent messages to students that completing each individual task was more important than greater intellectual work or engagement in science practices. In three separate incidents, groups were overheard discussing and applying their prior knowledge to the MEL activities as Melissa approached. She *initiated* the same question to each group prior to listening to their discussions ("*what about falsifiability")* and turned to leave without seeing if this spurred each group to deeper thinking. In each group, students' conversation stopped after her question. In this way, she may have sent messages which reinforced hierarchical systems cognitive authority. However, Melissa also taught high school, in which participation may simply be lower.

Coral appeared to send messages which cued comfortable and consistent participation in knowledge construction. Student conversation and discussion with the MEL materials were observed at every table. When Coral circulated the room, she paused, observed at each table and allowed them to work through their ideas before she interacted with them. Coral *responded* to student groups individually. This may have cued or reinforced messages that students' ideas and meaningful participation are central to classroom activity.

RQ 2: What are the impacts on students' epistemic agency?

I examined each teacher's framing moves to infer their instructional priorities during introductions and interactions, yet I saw evidence of students' epistemic agency in their observed participation and engagement. Each teacher established their instructional priorities which cued power dynamics that inhibited or elevated opportunities for students' students' epistemic agency (Sezen-Barrie et al., 2020). Similar to Stroupe (2014). One of the indicators I established for students' epistemic agency within the MEL activities was *if* or *how* teachers' positioned student ideas for the "communities science work," or as right or wrong (Stroup, 2014; p. 498.) While this observation was only a snapshot of the academic year, by analyzing students' participation and engagement, I can infer the established and sustained classroom cultures which define norms for participation and engagement.

As stated previously, epistemic agency, in this sense, is the *agency afforded by the MEL materials*. It is beyond the scope of this study to examine, as others have, how the instructor created space for student ideas (Ko & Krist, 2019), how students shaped and designed an activity (Zhang et. al., 2022; or how students use ideas at play in discussion (Cherbow & McNeill, 2022; González-Howard and McNeill, 2020). The MEL activities, by design, position students to make decisions and to engage with science practices of argumentation.

Within this space, I saw many more examples in Coral's class of students acting with epistemic agency as they took up the teachers' framing bids to engage with materials for constructing knowledge and doing science than I did in Melissa's class, where they took up her framing bids to engage with completing individual or isolated tasks. Notably, Coral adapted the activity and formed expert groups of students, effectively creating more "work," while Melissa had students' complete portions of the activities individually, not in groups. However, each modality may have been best suited for their respective aged groups and was certainly perceived as a best fit by both teachers, for their classes.

Melissa's class appeared to embody a *culture of compliance*, in which students learned individually and privately, for the sake of task completion. Students in Melissa's class worked quietly and acted as individuals. When Melissa approached groups (as seen on the GoPro video), they were quiet or immediately hushed (only one group talked quietly as she approached). Conversation, if it occurred, was hushed. When Melissa left a group, students sat in silence. While her initial framing moves during the task introduction established norms of compliance and authority ("*remember, name, date and period*"), Melissa' appeared to sustain these norms during her group interactions. Melissa's students had only brief moments in which they held cognitive authority. Melissa maintained an asymmetrical position of power, with exclusive pronouns (*"I don't want to guide you; I don't want to say go with those models, but…*") which situated her as the owner and evaluator of knowledge. Melissa's use of directives established her expectation that student contributions were either right or wrong, while limiting the possibility of further learning based on student inputs. Students hushed or simplified responses to her questions appear to reflect their role as "sub knowers" or less likely to contribute to knowledge construction (Carlone et al., 2021). Thus, Melissa's framing moves appeared to sustain a culture of compliance, which may have limited opportunities for students to act with epistemic agency.

Coral's class appeared to embody a *culture of collaboration*, framed by Coral and taken up by students, in which students learned collectively and publicly for the benefit of the classroom community (Stroupe, 2014). Students enthusiastically discussed the materials and collaboratively worked through activities without encouragement to participate. Students in Coral's class were eager to participate and share ideas. Coral appeared to complement group discussions, without disrupting them; discussions continued as she approached and left groups. Every single group (as seen from GoPro video), without reminders, were seen discussing and working with materials. Groups were engaged with the process and overheard in discussion of science ideas as they negotiated their choices. Students were comfortable and free to sit, stand, or move as they engaged in the activities, without redirection. They were respectful of the learning environment, and of others within it. While Coral did have moments of holding cognitive authority, these were typically brief and shifted back to students. Corals' framing moves appeared to sustain a culture of collaboration which may have fostered opportunities for students to act with epistemic agency.

RQ	Class	Teacher Established	Students Enacted
How does the teacher frame learning?	Coral	Science, process, community driven, ideas as public resources	Comfortable talking, sharing ideas, questioning and critiquing peers
	Melissa	Compliance, authority, completion, ideas individually held	Quiet, disengaged, task completion
What are the impacts upon epistemic agency?	Coral	Collaborative learning, public knowledge creation	Disciplinary discourse, collaborative roles
	Melissa	Traditional knowledge hierarchies, individual learning	Individual work, task related discourse

Figure 17 Summary of research questions

Summary

As in the first research question, I remind the reader that my observations were a snapshot into each classroom; the observed instances reflect only single occurrences, yet they allow me to infer the summation of these instances upon the established classroom culture, which may account for the difference in observed student behaviors. Two teachers' framing moves, at times explicit and others implicitly embedded within student interactions, are indicators of how each teacher framed learning for students, and the framing moves in turn impacted opportunities for students to act with epistemic agency. While teachers used many similar elements and practices in their classes, the distinct variations between student uptake in each class may provide clues to the messages or cues they were sent by each teachers' framing, which provide insight into varying opportunities for epistemic agency.

Coral demonstrated responsiveness towards students' interests and ideas while Melissa demonstrated responsiveness towards students' adherence with the materials. Melissa generally maintained a procedural focus to direct engagement, while Coral generally focused on practices to direct engagement. In this way, Coral may have fostered or been more receptive to "sparks" of student sensemaking than Melissa (Schellinger et al., 2022). Melissa's students generally were hushed or silent, with little observable data on student discourse. Coral's class appeared to value knowledge contributions of members, while Melissa's appeared to value completion and accuracy. Coral's students were participative and engaged, with large amounts of discourse data. From these observations, I inferred Melissa's framing towards compliance and authority, or *doing school*, which appeared to be maintained by the culture of the learning environment. I inferred Coral's framing towards collaboration, or *doing science,* which appeared to be maintained by the culture of the learning environment. Again, I must remind the reader that the teachers instructed different age groups--Melissa in high school and Coral in Middle--and each likely deployed distinct framing moves and pedagogical practices best suited to their respective students.

Discussion

Given identically structured teaching materials, variation between students' engagement and participation could be attributed, at least in part, to subtle and nuanced variation in teachers' framing, which cued different responses from students. The following section will explore the themes considering current classroom structures and implications for educators.

Framing Moves and Classroom Cultures

Examination of each teacher's "public talk" during their introductions allowed me to draw inferences about their established and sustained classroom cultures (Enyedy & Goldberg, 2004). While each teacher's framing moves may have sent cues or messages to students about their expected participation and engagement with the MEL materials, the dynamic variation observed in students' engagement is likely not a result of varied framing during this single class session. Coral and Melissa had subtle and nuanced differences in their framing moves; therefore, it is more likely that students, over time, picked up and acted upon the messages and cues sent by the teachers, to maintain a classroom culture aligned to those cues and messages. In other words, small and subtle differences in cues sent to students, over time, can add up to drastic differences in students' uptake, observed through participation and engagement.

I initially overlooked Corals' class as I sought suitable comparisons within the corpus of data; the students' freedom of movement in Coral's and the constant student talk initially appeared chaotic-yet talk was centered on the materials. I now understand this "chaos" to reflect the established classroom culture, fostered by Coral and maintained by students. Coral fostered, and students enacted, a culture of collaboration in which students freely communicated and conversed around their topics. Coral sent cues regarding acceptable *physical* participation; students were able to sit, stand or lean on or near their tables without redirection. A group of three tween boys was seen on task, engaged and equitably sharing the learning load for nearly 15 minutes without distraction. Coral's explicit emphasis towards collaborative decision-making framed learning as collective and publicly visible, which fostered opportunities for students' epistemic agency (Stroupe, 2014). Coral rarely used directives around how students approached and engaged in their activities. She read students' work, revoiced their ideas and prompted them to build on their knowledge without filling the spaces of uncertainty herself. She emphasized students' decision making and incorporated their ideas into whole class and small group interactions. In this way she elevated student ideas into the public plane (Stroupe, 2014). Coral fostered positive relationships through word choice, specific student feedback and commendation even related to procedures: "*you have to limit yourself to four, but I* *love how precocious you are*." The tone and inflection of Coral's voice was positive and encouraging; students were attentive and engaged.

Although not conclusive, observational evidence suggests that collaboration was not a typical component of Melissa's class. Students appeared to favor individual over group work, and repeatedly resisted Melissa's requests to talk to each other. This was evident when she approached groups (seen from her GoPro camera); students were often observed completing worksheets individually, and one student was seen with his head down. Possibly despite her intentions, Melissa's talk and actions framed learning for compliance and task completion. Her students took up this framing; the classroom was generally quiet, with some hushed conversations unrelated to the activities and frequent reminders to talk. I acknowledge that I have done this. However, this strategy seemed in service to her (and when I have done this, to my) instructional goals.

Power Structures and Students' Epistemic Agency

Many researchers (Bang & Medin, 2010; Bang et al., 2012; Stroup, 2014; Miller et al., 2018; Kawasaki & Sandoval, 2019; Ko & Krist, 2019; Berland et al., 2020; Carlone et al., 2021; Jaber et al., 2022) describe students' epistemic agency as potentially disrupting power structures often present in schools and school systems. Teachers' authority over knowledge may inadvertently encourage task completion instead of active sensemaking (Stroup, 2014). If canonical science content knowledge is prioritized, teachers tend to retain accountability for knowledge dissemination. When teachers prioritize understanding of the science process, they can share power amongst students and pursue their ideas to co-construct knowledge (Stroup, 2014; Miller et al., 2018; Sezen-Barrie et al., 2020; Carlone et al., 2021).

Melissa established and sustained an asymmetrical relationship between herself and students (Enyedy & Goldberg, 2004). She may have sent messages that reinforced her position of authority over correct knowledge, (i.e. "*I don't want to tell which to choose, but…")*. Melissa used directives in her questioning strategies which limited the engagement required of students. She emphasized task and materials management throughout the lesson. Melissa's interactions reinforced—or at least, didn't disrupt— her authoritative role over ideas and knowledge and limited opportunities for students to act with epistemic agency. Her uniform line of questioning for each group, at times interrupting productive sensemaking, reflected an embedded culture of compliance with established structures for purposes of completing tasks.

Notably, Melissa never referenced the socio scientific topic of the MEL. Similar to one teacher in Enyedy and Goldberg's (2004) study, this sent the message to students that the objective of the lesson was to "complete the task by the end of the class" (p. 917). The authors observed a teacher that failed to ground the work with an authentic question or connect it to prior work, and similar to Melissa, continued to emphasize following directions. Also, like Melissa, the teacher checked students' progress but not the meaning of their knowledge. This emphasis illustrates both teachers enacted “beliefs about science and the importance of performing” (p. 917). However, the objective of the MEL materials was for students to understand how scientists determine the plausibility of evidence and to understand differences between varying socio scientific arguments. Therefore, I am not arguing that, by adhering to the goals of the materials, Melissa is pedagogically off course. On the contrary-she attended workshops and training to use the materials for the purposes of students’ understanding these concepts in an age of misinformation. However, Coral attended the same training, and used similarly structured materials, yet approached them differently.

Coral appeared to establish and maintain a culture of equivalency and symmetry with students. Coral positioned students as “*experts*” to “*help each other make decisions*” thus removing her role as the cognitive authority. She was comfortable in silent spaces of student’s thinking or discomfort and used questioning strategies to build upon and expand their connections to science practices and sensemaking. Her emphasis on practices of science (i.e. “*in your analysis*;” *“you are not really doing the worksheet-don’t worry about that*”) cued students towards the intellectual work of scientists and minimized the school-based elements of completing assignments. Students appeared comfortable in these roles, and eagerly engaged with each other and the processes of the MEL activity. Students were seen standing, sitting, leaning and moving about the room, without correction. Coral appeared to trust students and used affirming language even when correcting behaviors. Students were observed (from GoPro and audio recordings) discussing materials at length, bringing in prior learning, and building on the ideas of others. Students appeared to function as a science community, with Coral alongside them as a guide. Coral's class appeared to disrupt traditional power structures between teachers and students as she shared and transferred cognitive authority to students.

Significance

This study is significant for teachers and teacher educators; the manner in which teachers approach instructional materials--be it highly structured or not--determine the objectives they establish, and framing moves they enact, which are ultimately taken up by students. The present study examined two teachers using similar materials with very different learning environments. This study supports the work of teachers (and researchers) finding space within materials to open space for student ideas, while also supporting the need for well-designed materials which allow for such space. Despite the concerns of some researchers that highly structured NGSS-aligned materials may cut off opportunities for epistemic agency or encourage "pseudo agency" (Elby, 2019; Miller et al., 2018; Morales-Doyle et al., 2019) it is possible to use those materials in a way that invites appreciable epistemic agency, like Coral. However, like Melissa (and as I acknowledge I have done myself), it may be easy to fall into "complacent enactment" focusing more on task completion at the expense of sensemaking without careful, mindful attention (Miller et al., 2018, p. 1056).

Epistemological framing as a theoretical construct has made little inroads into the hands of science teachers, yet these practitioners continuously send messages to students about expected participation within an activity, both intentionally and unintentionally. Many teachers likely experienced traditional science courses, in which teachers held authority over knowledge; they set up a topic, directed discussion and evaluated presented information (Berland & Hammer, 2012). Educators' conscious, mindful and reflective attention towards the impact of their own epistemological framing offers a unique opportunity to address desirable outcomes (science-as-practice; sensemaking) with minimal curricular modification. The present study offers insight towards understanding how teachers can use framing moves to work within the bounds of prescribed curricula to position students with epistemic agency and active participants in knowledge construction or to passively complete tasks. When teachers receive professional development, coupled with well-designed materials *and* time or space within the curriculum to embed opportunities for emergent ideas, they can thoughtfully and strategically center students' sensemaking and epistemic agency (Kirst et al., 2023; Ko & Krist, 2019).

Supporting Teachers

Shifting student frames from one of *doing school* to one of *doing science through* sensemaking belies the need for professional development to recognize, address and respond to student framing, particularly when using prescriptive materials (Hutchinson & Hammer, 2010). NGSS instruction requires a reorientation of instructional focus from the teacher to the learner (Miller et al., 2018). Discourse, collaboration and co-construction of knowledge through science practices require pedagogical shifts, which can be supported by professional development. Teachers must navigate the ever-present tensions between supporting students' epistemic agency and sensemaking and adhering to prespecified learning targets, which requires them to develop capacities to explicitly support students as epistemic agents (Ko & Krist, 2019; Manz & Suarez, 2018). Professional development can help teachers find spaces in specific curriculum for student ideas to drive knowledge building (Ko & Krist, 2019; Kawasaki & Sandoval, 2019; Krist et al, 2023).

Several authors demonstrate the effectiveness of professional development to support teachers' framing. Kawasaki and Sandoval (2019) designed a multi-year professional learning program for pre-service teachers to engage in science practices. The authors determined that teachers must experience the science practices as a student to effectively frame learning for students' epistemic agency. Jaber et al. (2022) conducted a year-long training for in-service teachers, focused on their experiences, vulnerabilities and emotions as a learner, to foster empathy. The authors determined that the professional development strongly impacted teachers' framing of prescriptive curricula, which created opportunities for students to authentically engage with science practices. The participating teachers reframed learning to prioritize thinking and "honor and support students' disciplinary work and progress" (p 246). As one participant noted-" we can't do this complete paradigm shift with the way that we teach science if we don't participate in it first" (p. 243). Similarly, Richards et al (2020) identified a framing-anchored approach to support novice teachers' attention to student thinking. They found that teachers' fluctuating framing of the classroom activity contributed to irregularity in their classroom practice of attending to student ideas, and they cited the need for novice teachers' professional learning about framing and its' effect on students. The authors sought to refine the skills and knowledge with and within particular framings in order to support responsiveness to student ideas (Richards et al., 2020).

NGSS is not a silver bullet; it is neither a curriculum nor a set of recommended instructions, yet it carries significant pedagogical implications for (Schwarz et al., 2017). Many science teachers struggled to reorient instruction towards science practices prior to the pandemic and continue to rely on supplemental or individually created curricula (EdReports, 2023). A recent report found that 97% of surveyed teachers felt that curricular materials were vital to implementing NGSS with fidelity, yet only 37% felt their materials met this need. Further, two thirds of science teachers report 0-5 hours of professional learning related to their curriculum materials (EdReports, 2023). NGSS-aligned materials can ease the instructional transition towards NGSS implementation, yet without adequate preparation, even exemplar materials may reinforce traditional, canonical hierarchies of science and compliance over productive sensemaking (EdReports, 2023; Elby, 2019; Morales-Doyle et al., 2019). Careful and iterative development of NGSS-aligned curricula, through specific professional development strategies, can lead to thoughtful, well tested materials and engaging science lessons.

Next Steps

These findings invite further research to explore the integrations of epistemological framing into existing curriculum-centered professional development- as an additive element, not the central focus- to shift teachers' instruction for task completion towards rich epistemic practices that foster epistemic agency within their curriculum. Professional development should provide opportunities for teachers to intentionally use framing bids to shift students' engagement, which teachers could practice on each other to provide immediate feedback. This would require little modification (of curriculum or professional development) to infuse framing moves within instruction related to phenomena, which are critical components of the NGSS (NRC, 2012). Teachers who receive preparation and exposure to framing moves and epistemological considerations of learning are better equipped to facilitate equitable and meaningful learning environments for all students, and to position their students as epistemic agents.

Video can be a powerful tool for teachers to recognize framing bids and how students take up framing bids. Teachers could be provided with video of their own or other classes to observe discourse within science classrooms and identify moments of productive knowledge construction and power dynamics which may go unrecognized in-the-moment. Teachers should have opportunities to see themselves interacting with their students, and to note power and framing dynamics at play during discourse. Preservice teachers should be provided with opportunities to practice framing moves and to identify productive and unproductive student framing (Hutchinson & Hammer 2010). Video of dialogue, such as in the present study, could also be used to help teachers recognize how language, tone and behaviors can establish and sustain classroom cultures and expectations of learning, which can create or eliminate opportunities for epistemic agency.

Alternative Explanations

Coral and Melissa taught differing grade levels; Coral taught middle school, while Melissa taught high school. Some variation in students' epistemic practices-observed through participation and engagement-may have been due to age difference, maturity, and social structures between different grades. This study investigated a single class session, without connection to or analysis of classes preceding or following; differences in previously established class and school culture likely contributes to the differences in student engagement. There may be other explanations for epistemic behaviors which were not observable in the present study. However, both lessons took place mid-year, when classroom routines and structures were established. For this reason, teachers' epistemic expectations are reasonably well established.

Conclusion

In this study, I investigated two teachers' use of a scaffolded activity to infer their respective framing, which impacted students' opportunities for epistemic agency. While epistemic agency in this sense was within the confines of prescriptive curricula, this reflects common classroom tensions between pedagogical and epistemological goals. Therefore, this study is relevant to the practice of teaching and the needs of teachers to incorporate student ideas and productive framing into their use and choice of curricular materials. Framing and epistemic agency researchers should consider developing research with and for teachers. The research realm may consider opportunities for students' epistemic agency in unusual contexts which don't mirror the significant challenges and barriers to implementation faced by most teachers. Working with teachers while using NGSS exemplar, prescriptive curriculum, such as the MEL materials, provide an excellent opportunity for researchers and teachers to delve into the nuance of responsive teaching, in the context of everyday classroom experiences.

References

A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas (p. 13165). (2012). National Academies Press. https://doi.org/10.17226/13165

Bang, M., & Medin, D. (2010). Cultural processes in science education: Supporting the navigation of multiple epistemologies. *Science Education*, *94*(6), 1008–1026. https://doi.org/10.1002/sce.20392

Berland, L. K., & Hammer, D. (2012). Framing for scientific argumentation. *Journal of Research in Science Teaching*, *49*(1), 68–94. https://doi.org/10.1002/tea.20446

Berland, L. K., Russ, R. S., & West, C. P. (2020). Supporting the Scientific Practices through Epistemologically Responsive Science Teaching. *Journal of Science Teacher Education*, *31*(3), 264–290. https://doi.org/10.1080/1046560X.2019.1692507

Carlone, H. B., Mercier, A. K., & Metzger, S. R. (2021). The Production of Epistemic Culture and Agency during a First-Grade Engineering Design Unit in an Urban Emergent School. *Journal of Pre-College Engineering Education Research (J-PEER)*, *11*(1). https://doi.org/10.7771/2157-9288.1295

Chen, Y.-C., & Terada, T. (2021). Development and validation of an observation-based protocol to measure the eight scientific practices of the next generation science standards in K-12 science classrooms. *Journal of Research in Science Teaching*, *58*(10), 1489–1526. https://doi.org/10.1002/tea.21716

Darling-Hammond, L. (2022). Breaking the Legacy of Teacher Shortages. *Educational Leadership*, *80*(2), 14–20.

Data Snapshot: K-12 Science Instructional Materials (2022). (2023, March 13). EdReports - Evidence-Rich. Educator-Led. Free. https://cms.edreports.org/resources/data-snapshot-k-12-science-instructional-materials-2022/

Elby, A. (n.d.). Getting Started with Research on Epistemologies and Expectations.

Elby, A. (2001). Helping physics students learn how to learn. *American Journal of Physics*, *69*(S1), S54–S64.

Elby, A. (2019). Did the Framework for K-12 Science Education trample itself? A reply to "Addressing the epistemic elephant in the room: Epistemic agency and the next generation science standards." *Journal of Research in Science Teaching*, *56*(4), 518–520. https://doi.org/10.1002/tea.21539

Elby, A., & Hammer, D. (2001). On the substance of a sophisticated epistemology. *Science Education*, *85*(5), 554–567. https://doi.org/10.1002/sce.1023

Elby, A., & Hammer, D. (2010a). Epistemological resources and framing: A cognitive framework for helping teachers interpret and respond to their students' epistemologies. *Personal Epistemology in the Classroom: Theory, Research, and Implications for Practice*, *4*(1), 409–434.

Elby, A., & Hammer, D. (2010b). Epistemological resources and framing: A cognitive framework for helping teachers interpret and respond to their students' epistemologies. In L. D. Bendixen & F. C. Feucht (Eds.), *Personal Epistemology in the Classroom* (1st ed., pp. 409–434). Cambridge University Press. https://doi.org/10.1017/CBO9780511691904.013

Engle, R. A., & Conant, F. R. (2002a). Guiding Principles for Fostering Productive Disciplinary Engagement: Explaining an Emergent Argument in a Community of Learners Classroom. *Cognition and Instruction*, *20*(4), 399–483.

Engle, R. A., & Conant, F. R. (2002b). Guiding Principles for Fostering Productive Disciplinary Engagement: Explaining an Emergent Argument in a Community of Learners Classroom. *Cognition and Instruction*, *20*(4), 399–483. https://doi.org/10.1207/S1532690XCI2004_1

Enyedy, N., & Goldberg, J. (2004). Inquiry in interaction: How local adaptations of curricula shape classroom communities. *Journal of Research in Science Teaching*, *41*(9), 905–935. https://doi.org/10.1002/tea.20031

Governor, D., Lombardi, D., & Duffield, C. (2021). Negotiations in scientific argumentation: An interpersonal analysis. *Journal of Research in Science Teaching*, *58*(9), 1389–1424. https://doi.org/10.1002/tea.21713

Gupta, A., & Elby, A. (n.d.). Beyond epistemological deficits: Incorporating flexible epistemological views into fine-grained cognitive dynamics. 2.

Gupta, A., & Elby, A. (2011). Beyond Epistemological Deficits: Dynamic explanations of engineering students' difficulties with mathematical sense-making. *International Journal of Science Education*, *33*(18), 2463–2488. https://doi.org/10.1080/09500693.2010.551551

Hammer, D. (1996). More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research. *American Journal of Physics*, *64*(10), 1316–1325. https://doi.org/10.1119/1.18376

Haverly, C., Calabrese Barton, A., Schwarz, C. V., & Braaten, M. (2020). "Making Space": How Novice Teachers Create Opportunities for Equitable Sense-Making in Elementary Science. *Journal of Teacher Education*, *71*(1), 63–79. https://doi.org/10.1177/0022487118800706

Hutchison, P., & Hammer, D. (2010). Attending to student epistemological framing in a science classroom. *Science Education*, *94*(3), 506–524. https://doi.org/10.1002/sce.20373

Inquiry in interaction: How local adaptations of curricula shape classroom communities—Enyedy—2004—Journal of Research in Science Teaching—Wiley Online Library. (n.d.). Retrieved July 9, 2024, from https://onlinelibrary-wiley-com.proxy-um.researchport.umd.edu/doi/10.1002/tea.20031

Irving, P. W., Martinuk, M. S., & Sayre, E. C. (2013). Transitions in students' epistemic framing along two axes. *Physical Review Special Topics - Physics Education Research*, *9*(1), 010111. https://doi.org/10.1103/PhysRevSTPER.9.010111

Jaber, L. Z., Dini, V., & Hammer, D. (2022). "Well that's how the kids feel!"—Epistemic empathy as a driver of responsive teaching. *Journal of Research in Science Teaching*, *59*(2), 223–251. https://doi.org/10.1002/tea.21726

Kang, N.-H. (2007). Elementary teachers' epistemological and ontological understanding of teaching for conceptual learning. *Journal of Research in Science Teaching*, *44*(9), 1292–1317. https://doi.org/10.1002/tea.20224

Kawasaki, J. N., DeLiema, D. J., & Sandoval, W. A. (2014). The Influence of Non-Epistemic Features of Settings on Epistemic Cognition. *Canadian Journal of Science, Mathematics and Technology Education*, *14*(2), 207–221. https://doi.org/10.1080/14926156.2014.903319

Kawasaki, J., & Sandoval, W. (2019). The Role of Teacher Framing in Producing Coherent NGSS-Aligned Teaching. *Journal of Science Teacher Education*. https://doi.org/10.1080/1046560X.2019.1657765

Knaack, P. (1984). Phenomenological Research. *Western Journal of Nursing Research*, *6*(1), 107–114. https://doi.org/10.1177/019394598400600108

Ko, M.-L. M., & Krist, C. (2019). Opening up curricula to redistribute epistemic agency: A framework for supporting science teaching. *Science Education*, *103*(4), 979–1010. https://doi.org/10.1002/sce.21511

Krist, C. (Stina), Machaka, N., Voss, D., Mathayas, N., Kelly, S., & Shim, S.-Y. (2023). Teacher Noticing for Supporting Students' Epistemic Agency in Science Sensemaking Discussions. *Journal of Science Teacher Education*, *0*(0), 1–21. https://doi.org/10.1080/1046560X.2022.2155355

Lee, S. W.-Y., Luan, H., Lee, M.-H., Chang, H.-Y., Liang, J.-C., Lee, Y.-H., Lin, T.-J., Wu, A.-H., Chiu, Y.-J., & Tsai, C.-C. (2021). Measuring epistemologies in science learning and teaching: A systematic review of the literature. *Science Education*, *105*(5), 880–907. https://doi.org/10.1002/sce.21663

Levin, D. M., Hammer, D., & Coffey, J. E. (2009). Novice Teachers' Attention to Student Thinking. *Journal of Teacher Education*, *60*(2), 142–154. https://doi.org/10.1177/0022487108330245

Lidar, M., Lundqvist, E., & Östman, L. (2006). Teaching and learning in the science classroom: The interplay between teachers' epistemological moves and students' practical epistemology. *Science Education*, *90*(1), 148–163. https://doi.org/10.1002/sce.20092

Limbere, A. M., Munakata, M., Klein, E. J., & Taylor, M. (2022). Exploring the tensions science teachers navigate as they enact their visions for science teaching: What their feedback can tell us. *International Journal of Science Education*, *44*(12), 1897–1915. https://doi.org/10.1080/09500693.2022.2105413

Lombardi, D., Bailey, J. M., Bickel, E. S., & Burrell, S. (2018). Scaffolding scientific thinking: Students' evaluations and judgments during Earth science knowledge construction. *Contemporary Educational Psychology*, *54*, 184–198. https://doi.org/10.1016/j.cedpsych.2018.06.008

Lombardi, D., Matewos, A. M., Jaffe, J., Zohery, V., Mohan, S., Bock, K., & Jamani, S. (2022). Discourse and Agency during Scaffolded Middle School Science Instruction. *Discourse Processes*, *59*(5–6), 379–400. https://doi.org/10.1080/0163853X.2022.2068317

Louca, L., Elby, A., Hammer, D., & Kagey, T. (2004). Epistemological Resources: Applying a New Epistemological Framework to Science Instruction. *Educational Psychologist*, *39*(1), 57–68. https://doi.org/10.1207/s15326985ep3901_6

Luna, M. J., Selmer, S. J., & Rye, J. A. (2018). Teachers' Noticing of Students' Thinking in Science Through Classroom Artifacts: In What Ways Are Science and Engineering Practices Evident? *Journal of Science Teacher Education*, *29*(2), 148–172. https://doi.org/10.1080/1046560X.2018.1427418

Manz, E., & Suárez, E. (2018). Supporting teachers to negotiate uncertainty for science, students, and teaching. *Science Education*, *102*(4), 771–795. https://doi.org/10.1002/sce.21343

Miller, E., Manz, E., Russ, R., Stroupe, D., & Berland, L. (2018). Addressing the epistemic elephant in the room: Epistemic agency and the next generation science standards. *Journal of Research in Science Teaching*, *55*(7), 1053–1075. https://doi.org/10.1002/tea.21459

National Academies of Sciences, E., and Medicine. (2021). *Call to Action for Science Education: Building Opportunity for the Future*. The National Academies Press. https://doi.org/10.17226/26152

Next Generation Science Standards: For States, By States. (2013). National Academies Press. https://doi.org/10.17226/18290

Nez, R., & Lombardi, D. (2019). *MEL2 Project Year 2* [dataset]. https://doi.org/10.17910/B7.860

Pinnow, R. J., & Zangori, L. (2024). Cueing Scientific Explanations: A Social Semiotic Perspective on Framing during Science Instruction in the Elementary School Classroom. *Cognition and Instruction*, *42*(2), 269–293. https://doi.org/10.1080/07370008.2024.2308283

Pope, D. C. (2001). "Doing School": How we are creating a generation of stressed-out, materialistic, and miseducated students. *New Haven, CT: Yale University Press.*

Richards, J., Elby, A., Luna, M. J., Robertson, A. D., Levin, D. M., & Nyeggen, C. G. (2020). Reframing the Responsiveness Challenge: A Framing-Anchored Explanatory Framework to Account for Irregularity in Novice Teachers' Attention and Responsiveness to Student Thinking. *Cognition and Instruction*, *38*(2), 116–152. https://doi.org/10.1080/07370008.2020.1729156

Rosenberg, S., Hammer, D., & Phelan, J. (2006). Multiple Epistemological Coherences in an Eighth-Grade Discussion of the Rock Cycle. *Journal of the Learning Sciences*, *15*(2), 261–292. https://doi.org/10.1207/s15327809jls1502_4

Russ, R. S., & Luna, M. J. (2013). Inferring teacher epistemological framing from local patterns in teacher noticing. *Journal of Research in Science Teaching*, *50*(3), 284–314. https://doi.org/10.1002/tea.21063

Saldaña, J. (2016). *The coding manual for qualitative researchers*. SAGE. https://eduq.info/xmlui/handle/11515/35868

Schafer, A. G. L., Kuborn, T. M., Schwarz, C. E., Deshaye, M. Y., & Stowe, R. L. (2023). Messages about valued knowledge products and processes embedded within a suite of transformed high school chemistry curricular materials. *Chemistry Education Research and Practice*, *24*(1), 71–88. https://doi.org/10.1039/D2RP00124A

Schellinger, J., Jaber, L. Z., & Southerland, S. A. (2022). Harmonious or disjointed?: Epistemological framing and its role in an integrated science and engineering activity. *Journal of Research in Science Teaching*, *59*(1), 30–57. https://doi.org/10.1002/tea.21720

Schwarz, C. V., Braaten, M., Haverly, C., & De Los Santos, E. X. (2021). Using Sense-Making Moments to Understand How Elementary Teachers' Interactions Expand, Maintain, or Shut Down Sense-making in Science. *Cognition and Instruction*, *39*(2), 113–148. https://doi.org/10.1080/07370008.2020.1763349

Sezen-Barrie, A., Stapleton, M. K., & Marbach-Ad, G. (2020). Science teachers' sensemaking of the use of epistemic tools to scaffold students' knowledge (re)construction in classrooms. *Journal of Research in Science Teaching*, *57*(7), 1058–1092. https://doi.org/10.1002/tea.21621

Sezen-Barrie, A., Stapleton, M. K., & Marbach-Ad, G. (2020). Science teachers' sensemaking of the use of epistemic tools to scaffold students' knowledge (re)construction in classrooms. *Journal of Research in Science Teaching*, *57*(7), 1058–1092. https://doi.org/10.1002/tea.21621

Sikorski, T., & Hammer, D. (2017). Looking for coherence in science curriculum. *Science Education*, *101*(6), 929–943. https://doi.org/10.1002/sce.21299

Stroupe, D. (2014). Examining Classroom Science Practice Communities: How Teachers and Students Negotiate Epistemic Agency and Learn Science-as-Practice: EXAMINING CLASSROOM SCIENCE PRACTICE COMMUNITIES. *Science Education*, *98*(3), 487–516. https://doi.org/10.1002/sce.21112

Suh, J. K., Hwang, J., Park, S., & Hand, B. (2022). Epistemic orientation toward teaching science for knowledge generation: Conceptualization and validation of the construct. *Journal of Research in Science Teaching*, *59*(9), 1651–1691. https://doi.org/10.1002/tea.21769

Wendell, K. B., Swenson, J. E. S., & Dalvi, T. S. (2019). Epistemological framing and novice elementary teachers' approaches to learning and teaching engineering design. *Journal of Research in Science Teaching*, *56*(7), 956–982. https://doi.org/10.1002/tea.21541

Zhang, J., Tian, Y., Yuan, G., & Tao, D. (2022). Epistemic agency for costructuring expansive knowledge-building practices. *Science Education*, *106*(4), 890–923. https://doi.org/10.1002/sce.21717

Zimmerman, H. T., & Weible, J. L. (2018). Epistemic agency in an environmental sciences watershed investigation fostered by digital photography. *International Journal of Science Education*, *40*(8), 894–918. https://doi.org/10.1080/09500693.2018.1455115

Chapter 4: Recognized and Realigned: A Veteran Teacher's Moves to Realign Familiar Forms of Epistemic Agency while using NGSS Inspired Materials

Introduction

Students may *do a science lesson* but never actually *do science.* The latest science education reform, the Next Generation Science Standards (NGSS) was designed for students to experience the processes and practices of science through pairing of scientific practices (SEP) and disciplinary ideas (DCI). This ideological pairing *should* center student sensemaking while closely mimicking professional science, in lieu of replicating or reproducing pre-constructed knowledge (Chen & Terada, 2021; Miller, et al, 2018; NRC, 2012; Stroupe, 2014). In other words, in NGSS classrooms, students act with epistemic agency. Epistemic agency is how members of a [classroom] community are positioned to evaluate and contribute to knowledge construction (Miller et al., 2018; Stroupe, 2014). This instructional shift invokes in-the-moment instructional skills to explicate the disciplinary substance of student thinking to position them as drivers of the learning process (Robertson et al., 2016). Thus, NGSS requires teachers to position students as *doers of science* instead of *doers of school.*

Reorienting instruction may be challenging for teachers, many of whom likely did not experience science in this way themselves. Traditionally, science teachers, as the sole authority over knowledge, delivered canonical facts to students who passively accumulated them (Stroupe, 2014). Many teachers use structured materials aimed at science practices and students' sensemaking of phenomena to assist with the transition towards NGSS instruction. Yet, without adequate preparation and careful attention, even NGSS exemplar materials may be enacted complacently (Miller et al., 2018)— used in a manner which transmits "correct" information—instead of meaningful engagement with practices of science. As such, these materials may fail to position students with intended agency to engage with science practices or sensemaking. Highly structured materials may conflict with established classroom cultures of learning in which teacher, but not students, have full authority over knowledge construction. Materials designed towards science practices may inadvertently promote "someone else's' science" by prioritizing practices selected by others, which may privilege dominant voices, reinforcing hierarchical views of "who" can do science and "whose" voice is counted (Bang et al., 2012; Miller, et al, 2018; Stroupe, 2014, p. 502).

Science teachers must navigate the tensions and tradeoffs between equipping students with opportunities to act with epistemic agency while engaged with science practices and adhering to pressures of pacing, assessment or curriculum which reduce these opportunities. Teachers may be able to use productive epistemological framing bids, or verbal and behavioral cues, to shift students from engaging in *school*-based tasks of completion and compliance towards *science* and *sensemaking* while using structured materials. Epistemological framing is how one interprets a particular situation, with respect to knowledge, which determine the sort of activity to engage in, while framing moves or *bids* are an attempt to prompt appropriate knowledge and behaviors through verbal and non-verbal cues (Berland & Hammer, 2012; Berland et al., 2020; Elby, 2001). Teachers use framing bids to prompt students to frame their activity a particular way, such as *having a discussion to figure something out*, or to *just get through a task by the time the bell rings*. The instructional decisions, adaptations and framing bids teachers deploy while navigating these tensions and tradeoffs send important epistemic messages about expected knowledge construction in classrooms (Krist et al., 2019; Russ, 2018).

Engagement and enactment with structured materials could be enhanced through epistemological considerations within existing curricular professional development. Few studies or professional development have supported educators to develop epistemologies to authentically engage with science practices, particularly when using highly-structured curricula. Fewer professional development efforts—and studies of the efficacy of those efforts— center teachers' ability to identify and leverage their embedded classroom cultures and the types of epistemic agency they are accustomed to enacting. More generally, implementation of and knowledge development through the science practices remains understudied (Chen & Terada, 2021). Epistemologically focused research has generally focused on pre-service teachers (Kawasaki & Sandoval, 2019; Ko & Krist, 2019; Stroupe, 2014), or coordinated curriculum (Cherbow, 2022) and professional development around epistemological practices (Jaber et al., 2022; Levin et al, 2009; Luna, 2018). This study uniquely investigates the role and impacts of teachers' adaptations to realign the epistemic agency *afforded* by structured curricula to the *established* classroom cultures in absence of such support, providing valuable insights into the skill sets of veteran teachers for professional development providers, teacher educators and fellow teachers.

The aims of this study are to characterize the epistemological framing bids and adaptations of a veteran science teacher while using NGSS exemplar materials and the impacts upon students' epistemic agency, as well as the teachers' perceptions of and responses to these impacts. As we will discuss, we amended our initial research plan to take into account the existing classroom culture, specifically the established *forms* of epistemic agency students were accustomed to enacting. We propose that when teachers identify and address potential mismatches between the familiar *forms* of epistemic agency the classroom culture incites and the forms of epistemic agency invited by the structured curricular materials, students can more successfully take up the intended science practices and epistemic agency afforded by the curricular materials (Kawasaki & Sandoval, 2019; Luna, 2018). We used a single case study with a veteran STEM teacher to investigate her epistemological framing moves and opportunities for epistemic agency while using highly-structured curricula, and how this was taken up by students (Yin, 1992). In conducting this study, we incorporated a collaborative planning model of interview-observation cycles which can inform research with and in support of teachers' practice (Ceven McNally, 2016).

The *original* questions guiding this investigation are: When using highly-structured curricula (1) *What framing moves support sensemaking?,* (2) *How do students act with epistemic agency?,* (3) *How do teachers [deploy framing moves to] successfully support students' epistemic agency and engagement with science practices?* And revised, after initial analysis: What role does the *form* of epistemic agency invited by a given classroom lesson play in (1) *Describing differences between lessons employing similarly prescriptive lessons*, 2) *Students' sustained enactment of science practices?*, and 3) *Characterizing teachers' moves to (re) align implementation of structured curricular materials with her classroom epistemological culture?*

Literature Review

NGSS Reform: Students as Scientists

Science education research and reform has long emphasized centering students to drive instruction and spur meaningful learning; NGSS is no exception (NRC, 2007; 2012). The Frameworks goal, particularly with the Science and Engineering practices, is for students to understand "how science is done" through constructing explanations, developing models and iterative investigation (*A Framework for K-12 Science Education*, 2012, p. 44). NGSS is thus an opportunity for students to develop scientific skills as scientists do (Miller et. al., 2018; Chen & Terada, 2021). Levin, Coffee and Hammer (2009) found that eliciting and attending to student ideas “can help students construct understanding of scientific concepts, reason scientifically, appreciate the nature of science, and engage in scientific practices” (p. 152). In this sense, students should be “figuring out” more than “learning about” through participation, collaboration and ideation (NRC, 2012; Schwarz et al, 2017). In other words, the NGSS necessitates students acting with *epistemic agency*. Epistemic agency is how members of a [classroom] community take, are granted responsibility or *positioned* to evaluate and contribute to knowledge construction (Stroupe, 2014; Miller et al., 2018).

The NGSS highlights the role of student sensemaking of phenomena in three-dimensional science learning through an entanglement of content in the Disciplinary Core Ideas through practice in the Science and Engineering Practice, while interwoven with Cross Cutting Concepts (NRC, 2013). Sensemaking, in the context of science instruction, is how one “wrestles with ideas, language, experiences and perspectives in a community to figure out how and why the world works” (Schwarz et al., 2021; 113). Modeling, explanation and argumentation provide natural opportunities for sensemaking. Sensemaking may occur within discussion, argumentation or investigation, or may require intentional planning and facilitation as students attempt to resolve gaps in knowledge (Schwarz et al., 2017; Manz & Suarez, 2018). While *researchers* have generally moved away from the notion of correcting misconceptions and embraces the role of everyday language in sensemaking, *teachers* may reference sensemaking as correcting misconceptions[9] (Bang et al., 2012; Hutchinson & Hammer, 2010; Schwarz et al., 2021).

The Framework, like prior reforms, is not a silver bullet; the coupling of *content* through *practice* in the Science and Engineering Practices has led to debate amongst researchers who find the ideological pairing to hinder authenticity and applicability, which in turn, can limit the intended goals of opportunities for sensemaking and epistemic agency (Elby, 2019; Morales-Doyle et al., 2019). Implementation within classrooms may be inauthentic and complacently enacted, positioning students to drive learning only to the extent of materials, or ignored entirely (Miller et al., 2018). Complacent enactment of NGSS and NGSS aligned materials may further separate marginalized students from science by elevating privileged or canonical ideas while dismissing attempts at knowledge construction, such as everyday language, which may be productive for learning Over time, this can perpetuate academic and societally held hierarchies, particularly within sciences (Bang et al., 2012; Hutchinson & Hammer, 2010; Miller et al., 2018). Teachers may not understand how to orient instruction towards student ideas or student generated knowledge, particularly while using highly structured materials. Teachers must navigate the tensions between

[9] We realize that within educational research, this term is frowned upon, however we use this here to highlight differences in ascribed meaning between research and practice communities.

adhering to curriculum, which may have been adopted and purchased by their district, and applying locally constructed, meaningful, and relevant student- driven learning opportunities (EdReports, 2022; Kawasaki & Sandoval, 2019; Morales-Doyle, 2019).

Framing the Game

Epistemological *framing* likely drives many interactions within school (Hammer et al., 2004; Russ & Luna, 2013). Framing is a theoretical construct, originating in sociolinguistics and anthropology literature, to describe the process of interpreting a situation (Elby, 2001; Elby & Hammer, 2010; Levin et al., 2009). In terms of teaching, framing is the "moment-to-moment understanding of what is going on with respect to knowledge and learning" which drives instruction (Russ & Luna, 2013). Framing is the cognitive means by which a student answers the tacit question "what are we doing here?" (Berland & Hammer, 2012).

Teachers' epistemological framing can drive what and how they attend to activities (Elby & Hammer, 2010; Russ & Luna, 2013). Russ and Luna (2013) used video tagging technology to capture what a teacher noticed and responded too during science class to infer her framing. They characterized two distinct framing moves from the teachers' tagged moments during lab activities and class discussions, which she reflected on afterwards to describe what she noticed. During the lab activity, the teacher noticed and responded to logistical talk, and rarely referenced students' science ideas. Afterward, she reflected on students following instructions and reading directions. The authors determined the teacher framed these moments for *procedural* *knowledge*, which determined what she noticed and responded too in these moments. During discussions, the same teacher noticed and responded to students' science ideas; she expected students to pose questions, provide explanations and discuss amongst themselves. The authors determined that during discussion, the teacher framed for *disciplinary knowledge.* This study illustrates a critical concept-that the same teacher may vary their framing moves in particular situations, (i.e. lab and discussion) which can drive what they notice and attend too. In this way, framing explains variability within similar classrooms and even within a single teacher (Levin et al., 2009; Russ, 2018; Russ and Luna, 2013).

Teachers' framing of activities drives what they notice and attend to, while students' framing of activities can determine their established means of participation and engagement (Russ & Luna, 2013). Teachers' framing largely determines the culture and norms of a classroom, or the frames through which students interpret classroom activities (Miller et al., 2018; Kawasaki & Sandoval, 2019). Framing can integrate what the teacher *brings* to the classroom with the interactions *within* the classroom (Luna, 2018). In other words, teachers framing can establish and embed classroom cultures, defining acceptable means of participation, contribution, engagement, and expression (Carlone et. al., 2021; Russ, 2018).

Much of the epistemological framing literature focuses on *students'* framing of science, particularly the work of Hammer (e.g. Berland & Hammer, 2012; Disessa et al., 2002; Hammer et al., 2004; Hutchison & Hammer, 2010) while less focus on *teachers'* framing (e.g. Kawasaki & Sandoval, 2019; Russ & Luna, 2013; Wendell et al., 2019). Students' frame classroom activities based on prior experience, which can determine their established means of participation (Russ & Luna, 2013). For example, students may approach a task for completion and compliance, to produce acceptable answers, when they frame their activity as *doing school* or *getting through the assignment*; or they may puzzle over uncertainty if they frame the activity as *solving a puzzle* or *figuring something out*. For our purposes, we focus on how teachers frame learning for students, particularly when using structured materials, and how this framing is taken up by students.

Teachers Framing Moves.

Student's framing can be influenced by teachers' explicit or implicit signals such as means of instruction, vocal tone or body language (Berland & Hammer, 2012). We call these signals "framing moves." We also refer to the teachers' framing *moves*, or framing *bids*, as the activations or cues the teacher uses to sustain, shift or redirect students' approaches to learning activities. Teachers may use framing bids to harness engagement in different instructional activities (i.e. collaborative discussion, design, experiment), while ensuring students enact the appropriate practices. .

Epistemological framing research can integrate attempts to characterize teachers' attention, noticing, or responsiveness to student ideas. Russ (2018) found that research has generally compartmentalized practice along these lines, which may benefit research agendas by allowing researchers to "easily see consistency across groups of teachers or within a single teacher" (p. 96). This work has answered questions such as: How do teachers attend to ideas, what knowledge do they need to do so, and how well are they doing it? However, these generalizations may fail to fully capture the nuance of in the moment teacher practice, as it relates to attention, noticing or responsiveness. Therefore, we include each of these considerations in our view of epistemological framing to describe the moves of the teacher and uptake of students.

Two types of framing are imperative to this work: framing for *school* and framing for *science* (and sensemaking). Students framing their activity as *doing school* (or as some finer-grained activity within that broader framing) accept that the teacher or other source of knowledge (textbook, worksheet) hold authority of "correctness" while students framing their activity in a way consistent with authentic science—*having a discussion to figure something out*, *brainstorming explanations*, and others would assess a knowledge claim based on whether it makes sense or fits within their understanding of evidence (Berland & Hammer, 2012). We discuss each type of framing and the implications of each in the following sections.

Framing As "Doing School" or "Doing School Science".

Students use prior experience to determine how they frame learning, which often emphasizes the practice of school and acceptable answers over the processes of science and sensemaking (Hutchinson and Hammer, 2010; Lemke, 2012). Achievement (accuracy) separates schools, districts, states and university acceptance.

High achievement is highly rewarded, while low achievement has been met by negative and sometimes punitive measures. Knowledge production processes are difficult to measure and assess. Over time, the process of producing and being rewarded with the right answer embeds in classroom interpretation and contributes to the framing of learning, often to unproductive ends. Pope (2001) characterized school activity with socially desirable ends through accumulated facts, accuracy and efficiency, yet lacking relevance. She further separated high achieving grades from learning or retention of skills:

> "*...the grades proved that students were adept at providing the teachers with the information required on tests and quizzes, and that they memorized these facts and figures just long enough to 'ace' the exams and move on to the next set of tasks"* (p. 156).

School science typically centers accumulation of factual information over "engaging students as capable sense makers (Schwarz et al., 2021, p. 141). Similarly, Hutchinson and Hammer (2010) described science classes in which "students use sanctioned methods to produce answers, which then serve as a sort of currency to be exchanged for a grade" (p. 508). Other researchers (Brousseau, 1997; Herbst & Kirkpatrick, 1999) describe this tactic as a "didactical contract." This contract between students and teachers may value the culture and values of [predominantly European, white] educators over that of [non-white] students. This can easily devalue, and diminish the voice of some while elevating others, which can further separate many students from science and STEM (Bang and Medin, 2012; Hutchison & Hammer, 2010; Miller et al., 2018; Kawasaki & Sandoval, 2019).

Framing As Science (Sensemaking about Natural Phenomena).

Conversely, Hutchinson and Hammer (2010) determined that when students understand and make sense of phenomena, they recognize that knowledge can come from anywhere-not just a textbook or teacher. Framing science for sensemaking allows student ideas to drive “the intellectual work of figuring out core science concepts to explain a phenomenon of interest” (Krist and Shim, 2023, p. 4). Teachers' moves and interactions shape students’ sensemaking (Schwarz et al., 2021). Stroupe (2014) identified teachers’ who supported productive sensemaking when they treated science ideas as resources for the “community's science work rather than positioned as ‘right’ or ‘wrong’ “(p 498).

In science classes framed around sensemaking of phenomena, students understand their role to assess and contrast knowledge with their reasoning and experience, which closely resembles the practice of science, and echoes the learning goals defined by the National Research Council (2007; 2010) and National Academies of Science (2007; 2013; 2021) which underlie the NGSS (2013). Sensemaking promotes students' ability to be “active constructors of knowledge,” requiring considerations of students' choice and evaluation of knowledge construction (Miller et al., 2018, p. 1057).

Several pedagogical strategies and school structures contribute to helping or hindering students to take on and maintain a sensemaking frame. Project based learning and engineering design activities afford students opportunities to engage in sensemaking (Carlone et al., 2021; Schwarz et al., 2021). Engaging students with uncertainty and puzzlement provide rich opportunities for sensemaking, however teachers may struggle with opening their instruction to such uncertainty (Manz & Suárez, 2018). Repeated exposure to sensemaking and student constructed knowledge has long term implications informing who participates and whose ideas "count" in science (Bang et al., 2017).

The manner in which teacher's take up student ideas can influence whether a sensemaking frame persists. Sensemaking specific pedagogies are critical for deep understanding required in knowledge building practices of science (Schwarz et al., 2021). Schwarz et al (2021) conducted a qualitative case study with 16 elementary teachers to identify and characterize their sensemaking episodes. The authors highlighted cases in which teachers expanded, maintained or shut down sensemaking to theorize consequences of such moments for students and teachers. They found that, in addition to inviting contributions from all students which enabled public layering of discourse, the teacher who expanded sensemaking also capitalized on common experiences to craft a context for an explanation. They determined that the difference between expanding and maintaining sensemaking was the teacher's ability to "build upon, extend or otherwise make use of students' contributions" (p. 136). Teachers' attention and responsiveness towards sensemaking can foster equitable and meaningful participation through valuing diverse contributions to knowledge construction (Bang et al., 2012; Berland et al., 2020; Schwarz et al., 2021).

Of course, school structures and culture also affect whether students are likely to frame their activity as sensemaking. Traditional school structures and classroom activities with canonical scientific language often perpetuate skills-based, memorization-oriented activities, removing opportunities for students to actively participate in knowledge construction (Carlone et al., 2021, Hutchinson & Hammer, 2010). This can be exacerbated while using highly structured materials, which may reinforce school based systems.

Most researchers agree that including everyday language in sensemaking can broaden “what counts” as valued disciplinary knowledge by incorporating relevant real-world experiences (Bang et al., 2012; Carlone et al., 2021; Ko & Krist, 2019; Hutchison & Hammer, 2010; Miller et al., 2018; Rosebery et al., 2016). However, simply drawing upon everyday language, which is highly context dependent and flexible, is insufficient for deeper connection. Levin et al (2012) described the need to recognize and cultivate students’ science ideas, as presented in their language. The authors describe refinement of everyday thinking to progress towards cohered science ideas. This may look like “foothold ideas” which fit and support each other, and perhaps make predictions (p. 39). Overtime, productive footholds form beliefs. Refining students' ideas in sensemaking into productive science ideas may incorporate structured materials. As we will discuss, structured materials can inform instruction, which has implications for students’ sensemaking and engagement in science practices.

Student Ideas in Sensemaking

What teachers notice can drive what they attend too, which further drives their noticing (Russ and Luna, 2013). In Russ and Luna's (2013) study mentioned previously, the authors describe how the teachers' framing in both situations–lab activities and discussions–drove what the teacher noticed and responded to in student talk, which reinforced her framing, which created a feedback loop of self perpetuating frames. When using high-structured materials, teachers may establish and maintain such self perpetuating frames focused on completing the lesson elements. Shifting students' framing towards engaging in sensemaking with highly-structured materials thus requires teachers to notice their ideas within the context of the materials, in order to frame for further sensemaking.

A growing body of scholarship recognize the role of embracing student ideas in sensemaking to support authentic engagement in science practices (Berland et al., 2020; Levin et al., 2009; Cherbow et al., 2020; Ko & Krist, 2019; Haverly et al., 2020; Krist et al., 2023; Krist & Shim, 2023; Schwarz et al., 2021, Windschitl et al., 2020). Science education research has attempted to map and sequence teachers' pedagogical decisions regarding the pursuit of student ideas (Richards et al., 2020; Krist and Shim, 2023). Recent work by Krist and Shim (2023) attempted to examine the "trade-offs and tensions teachers consider" when deciding which student ideas to pursue, and how these support the often uneasy terrain of student sensemaking (p. 2). Professional development can create opportunities for teachers to practice attending and responding to student ideas for purposes of adapting instruction (Levin et al., 2009).

Attending to student ideas may be easier for researchers to emphasize than for teachers to enact; as Levin and colleagues (2009) succinctly summarized, "asked to pay attention to curricular objectives, standards, and their own behavior, it is not surprising that they do not notice the substance of student reasoning" (p. 152). On the other hand, Krist (2024) determined that focusing on student ideas as an instructional *goal* can minimize relational aspects of teaching. She advocates for researchers and professional development providers to focus less on the teaching moves associated with eliciting student ideas and more on how students experience these practices.

Supporting Students as Epistemic Agents

Students are unlikely to maintain a sensemaking frame if they are unable, due to any number of factors, to exert some agency over how knowledge is constructed and evaluated in the classroom. In other words, for students to maintain a sensemaking frame, they must be positioned as-and position or see themselves as-*epistemic agents.* Stroupe (2014) described students' roles in NGSS classes as epistemic agents-in positions to shape and contribute to knowledge construction and knowledge practices of the classroom community (Damsa et al., 2010; Stroupe, 2014; Miller et al., 2018). Early studies indicated that when students are granted greater epistemic agency, both teachers and students were more likely to incorporate authentic science practices (Minstrell, 1982; Warren & Roseberry, 1995).

Traditional school systems position teachers and other authoritarians (textbooks, worksheets, administrators) as the sole epistemic agent in the room; they determine the accuracy and value of ideas and the appropriate standards of knowledge construction (Carlone et al., 2021; Krist, 2024). Alternately, Stroupe (2014) included and expanded upon elements of Ambitions Instruction to describe classrooms which center student ideas as valuable, in the public plane, for students to negotiate "what counted" as science ideas and to shape the knowledge community. In such classrooms, students enact instructional authority to determine information as "right" or "wrong," which redistributes cognitive authority. Over time, this redistribution or retention of cognitive authority places science learning as "public" or "private" which determines participation and holds members in a learning community accountable to standards of evidence, reasoning, and clarity.

Several research efforts characterize the impact of epistemic agency upon knowledge construction in science classrooms (Carlone et al., 2021; Ko & Krist, 2019;Miller et al., 2018; Sezen-Barrie et al., 2020; Stroupe, 2014). Classrooms which promote students' epistemic agency value diversity in language, background, culture and experience to establish rich knowledge building landscapes (Bang et al, 2012; Miller et al., 2018; Sezen-Barrie et al., 2020; Stroupe, 2014). Teachers can foster students' epistemic agency by eliciting ideas and allowing those ideas to shape discussion or to guide instruction (Bang et al, 2012; Carlone et al., 2021; Ko & Krist, 2019; Stroupe et al., 2018). Students enacting epistemic agency may take up roles typically afforded by authority figures, such as critiquing ideas of peers or scientists (González-Howard & McNeill, 2020), choosing experimental elements such as procedures, data collection or research questions (Cherbow & McNeill, 2022; Ko & Krist, 2019; Miller et al., 2018), they may propose alternative solutions or choose their method of demonstrating understanding (Ko & Krist, 2019; Krist et al., 2023; Zimmerman & Weible, 2018), or they may determine sources of information (Miller et. al., 2018; Stroupe, 2014). In science classrooms that foster students' epistemic agency, the teacher's absolute authority over knowledge is minimized in favor of students' autonomy (Carlone et al., 2021).

Kawasaki and Sandoval (2019) assessed lesson tasks and participation structures to define and rate the epistemic agency afforded by a teacher over 14 lessons within an instructional unit. The study teacher had been a long term participant in professional development aimed at shifting instruction towards NGSS and "opening up" activities to student ideas, yet still struggled to shift authority to students over learning. The teacher made connections for students and supplied "correct" concepts in their moments of uncertainty, removing their ability to act as epistemic agents and ultimately decreasing participation by "taking back" cognitive authority. Alternatively, when the teacher framed activities around an anchor phenomenon and opened up students' roles to include decision making, their participation resembled that of a true scientific community. However, these instances were inconsistent.

As highlighted in Carlone et al., (2021), the literature does not have a unified definition of epistemic agency; Carlone et al., (2021) found that student engagement as "contributors, joiners, distractors or silent observers" (p. 176) in knowledge generating discussions are evidence of epistemic agency. Stroupe (2014) and Miller et al (2018) described epistemic agency as students positioned with *perceiving and acting upon* opportunities to shape knowledge and learning in their classroom communities through public knowledge construction, accountability and evaluation. Zimmerman and Weible (2018) characterize epistemic agency as practices around *building disciplinary knowledge* and distinctly separate from meaning making. Many articles describe epistemic agency as *acted on, granted or taken authority to construct knowledge* (Berland et al., 2020; Haverly et al., 2020; Kawasaki & Sandoval, 2019; Kelly & Cunningham, 2019; Ko & Krist, 2019; Stroupe, 2014). Alternately, Krist at al (2023) determined that epistemic agency was "dynamically negotiated through interaction" (p. 5). We align with Stroupe (2014) to describe epistemic agents and science practice communities who determine "who knows" and who hold cognitive authority to determine what counts as knowledge worth knowing, yet as we will discuss, we do not ascribe uniformity to this construct.

Creating opportunities for students to act with epistemic agency may be counterintuitive; teachers typically hold authority and power over knowledge, and may struggle with releasing the reins of learning to their students (Stroupe, 2014). Students' uncertainty or puzzlement may prompt teachers to “fill the gaps” for students (Kawasaki & Sandoval, 2019). Stroupe (2014) described *breadcrumb epistemology* as teachers leading students down a predetermined path, or inauthentically framing learning as centered on students’ ideas.

Markers of Epistemic Agency.

Characteristic markers or indicators of epistemic agency are as ambiguous as a definition, yet heavily reliant on discourse during discussion; numerous studies (Carlone et al., 2021; Damsa et al, 2010; Miller et al., 2018; Stroupe, 2014) described indicators of epistemic agency as verbal interactions to construct shared knowledge and cognitive authority over valued knowledge. Stroupe (2014) categorized teachers’ discursive moves to assign value to science ideas such as publicizing, signaling, or questioning. Ko and Krist (2019) described how teachers can “open space” for epistemic agency such as students’ proposing alternative claims, identifying patterns, and brainstorming. Carlone et. al., (2021) similarly identified verbal evidence of epistemic agency in first grade students such as connecting ideas from prior lessons, translating others’ ideas and drawing personal connections. Cherbow (2022) used student constructed consensus models as evidence of epistemic agency, while Zhang et al (2022) designed a year long study on body systems with embedded “decision points" for students to redirect their learning. González-Howard and McNeill (2020) evaluated language moves and interactional patterns at play through instances of critique during argumentation, which valued all ways of knowing to support sensemaking.

Alternately, Zimmerman and Weible (2018) analyzed students' digital data capture, annotation, and creation of digital displays to investigate photography as a marker for and aid in expression of epistemic agency. The authors investigated students' digital artifacts including their annotations, their data collection and how they saw themselves as scientists to denote how they acted with epistemic agency during an environmental science field study. They found that students could not only engage as scientists, but they could document their confidence as knowledge builders to their peers. Notably, the authors refined and characterized additional subcomponents of epistemic agency absent in prior studies, to include students' "external recognition for themselves as producers of scientific knowledge" (p. 913). We must consider equity and cultural responsiveness to expand the notion of epistemic agency to include non-verbal indicators, particularly with learners in communities and cultures which may discourage speaking up in classrooms. Daily classroom interactions, particularly in science, may inadvertently sustain societally embedded hierarchies (Bang et al., 2012; Levin et al., 2009; Rosebery et al., 2016). While unintentional, reliance on discourse and verbalized patterns of interaction as "best-practices" may reinforce and reproduce academic hierarchies and power-laden dynamics (Phillips et al., 2019). Further, reliance on discourse overlooks contributions from multilingual learners and privileges Eurocentric perspectives (Bang et al., 2012).

Despite these critiques of discourse-centric analysis of epistemic agency, we rely on this form for our analysis due to a) the discourse-heavy nature of the MEL activities and b) the kinds of data we were able to collect given the logistical and IRB constraints.

Forms of Epistemic Agency.

The pervasive emphasis on discourse and discussion may mask the differing forms of epistemic agency. Miller et.al. (2018) determined that across settings differing forms of agency may be valued and available, which may impact students' position within the knowledge community. Stroupe (2014) identified components of epistemic agency including making scientific claims, integrating science ideas, and advancing science ideas to the public plane and promoting science ideas as valuable. Most of the literature does not distinguish agency over *sources* of knowledge from agency over the *direction* of knowledge production. Building on this work, we seek to expand the corpus of epistemic agency beyond a monolithic construct to identify how *forms of epistemic* agency may manifest, as well as *who* and *what* the agency is for. In this way, we seek to advance the work of prior authors which describe indicators of epistemic agency (Cherbow, 2022), moves to foster epistemic agency (Ko & Krist, 2019), promoting student choice to shape and reshape aspects of inquiry (Zhang et al., 2022), professional development for teachers to foster epistemic agency (Jaber et al, 2022) and holistic descriptions of how epistemic agency manifests (Stroupe, 2014; Zimmerman & Weible, 2018). We wish to extend this work to suggest that epistemic agency can be *for* a task or purpose in support of constructing knowledge. A major implication of the empirical case study presented below is that it is productive for instructors and researchers to distinguish between different forms of epistemic agency in these elements.

Connections Between Building Relationships and Inviting Epistemic Agency.

While supporting productive student talk and eliciting ideas has been well documented as a high leverage practice of science teaching (OpenSciEd, 2019; NRC, 2012; Windschitl et al., 2020), Krist (2024) noted that "these descriptions tend(s) to frame students as (at best) neutral agents who will supply their thinking if it is properly elicited" (p. 215) and may be insufficient for promoting equity. Krist (2024) examined the role of a teacher's relationality with students and supported their collective development of science ideas. Through critical case study, she analyzed relational dynamics and characterized role negotiations by students and the teacher to highlight their application towards responsive science teaching. She determined that a singular focus on practice around supporting student ideas without consideration of students' experience about sharing those ideas and making their vulnerabilities public may perpetuate institutional hierarchies of schooling and science. Such a focus may inadvertently "coerce risk taking rather than cultivate a trusting environment" (p. 215) to explore and engage with science ideas and practices, which is the antithesis of epistemic agency (Miller et al., 2018). Therefore, we cannot separate a teachers' relational commitments towards students and the collective classroom culture from efforts to foster opportunities for students' epistemic agency and engage with science practices. We find this particularly poignant when using structured materials which may inadvertently confine or restrict opportunities to incorporate student ideas.

Similarly, Philip et. al. (2019) emphasized the role of listening to support the work of positioning students as contributing members of the classroom community. The authors determined that generic, "best-practice" focused teaching anchored in discoursed-based interactions may skirt reflective opportunities to apply epistemic, equity anchored pedagogy.

Epistemic Agency for Equity.

Many authors (Carlone et al., 2021; Haverly et al., 2020; Krist, 2023; 2024; Ko & Krist, 2018; Miller et al., 2018; Stroupe, 2014; Stroupe et al., 2018) connect epistemic agency to justice driven teaching which empowers all student ideas as valuable to the classroom community. Carlone et al. (2021) identified justice driven means of "participation in knowledge-generating practices" (p. 176) which may uphold or tear down traditional classroom hierarchies as a marker of epistemic agency. The authors describe the traditional role of classrooms, particularly those serving marginalized students, to perpetuate "compliance and skills-based, decontextualized, rote memorization activities" which remove opportunities for students to construct knowledge (p. 172). Their study highlighted the role of a teachers' epistemology of love which treated student ideas as an asset and vital to the classroom community to "speak-back" to deficit narratives, particularly in urban schools serving black and brown students (Carlone et al., 2021, p. 189).

Epistemic Agency with Structured Curriculum

Instructional materials can determine and direct teachers' focus and practice (Ko & Krist, 2019). Prescriptive or highly-structured materials may prioritize procedures over practices, or send epistemological messages regarding appropriate sources of knowledge and activities to construct such knowledge, which can limit opportunities to act with epistemic agency (Carlone et al., 2021; Russ, 2018). Teachers may unintentionally reinforce unproductive framings of school science as the "school game" with only right, wrong, expert and novice when using structured curricula. However, they may be able to cue students' enactment of appropriate science practices, or to create or reinstate opportunities for epistemic agency through framing bids (Berland, et al., 2018; Kawasaki & Sandoval, 2019; Luna, 2018).

Several studies describe *complacent enactment* as the pseudo agency of transferring cognitive authority and decision-making power to students only to the extent consistent with students' making steady progress toward the learning goals pre-determined by the curriculum and teacher, which can remove or diminish opportunities for epistemic agency and engagement in science practices (Cherbow, 2022; Cherbow & McNeill, 2022; Ko & Krist, 2019; Miller et. al., 2018; Sezen-

Barrie et al., 2020; Stroupe, 2014). Even NGSS aligned or exemplar curricular materials may promote complacent enactment in which teachers inadvertently emphasize canonical definitions as "correct" and knowledge building attempts that don't lead to the intended conclusion as "incorrect" (Ko & Krist, 2019; Miller et al., 2018). Teachers may complacently enact science practices or fail to treat practices as locally constructed and meaningful (Miller et al., 2018). Curriculum may limit local relevance, meaningful connection or opportunities for application (Morales-Doyle, 2019). Guy-Gaytán and colleagues (2019) warn that practice-oriented curricular progressions were insufficient to promote engagement with science practices; that, without proper support, teachers may perceive and frame such progressions as content to be learned instead of as a tool for engaging students in sensemaking. Yet, navigating the space between pseudo agency and responsive teaching should be "embraced in opening up space for redistributing epistemic agency"(Ko & Krist, 2019, p.1001). We ground our study in this tension that navigating this space is inevitable, achievable and applicable in science teaching.

While curricular materials may constrain opportunities for teachers to elicit student ideas and for students to act with epistemic agency, sensemaking is possible: Zhang et al (2022) illustrated how teachers can establish "decision points" to increasingly shift towards student co constructed knowledge within structured or planned activities. In this way, teachers can adaptively guide inquiry activities while allowing student questions and interests to shape the course of their investigations and to determine their group structures. Ko and Krist (2019) documented teachers' efforts to position student ideas to shape investigations, to problematize models and to make alternative claims or expand upon an anchoring phenomena. They propose incremental shifts in teachers practice to identify and act upon students' ownership over knowledge and participation in knowledge construction.

Some learning activities, such as project-based learning, offer distinct opportunities for students' epistemic agency. Zhang et al (2022) observed and characterized how students shaped and reshaped aspects of a long term project on body systems in ways that engaged epistemic agency. While the teacher initiated the original activity, the project was activated by student interests and emergent questions. Students maintained flexible and fluid group structures which emerged from ongoing questions, interests and reflections. Students coc onstructed their collective knowledge work, which they published at the projects' conclusion, as they formed and reformed interest groups. Materials such as storylines may afford opportunities to move from student questions to investigations, however teachers should have space to deviate, improvise and create dialogic space for students to act with epistemic agency (Cherbow, 2022; Rosebery et al., 2016).

Ko and Krist (2019) illustrated how teachers could "open up" space within constraints of curricula to redistribute students' epistemic agency. They described a teacher who used an NGSS exemplar curriculum with a demonstration differentiating two substances. Instead of demonstrating various tests, the teacher chose to invite students into the decision making process to determine ways to investigate differences, which data to collect and how that may be used to support their claims. Students took up the teachers' invitation to co-construct an investigation, however this stopped when they realized that their ideas served the goals of the prescribed, predetermined curricula and not the collective work of investigation. One student felt “tricked” when the teacher produced a worksheet with the concepts students thought they produced. While the teacher fluidly moved between the curriculum and student ideas, even reassuring them that their ideas did drive the investigation, this may have felt disingenuous and removed opportunities for redistributing agency to students. The authors emphasize the need to ensure students’ ideas are valued and consequential to learning, even if activities are planned or highly-structured.

With that in mind, we recognize that the ability to adapt or open up instruction requires one critical element: time. Deviation from highly-structured materials may conflict with school or district goals or pacing, which often align with assessments. School systems (and society) largely favor accuracy and achievement, while science favors process and iteration. These conflicting goals must coexist towards mutually supportive ends. We acknowledge that time may limit educators far more than we in the research realm concede. As we will discuss, the teacher in our study was also restricted by this variable.

In summary, previous research establishes that framing school science as opportunities to construct valued knowledge offers opportunities and obstacles for teaching, particularly with structured materials. We would be remiss if we did not acknowledge the tensions and trade-offs felt in creating authentic science learning with rich opportunities for students' epistemic agency while adhering to institutional or systemic pressures; the instructional reorientation towards authentic science practices may be at odds with pacing and evaluation, which reduce those opportunities. It may not be feasible to allow students to determine and drive the learning trajectory or to guide instruction, particularly with highly-structured curricula. Teachers must navigate the often fuzzy line between teaching for epistemic agency and using highly-structured materials; yet even amid planned or structured activities, students understand and respond when they feel their ideas and decision making matter (Ko & Krist, 2019). Stroupe (2014) noted that students '*want to do science, not someone else's science. They don't want a prescribed path*" (p. 502). Thus, the tensions felt are inevitable, and characterize the challenges in teaching responsively.

Study Aims

Here, we wish to clarify that we do not ascribe to rules or practices associated with determining or positioning epistemic agency. We find that elements or flavors of epistemic agency may abound in previously uncharacterized spaces, and seek to understand where, how, when and for whom these instances occur. We wish to extend the markers of epistemic agency beyond discourse or a learning product, to locate evidence of epistemic agency within the situated, contextualized and collective science work of classrooms. Similar to Philip (et al., 2019) and Krist (2024), we find that to generalize or standardize teaching moves or decisions specifically to position students with opportunities for epistemic agency would be in conflict with the spirit of epistemic agency (and NGSS) and could obscure the diversity and individualism of both teachers and students. Philip and colleagues (2019) propose an improvisational approach to teaching as opposed to prescriptive practices in response to deficit-based problems. We find this approach to value the professionalism of teachers while honoring the diversity of student contributions which underlie the culture of productive classroom learning communities. As we will explain, this work initially focused on the impact of teachers' framing moves upon students' epistemic agency while using structured materials, which allowed us to establish our A Priori coding. Also ,as we will discuss, the data led us elsewhere.

Methods

Study Design Overview

This single case study drew on classroom observations and interviews to interpret a teacher's framing moves and their impact on students' epistemic agency when using structured "guided inquiry" materials. Initially, we tried to document patterns relating the teacher's framing moves to students' uptake of epistemic agency. However, following our initial analysis, we revised our research questions, which we present at the conclusion of this section. We used an exploratory, inductive approach to allow the nuance in the data to drive our analysis. We describe our participant and methodology below. As we will discuss in the following section, we refined our research questions from our initial research plan. Our *initial* questions were: When using scripted or prescriptive curricula (1) *How can teachers successfully support students' epistemic agency and engagement with science practices?* (2) *What epistemological framing moves do teachers deploy to cue engagement with science practices?*

Materials

The teacher in this study was using Model-Evidence-Link (MEL)[10] materials designed by Lombardi et al (2013, 2018). MEL activities are a mechanism to facilitate students' learning about controversial socioscientific issues. The activities use an instructional scaffold to facilitate students' evaluation of scientific and unscientific models of phenomena (i.e. fossils, freshwater, eutrophication[11]) and their connection to lines of evidence through use of a diagrammatic framework. Students

[10] See all materials here: *https://serc.carleton.edu/mel/teaching_resources/index.html*

[11] According to Dictionary.com: excessive *richness* of *nutrients* in a lake or other body of water, frequently due to *runoff* from the land, which causes a dense growth of plant life and death of animal life from lack of oxygen.

"develop and defend evidence-based claims" as they evaluate, determine and deploy skills of argumentation and negotiation to determine the connections between evidence and alternative explanations (Governor et al., 2019). Students engage in scientific practices throughout—negotiation, argumentation and scientific reasoning—to mirror how scientists co-construct understanding of phenomena. Students are given models and lines of evidence based on each topic. Each line of evidence is supported by a one-page evidence text with information supporting that particular explanation. Students determine the plausibility of each model and connect them to plausible lines of evidence based on the strength of the connection (Figure 1). Students use different kinds of varying arrows (as shown in Figure 1) to represent their decisions. In the original MEL activity (pcMEL, or preconstructed MEL), students are given two models and four lines of evidence and add arrows to the diagram includes all of the lines of evidence[12].

---

[12] The third iteration, lrMEL (lateral-reading-MEL), introduces lateral reading strategies to facilitate discussion and source evaluation of emergent socioscientific issues. The lrMEL ideally pairs science and social studies teachers at the same school site. .

pcMEL Materials: Students are given four lines of evidence and must add arrows (below) to determine the strength of their connection to the models. .

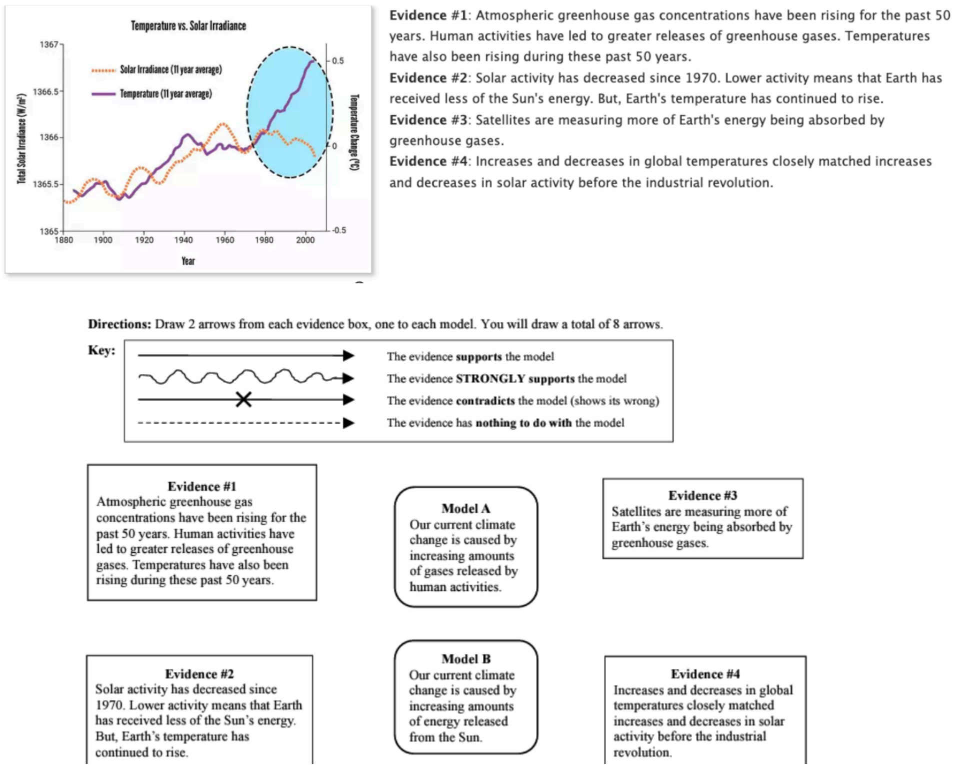


Figure 18 pcMEL Materials

We investigated two flavors of the MEL, the pcMEL and baMEL, in the present study. In the baMEL (build-a-MEL) scaffold, students select two models to pursue from three options, and select four lines of evidence from eight options. Students are given a blank diagram (Figure 2), and fill it in based on their arguments and reasoning. In the present study, students were given a large dry erase diagram and could revise their thinking as a group through discussion.

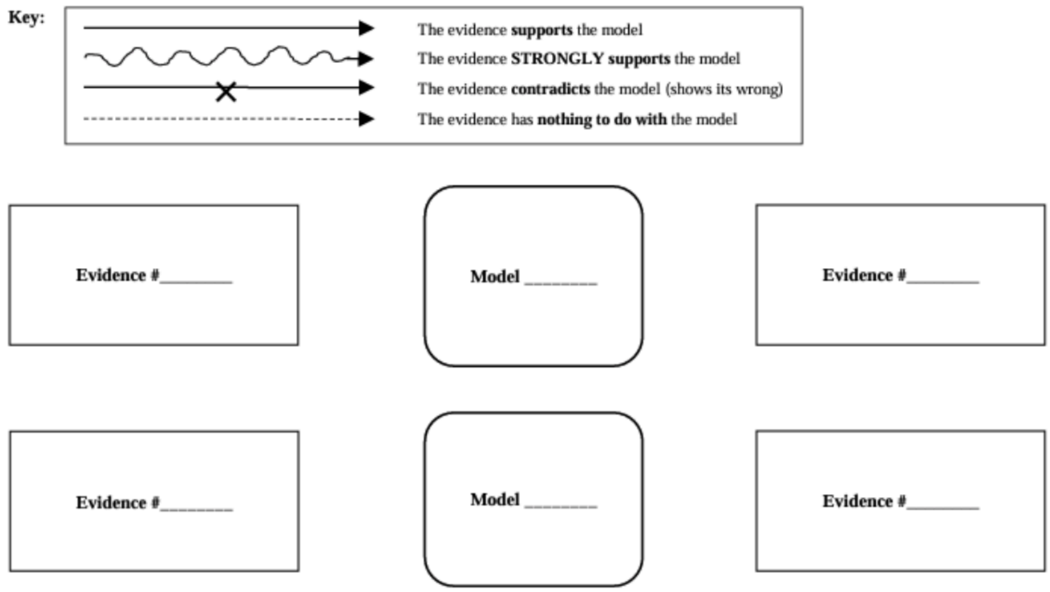


Figure 19 Blank MEL Diagram

Case Study Participant

The participating teacher in this case study, Amy, is an experienced master STEM teacher and teacher mentor. Amy is a decorated and respected teacher leader; she is the department chair for both middle school and the STEM department, she coaches a Lego robotics team, is a faculty member in the National Junior Honor Society, mentors new teachers and is amidst a leadership administration degree. During many days of interaction and observation, we observed numerous examples of Amy's commitment to supporting students' engagement with science practices and her deep understanding of NGSS. Amy is regularly visited by district leadership, and her teaching is often highlighted by the school. She established numerous industry partnerships which provide equipment and student mentorship, and she secured various grants for student projects. Amy is a veteran MEL teacher; she used all previous iterations of MEL materials, attended workshops and assisted in materials development. Prior to this study, Amy served as research assistant during a summer workshop introducing the lrMEL to teacher pairs.

Study Setting

Amy's class is 7th grade STEM elective at a performing arts charter school in the center of a large Northeastern urban city serving grades 6-12. The school is Title 1, and provides free breakfast and lunch to all students. Students are admitted through a randomized lottery system. Students select a major to pursue and are expected to be experts within that field by the time they graduate: "*that's our school culture- everybody's an expert in your major, like the dance majors go on to actually perform real and real ballets in New York City*" (planning interview, class 4). The STEM elective, according to Amy, may be a default if they lack interest in the Arts, however all students in the STEM major take the STEM elective. Typically, STEM majors will be with Amy throughout middle school (6-8), however this was her first year with this particular cohort of students. The school is also paper free; all students have district iPADs, and teachers use Canvas, Google Suite and numerous apps to draw, annotate and create digital models. The present study was the first-time students had done any work on paper following the COVID-19 pandemic. Amy had to obtain district permission to print the study materials, as teachers are prohibited from printing. The school is predominantly African American, yet the class observed in the present study had more white than African American students (11 and 5, respectively). Amy's class consists of 22 students: 14 boys, 8 girls, 5 with math support, 2 with 504's, 3 with Individual Education Plans (IEP), and 2 language learners. Five parents did not consent to their students being a part of the study.

Data Sources

We gathered data from five days of classroom observations, field notes, and transcribed audio of teacher-student interactions and 10 semi structured interviews. Additionally, the first author observed a class prior to the study to provide a window into classroom cultures, norms and practices. Video data collection was not approved by the district. Each data source is described in detail below.

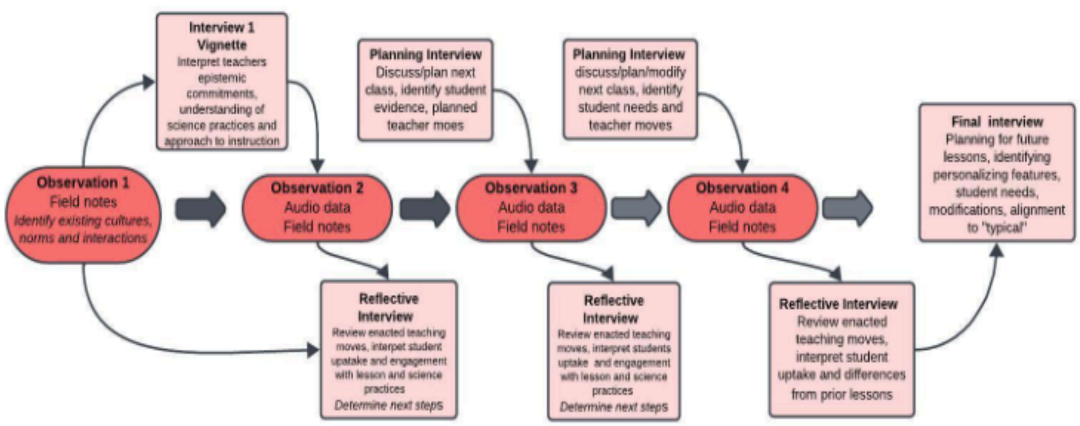


Figure 20 Observation and interview flow (created in LucidSpark)

Interviews.

The interviews themselves were *originally* intended to be abbreviated instructional coaching sessions, derived from "disciplined observation" cycles, for the complementary benefit of the study teacher and the research field (Ceven McNally, 2014; Santagata et al., 2007) . This method was selected to guide classroom observations (based on elements of her practice the teacher chooses to focus upon) and to provide coaching and mentorship to the study teacher. We had planned to use audio-based stimulated recall to promote explicit framing moves for sensemaking through reflection and self-analysis. However, as interviews and observations progressed, pre-observation interviews organically evolved into collaborative planning time, while post-observation interviews focused on lesson reflection and future modification. This felt like a more natural collaboration, eliminating the structural hierarchy between researcher and teacher inherent in the “disciplined observation” model. As such, we will similarly refer to ourselves by our first names as we do for Amy instead of “the first author” or “research team:” the first author is Christine, the second author is Andy.

Christine conducted and transcribed 10 semi-structured interviews. Planning interviews preceded each class to better understand Amy’s instructional intentions, and a reflective interview followed each lesson to better understand her impressions. Each interview lasted between 30-45 minutes. By planning and reflecting with Amy throughout her lesson sequence, we hoped to see how an explicit focus on her intended framing of classroom activities would be reflected in her enacted classroom moves and in students’ uptake of those framing moves. We intended to conduct separate pre-observation and post-observation interviews. However, due to logistical constraints, some post-observation interviews occurred at the same time and naturally blurred into the next lessons' pre-observation interview. Each interview included different questions; for example, two baMEL lessons were used, so questions focused on the use of baMEL materials for observation 3. The first interview differed from the others, and consisted of Amy's interpretation of a vignette to identify elements of imaginary teachers' practice and the predicted impacts upon students' science learning. Each data source is described in detail below. See Appendix for interview protocol.

Interview 1.

During interview one, Amy was invited to interpret two teachers' framing of similar lessons in a vignette and to discuss the advantages and disadvantages of the teachers' different approaches. The Vignette (Appendix A) included fictional classroom scenarios and dialogue from similar lessons on light taught by Ms. Lumen and Ms. Lightbulb. The first author heavily adapted a vignette from the 2016 California science framework (California Department of Education, 2018) and created the second. In the Vignette, Ms. Lumen (teacher 1) created student stations to investigate properties of light with concave and convex lenses. Students had tasks at each station, such as measuring the refraction or reflection angles of light. When they had questions, Ms. Lumen provided the answers. At the end of the lesson, Ms. Lumen created a model of properties of light for students to copy. Ms. Lightbulb began class by asking students to manipulate lenses and mirrors to redirect the path of light at low and high angles. Next, she asked students how they created each angle, the evidence of the angle and what they noticed. Ms. Lumen recognized non-canonical words, such as "spread out" to describe what happened to the light. Then she gave students materials and asked them to set up their own experiment to determine how each lens changed the path of light and their method of data collection. She has each group come up and share what they did, and asks them to expand on words like reflect and refract in their claims. She asks each student to draw a model of what happened to the light, which they swap with other students to build upon. In this way, student thinking was visible, public and everyday language was valued. After she read the vignette, Amy was asked to locate where learning occurred, and to interpret elements of each teachers' practice. The vignette also allowed Amy to apply her knowledge of NGSS and science practices. Amy identified *critical thinking and reasoning* as her goals for science practice in general, and for student engagement with MEL materials.

Pre-Observation Interviews.

These discussions between the researcher and teacher allowed Christine to draw out Amy's intended goals and her anticipated evidence of students meeting her goals. Amy walked through each step, transition, and anticipated pedagogical move, which allowed for discussion between Amy and Christine, sometimes leading to refinements of the lesson plan. Amy's explanations of her intended pedagogical moves and rationale also provided classroom context and insight into her beliefs about science learning, students, and her instruction. Pre-observation interviews revealed her goals for students' practice, anticipated evidence of students' uptake, and pedagogical intentions. Sample questions are provided below:

1. What scientific practices do you see students enacting?
    a. How will you know if they are?
    b. What will be your evidence?
2. What part of your practice or interactions with students do you think you could focus on during the MEL lessons?
3. You had mentioned you thought the baMEL would be more fun for students. How so?
    a. How does the baMEL more closely mimic what students do each day?
4. What do you see as the purpose of the activity?

Post Observation Interviews.

The observation took place during the last class period of the day, which enabled post-observation interviews to occur immediately after these observations. Due to logistical constraints, the post observation interview for day 3 interview occurred immediately before pre observation day 4 interview. Post observation interviews involved debrief, reflection on the lesson flow and discussion of Amy's enacted versus planned lesson flow and outcomes. Initially, we planned to use audio-stimulated recall to highlight specific classroom occurrences. However this was cumbersome and unnecessary, as Amy recalled each instance in question without aid of audio. Post-observation interviews allowed Amy to identify and interpret evidence of students' uptake of her framing, and for evidence of their engagement with the "critical thinking" practice she identified as her broad instructional target across the MEL lessons. Often, post-observation interviews included explanations about deviation from the plan, or questions about particular interactions. For example, the first lesson was largely disrupted due to a last-minute realization (by Amy and the research team) that a pretest was needed, which encompassed the majority of the class. The second interview was focused on her framing moves within the previous disruption, and to identify her planned moves for the upcoming class. Sample questions are provided below:

1. You had to manage a lot of behaviors. Do you think that was due to the nature of the task? Or is that just how that class goes?
    a. How can you or do you juggle managing behaviors or task management with engaging in science?
2. You did try to shift some kids away from thinking about the task as "school" or "grade" driven, and towards supporting their thinking. What does it look like when they respond to that?
    a. What is your evidence of moving or shifting their framing of the task?
3. You had wanted to focus on critical thinking -which will look different using this than doing research. What do you think it looks like in this context?

Classroom Observations.

Christine observed, audio recorded and transcribed four 90 minute classes to 7th graders doing MEL activities, for a total of 360 minutes of observation. Christine also observed and recorded a "normal", (non-MEL) class to infer Amy's typical framing moves, her interactions with students and classroom dynamics. MEL observations occurred the following week. Christine and Andy met after each observation to discuss notes and to plan analysis towards the teachers' framing bids and students' reactions to these bids.

Amy placed a digital recording device in her pocket to record her interactions with students. The application records audio which is sent to a password protected computer. Student talk data at each table was also audio recorded on separate recorders for the larger project but was excluded from this study. Christine created an observation table to note framings or actions with student responses and other dialogic interactions for rapid retrieval of particular instances after each observation. She also noted the time and nature of interactions to probe during the following interview. Following Russ and Luna (2013) and Russ (2018), we looked for patterns of framing moves towards sensemaking discussion (*science* practices) vs. completing the task (e.g., "doing *school*"; Pope, 2001; Windschitl, 2019), and following Krist et al (2023) looked for instances and evidence of students "taking up" practices of *school* or *science*. We used categories described by Russ and Luna (2013) to categorize and separate substantive, disciplinary talk from procedural talk. A degree of procedural talk was expected, however we specifically looked for instances in which students discussed, critiqued, and debated information or otherwise applied concepts from the activities. Since Amy held the recording device, some student dialogue was captured in notes and memos only. Student dialogue was difficult to collect in recordings even when Amy was standing near. Christine attempted to observe and document interactions at each table and with Amy, but inevitably missed interactional elements.

Obs.	Lesson topic	Summary	Lesson materials
0. 1/17	non-MEL lesson-Science fair	Students working on science fair projects.	Student iPads, classroom science equipment, internet, student designed Google Slides
1.. 1/22	MEL-pre test,introduction to plausibility	The plan was to begin with reading evidence text, but Amy and I forgot that students had to do pre-survey material. This took the majority of class, and required them to read and respond to a 7 page survey instrument, determine definitions of plausibility, falsifiability, and complete initial plausibility ranking task	Socioscientific issues survey, plausibility ranking task, pencil
2.. 1/23	Climate change pcMEL	Read all 4 articles, discuss with group, determine which evidence strongly supports, strongly supports, contradicts or has nothing to do with.	Climate change evidence text, diagrams
3.. 1/25	Food Security	Read 8 articles, discuss, choose models and evidence, place on white board.	baMEL Diagram, white boards with blank
4. 2/1	Eutrophication	Complete chaos	Eutrophication evidence text, baMEL Diagram, white boards with blank diagrams, iPds

Figure 21 Lesson topics

Initially, the observation plan was to note times spent on instructional elements based on Russ and Luna (2013) (teacher led discussion, student led work or discussion, and transitioning), however these categories didn't capture much of the classroom talk, as described below. We wanted to keep an open mind toward sensemaking and the science practices, as well as Amy's in-the-moment framings, and following the initial observation (Day 0) created an open observation template to track framing bids and responses, as they occurred.

Analysis

This qualitative study drew upon grounded theory tools such as inductive coding and open mindedness towards seeing the unexpected. As we will discuss, our initial and actual analysis differed as the data led us in a different direction than we intended.

Initially Planned Analysis.

Initially, we intended to use content analysis to characterize and infer meaning from the teachers' epistemological framing moves, and to interpret students' uptake with scripted MEL materials. We were looking for how the teacher shifted students from "playing school," in this case simply trying to complete the MEL worksheet, towards engaging in practices of science afforded by the MEL materials, such as argumentation and explanation-building (Hutchinson & Hammer, 2010; Russ, 2014). We predetermined initial categories of *substantive talk* based on Russ and Luna (2013), oriented toward engagement in science practices, and *procedural talk*, oriented toward completing the task. Due to the highly-structured nature of the activity, which could have been taken up as procedural and "schoolish," we anticipated a large degree of procedural talk. We wanted to see how Amy framed potentially procedural tasks within the MEL for sensemaking and attended to degree of engagement in science practices (Krist et. al., 2023). We intended to identify and characterize framing moves and student responses, which we would then discuss with Amy during the post-observation interviews. We were also looking for spaces in which students acted with epistemic agency, and the correlation, if any, to the teacher's framing moves. However, our plan of analysis shifted to accommodate our observable data and emergent research foci, as we now explain.

Patterns in Framing; Initial Changes in Focus.

We began analysis of transcripts and field notes after our first observation cycle, which we used to create iterative analytic memos. We applied inductive coding to the transcripts and field notes to characterize framing moves, which we connected to her expressed intentions and rationale from interviews. We added additional notes and tagged moments within the transcripts after interviews, which were also used in the analysis. Initially, we were particularly looking for framing moves and student shifts from engagement with *school* (focused on task completion) to engagement with *science* (i.e., engagement in science practices and sensemaking) and sought indicators of those enactments such as disciplinary talk. We noticed that Amy consistently worked to establish *Relationships* and *Community* when she attended to *Tasks* and *Behaviors* (see examples in Findings). Her language and tone consistently supported these commitments, and Amy confirmed her intentions to build community and form positive relationships with students in the first interview, so these became our initial categories (*Relationships, Community, Tasks, Behaviors*). As we continued our analysis, we also noticed that she framed for sensemaking in many instances, including when she noticed students "playing school" or focused on completion for a grade, or to encourage them to continue in their sensemaking. When she attended or responded to behaviors, she embedded her commitments to nudge them towards sensemaking such as and/or productive engagement, such as probing them to "tell me what you think" or "we are all discussing this evidence, we need you to join us." We then modified our initial categories to include framing moves which nudge students to engage in a particular way, such as for*, Sensemaking and Engagement*, to connect to what Amy noticed or responded to, based on Krist et al (2023).

We created a table with examples of each framing bid-for *Sensemaking* or *Engagement* (Figure 22) to investigate the nuanced entanglement of relationship building and Amy's moves to support epistemic agency, as described in Krist and Shim, (2023). We were searching for connections between Amy's framing bids and students' uptake of her framing through engagement in science practices, to indicate their acting with epistemic agency. However, until Day 4, there was not enough evidence of students' substantive disciplinary talk to retain this as an analytical element. We anticipated a linear connection between productive framing bids, epistemic agency, and evidence of uptake, yet we found that the "evidence" was either based on the inference of Amy or Christine, and may not connect to student dialogue or work. We were specifically looking for a correlation between Amy's framing moves to encourage sensemaking and students' uptake of sensemaking practices. However, after creating the following table, we did not see any clear patterns or answers to our questions and were left with, "so what's going on? Figure 22 Framing for sensemaking or engagement

Framing Bid	Description	Quote	Evidence of Uptake	Epistemic agency
Sensemaking	Framing bid to shift from engaging in tasks for purposes of "school" or accuracy.	"I love to hear what you think. I'm asking your	Students appear to think through responses before writing.	Students were encouraged to apply logic and prior knowledge.

		opinion. It's not for a grade."		
	Framing bid to shift from focus on completion towards practices.	"I want to know what you think. Tell me your opinion."	Students thinking through responses, citing prior knowledge.	Personalizing tasks, driven by student thinking not the worksheet.
Engagement	Uses "we" to disrupt hierarchies of learner and teacher.	"We are all discussing this evidence, and we need you to join us."	Students begin to listen to and respond to discussions	Collective knowledge, community of learning.

Figure 23 Framing for sensemaking or engagement

So, we went back to the data (see Appendix B for tables which guided our analysis). We noticed that nearly all of Amy's sensemaking moves co-occurred with her commitments towards community building and relationships. We consistently saw these commitments across nearly every aspect of Amy's speech and interaction with students, whether she was making framing bids toward sensemaking, making framing bids towards completing the assignment, or interacting with students in other ways. Initially, we interpreted this to be the *goal* of her framing- what she was framing for- but later determined that these components of her speech were actually culture-building elements and commitments embedded *into* her framing, and also within other interactions nudging students towards elements task completion or behavior management. Thus-these commitments were "baked" into her framing moves.

Embedded Commitment	Framing for Sensemaking	Framing for Engagement
Community building	"You are the expert in your article."	"We are all reading these, and we need you to be a part of our work."

	“I want everyone to learn from each other. That’s why we are sharing.”	“My friends, why am I not happy right now? What should we be doing?
Relationships	“I love to hear what you think. I’m asking your opinion. It’s not for a grade.”	“I would really love it if you took out your airpods.”
	“I like to read it. I love to know what my students write. ”	“You seem a bit distracted today. How can I help you?”

Figure 24 Embedded commitments

These observations-though interesting and consistent - failed to provide evidence of the impact of her framing on students’ engagement with science practices and epistemic agency. While we did observe apparent cause and effect in particular instances, we did not observe a clear, consistent correlation between framing for sensemaking and student uptake. We anticipated each framing move would be met with a categorizable response; while we did see some instances, the responses were generally negative and not what we expected. In fact, while the teacher consistently planned for engagement and deployed productive framing moves—the kinds of framing moves that previous literature suggests helps students frame their activity as a sensemaking discussion—students were increasingly resistant and unresponsive. Students pushed back against the increased structure (compared to what they were used to) provided by the lesson and Amy was forced to manage behaviors. This prompted us to revisit the transcripts, notes and memos to search for nuance. During this stage of analysis, we also revisited our research question and opted to explore why the framing bids towards sensemaking documented in other literature were unsuccessful in this instance.

Revised Analysis: Allowing the Data to Speak

Christine listened to every interview and observation again, and added new, open codes and notes without predetermined categories or themes. In some cases, codes were added where they were not previously, old codes were revised, in others, new codes aligned or supported the previous. The new codes, such as *Consensus*, *Collaboration*, and *Sensemaking (*initially-we used school and task management to describe what she was shifting students from, not towards) allowed us to search across chunks of dialogue to infer meaning and connection. Open, emergent coding across interviews and observations guided our search for patterns, particularly between the days in which the lessons "worked" and when they did not, but codes were not used for any other aspect of analysis. Christine and Andy met numerous times and discussed major differences between lessons 1-3 and lesson 4, to determine major claims. Next, Christine created and adapted joint displays (Figure 23) connecting evidence to inference based on Convergent Mixed Methods design (Creswell, 2015 and 2021). In each table, an overarching claim from patterns in the data was explained by reasons and supported by evidence (quotes from transcripts). A conclusion followed each claim. Each claim included multiple reasons, each connected by supporting evidence. This process of connecting claims to reasons and evidence to construct overarching conclusions allowed us to see nuance in the data. We were then able to identify categories by condensing claims, and themes by looking across the categories and synthesizing conclusions. One new theme that ended up playing a large role in

Claim	**Teacher consistently established relationships and community**			
Reasons/inferences supporting claims	Teacher consistently used “we” to frame learning.	Reinforces relationships to establish purpose of tasks.	Teacher includes herself in instructions.	Uses a positive tone and affirming language.
Evidence for claim (direct supporting quotes)	*“What do we think truthfulness in science means? Think about our science fair projects. “* *“What do we think that means?”*	“We got to read so I made something different today. Because I didn't think it was. I don't think we remembered everything we read when we did eight pages ourselves. Am I right in assuming that.”	“We are all reading these, and we need you to be a part of our work.	“I love to hear what you think.” You seem to be a bit distracted today. How can I help you?”
Findings/ conclusions	Consistent and persistent talk and action which reinforced classroom cultures was insufficient to engage students in scientific practices.			

Figure 25 Adapted joint display from Creswell (2015; 2022)

Patterns in Epistemic Agency.

We realized that in each interview, Amy described how students constructed knowledge in a typical class. We initially sought to connect framing to epistemic agency, but realized the importance of epistemic agency, as a classroom culture; students were *accustomed* to acting with epistemic agency *in particular ways* (details in findings and discussion). We used the initial, non-MEL lesson to determine the forms of typical epistemic agency the teacher regularly invited and the students regularly enacted. We initially inferred the student-driven culture of the school to naturally facilitate epistemic agency in all forms, yet realized that in absence of the form of epistemic agency with which students were most familiar and comfortable in Amy’s class, students pushed back against the entirety of the lesson. The MEL activities—baMEL in particular—embedded opportunities for epistemic agency as students selected models and paired them with supporting evidence. However, we only observed students exhibiting sustained epistemic agency, as identified in previous literature, on day 4. Therefore, we applied holistic, segmented coding to focus solely on the ways epistemic agency was normally enacted by revisiting our initial observation—Day 0, the pre-MEL lesson—and interview transcripts to identify where and how Amy described *typical classes'* epistemic agency. We identified examples of students acting with epistemic agency, which we used to create categories, then collapsed into the overarching theme of *student expertise.* This theme arose in part from interview data describing the school culture of "acting as experts" which grounded our analysis of epistemic agency *form*.

The data indicated that the *form* of epistemic agency was more important to student engagement than *where* and *how*. This revelation altered the course of analysis. Through this lens, we used interview and observational data to highlight instances of epistemic agency, regardless of framing moves.

Theme	**Category of epistemic agency**	**Displayed epistemic agency**
(form) Student Expertise	Student autonomy	Determined procedures, necessary materials, where to obtain materials
	Determining sources of information	Students review sources and revise info related to their project
	Determined method of documentation	Could present in a video, infographic or other display
	Engaged in sensemaking	Formulate ideas and arguments

Figure 26 Example themes

We created categories related to matched or mismatched epistemic agency and characterized causal relationships between instructional actions and student reactions.

Matched means a form of epistemic agency that students were accustomed to enacting in Amy's class, and mismatched means students are invited to enact epistemic agency in a way they are not accustomed to doing. This allowed us to identify the co-occurence of our previously coded framing and culture-building bids as themes of sensemaking, relationships and community and allowed us to incorporate our observed student response or action with fidelity. We determined that, while categorizing framing moves was important to understanding best practices, the greater takeaway was the holistic analysis of where and why students resisted, and when they did not.

Epistemic agency	Instructional action	Student reaction
Mismatched Form	Students given articles with sources of information	Verbal and behavioral **pushback**. Chaos.
	Students discuss article info	Students **refuse** to discuss
Matched Form	Students choose which articles to read	Students **leapt** to pile of articles
	Students determine strength of lines of evidence support to support each model	Students immediately center on group diagram, **discuss** and **critique** arguments, **build** on ideas,

Figure 27 Matched or mismatched form of epistemic agency

We previously used data displays to identify framing moves with examples, however we determined that this was insufficient based on our final analysis. We decided to present the interviews and observations chronologically, to thoughtfully document the mismatch between the form of epistemic agency to which students were accustomed in this class and the forms of epistemic agency invited by the MEL lessons. In each, we identify the culture-building moves as either *Sensemaking*, *Relationships* or *Community* to provide the reader with clarity and insight into Amy's robust pedagogical expertise, partly so readers can reach their own conclusions about what's happening in these class sessions and partly to help rule out a teacher-blaming explanation of why the lesson didn't go as well as we hoped on Days 1-3. A great teacher enacting framing moves that often "work," according to previous literature, was insufficient to promote sustained sensemaking and engagement with science practices during many of the MEL lessons[13]. Despite an expert teacher understanding and deploying expert framing, the form of epistemic agency invited by the lesson implementation had a major influence on learning. Thus, we revised our research question to explore the nuance in the forms of epistemic agency, and how the teacher identified and addressed this mismatch.

Our revised research question:

What role does the *form* of epistemic agency invited by a given classroom lesson play in 1) describing differences between lessons employing similarly prescriptive lessons, 2) students' sustained enactment of science practices?, and 3)

13 We do not mean to imply that Amy NEVER framed towards task completion, as all teachers must at given points, however that this was not her typical framing bid.

characterizing teachers' moves to (re) align classroom epistemological cultures while using prescriptive lessons?

Discussion

Professional Science or Science Class?

Equating science education with professional science allows for recognizable norms, and promotes epistemologies *of* science (Berland & McKneill, 2010; Russ, 2014). However, Russ (2014) determined that models which align the work of scientists and students reinforces a deficit model of learners as hierarchically novice, and promotes unilateral thinking about learning simply "because scientists do it" (Russ, 2014, p. 392). Further, attempts to replicate professional science practices may promote ritualized performance rather than intended engagement with practices (Berland et al., 2016). Instead, Russ (2014) refined a model to describe the mutual goals of both scientists and learners of science to make sense of the natural world (Figure 1). From this perspective, professional science is no longer the sole source of what constitutes "correct" practice, but instead that which is *for* and *from* learners must guide practices and metrics defining productive sensemaking and knowledge generation (Russ, 2014). Such a stance decentralizes the role of professional science as an end product and instead places it into a toolbox of productive sensemaking.

Elby and colleagues (Elby & Hammer, 2001; Elby, 2001; Hammer & Elby, 2002; Louca et al., 2004; Hutchison & Hammer, 2010) have long argued that productive epistemologies allow for a more meaningful parallel to mediate the work of scientists and students. Epistemologies *for* science, they argue, better reflect the mutual work of constructing knowledge and understanding about the world undertaken by both students and scientists (Russ, 2016). Based on this relocation of epistemological work by scientists and learners, we posit a new model which includes *mediating* and *influence* by educators, and is particularly useful while using highly-structured curriculum, such as in the present study. Below is a model of three epistemological relationships:

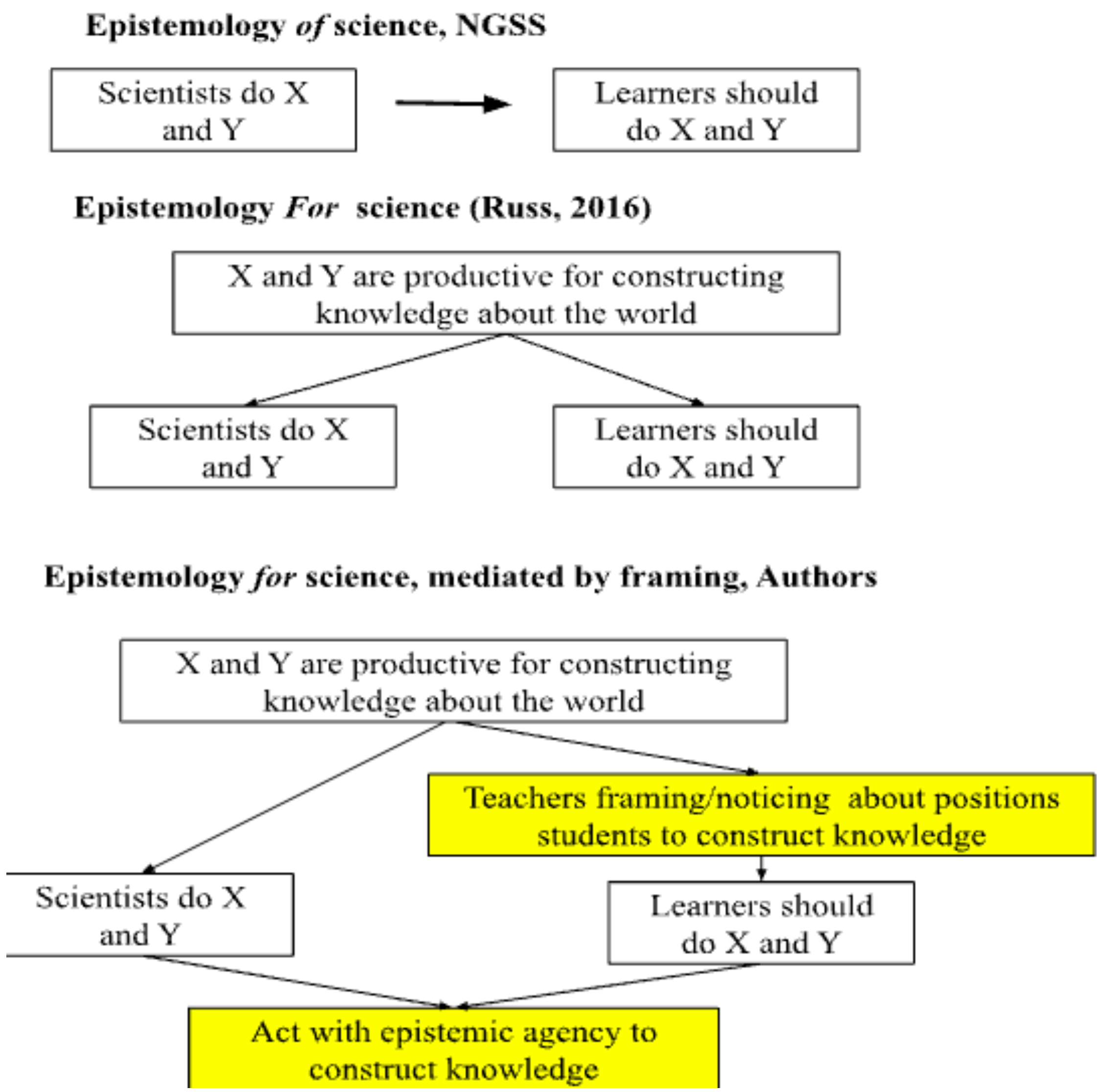


Figure 28 Our model of epistemological relationships

Epistemic agency… to do what?

Epistemic agency is not homogenous or monolithic. The present study demonstrated the observable push back when the *form* of epistemic agency students were accustomed to was not matched by the epistemic agency "invited" by the curriculum. Research cites recommendations for teachers to foster epistemic agency and promote sensemaking within discourse or classroom discussion (Carlone, et. al., 2011; Haverly et al., 2020. Stroup, 2014). This study demonstrated that discourse invited by the curricular materials were insufficient to replicate and align familiar forms of familiar epistemic agency which had previously moved students towards sensemaking. The materials included discussion-based elements which could have fostered epistemic agency, yet they did not. Building on the work of Ko and Krist (2019) and Haverly et.al. (2020), which emphasize opening up space for student voice, we propose the importance of *choice*, even in absence of student *voice*. In this and similar classrooms, we posit that teachers could mindfully create places within lessons for students to make *choices* about sources of knowledge. Thus-if students are accustomed to holding cognitive authority over sources of knowledge, they will notice and respond if this is removed. This aligns with Stroup's (2014) description of epistemic agency as one with authority to validate knowledge and to determine the standards of which this authority rests.

We push back on constructs of epistemic agency which place students as the consistent and constant source of instruction and drivers of instruction, which promote an unrealistic expectation for teachers and students. The present study demonstrated, and prior literature supports, that students act with epistemic agency over sources of knowledge; we refine this argument to include the "agency to look up information." While this may initially be perceived as un NGSS-like, we remind the reader that scientists also look up information, and do not discover all sources of knowledge from scratch. Scientists build upon information gathered by others and use this information to inform meaning towards other information. Students may also act with epistemic agency to determine their own sources, even if they are not the creators of those sources. Students may use that information to act with epistemic agency in arguing from and making sense of evidence from other sources, as scientists do. Teachers embed, and students take up, available epistemic agency; when this is removed by curriculum or otherwise, students recognize, and may push back. When this is reintroduced, it is not at the expense of other epistemic agency, but necessary to sustain it.

Mismatched Epistemic Agency

The *form* of epistemic agency is significant and impactful. Structured curricula may present a mismatch between typical and available epistemic agency. While we expected the schoolwide student-centered learning culture to foster significant agentic opportunities, we did not expect a mismatch between students *typical* epistemic agency and that afforded by the MEL materials. In Amy's class, students were accustomed to epistemic agency centered on *choice:* students regularly had choice in their assignments to locate and verify sources of knowledge and determine the direction of investigations. The baMEL materials on days 3-4 afforded opportunities for matched epistemic agency form as students selected models and paired evidence[14], yet day 4 appeared to prompt greater participation, engagement and enthusiasm than day 3. On day 4, students were positioned as *experts* to determine sources of knowledge (even selecting articles and searching definitions of eutrophication), which replicated the established school and class culture. As experts, students argued for their lines of evidence and referred to their articles within their arguments. The nature of their discussion was notably different: students listened to and built on others' ideas, held each other accountable and applauded peers. When students' ability to choose external knowledge sources was removed, students were observably disengaged and expressed annoyance (Observations 1-3). In short—when the form of epistemic agency afforded by the materials was matched with familiar epistemic opportunities-engagement (and excitement) with the scientific practices as intended by the materials dramatically increased.

Greater epistemic agency does not always mean less structure.

Amy was only able to replicate students' typical form of epistemic agency on day 4 by making the lesson more structured than a typical MEL , even though students were unaccustomed to this much structure. Below, we identify the reasons

---

14 Evidence, in this sense was from articles and text, not student derived, which may uphold traditional hierarchies in science. However, this may be different with older learners or traditional, non-elective science courses with greater context.

this modification to increase structure *may* have “worked” to encourage students' joyful participation and increased engagement with the intended scientific practices of argumentation and explanation building.

Reduced reading load.

On days 1-3, all students read every article and were prompted to “*tell your partner what you read*.” This framing of the task required a tremendous amount of time to complete and seemingly endless behavioral redirection. Students were also unable to recall or apply the information when determining which evidence supported each model. As Amy applied more structure to reading and discussion activities, she was able to create space for student sensemaking, in-the-moment [15]deep connection to learning concepts, and engagement with practices of argumentation and discussion with less focus on redirection. Additionally, this may also have focused student attention during reading by reducing the number of required articles.

Greater Participation in Group Work.

When Amy increased the structure on day 4, she deployed productive framing bids towards sensemaking to groups instead of individuals, fostering learning communities of shared accountability. On previous days of instruction, Amy shifted

[15] While students displayed deep connections to the concepts, long term learning is outside the purvue of this study.

from “*teaching to managing*” (Planning, Day 4). On these days, her framing bids towards sensemaking were generally overruled by behavioral and task management as students’ disengagement led to disruption. Students were increasingly unresponsive to her sensemaking bids, which prompted her to individually address and redirect student behavior. On day 4, student groups collectively responded to her sensemaking bids and engaged in the intended science practices afforded by the materials.

Realigning Mismatched Epistemic Agency.

On Day 4, Amy was able to realign the mismatch in epistemic agency form provided by the materials to students’ familiar forms of epistemic agency. Amy intentionally increased structure to recreate students' familiar roles as *experts* and facilitate familiar epistemic agency of *choice over knowledge source*, which students immediately recognized and responded too. Students determined how to find unknown words and concepts, even though they relied on someone else’s knowledge (such as the’ author of the evidence text articles). When Amy modified the lesson for students to locate definitions and to make meaning of topics, she redistributed cognitive authority for students to shape their knowledge space, and elevated their role within the learning community, consistent with Stroup (2014) and Carlone et al. (2021) who aligned with the tenants of ambitions instruction (Windschitl et al., 2020). This is an interesting deviation from much of the literature; the *act* of determining where and how to search seemed to overrule the *source* of knowledge. In other words, the epistemic agency gained from selecting sources of knowledge seemed more salient than the threat of lost epistemic agency from reliance on those sources as authority over knowledge.

The corpus of literature typically assumes that increased curricular structure decreases students' epistemic agency by positioning students as receivers of facts or "replicating school versions of science practice" (Kawasaki & Sandoval, 2019, p. 13; Ko & Krist, 2019; Miller et al., 2018). However, as we observed, the process of reinstating familiar *forms* of epistemic agency required increased structure. In this sense, while the materials may have provided facts, on Day 4 students were able to make sense of the information in ways familiar to them and were then able to enact the forms of epistemic agency supplied by the materials. Therefore, as curricular materials increase classroom structure and reduce opportunity for students to enact their 'typical' forms of epistemic agency, teachers could respond by scaffolding instruction to replicate and reinstate students' typical form of epistemic agency.

Trusting Students

Amy demonstrated trust in her students when she modified the lesson for them to look up definitions and to search for meaning, which replicated their typical activity. Trusting students to seek out their own understanding, even if they were not the sources of the knowledge, redistributed cognitive authority, and allowed students to shape the knowledge space as she positioned students' science ideas as "public" (Stroupe, 2014). Students in Amy's class were typically "trustworthy" to carry out investigations and design their learning experiences; they immediately recognized when their role shifted to *receive* elements of instruction although this was not the intention of the materials. This shift temporarily removed power from students and may have contributed to their "push-back."

Framing Moves are Important…but Insufficient

Amy consistently and persistently applied framing moves towards sensemaking in her attempts to manage behaviors and tasks which could have been productive. Her underlying commitment to fostering a safe space was evident, yet ineffective to permanently shift students towards engaging in the practices of science. On Day 1, which required extensive reading and writing, Amy used framing bids to shift her "*grade chasers*" from responding for the right answers to "*tell me what you think."* On Day 3, she told students to "s*how me the receipts*" as they decided and determined the strength of models and evidence. Although these moves seemed to temporarily shift students out of searching for the correct answer, shifts appeared minor and temporary. Students *appeared* to be thinking and carefully writing their answers, however reverted to "playing school" by quickly rushing to complete the worksheet in subsequent tasks. On Day 4, students engaged with practices of science when framing for sensemaking was coupled with matched epistemic agency. When students were able to "*be the experts"* they immediately engaged with sustained enthusiasm and participation. Amy noted that students did not need prompting and "*started before I finished.*" Conversations shifted, students made decisions and discussed their topics, and notably did not need behavioral or task reminders of previous days.

As the structure of the lesson increased on Day 4, framing moves were necessary to promote engagement with science and sensemaking, not to just keep students on task. Notably, Day 4 was more cognitively demanding than previous lessons, with many unknown concepts and terms: this lesson *could* have shifted students towards engagement with school-based tasks of completion and compliance, yet instead, it afforded the greatest engagement with science practices. In other words, the increased structure created space for sensemaking by reducing time spent on behavior management and positioning students in a “better space” cognitively and emotionally for sensemaking.

Classroom Epistemic Culture Embedded in Framing.

Amy’s commitments towards *relationships* and *community* were consistently embedded into her framing bids, which supported students' disciplinary knowledge. Amy’s connected practice embodied prior work of Krist (2024) and Bang et al (2012) which highlighted the connections and dependencies of relational and epistemic dimensions of science teaching and learning. Whether attending to procedures, tasks or sensemaking, Amy consistently emphasized these commitments. Throughout the MEL, she framed tasks as originating from her instead of an external author (*“I want to know what you think; I’m asking your opinion”*) to prompt sensemaking (see Observations Days 1-4). Interestingly, Amy was unaware of her tendency to use collective language; the invisibility of her collective language indicated how deeply ingrained her commitments were in her speech patterns. Amy's tone and language consistently reflected her value and commitment towards students when directing or redirecting behaviors (Observations 2 and 3). On Day 3, Amy's "pure" behavioral management moves consistently highlighted her established culture and commitments, while students reflected the embedded culture on Day 4 when they visibly created collective knowledge (Carlone et al., 2021). Amy described her pride in her relationships and as a "safe teacher" (Planning, Day 3) and demonstrated these commitments with phrases such as "*my friends; I would love it if you…Thank you for sitting back in your seats"* (Observation 3). Thus-her framing reflected the established culture of the class. This feature, though present throughout, became especially apparent on Day 3, when student behavior deteriorated yet her emphasis remained.

Similar to Krist (2024) and others (Bang et al., 2012; Carlone et al., 2021; Morales-Doyle et al., 2019) we see the connections and entanglement between relationship building and disciplinary activity in science classrooms, and the continuously evolving expectations of learning through established relational histories. Amy clearly recognized the impact of her relationships with students upon their position in the science classroom and their participation in knowledge building. Students' bids for participation could have been perceived as off-topic, distracting or disruptive (as Christine perceived them) yet Amy maintained and upheld students' roles as valuable and their ideas as legitimate to the classroom community, which created and reinforced space for them to act with epistemic agency.

Most literature on teachers' relationships-building has not foregrounded their enactment of framing moves toward sensemaking, while most literature on teachers' framing moves has not foregrounded their relationship-building actions. Our analysis, by contrast, demonstrated how reinforcement of relationships and community was "baked into" the teacher's framing moves toward sensemaking, not just towards behavioral or task management. This, and the recent work of Krist (2024) center the connections between relationship-building moves and framing moves upon students' disciplinary knowledge. These findings suggest that researchers could attend to this connection between teachers' relationship and community building, and their epistemic culture building to support engagement with science practices, particularly when using structured curricula.

Teachers Recognize Established Classroom Cultures

Teachers' everyday practices and framing moves establish and reinforce classroom culture, tone, and expectations, which determine how students engage and respond (Carlone et., al., 2021; Russ & Luna, 2013). Throughout the MEL activities, Amy was acutely aware of both the epistemic and socioemotional culture of her classroom-and when her teaching was in tension with those norms. She recognized that "students' contributions to classroom culture are acts of agency" and actively worked to restore this mismatch (Carlone et. al., 2021; p. 176). Reflections of Day 4 described Amy's established culture for students to *"do the learning on their own without ....guidance from me."* She demonstrated "accomplished" practice informed by empathic reasoning of students and contexts of learning (Philip et al., 2019). Amy's trust of students created spaces for them to direct knowledge construction and to drive sensemaking. She clearly identified students' discomfort with the authoritative shift between her *teaching* and their *learning* (reflection, day 4). Students expressed this discomfort and pushed back-which was also an act of agency: they chose how to engage and participate, and when to resist. Students pushed back on the structured material, in part, because the materials didn't invite them to exercise some of the familiar or typical forms of epistemic agency.

Learning to listen to students is an often overlooked yet imperative skill of improvisational teaching (Philip et al., 2019). Amy's deep understanding of her students' prompted her to mitigate and combat this mismatch. Amy was deeply bothered that she was *"managing rather than inspiring*" (Reflection, Day 3; Planning, Day 4), and recognized the need to align her implementation of the lessons with the "normal classroom epistemic culture." When Amy understood and acted to mitigate the impact of mismatched epistemic agency, her sensemaking bids were taken up by students. In Planning Day 4, Amy pushed back on Christine's suggestion to assign readings, insisting that students had to decide for themselves; she was right. Amy's frequent speculation and consideration of the causal connection between her framing bids and student engagement underscores her understanding of the established classroom culture. Amy's ability to identify, address and realign the cultural mismatch afforded by the materials demonstrate the relational-epistemic entanglement of responsive teaching (Krist, 2024).

We agree with Philip et al.'s (2019) conclusion that determining which best practices work, when and for whom cannot be determined A Priori, and must be negotiated by specific teachers in their specific classrooms to honor the role of each actor. In this sense, the relational, human aspect of teaching cannot be separated from opportunities for epistemic agency, which are grounded in classroom cultures and sustained by and through teacher-initiated relationships. We take this a step further to describe teaching based solely on "best-practices" and with practice oriented materials may minimize opportunities for epistemic agency.

Implications

Framing With Structured Science Materials.

Although highly structured NGSS-aligned curricula were created to counter "complacent enactment" of science practices, the present study suggests that these materials are *more* likely to "work" if the teacher modifies and adapts them to afford the epistemic agency to which students are accustomed (Miller et. al., 2018). Amy demonstrated the ability to identify and address the mismatch in epistemic agency, even if she did not refer to it as such. The MEL materials were the most effective in Amy's class when she applied structures to promote familiar epistemic agency, which created space for framing towards sensemaking.

The prevalence of bundled or structured NGSS curricula is daunting: *Achieve* identified and provided examples from 22 curriculum developers receiving highest marks on the EQuIP rubric to "address the issue of insufficient and inadequate exemplars of science instructional materials designed for the NGSS" (NextGenScience Peer Review Panel, retrieved May 6, 2024). Many more curricular companies market profit-driven solutions to address the material gap. In a recent report, of 45 evaluated materials for elementary and middle school, only 1 was found to meet expectations (EdReports, 2022). Many science teachers struggled to reorient instruction towards science practices prior to the pandemic, and continue to rely on supplemental or individually created curricula (EdReports, 2023). A recent report found that 97% of surveyed teachers felt that curricular materials were vital to implementing NGSS with fidelity, yet only 37% felt their materials met this need. Further, two thirds of science report 0-5 hours of professional learning related to their curriculum materials (EdReports, 2023). Availability and equitable access to quality NGSS materials remain a persistent barrier, particularly in schools serving predominantly students of color and under-resourced schools (NASEM, 2021).

Many studies (Berland et al., 2020; Cherbow & McNeill, 2022; Haverly et al., 2020; Jaber et al., 2022; Sandoval and Kawasaki, 2019) situate epistemologically oriented curriculum or professional development to "create space" for student ideas and foster epistemic agency. In absence of specific curricula or professional development, teachers may "complacently enact" the science practices of NGSS in ways which limit epistemic agency (Miller et al., 2018). Thus, structured curriculum *require* teachers to seek out means of replicating students' typical epistemic agency, as Amy did.

Professional Development Integrations.

Shifting students from engaging with school to engaging with science and *sensemaking* belies the need for professional development to recognize, address and respond to students' knowledge framing in science classes (Hutchinson & Hammer, 2010). Too often professional development centered on specific curriculum strives for "high-fidelity" enactment centered on "best-practices" (Phillips et al., 2019). This study demonstrated the importance of teachers' recognition of varying forms of epistemic agency associated with practices of science. Classroom environments offer distinct cultures, which may be emphasized by school structures. Professional development can assist teachers to identify and work within their established cultures to align the epistemic agency afforded by materials to that of their classes, as Amy did when she adapted the lesson on day 4. Third party examples such as vignettes and video study of other teachers can prompt reflection on one's practice. This can be coupled with curricular professional development and teacher education to support teachers' existing, established practice.

While the field generally recognizes teachers' ability to understand and act upon their knowledge of their students, we extend recognition to experienced teachers, such as Amy, who can identify students' familiar and comfortable forms of epistemic agency at the individual and classroom level. This knowledge should be leveraged and supported in order for teachers to authentically foster epistemic agency and engagement with science practices. Professional development priorities should shift from operationalizing achievement outcomes towards assisting teachers to operationalize their individually established *classroom* epistemic agency and culture while using structured materials. District leaders, curriculum developers and professional development providers should reconsider inserting curriculum into classrooms, and instead consider supporting educators to diagnose and address mismatched epistemic agency afforded by materials and their classes, as Amy did on day 4. Not only does this approach allow teachers to adapt to their specific classrooms, but this honors and elevates teachers as professionals. We do not specify pre-service preparation programming because we strongly believe these to be metacognitive skills associated with experience, reflection and repetition.

Professional development providers and teacher educators should view Amy's case teaching point toward improvisation and in the moment judgements instead of generic practices to address specific problems (Philip et al., 2019). Amy clearly demonstrated the impact of listening to students' implicit and explicit needs and adapting. Had she simply followed prescriptive "best practices" Day 4 would have been similar to the days preceding. Teaching through the "mangle of practice" requires rapid adaptations and improvisations which cannot be mastered in a single sitting (Pickering, 1995). Kawasaki and Sandoval (2019) illustrated the insufficient focus on practices for professional development; despite a 3 year study aimed at shifting teachers practice to center on students' disciplinary engagement with science practices through productive framing, the study teacher was uncomfortable with students' puzzlement and took back authority. The authors suggest that professional development should not only provide teachers with opportunities to experience sequences of practices, but also to support "teachers in providing their students with opportunities to demonstrate their capabilities, and teachers with the tools to recognize those capabilities" (p. 15). Jaber and colleagues (2022) described a model for professional development which positions teachers as learners to center their feelings of vulnerability and ultimately to foster empathy. Perhaps instead of teaching about practices and disciplinary engagement from a deficit stance, professional development should center teachers' as professionals to improvise, to experience and to adapt materials as only professionals can.

Final Thoughts on Trusting Teachers .

Attempts to categorize, classify and define teachers' pedagogical decisions without considering the multitude of influence upon those decisions paints an incomplete picture. Teachers face professional criticism magnified by political actors and fueled by misinformation campaigns designed to decrease support for public education. A recent study focused on COVID-19 safety measures and teaching about race, racism or bias during the 2021-2022 school year found that 40% of teachers and 48% of principals reported job stressors associated with political issues, while 37% of teachers and 61% of principals reported being harassed, which decreased physical and mental well-being and influenced decisions to leave the profession (Woo et al., 2022). Another report found that one quarter of U.S. teachers reported restrictions which influence their instructional practices; one-fifth of teachers in states without restrictions also cite these influences (Diliberti et al., 2023). Many schools and districts use market based curricular materials, which may restrict their efforts to individualize and localize science teaching (EdReports, 2022; Morales-Doyle, 2019). A holistic approach to research on teachers' and teaching is necessary to consider or categorize teachers' pedagogical choices amid the current climate of teaching, while using prescriptive or scripted curricular materials.

Limitations, Alternative Explanations and Next steps

We recognize the unique nature of Amy's school as systemically fostering epistemic agency. While we initially intended this to be a critical case study which could be extrapolated to other cases, we acknowledge that Amy's case may be an extreme example. However, we see this as additive to the corpus of epistemic agency and teaching literature: the nature of her school created a lens for us to "see" the evidence of mismatched epistemic agency in a way that we would likely have overlooked if we were in a more "traditional" non-project based school. This study was also constrained by time; the present study co occurred within the larger study to examine changes in students' plausibility judgements, and as such, did not allow for significant modifications or adaptations. Amy repeatedly expressed the tradeoffs described in Ko and Krist (2019; she clearly identified the need to take longer, and her desire to modify, adjust and expand on the lessons to replicate a “typical” science lesson in her class. While she was able to realign the form of familiar epistemic agency in this short timeframe, additional research is needed to investigate the impact of longer term curricular decisions and modifications on students' knowledge construction, as well as consideration of the epistemic messages sent through her decisions (Russ, 2018). We also acknowledge the embedded tensions within examining epistemic agency when using scripted curricula, which may include expected or correct responses, yet see opportunities, however incremental, demonstrated in this study. While these incremental changes may not permanently shift power structures or address significant issues of justice typically identified in epistemic agency literature, they provide a starting point and strategies to navigate these real tensions in the classroom. Further research is needed to understand the additive and complementary impacts of these incremental changes within the larger mechanisms of learning units, classroom dynamics and knowledge construction.

Conclusion

NGSS is the latest science reform effort; the framework is built on the assumptive failure of science education to meet national needs and designed to “directly address and overcome these weaknesses” (*A Framework for K-12 Science Education*, 2012, p. 1). This deficit view of education has critical consequences for public perception and de-professionalization of educators. Top-down mandates and "teacher proof" curriculum[16] stem from this rationale and feed the cycle of teacher shortages (Darling-Hammond, 2022). Structured, NGSS exemplar materials such the MEL, demonstrate the capacity of experienced teachers to modify and adapt materials to maximize the spirit and goals of the materials. Epistemologically focused professional development and curricular elements can provide educators with a means to promote engagement with science practices within the affordances of structured materials.

We push back on constructs of epistemic agency placing students as the consistent and constant source of instruction and drivers of instruction, which promote an unrealistic expectation for teachers and students. The present study demonstrated, and prior literature supports, that students act with epistemic agency over sources of knowledge; we refine this argument to include the *agency to look up information*. While this may initially be perceived as un NGSS-like, we remind the reader that scientists also look up information, and do not discover all sources of knowledge from scratch. Professional scientists seek out, build upon and reference information gathered by others, and use this information to inform meaning making of other information. Students may also act with epistemic agency to determine their

---

[16] We are NOT implying that the MEL materials are teacher proof; on the contrary-the materials were designed by and for teachers to support gaps in their argumentation (see Lombardi et al., 2018).

own sources, even if they are not the creators of those sources. Students may use that information to act with epistemic agency in arguing from and making sense of evidence from other sources, as scientists do. Teachers embed, and students take up, available epistemic agency; when this is removed by curriculum or otherwise, students recognize, and may push back. When this is reintroduced, it is not at the expense of other epistemic agency, but necessary to sustain it.

NGSS requires a significant reorientation of instruction to situate students as epistemic agents in the science classroom. Although a growing body of literature supports the role of students' epistemic agency upon engagement with science practices, the corpus largely aggregates epistemic agency into a singular category. Through a single case study, we have illustrated the multidimensionality of epistemic *agency*; on one hand, opportunities for epistemic agency have been largely correlated to students' engagement with science practices. Yet, this study demonstrated the role of epistemic agency *form*, which delves into the nuance and tension surrounding authentic, classroom-based science. We propose a consideration of teachers' professional expertise and knowledge of their classroom cultures when adopting NGSS curriculum: how teachers understand, identify, interpret and adapt structured curriculum to align to familiar epistemic agency is critical to increasing student engagement in science. We must trust teachers, as professionals, to do just that.

References

A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. (2012a). National Academies Press. https://doi.org/10.17226/13165

Bae, Y., Hand, B. M., & Fulmer, G. W. (2022). A generative professional development program for the development of science teacher epistemic orientations and teaching practices. *Instructional Science*, *50*(1), 143–167. https://doi.org/10.1007/s11251-021-09569-y

Bang, M., & Medin, D. (2010). Cultural processes in science education: Supporting the navigation of multiple epistemologies: Improving Science Learning for Indigenous Students. *Science Education*, *94*(6), 1008–1026. https://doi.org/10.1002/sce.20392

Bang, M., Warren, B., Rosebery, A. S., & Medin, D. (2012). Desettling Expectations in Science Education. *Human Development*, *55*(5–6), 302–318. https://doi.org/10.1159/000345322

Berland, L. K., & Hammer, D. (2012). Framing for scientific argumentation. *Journal of Research in Science Teaching*, *49*(1), 68–94. https://doi.org/10.1002/tea.20446

Berland, L. K., Russ, R. S., & West, C. P. (2020). Supporting the Scientific Practices through Epistemologically Responsive Science Teaching. *Journal of Science Teacher Education*, *31*(3), 264–290. https://doi.org/10.1080/1046560X.2019.1692507

Boon, M., Orozco, M., & Sivakumar, K. (2022). Epistemological and educational issues in teaching practice-oriented scientific research: Roles for philosophers of science. *European Journal for Philosophy of Science*, *12*(1), 16. https://doi.org/10.1007/s13194-022-00447-z

Bowen, G. A. (2006). Grounded Theory and Sensitizing Concepts. *International Journal of Qualitative Methods*, *5*(3), 12–23. https://doi.org/10.1177/160940690600500304

Carlone, H. B., Haun-Frank, J., & Webb, A. (2011). Assessing equity beyond knowledge- and skills-based outcomes: A comparative ethnography of two fourth-grade reform-based science classrooms. *Journal of Research in Science Teaching*, *48*(5), 459–485. https://doi.org/10.1002/tea.20413

Carlone, H. B., Mercier, A. K., & Metzger, S. R. (2021). The Production of Epistemic Culture and Agency during a First-Grade Engineering Design Unit in an Urban Emergent School. *Journal of Pre-College Engineering Education Research (J-PEER)*, *11*(1). https://doi.org/10.7771/2157-9288.1295

Ceven McNally, J. (2016). Learning from one's own teaching: New science teachers analyzing their practice through classroom observation cycles. *Journal of Research in Science Teaching*, *53*(3), 473–501. https://doi.org/10.1002/tea.21253

Chen, Y., & Terada, T. (2021). Development and validation of an observation-based protocol to measure the eight scientific practices of the next generation science standards in K-12 science classrooms. *Journal of Research in Science Teaching*, *58*(10), 1489–1526. https://doi.org/10.1002/tea.21716

Cherbow, K. (2022). Responsive instructional design for students' epistemic agency: Documenting episodes of principled improvisation in storyline enactment. *Journal of Research in Science Teaching*, *n/a*(n/a). https://doi.org/10.1002/tea.21818

Cherbow, K., McKinley, M. T., McNeill, K. L., & Lowenhaupt, R. (2020). An analysis of science instruction for the science practices: Examining coherence across system levels and components in current systems of science education in K-8 schools. *Science Education*, *104*(3), 446–478. https://doi.org/10.1002/sce.21573

Cherbow, K., & McNeill, K. L. (2022). Planning for student-driven discussions: A revelatory case of curricular sensemaking for epistemic agency. *Journal of the Learning Sciences*, *31*(3), 408–457. https://doi.org/10.1080/10508406.2021.2024433

Chi, M. T. H., & Wylie, R. (2014). The ICAP Framework: Linking Cognitive Engagement to Active Learning Outcomes. *Educational Psychologist*, *49*(4), 219–243. https://doi.org/10.1080/00461520.2014.965823

Clark, H. F., Sandoval, W. A., & Kawasaki, J. N. (2020). Teachers' uptake of problematic assumptions of climate change in the NGSS. *Environmental*

Education Research, *26*(8), 1177–1192. https://doi.org/10.1080/13504622.2020.1748175

Cooper, A. C., & Bolger, M. S. (2024). The Classroom-Research-Mentoring Framework: A lens for understanding science practice-based instruction. *Science Education*, *108*(1), 275–307. https://doi.org/10.1002/sce.21835

Damşa, C. I., Kirschner, P. A., Andriessen, J. E. B., Erkens, G., & Sins, P. H. M. (2010). Shared Epistemic Agency: An Empirical Study of an Emergent Construct. *Journal of the Learning Sciences*, *19*(2), 143–186. https://doi.org/10.1080/10508401003708381

Darling-Hammond, L. (2022). Breaking the Legacy of Teacher Shortages. *Educational Leadership*, *80*(2), 14–20.

Data Snapshot: K-12 Science Instructional Materials (2022). (2023, March 13). EdReports - Evidence-Rich. Educator-Led. Free. https://cms.edreports.org/resources/data-snapshot-k-12-science-instructional-materials-2022/

Ebneyamini, S., & Sadeghi Moghadam, M. R. (2018). Toward Developing a Framework for Conducting Case Study Research. *International Journal of Qualitative Methods*, *17*(1), 160940691881795. https://doi.org/10.1177/1609406918817954

Effects of a professional development program on science teacher knowledge and practice, and student understanding of interdisciplinary science concepts—

Yang—2020—Journal of Research in Science Teaching—Wiley Online Library. (n.d.). Retrieved November 27, 2023, from https://onlinelibrary-wiley-com.proxy-um.researchport.umd.edu/doi/full/10.1002/tea.21620?sid=worldcat.org

Elby, A. (1999). *Getting Started with Research on Epistemologies and Expectations*.

Elby, A. (2001). Helping physics students learn how to learn. *American Journal of Physics*, *69*(S1), S54–S64.

Elby, A. (2019). Did the Framework for K-12 Science Education trample itself? A reply to "Addressing the epistemic elephant in the room: Epistemic agency and the next generation science standards." *Journal of Research in Science Teaching*, *56*(4), 518–520. https://doi.org/10.1002/tea.21539

Elby, A., Macrander, C., & Hammer, D. (2016). Epistemic cognition in science. *Handbook of Epistemic Cognition*, 113–127.

González-Howard, M., & McNeill, K. L. (2020). Acting with epistemic agency: Characterizing student critique during argumentation discussions. *Science Education*, *104*(6), 953–982. https://doi.org/10.1002/sce.21592

Guy-Gaytán, C., Gouvea, J. S., Griesemer, C., & Passmore, C. (2019). Tensions Between Learning Models and Engaging in Modeling: Exploring Implications for Science Classrooms. *Science & Education*, *28*(8), 843–864. https://doi.org/10.1007/s11191-019-00064-y

Haverly, C., Calabrese Barton, A., Schwarz, C. V., & Braaten, M. (2020). “Making Space”: How Novice Teachers Create Opportunities for Equitable Sense-Making in Elementary Science. *Journal of Teacher Education*, *71*(1), 63–79. https://doi.org/10.1177/0022487118800706

Hayes, K. N., Lee, C. S., DiStefano, R., O’Connor, D., & Seitz, J. C. (2016). Measuring Science Instructional Practice: A Survey Tool for the Age of NGSS. *Journal of Science Teacher Education*, *27*(2), 137–164. https://doi.org/10.1007/s10972-016-9448-5

Hoeg, D. G., & Bencze, J. L. (2017). Values Underpinning STEM Education in the USA: An Analysis of the Next Generation Science Standards. *Science Education*, *101*(2), 278–301. https://doi.org/10.1002/sce.21260

Hutchison, P., & Hammer, D. (2010). Attending to student epistemological framing in a science classroom. *Science Education*, *94*(3), 506–524. https://doi.org/10.1002/sce.20373

Jaber, L. Z., Davidson, S. G., & Metcalf, A. (2023). “I Loved Seeing How Their Brains Worked!”—Examining the Role of Epistemic Empathy in Responsive Teaching. *Journal of Teacher Education*, 00224871231187313. https://doi.org/10.1177/00224871231187313

Jaber, L. Z., Dini, V., & Hammer, D. (2022). “Well that’s how the kids feel!”—Epistemic empathy as a driver of responsive teaching. *Journal of Research in Science Teaching*, *59*(2), 223–251. https://doi.org/10.1002/tea.21726

Kawasaki, J. N., DeLiema, D. J., & Sandoval, W. A. (2014). The Influence of Non-Epistemic Features of Settings on Epistemic Cognition. *Canadian Journal of Science, Mathematics and Technology Education*, *14*(2), 207–221. https://doi.org/10.1080/14926156.2014.903319

Kawasaki, J., & Sandoval, W. (2019). The Role of Teacher Framing in Producing Coherent NGSS-Aligned Teaching. *Journal of Science Teacher Education*. https://doi.org/10.1080/1046560X.2019.1657765

Kelly, G. J. (n.d.). *Methodological Considerations for the Study of Epistemic Cognition in Practice*.

Kelly, G. J., & Cunningham, C. M. (2019). Epistemic tools in engineering design for K-12 education. *Science Education*, *103*(4), 1080–1111. https://doi.org/10.1002/sce.21513

Ko, M.-L. M., & Krist, C. (2019). Opening up curricula to redistribute epistemic agency: A framework for supporting science teaching. *Science Education*, *103*(4), 979–1010. https://doi.org/10.1002/sce.21511

König, J., Santagata, R., Scheiner, T., Adleff, A.-K., Yang, X., & Kaiser, G. (2022). Teacher noticing: A systematic literature review of conceptualizations, research designs, and findings on learning to notice. *Educational Research Review*, *36*, 100453. https://doi.org/10.1016/j.edurev.2022.100453

Krist, C. (2020). Examining how classroom communities developed practice-based epistemologies for science through analysis of longitudinal video data. *Journal*

of Educational Psychology, *112*(3), 420–443.
https://doi.org/10.1037/edu0000417

Krist, C., Schwarz, C. V., & Reiser, B. J. (2019). Identifying Essential Epistemic Heuristics for Guiding Mechanistic Reasoning in Science Learning. *Journal of the Learning Sciences*, *28*(2), 160–205.
https://doi.org/10.1080/10508406.2018.1510404

Krist, C. (Stina). (2024a). Striving for Relationality: Teacher Responsiveness to Relational Cues When Eliciting Students' Science Ideas. *Cognition and Instruction*, *42*(2), 207–242. https://doi.org/10.1080/07370008.2024.2308303

Krist, C. (Stina). (2024b). Striving for Relationality: Teacher Responsiveness to Relational Cues When Eliciting Students' Science Ideas. *Cognition and Instruction*, *42*(2), 207–242. https://doi.org/10.1080/07370008.2024.2308303

Krist, C. (Stina), Machaka, N., Voss, D., Mathayas, N., Kelly, S., & Shim, S.-Y. (2023). Teacher Noticing for Supporting Students' Epistemic Agency in Science Sensemaking Discussions. *Journal of Science Teacher Education*, *0*(0), 1–21.
https://doi.org/10.1080/1046560X.2022.2155355

Krist, C. (Stina), & Shim, S.-Y. (n.d.). Which ideas, when, and why? An experienced teacher's in-the-moment pedagogical reasoning about facilitating student sense-making discussions. *Journal of Research in Science Teaching*, *n/a*(n/a).
https://doi.org/10.1002/tea.21908

Lee, S. W., Luan, H., Lee, M., Chang, H., Liang, J., Lee, Y., Lin, T., Wu, A., Chiu, Y., & Tsai, C. (2021). Measuring epistemologies in science learning and teaching: A systematic review of the literature. *Science Education*, *105*(5), 880–907. https://doi.org/10.1002/sce.21663

Lee, S. W.-Y., Luan, H., Lee, M.-H., Chang, H.-Y., Liang, J.-C., Lee, Y.-H., Lin, T.-J., Wu, A.-H., Chiu, Y.-J., & Tsai, C.-C. (2021). Measuring epistemologies in science learning and teaching: A systematic review of the literature. *Science Education*, *105*(5), 880–907. https://doi.org/10.1002/sce.21663

Lehrer. (2015). *Handbook of Child Psychology and Developmental Science, Cognitive Processes*. John Wiley & Sons.

Lehrer, R., & Schauble, L. (2015). The Development of Scientific Thinking. In *Handbook of Child Psychology and Developmental Science* (pp. 1–44). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118963418.childpsy216

L'Estrange, L., Walker, S., Lunn-Brownlee, J., Ryan, M., Bourke, T., Rowan, L., & Johansson, E. (2023). Capturing epistemic reflexivity for teacher educators teaching about/to/for diversity in teacher education. *Heliyon*, *9*(2), e13754. https://doi.org/10.1016/j.heliyon.2023.e13754

Levin, D., Hammer, D., Elby, A., & Levin, D. (2012). *Becoming a Responsive Science Teacher: Focusing on Student Thinking in Secondary Science*. National Science Teachers Association. http://ebookcentral.proquest.com/lib/umdcp/detail.action?docID=1416102

Levin, D. M., Hammer, D., & Coffey, J. E. (2009). Novice Teachers' Attention to Student Thinking. *Journal of Teacher Education*, *60*(2), 142–154. https://doi.org/10.1177/0022487108330245

Limbere, A. M., Munakata, M., Klein, E. J., & Taylor, M. (2022). Exploring the tensions science teachers navigate as they enact their visions for science teaching: What their feedback can tell us. *International Journal of Science Education*, *44*(12), 1897–1915. https://doi.org/10.1080/09500693.2022.2105413

Lombardi, D., Bailey, J. M., Bickel, E. S., & Burrell, S. (2018). Scaffolding scientific thinking: Students' evaluations and judgments during Earth science knowledge construction. *Contemporary Educational Psychology*, *54*, 184–198. https://doi.org/10.1016/j.cedpsych.2018.06.008

Louca, L., Elby, A., Hammer, D., & Kagey, T. (2004). Epistemological Resources: Applying a New Epistemological Framework to Science Instruction. *Educational Psychologist*, *39*(1), 57–68. https://doi.org/10.1207/s15326985ep3901_6

Luna, M. J. (2018). What Does it Mean to Notice my Students' Ideas in Science Today?: An Investigation of Elementary Teachers' Practice of Noticing their Students' Thinking in Science. *Cognition and Instruction*, *36*(4), 297–329. https://doi.org/10.1080/07370008.2018.1496919

Manz, E., & Renga, I. P. (2017). Understanding how teachers guide evidence construction conversations. *Science Education*, *101*(4), 584–615. https://doi.org/10.1002/sce.21282

Manz, E., & Suárez, E. (2018). Supporting teachers to negotiate uncertainty for science, students, and teaching. *Science Education*, *102*(4), 771–795. https://doi.org/10.1002/sce.21343

McComas, W. F., & Nouri, N. (2016). The Nature of Science and the *Next Generation Science Standards*: Analysis and Critique. *Journal of Science Teacher Education*, *27*(5), 555–576. https://doi.org/10.1007/s10972-016-9474-3

Miller, E., Manz, E., Russ, R., Stroupe, D., & Berland, L. (2018). Addressing the epistemic elephant in the room: Epistemic agency and the next generation science standards. *Journal of Research in Science Teaching*, *55*(7), 1053–1075. https://doi.org/10.1002/tea.21459

Morales-Doyle, D., Childress Price, T., & Chappell, M. J. (2019). Chemicals are contaminants too: Teaching appreciation and critique of science in the era of Next Generation Science Standards (NGSS). *Science Education*, *103*(6), 1347–1366. https://doi.org/10.1002/sce.21546

National Academies of Sciences, E., and Medicine. (2021). *Call to Action for Science Education: Building Opportunity for the Future*. The National Academies Press. https://doi.org/10.17226/26152

Nel, B. P. (2022). Professional learning by mathematics teachers through video-stimulated recall. *Perspectives in Education*, *40*(4), 152–164. https://doi.org/10.38140/pie.v40i4.6133

Next Generation Science Standards: For States, By States. (2013). National Academies Press. https://doi.org/10.17226/18290

Nez, R., & Lombardi, D. (2019a). *MEL2 Project Year 2* [dataset]. https://doi.org/10.17910/B7.860

Olmstead, M. (2024, March 12). *STEM Teachers Needed*. American Board Blog. https://www.americanboard.org/blog/stem-teachers-needed/

Osborne, J. (2014a). Teaching Scientific Practices: Meeting the Challenge of Change. *Journal of Science Teacher Education*, *25*(2), 177–196. https://doi.org/10.1007/s10972-014-9384-1

Osborne, J. (2014b). Teaching Scientific Practices: Meeting the Challenge of Change. *Journal of Science Teacher Education*, *25*(2), 177–196. https://doi.org/10.1007/s10972-014-9384-1

Osborne, J. (2014c). Teaching Scientific Practices: Meeting the Challenge of Change. *Journal of Science Teacher Education*, *25*(2), 177–196. https://doi.org/10.1007/s10972-014-9384-1

Park, S., Kite, V., Suh, J. K., Jung, J., & Rachmatullah, A. (2022a). Investigation of the relationships among science teachers' epistemic orientations, epistemic understanding, and implementation of Next Generation Science Standards science practices. *Journal of Research in Science Teaching*, *59*(4), 561–584. https://doi.org/10.1002/tea.21737

Park, S., Kite, V., Suh, J. K., Jung, J., & Rachmatullah, A. (2022b). Investigation of the relationships among science teachers' epistemic orientations, epistemic understanding, and implementation of Next Generation Science Standards science practices. *Journal of Research in Science Teaching*, *59*(4), 561–584. https://doi.org/10.1002/tea.21737

Philip, T. M., Souto-Manning, M., Anderson, L., Horn, I., J. Carter Andrews, D., Stillman, J., & Varghese, M. (2019). Making Justice Peripheral by Constructing Practice as "Core": How the Increasing Prominence of Core Practices Challenges Teacher Education. Journal of Teacher Education, 70(3), 251-264. https://doi-org.proxy-um.researchport.umd.edu/10.1177/0022487118798324 https://doi.org/10.1177/0022487118798324

Penuel, W. R., Allen, A.-R., Deverel-Rico, C., Singleton, C., & Pazera, C. (2023). How Teachers' Knowledge of Curriculum Supports Partnering with Students in Their Science Learning. *Journal of Science Teacher Education*, *34*(8), 861–882. https://doi.org/10.1080/1046560X.2023.2167508

Pope, D. C. (2001). *"Doing school": How we are creating a generation of stressed out, materialistic, and miseducated students*. Yale University Press. http://site.ebrary.com/id/10167915

Quality Examples of Science Lessons and Units | Next Generation Science Standards. (n.d.). Retrieved May 6, 2024, from https://www.nextgenscience.org/resources/examples-quality-ngss-design

Read "A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas" at NAP.edu. (n.d.). https://doi.org/10.17226/13165

Richards, J., Elby, A., Luna, M. J., Robertson, A. D., Levin, D. M., & Nyeggen, C. G. (2020). Reframing the Responsiveness Challenge: A Framing-Anchored Explanatory Framework to Account for Irregularity in Novice Teachers' Attention and Responsiveness to Student Thinking. *Cognition and Instruction*, *38*(2), 116–152. https://doi.org/10.1080/07370008.2020.1729156

Robertson, A. D., Scherr, R., & Hammer, D. (2015). *Responsive Teaching in Science and Mathematics*. Routledge.

Rosebery, A. S., Warren, B., & Tucker-Raymond, E. (2016). Developing interpretive power in science teaching. *Journal of Research in Science Teaching*, *53*(10), 1571–1600. https://doi.org/10.1002/tea.21267

Russ, R. S. (2014). Epistemology of Science vs. Epistemology for Science. *Science Education*, *98*(3), 388–396. https://doi.org/10.1002/sce.21106

Russ, R. S. (2018a). Characterizing teacher attention to student thinking: A role for epistemological messages. *Journal of Research in Science Teaching*, *55*(1), 94–120. https://doi.org/10.1002/tea.21414

Russ, R. S. (2018b). Characterizing teacher attention to student thinking: A role for epistemological messages. *Journal of Research in Science Teaching*, *55*(1), 94–120. https://doi.org/10.1002/tea.21414

Russ, R. S., & Luna, M. J. (2013). Inferring teacher epistemological framing from local patterns in teacher noticing. *Journal of Research in Science Teaching*, *50*(3), 284–314. https://doi.org/10.1002/tea.21063

Saldaña, J. (2016). *The coding manual for qualitative researchers*. SAGE. https://eduq.info/xmlui/handle/11515/35868

Santagata, R., & Guarino, J. (2011). Using video to teach future teachers to learn from teaching. *ZDM*, *43*(1), 133–145. https://doi.org/10.1007/s11858-010-0292-3

Santagata, R., & Yeh, C. (2014). Learning to teach mathematics and to analyze teaching effectiveness: Evidence from a video- and practice-based approach. *Journal of Mathematics Teacher Education*, *17*(6), 491–514. https://doi.org/10.1007/s10857-013-9263-2

Schellinger, J., Jaber, L. Z., & Southerland, S. A. (2022). Harmonious or disjointed?: Epistemological framing and its role in an integrated science and engineering activity. *Journal of Research in Science Teaching*, *59*(1), 30–57. https://doi.org/10.1002/tea.21720

Schwarz, C., Passmore, C., & Reiser, B. J. (2017). *Helping students make sense of the world using next generation science and engineering practices* (1–1 online resource). National Science Teachers Association. http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=1460312

Schwarz, C. V., Braaten, M., Haverly, C., & De Los Santos, E. X. (2021). Using Sense-Making Moments to Understand How Elementary Teachers' Interactions Expand, Maintain, or Shut Down Sense-making in Science. *Cognition and Instruction*, *39*(2), 113–148. https://doi.org/10.1080/07370008.2020.1763349

Sezen-Barrie, A., Stapleton, M. K., & Marbach-Ad, G. (2020). Science teachers' sensemaking of the use of epistemic tools to scaffold students' knowledge (re)construction in classrooms. *Journal of Research in Science Teaching*, *57*(7), 1058–1092. https://doi.org/10.1002/tea.21621

Sherin, M. G., Russ, R. S., & Colestock, A. A. (2012). *ACCESSING MATHEMATICS TEACHERS□' IN-THE-MOMENT NOTICING*.

Stroupe, D. (2014). Examining Classroom Science Practice Communities: How Teachers and Students Negotiate Epistemic Agency and Learn Science-as-Practice: EXAMINING CLASSROOM SCIENCE PRACTICE COMMUNITIES. *Science Education*, *98*(3), 487–516. https://doi.org/10.1002/sce.21112

Stroupe, D. (2017). *Reframing Science Teaching and Learning: Students and Educators Co-developing Science Practices In and Out of School*. Taylor & Francis.

Stroupe, D., Caballero, M. D., & White, P. (2018). Fostering students' epistemic agency through the co-configuration of moth research. *Science Education*, *102*(6), 1176–1200. https://doi.org/10.1002/sce.21469

Suh, J. K., Park, S., & University of Iowa. Department of Teaching and Learning. (2016). *Examining teacher epistemic orientations toward teaching science (EOTS) and its relationship to instructional practices in science* [University of Iowa]. http://ir.uiowa.edu/etd/3198

Taking Science to School: Learning and Teaching Science in Grades K-8 (p. 11625). (2007). National Academies Press. https://doi.org/10.17226/11625

The ICAP Framework: Linking Cognitive Engagement to Active Learning Outcomes. (n.d.). Retrieved November 27, 2023, from https://www.tandfonline.com/doi/epdf/10.1080/00461520.2014.965823?needAccess=true

Wendell, K. B., Swenson, J. E. S., & Dalvi, T. S. (2019). Epistemological framing and novice elementary teachers' approaches to learning and teaching engineering design. *Journal of Research in Science Teaching*, *56*(7), 956–982. https://doi.org/10.1002/tea.21541

Windschitl, M. (2019). Disciplinary Literacy Versus Doing School. *Journal of Adolescent & Adult Literacy*, *63*(1), 7–13. https://doi.org/10.1002/jaal.964

Windschitl, M., Thompson, J. J., & Braaten, M. L. (2020). *Ambitious science teaching* (1–1 online resource (viii, 304 pages) : illustrations). Harvard Education Press. https://public.ebookcentral.proquest.com/choice/PublicFullRecord.aspx?p=7263019

Woo, A., Wolfe, R. L., Steiner, E. D., Doan, S., Lawrence, R. A., Berdie, L., Greer, L., Gittens, A. D., & Schwartz, H. L. (2022). *Walking a Fine Line—Educators' Views on Politicized Topics in Schooling: Findings from the State of the American Teacher and State of the American Principal Surveys*. RAND Corporation. https://www.rand.org/pubs/research_reports/RRA1108-5.html

Yang, Y., Liu, X., & Gardella Jr., J. A. (2020). Effects of a professional development program on science teacher knowledge and practice, and student understanding of interdisciplinary science concepts. *Journal of Research in Science Teaching*, *57*(7), 1028–1057. https://doi.org/10.1002/tea.21620

Yin, R. K. (1992). The Case Study Method as a Tool for Doing Evaluation. *Current Sociology*, *40*(1), 121–137. https://doi.org/10.1177/001139292040001009

Zhang, J., Tian, Y., Yuan, G., & Tao, D. (2022). Epistemic agency for costructuring expansive knowledge-building practices. *Science Education*, *106*(4), 890–923. https://doi.org/10.1002/sce.21717

Zimmerman, H. T., & Weible, J. L. (2018). Epistemic agency in an environmental sciences watershed investigation fostered by digital photography. *International Journal of Science Education*, *40*(8), 894–918. https://doi.org/10.1080/09500693.2018.1455115

Appendix

A. Coding for paper 2

Code	Sub codes	Description	Example
Epistemic stance: *School*		Teacher frames activities for the purposes of correct, completion or compliance over engagement with science	decide which 2 to focus on, make sure they are recorded on your paper, and make sure you've share what you chosen, which you've chosen and why
Epistemic stance: *Science*	Collective learning Student ideas	Teachers' framing supports students engagement with science practices, such as collaboration, arguing or evaluating evidence	Today your goal is to get a look at everything and to start making decisions on what you want to look into more, so you are not really going to be filling out the worksheet.
T_authority	With students Transferring authority	Teacher defines terms, finishes sentences, directs scope of ideas	Keep in mind you have all categories open to you and that sometimes, we use falsifiability, right? to support, so something that is falsifiable actually ends up supporting something else so keep that in mind as you are looking through your evidence.
S_authority	Students decide Learning with students	Teacher frames learning and action within the activity as student driven and collaborative	And if you like number 1, you can choose it as a group. But your job is to try to narrow it down to 4. You can worry about the models later, you can do the models now, but you should be making the decision as a group not independently.
Validating	Positive Valuing	Teacher affirms student ideas or thinking in a positive manner	You can do the arrows together, but you don't have too. You can discuss it, and I think thats a great idea.
Procedural	Task management	Teacher attends to menial tasks within the activity such as where to put items	Make sure you have an A a B and a C. Does everyone have an A a B and a C?

B. Vignette for Paper 3

Questions

1. What messages do you think each teacher sends to students about:
    a. What they learn
    b. How they learn it
    c. What counts as learning
2. How do you think students' responses or actions reflect these messages?
3. What do you think each teachers' goals were for their lesson?

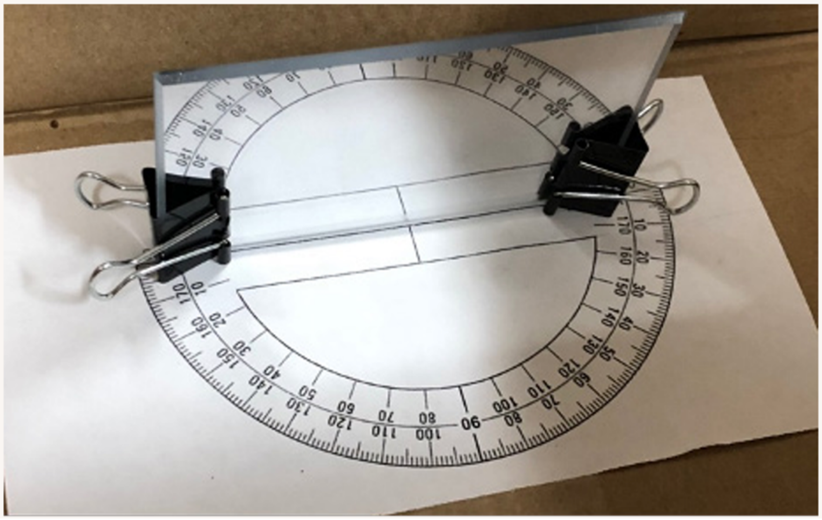
Teacher 1: Ms. Lumen

During a science lesson, Ms. Lumen (pseudonym) was teaching her grade 8 students about properties of light. She had set up a series of lab stations around the room for students to investigate how light waves interact with various materials. Each station had step-by-step instructions telling students what to do. Below is a sample of dialogue from one group:

> *Student 1: The procedures said to put the mirror here and attach it to the protractor.*
> *Student 2: When I hold the laser at 20, the angle is 40. Write that down.*
> *Student 3: I think…we didn't measure that right. But we should move on.*
> *Student 2: Ok next hold it at 40.*
> *Ms. Lumen: How many angles have you done?*
> *Student 1: We did 20 and 40.*
> *Ms. Lumen: Be sure each of you put your answers in the data table. And you need to set the mirror against the protractor, like this.*

When students had different answers about the angles that the light reflected at one of the stations, the teacher explained through a demonstration of the lab on the overhead projector that if their mirror was not exactly parallel to their protractor, the laser would not bounce off the center of the protractor, leading to consistently inaccurate measurements (see figure).

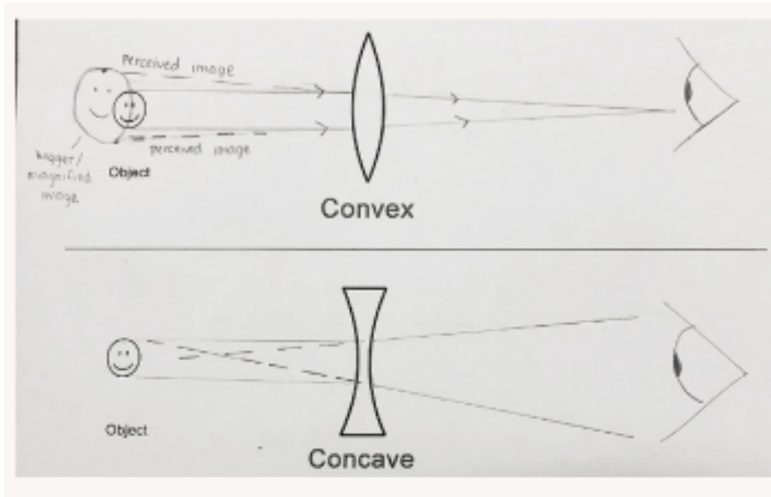
Figure 5. Reflected light station setup



After students had experienced the investigations, Ms. Lumen reconvened the class. With a worksheet on the overhead projector, she questioned students on what they saw at the refracted, absorbed, and reflected light stations.

Ms. Lumen:	What did you see at the refracted station? Did light bend or bounce?
Student 1:	it bounced.
Ms. Lumen:	Anyone else?
Student 2:	It was bent.
Ms. Lumen:	That's right! It bent. So refraction shifts the path of light. And we know that because you measured the angles. What about at the reflection station? Did it bend or bounce?

Then Ms. Lumen drew models of what they should have seen at the stations. While the students did these investigations themselves, the teacher brought them together to come to the correct answer that she added to the projected worksheet. Next, students were instructed to summarize their results from each test in their worksheets and develop models for what happened to the path of light in the experiments.



A few students shared their answers, and one student in particular received praise from the teacher for providing multiple answers: “You guys are lucky to have [student] in your class because she gives you all the answers.” The teacher asked the class to try and come up with “one rule for light” to put in the conclusions section of their worksheets. Several students contributed responses, and the teacher wrote them down on the overhead. The teacher asked if they all agreed with everything said so far, and some students seemed hesitant to offer their ideas. No one disagreed. Ms. Lumen erased the prior answers, and wrote a new definition on the board and asked students to write it in their conclusions.

She wrote: *When light waves come into contact with objects, they can be refracted, reflected or absorbed depending on the material of the object.*

Teacher 2: Ms. Lightbulb

Ms Lightbulb (pseudonym) began a class for her 8th grade students by placing flashlights, mirrors and various lenses at each table of 4 students. Ms Lightbulb set a timer and gave students 2 minutes to try to figure out which combination of mirrors and lenses could redirect the path of light at high and low angles. Student groups began talking, manipulating and arranging their materials. Below is a sample of one groups dialogue:

> Student 1: Lets see what happens when we put this lens in front of the mirror.
> Student 2: Whoa-it moved the light over here! What about this one?
> Student 3: So that's a high angle, right? Because if you follow the path of the light its over 90.
> Student 2: So lets try this other lens then to make a low angle.

Ms. Lightbulb: So what do you guys think? How did you move the light?
Student 3: We think that if we shine the light through the convex lens it bounces over here, and we think that since it's over 90 degrees, it's a high angle.
Ms. Lightbulb: I like your thinking! Is there anything else you notice about the light?
Student 2: We noticed that it gets really dim with this lens, and with the other, it doesn't.
Ms. Lightbulb: That is a great observation! So it changes the direction and brightness of the light. What else can you do to change the light?

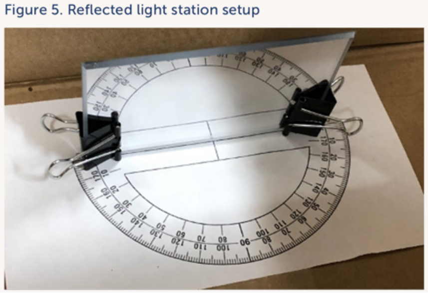
When the timer went off, Ms Lightbulb asked groups to share how they created each. The first group stated that they put a concave lens in front of the mirror to get a low angle. Ms Lightbulb asked the rest of the class if they agreed. She asked another group how they knew if they had created a low angle or not. The group said they saw the light, but it was really spread out. Another group said they moved the lens closer to the mirror which created a solid beam of light. Ms. Lightbulb gives the class a minute to check if they all saw the light as spread out or a solid beam.

Student 1: Why does it do that? Why does one make the light so much more dim?
Ms. Lightbulb: That's a great question! Let's figure it out together. What was the mirror doing to the light?
Student 2: It reflects it.
Ms. Lightbulb: How do you know? What does light "do" when it is reflected? In your groups, create a model of what is happening to the light in each lens.

Next she asks them if light can do anything else, allowing students to respond to each other, without indicating right or wrong.

Ms. Lightbulb gives each group materials (laser pointer, mirror, lenses, protractor, clips) and tasks them with setting up an experiment to figure out how each lens changes the path of light. Each group has to figure out their setup, and draw their design. Groups have to make a claim about each lens and support their claim with numerical data. Groups also determine how many tests to do, and create a way to track their data. After about 10 minutes, she asks a group to come up, share their claim, and show on the projector what they did with each lens. She asks their class what worked about their setup, and what could be improved. Then she asks the class if their claim is supported with their data, and how. She asks if every group had the same answers, and for other groups to come up and share. For each group, she calls on another group to identify the strengths and weaknesses of their setup and to make suggestions. As groups present varying answers, she asks the class why that might be. A student suggests that the mirror was not parallel to the protractor each time. Ms Lightbulb asks if that could make a difference

Figure 5. Reflected light station setup



or not, allowing students to answer. Next she gives a few minutes to revise their experiments, claims and data back at their tables.

Then she asks the class what each lens is actually doing to the path of light. As students respond, she uses their words to revoice their definitions. As students use words like *reflect* or *refract*, she asks them to clarify meaning from their experiments. Some students say that when light is reflected, it goes the opposite direction. Others say that when it is reflected, it bounces back in the same direction.

Ms Lightbulb asks each student to draw a model of what happens to a path of light through each lens. Groups can experiment with and manipulate the lenses to better understand what happens to the light. Each group shares their models with a neighboring group, who adds strengths and weaknesses to their drawing. When students get their drawings back, they make revisions.

Ms Lightbulb asks students to draw their models on the projector and to share their ideas. The class creates definitions for the terms *reflect*, *refract* and *absorb* from their models.

C. Joint Displays for Analysis

Claim	Teacher consistently framed for relationships and community			
Reasons	Teacher consistently used "we" to frame learning.	Reinforces relationships to establish purpose of tasks.	Teacher includes herself in instructions.	Uses positive tone and affirming language.
Evidence (quotes)	"What do we think truthfulness in science means? Think about our science fair projects. " "What do we think that means?"	"We got to read so I made something different today. Because I didn't think it was. I don't think we remembered everything we read when we did eight pages ourselves. Am I right in assuming that."	"We are all reading these, and we need you to be a part of our work.	"I love to hear what you think." You seem to be a bit distracted today. How can I help you?"
Findings/conclusions	Consistent and persistent framing which reinforced classroom cultures was insufficient to engage students in scientific practices.			

Claim	The Form of epistemic agency matters.			
Reasons	Mismatched removed cognitive authority from students.	Students were accustomed to determining sources of information and knowledge.	Student behaviors and engagement are connected to matching forms of epistemic agency.	All epistemic agency is not the same.
Evidence (quotes)	"They always feel like they're experts because they do all the research. I do none of the talking or teaching all of my projects are geared towards students centric learning	When given articles to read, students did not read all of them, disengaged from task, engaged in	When given the choice of articles, students enthusiastically engaged by jumping out of their seats to grab at articles.	In this case, students reacted to the loss of choice, and responded when this was returned.

	where they do the research, they do the learning on their own with help from me, and guidance from me.	disruptive behaviors.		
Findings/conclusions	Epistemic agency is not homogenous or monolithic. Varying form may be emphasized, and recognized when absent. .			

Claim	Teachers know their students and cultures.		
Reasons	Teachers recognize the need to match a structured experience to "typical" class.	Teachers recognize the impact of mismatched format-in this case it was digital vs paper.	Teachers recognize the mismatched components within structured curricula to established classroom cultures.
Evidence (quotes)	I think I'm gonna let them choose each pile on a desk and just say every article has to be read. So take what you want to read at least two " I'll definitely say that like,' this is your choice. This is your MEL now now you get to choose.' So use that type of language. Then when students are actually working- my body language- I might say, 'Okay, well lay the cards out. You pick four of these and two of these' and like point to the cards to show them that they pick anything in front of them. I think that will show them like our normal sense of 'I get to pick I get to lead my learning,' even though it's something already crafted for them,	"Then they can either hand write or type. So they get some choice."	"They're like being taught rather than they're doing the learning." But with baMEL they have choices and I think that was better
Findings/conclusions	Curricular based professional development should emphasis teachers adaptation towards and reflection of their established cultures, while allowing time for practice, support and planning.		

Claim	Framing was overruled by the need for matched epistemic agency.			
Reasons	Teacher **consistently** framed task management towards sensemaking. Framing bids should have been productive.	Attempts to shift students from engaging with tasks of school towards practices of science were temporarily productive or superficial .	Mismatch led to student pushback, and increased emphasis on framing towards managing behaviors.	When framing moves were coupled with matched epistemic agency, students engaged with practices of science.
Evidence (quotes)	I love to hear what you think. I'm asking your opinion. It's not for a grade. "I don't want you to take it and just reword it. I want you to explain in your own words." Try again, my friends don't throw papers at me you don't randomly circle I would love to see your actual thoughts. "And again it's not graded. It's- so don't stress I could see you stressing already so it's not graded, truly" "that's we're really looking at how you think your thinking process right? So don't stress yourself out"	"I don't want you to take it and just reword it. I want you to explain in your own words." Appeared to thoughtfully consider response, wrote a lot. "You seem a bit distracted today. How can I help you? Student read article for 1-2 minutes, went back to off task, talking, texting.	"This is what we are doing now, and we need you to be a part of this." "I would really love you take your airpods out." "Why am I unhappy right now?"	"You are the expert on the article you read; every person at the table needs to fully understand all the articles. That's where you-your job is to talk and tell each other about it comes in. Is that clear? Okay, I'm giving you 10 minutes to discuss. I want to actually hear you talk about what you read, what you wrote down." (student) "I learned that eutrophication can like increase the population and there's like many dead zones to where it's like leading to a bigger problem. Like the claim was that it

				can increase fish like it can increase populations and it has like towns downsize .”
Findings/conclusions	Framing towards sensemaking was insufficient when epistemic agency was mismatched.			

D. Interview Protocol, Paper 3

Interview 1

From Vignette

1. What messages do you think each teacher sends to students about:
   a. What they learn
   b. How they learn it
   c. What counts as learning
2. How do you think students' responses or actions reflect these messages?
3. What do you think each teachers' goals were for their lesson?

For MEL:

1. In thinking about how you will facilitate the MEL; what are your instructional goals?
   a. What are your goals for student learning?
   b. What is your pedagogical focus?

2. What scientific practices do you see students enacting during the MEL?
   a. How will you know if they are? What will be your evidence?
   b. If students are not enacting this, what could or would you do to promote them?
   c. Do you think this is easier or more difficult since it is semi scripted?

3. What challenges or opportunities does a scripted curriculum like this allow for?
   a. What strategies can you use to promote students engaging with science instead of school, while using the materials?

4. What part of your practice or interactions with students do you think you could focus on during the MEL lessons?

Chapter 5: Research Synthesis and Next Steps

Driving question: How do teachers create classroom opportunities for students to enact authentic science?

Introduction

This three-paper dissertation was driven by the question: *How do teachers create classroom opportunities for students to enact authentic science?* My intention with this study was first through the disciplinary lens of astronomy, and then from the theoretical lens of theaters' epistemologies, to characterize the Science and Engineering Practices (SEP) of the *Next Generation Science Standards* (NGSS Lead States, 2013), as an identifier of authentic science.

Operationalizing Authentic Science: Science Practices

I characterize markers of authentic science in alignment with and operationalized by the Practices of NGSS to define and locate authentic science throughout each study. According to the NRC (2012), engaging in the Science and Engineering Practices:

> " *helps students' understand how scientific knowledge develops; such direct involvement gives, the, an appreciation of the wide range of approaches that are used to investigate, model, and explain the world…..Participation in these practices also helps students form an understanding of the crosscutting concepts and disciplinary ideas of science and engineering; moreover, it makes students' knowledge more meaningful and embeds it more deeply into their worldview."* (p. 42).

In this sense, *authentic science* serves the purpose of providing greater context for scientific literacy, mindset and an informed understanding of the world, rather than producing an endpoint such as STEM majors or workforce pipeline. The applicability of the Practices across contexts foregrounded each investigation, as described in the following model first published in Osborne (2011):

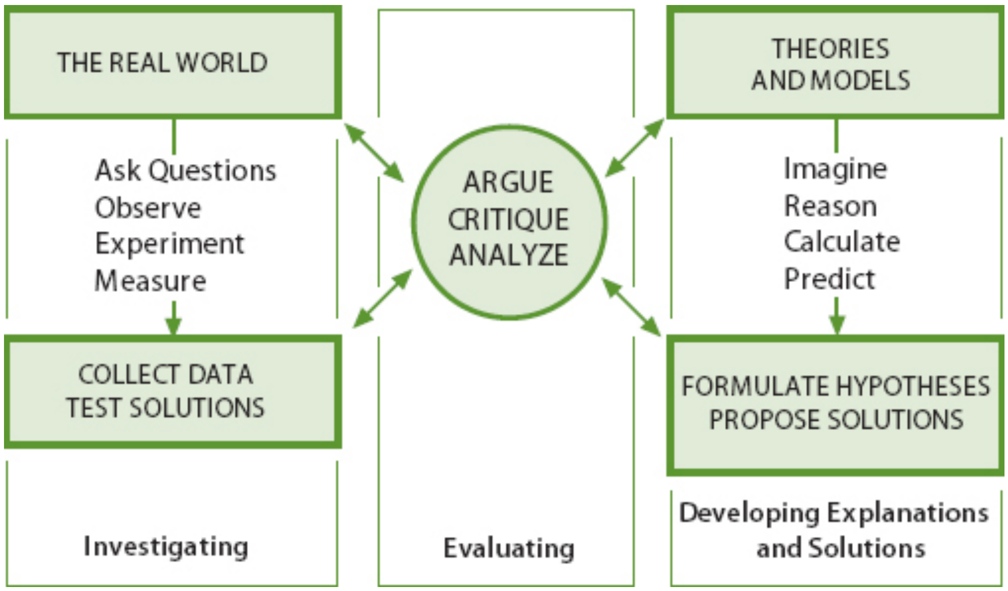


Figure 29 NRC, 2012; Three spheres of activity for students and scientists (p. 45); Osborne (2011), p. 181.

The three investigations of my dissertation comprise the empirical elements of the left side of the diagram and the middle of the iterative evaluation processes, and less so the right side of developing solutions. As such, critical thinking and idea refinement are centered, with less emphasis on designing solutions, yet I acknowledge that professional scientists move fluidly between each sphere.

My investigations operationalized *authentic science* as a holistic function of the overall practices which students engage in, both collectively and as individuals, without drawing attention to any one *specific* practice as more important than others (such as e*xplanation from evidence* over *argumentation*). In other words, I investigated students' classroom engagement with scientific practices as an inquiry process, similar to practices of professional scientists. Additionally, I operationalized authentic science as that which was meaningful to students-that which students see as making progress on questions they derived, rather than following a set of procedures; in other words, *authentic science* actively involves students in the entire cycle of learning (Berland et al., 2020; Reiser et al., 2021).

Whilst this model embodies what scientists (and students) should do, I was more interested in how the practices catalyze deeper thinking and knowledge construction. Afterall, the practices are only of value if they help students develop deeper understanding and more effectively spur knowledge construction while more closely replicating professional science than science education in absence of the practices (Osborne, 2014). Therefore, I set my studies amidst the work of teachers to foster the cognitive and collective demands of the practices in pursuit of classrooms engaging in *authentic science.* My investigations ground *authentic science* within the work of Berland et. al (2016 & 2020) which merged strands of responsive teaching and teaching for science practices to articulate meaningful participation in practices; rather than students' actions as a necessary means to an end of assignment or unit assessment, students see themselves as an integral component of learning. For science to be authentic, it must be *meaningful* to students: this may be a phenomenon of interest or involve students in planning an investigation. My integration of astronomy as a discipline was intended to provide this meaning, while papers 2-3, centered on epistemic agency and epistemological framing, positioned pedagogical moves and culture building to foster such meaning.

I am particularly interested in constructs of *agency* as characteristic of *authentic science* in science classrooms. Student agency has emerged in the past decade, reflecting shifts towards understanding social constructs of learning which impact engagement (Arnold & Clarke, 2014). Early studies of this genre merge anthropological and sociological frameworks to characterize agency; Basu (2008) described agency as a student's purposeful action to consider and enact change based on one's beliefs and goals through lesson design, while Barton and Tan (2010) described students' agency as their role assertions in community focused energy studies. Arnold (2012) determined that a students' *positioning* in conversation was synonymous with agency. My dissertation chapters weave together these constructs to explore how teachers' can foster agentic opportunities for students to *do* science.

Study Snapshots

In paper 1, I sought evidence of authentic science amidst international contexts of astronomy education. I hoped to find concrete examples and takeaways for use in U.S classrooms. Many teachers are ill prepared for NGSS instruction, which not only pair content with practice, but also infuse robust elements of astronomy (MS-ESS1-1-6, MS-ESS2-1-2, 6; HS. ESS1-1-6, HS. ESS2-1, 2, 3, 6-7). Through surveys and interviews with educators, teacher educators and education leaders, I investigated unique learning opportunities available by studying space that could promote students' authentic engagement with science and embody the spirit of the science practices. Astronomy offers opportunities for students to engage in authentic science through telescopic observations, partnerships with space agencies and other learning opportunities to create rather than replicate known knowledge. In this way, astronomy may foster authentic science learning.

In papers 2 and 3, I explored how teachers created opportunities for students to engage in authentic science while using exemplar NGSS lesson materials investigating controversial socio scientific topics with embedded connections to science practices. These materials were of interest because they were designed towards features of the Practices, while requiring the thoughtful enactment to foster meaningful discussion, collaboration, critique and critical thinking.

In my first paper, I learned that many of the best examples were informal, localized, individually led, and not easily replicable. However, I noticed that each offered opportunities for students to design or construct some aspect of their learning. With this in mind, I set out to locate such opportunities in a "typical" classroom, with expert teachers using vetted, evidence-based materials. In paper 2, two teachers used similar strategies of introduction, group work, small group interaction and discussion, however the subtle and nuanced variation between their framing moves may have contributed to differences in student uptake, engagement and participation. The subtleties may also indicate variation between each teachers' established classroom cultures, which may have also contributed to differences in student uptake. This study emphasizes the role of such nuance, which eliminates the possibility of a singular method to identify sources of classroom variation. In paper 3, I found that, despite an expert teaching consistently framing for sensemaking, students noticed and acted upon differences in epistemic agency invited by curricular materials and that which they are accustomed too. The teacher in this study demonstrates how teachers can identify, address and "realign the mismatch" by reinstating familiar forms of epistemic agency, such as looking up definitions or other information. These findings push against the corpus of literature which largely describe epistemic agency as students driving most aspects of learning through choice and discourse. The study provides evidence for practitioners and researchers regarding the significance of epistemic agency *form*.

Study Contributions to Research and Practice

Paper 1: Space for All

In Space for All, I sought international examples and exemplars to provide guidance to formal educators in NGSS-implementing classrooms, which center integration of Earth and Space sciences within all grade levels (NRC, 2012). This study built upon and provided guidance to a prior curricular survey through qualitative methods, integrating stories from across the globe to present snapshots of practice. I sought instances of authentic science in practice, yet I found largely localized and not-scalable examples. While this added to the literature–particularly regarding the significance of informal astronomy education–I did not find the rich curricular and pedagogical classroom examples I sought to share with the science education community. To better understand this, I must foreground the context of Astronomy Education Research.

The field of Astronomy Education Research (AER) is a distinct field of discipline-based research (DBER), branching out from Physics Education Research (PER) in the 1990's, yet has remained largely localized to United States Undergraduate endeavors (Salimpour et al., 2024). Qualitative research in astronomy education, particularly in pre-university settings, is minimal; Salimpour and colleagues completed quantitative studies of curricular documents including one which motivated my research (2021, and a second (2024), confirming the scarcity of qualitative study (11%). The Big Ideas (Retre et al., 2019), intended to inform curriculum and policy, was developed to support astronomical research scientists, whose interest in education may not extend to pre-university settings (Salimpour et al., 2024). Yet, this document has been the general standard of much astronomy education research, particularly that undertaken by international astronomy education researchers.

Unlike other subdisciplines of science education research (such as physics), the astronomy education research community is predominantly composed of professional astronomers, not educators. The Education working groups in the American Astronomical Society and International Astronomical Union are largely composed of research scientists, not educators. Membership in the International Astronomical Union requires a Ph. D. in astronomy, astrophysics or closely related fields. There is no option for educator membership. However, the Office of Astronomy for Education deploys National Astronomy Education Coordinators in 109 countries and territories to coordinate astronomy education activities (Astro4Edu, n.d.). Similarly, the AAS Education committee has 14 members, 11 of whom are either professional astronomers or astronomy faculty. Only one person on the committee is in a dedicated education role, while two work at the intersection of outreach and astronomy (American Astronomical Society, n.d.). While their website contains a link to *Astronomy Education Research Review*, this link instead connects to a history of the organization with no mention of education. Given the general lack of professional educators conducting AER, It comes as no surprise that few studies situate astronomy education within pre-university settings (Salimpour et al., 2024).

Several recent studies demonstrated the rich opportunities afforded by astronomy education, which I plan to build upon in my future studies. Bailey and colleagues (2024) situated space exploration to understand student thinking and factors which influenced their decision making. While not a specific focus of the study, the topic of space exploration is highly resonant with recent work of Singleton and colleagues (Singleton et al., 2024) which signified the impact of students' interest upon their achievement and engagement in science; in other words–the ability and opportunity to engage in authentic science practices–mediated by astronomy. Rodrigues and colleagues (2024) conducted a document analysis of Chilean curriculum to describe the direct and indirect opportunities for astronomical learning, with consideration of cognitive processes within topics, to inform interdisciplinary study. While not anchored in enacted practice, this study provided guidance which can inform planning of authentic science infused astronomy teaching and serves as a rare research example of planning astronomy as a "gateway science" Salimpour et al., 2024.

Astronomy is broadly considered a gateway science, yet minimal research has explored this realm (Salimpour et al., 2024); I see my current and future research as filling this void. The research participant from Mexico in the present study offers a glimpse of astronomy as authentic science, and a gateway; M used telescopes to foster interest in science and careers, and as a lever for social mobility. Students built telescopes, used them in their communities, and gained university access they would not have otherwise. In other words, they gained access to real world learning mediated by astronomy. Yet, M's scenario may not be replicable or scalable. Every participant in my study confirmed previous study by Salimpour et al. (2020; 2024) noting teachers' lack of comfort with astronomy topics and the need for professional development. For astronomy to be leveraged as authentic science, pre-service teachers and professional development providers should be engaged with AER. Using my knowledge of both education and astronomy fields, I plan to address this gap in research and practice in my future work. I have already begun data collection to characterize teachers' use of space experiments in general science classrooms, and I am in the process of designing professional development opportunities for teachers. It is my hope that AER in the next decade will center authentic science opportunities and expand into the interdisciplinary "gateway."

Paper 2: A Tale of Two Classrooms

In my second paper, I wanted to investigate why two classrooms with similar instructional elements and curricular activities exhibited dramatically different forms of engagement and participation. I initially thought that the teachers' varied framing of individual elements within their instruction could provide explanation, yet I determined that the subtle nuance within those elements provide insight into the cumulative impact of cues and messages sent to students. Thus, I posited that the observed lesson provided a snapshot into the daily cues and messages sent to students, the additive effect of which determined the observed variation in participation and engagement.

Looking broadly across the literature, additional explanations and insights can be found beyond epistemological framing. Relational teaching, which positions teachers alongside students as learners could offer insight into the cues sent to students (Krist, 2024). In this sense, relational teaching opposes traditional hierarchies placing teachers as holders and facilitators of knowledge. A relational stance towards teaching, in this sense, can explain the moment-to-moment interactions which signal, cue, reinforce and govern expectations and formulations of participation and engagement (Berland et al., 2016). In other words, by observing microlevel interactions, I can infer the meso and macro level classroom cultures in each class.

Other insights may be teachers' cumulative approaches to science practices. In describing differences between Coral and Melissa, I determined that Melissa had more instances of isolating specific tasks within the MEL activities; another explanation for the variation in classes was that each teacher isolated individual practices within the MEL, but in different ways ("making decisions" vs "you should have discussion"). The MEL activities necessitated student involvement in discussion, which required their risk taking and vulnerability. While student engagement in discussion is cited as a core practice in *Ambitious Teaching (*Windschitl et al., 2020*)*, teachers' activities to emphasize this practice in isolation may position students as merely responding to a properly coerced elicitation (Krist, 2024). In Coral's class, for example, students appeared to be comfortable with risk taking and making their ideas public, which implies that throughout the year, Coral had in some way attended to social interactions which cultivated a trusting environment. In contrast, Melissa's focus on the practice of facilitating and eliciting responses implies tactics focused solely on the practices of eliciting student ideas, which over time, may “background students’ inherent vulnerabilities” (Krist, 2024; p. 215).

Beyond constructs of framing and epistemic agency, it is important for practitioners and researchers to understand the ways in which teachers' messages shape the culture of classrooms, and how the development of such classroom cultures shape learning opportunities for students (Ke & Schwarz, 2021; Russ, 2018). Singleton et al. (2024) pointed to the significance of cultures which foster student interest in achievement and persistence in STEM, and the classroom level factors which support or dampen students’ interest such as caring relationships and collective enterprise. Russ (2017) described the messages teachers send to students regarding appropriate and valued ways of thinking in how they listen and respond to students. These moment-to-moment engagements-such as revoicing student ideas or adhering to canonical definitions- are seen in teachers framing moves. Therefore, this study highlighted the relationships between often subtle framing moves and the impacts on macro level cultures which inform students participation, connecting often disconnected bodies of literature.

Paper 3: Recognized and Realigned

In my third paper, I wanted to highlight an expert teacher's moves to foster epistemic agency while using structured materials through framing for sensemaking. However, I found that students were highly attuned to forms of epistemic agency and pushed back on teachers' otherwise productive framing moves. As I analyzed and revisited the data to determine why one lesson "worked" while others' did not, I determined that commonly accepted definitions for epistemic agency failed to fully capture the epistemic agency students' were accustomed too, and that part of a teachers' work in using structured curricula should be to identify and address mismatches between the agency afforded by materials and that in which students are accustomed too.

Epistemic agency expands on and applies concepts of agency to describe student participation in knowledge construction activities and resources, and how they use or resist using those resources (Zimmerman & Weible, 2018). Epistemic agency research relies heavily upon discourse during discussion to identify and locate agentic episodes and opportunities (Bang et al, 2012; Carlone et al., 2021; Ko & Krist, 2019; Stroupe et al., 2018). For example, Ko and Krist (2019) described how teachers can "open space" for students' epistemic agency by creating opportunities to brainstorm, propose alternate claims, and identify puzzling patterns through classroom discussions. Similarly Carlone et al. (2021) characterized evidence of epistemic agency as students connected ideas from prior lessons, claimed voice, and translated one another's' ideas during discussions. The continued emphasis on discourse may have multiple origins, such as Arnold and Clarke (2014)'s synthesis, which described shifts in agency research towards understanding student discourse (see also Arnold 2012). An informal forward chain from this article included nearly every study and author cited in the corpus of epistemic agency research (i.e. Cherbow & McNeill, 2022; Gonzalez-Howard & McNeill, 2020; Miller et.al., 2018; Stroupe, 2014). Conversely, Clark et. al. (2016) cited the interplay between social contexts of learning and the historical structures which shape the social contexts to raise questions regarding the validity of continued reliance on whole class discussions to classify and categorize incidences of agency.

Literature on student agency offers insight into epistemic agency research, and here I wish to integrate the former for purposes of refining the latter. Agency is described by sociological thought as embedded in social structures, and by psychological constructs of self-regulation, yet both center an *agent* and an *action* typically described as active participation in dialogue (Clarke et. al., 2016). Agency is anchored in two dimensions of student voice–*perspectives* of sharing ideas and *participation* of enacting them (Limbere et al., 2022). Clark et. al. (2016) conceptualizes the duality of social structures and students' self-appraisals to suggest that students act as agents when they have both "intention and power to take action in learning activities, to change the trajectory of their learning" (p. 30). In this sense, the actions taken by students in Amy's class–both during days 1-3 and the final day–were agentive, yet on day 4, students were given the *capability* and applied *intentional actions* which more closely resembled a typical class to drive their learning. This distinction is critical to characterize specific *forms* of epistemic agency, in which students positioning promotes their choice and decision making for the purposes of knowledge building.

Study 3 has potential to move the field beyond discursive metrics to identify and locate episodes of epistemic agency, and to ground the more micro level constructs of agency within the ubiquitous and macro level constructs of *epistemic* agency. Notably, agency research acknowledges *individual* agency, whereas epistemic agency emphasizes the role of *community* or *collective* agency (Clarke et al., 2016; Fu & Clarke, 2019). Students (*agents*) in study 3 acted with epistemic agency throughout lessons 1-3 to resist (*action*) what they may have perceived (*perspective*) as removal of their typical classroom roles; I observed this evidence in non-verbal patterns of body language and resistance as students refused to engage, despite otherwise productive framing bids and curricula with embedded agentic opportunity. I realized that typical definitions of collective epistemic agency did not apply to my observational data, which centered the role of individual action. Students in study 3 had familiar forms of epistemic agency, in this case responsibility and control, realigned when they were able to *look up and verify information*, instead of receiving information from authority (teacher or worksheet). Only then were they able to enact appropriate forms of epistemic agency in collective discussion, engaging in authentic science, and offering important insights for practitioners using prescriptive curricula and science education researchers who may miss such micro level instructional refinements in search of macro level indicators of students driving instruction.

Personal Meaning and Meta Reflection

The Journey

This dissertation contains three studies: one on international astronomy education, one comparing two teachers' framing, and one a case study and collaborative interview cycle. I realize that three papers, with one not related to the other two, may not be traditional, yet no part of my journey has been. These papers are each critical elements of my dissertation journey. If dissertations are comparable to climbing a mountain, each of these papers represent waypoint stations to resupply, regroup, rebuild and refine. I use this analogy to emphasize that in each, I had to take a deep dive when I am more comfortable with breadth, and to stay there until the analysis yielded something interesting and defensible. Only then could I move on.

The astronomy paper was the beginning of my mountain climb. It represents my incoming interests, and what I thought I would be contributing to the field. But I realized that I could not contribute anything to the field of knowing (e.g., about astronomy) if I did not learn about learning. On Dr. Lombardi's suggestion, I delved into Dr. Elby's framework, which led me to the construct of epistemic agency, which provided a theoretical justification to align with my pedagogical commitments. There I dove into paper two, looking for such evidence—that what I considered to be “good” teaching leads to students’ epistemic agency. Instead, I found nuance. I continued my journey, but paper two was not done. I would have to come back for that one. I began paper three at an interesting time-just before a life changing surgery, which made writing and analysis difficult for many months. Paper three did not reveal anything I expected, and I initially thought there may be nothing to analyze at all given that the class sessions mostly did not go as planned, yet once I saw the evidence, I returned to the data to see it through. Only then, after I completed paper three, did I return to two.

The journey refined me. I had to stay with the problems long enough to see insight, a satisfactory method, or an interesting conclusion. This required me to be comfortable with the uncertainty, just as I described in papers two and three. And in the process, I learned about teaching and learning.

Synthesis.

In the summer of 2023, I designed a brief professional development session (within a multi-day professional learning opportunity) focused on framing, in which I showed teachers videos of Melissa and Coral. While some teachers immediately saw what I ended up seeing in terms of sensemaking and epistemic agency, others saw chaos in Coral’s class and preferred the order and quiet of Melissa’s. As I said-I did initially as well. Also, as I said--I have been Melissa--likely far more than I have been Coral. I do not believe that Melissa’s class precluded epistemic agency, or that mine did. In fact, I think that my students acted with more epistemic agency than most!

Yet, I ran a strict and orderly class, and likely still would. Students in my class acted with epistemic agency because of the opportunities I fostered for their authentic engagement in science, amidst structure, similar to Amy in paper three.

Coral from paper two and Amy from paper three were strikingly similar in their framing and implementation even though they had no connection to each other; they used similar positive tone and inflection, they both used inclusive pronouns to unify them with students, and embedded commitments for community and relationships into their framing moves for sensemaking. They also slightly modified the standard flow of the MEL lesson to adapt to their classes. Their classroom cultures and embedded commitments (although not assessed in paper two) present an interesting paradox-how can teachers foster similar cultures inviting of students' epistemic agency, particularly if they have a highly structured, teacher-led class? It is common, even encouraged, for teachers to manage behaviors. As Amy and Coral demonstrated, behavioral management, even task management, need not come at the expense of epistemic agency. Both teachers also increased the level of instructional support and structure (from a typical MEL lesson) yet the increased structure *enabled* opportunities for epistemic agency.

Relational Teaching and Language

In paper two, after I overhauled the entire analysis, I saw the role of tone in both Amy and Coral's instruction. I found Enyedy and Goldberg (2004) late in my analysis, and this caused me to go back to the data (from paper two) and analyze through the lens of pronoun usage. I am intrigued by this relationship to epistemic agency and framing, but as the two teachers in paper two exhibit-pronouns do not exist in a discourse vacuum. There were times that Coral used exclusive pronouns, and Melissa used inclusive pronouns. I saw consistent integrations of tone, language and relationships in papers two and three with clear implications for epistemic agency. When Krist (2024) published her work on relational teaching, I felt a distinct pedagogical resonance from my time in the classroom. Relational teaching—emphasizing relationship-building and epistemic culture in an entangled way—is what I saw in both Coral and Amy's class, and what I always knew as central to my own practice. However, this was the first study I read that mentioned the role of emphasizing and leaning on positive relationships *as* integrated with building an epistemic culture. In both Coral and Amy's classes, their relationships with students were able to overrule behavioral correction which could have been negative. In my observation of a non-MEL, Amy held a difficult conversation about the need for personal hygiene which was *only* possible because of her relationships. Students trusted her, and she created a safe space to discuss behaviors without targeting individuals.

That is not to say that Melissa did not have positive relationships with students. She thanked them many times for their compliance ("with record keeping") and at the beginning of the class prior to beginning anything MEL related, she discussed nearly hitting a deer the day before. She had a comfortable and natural conversation with students, who listened and responded. Hers was a high school class; the relationships would likely manifest differently than in Amy and Coral’s middle school classes.

Digital Natives

One issue I saw in Amy’s class is that some schools are largely or entirely digital; students work independently on tablets or laptops from the beginning of class to the end. Amy had to seek out permission to use an archaic district printer, and students complained about having to hold pencils. Many said they had not physically written in years. This presented a significant challenge for students, and likely influenced their engagement with the materials. Researchers and curriculum developers must consider this moving forward and adjust their methods accordingly. Amy quickly and easily demonstrated how to integrate familiar technologies while using the MEL. The ability to adapt materials seems a necessary component to support students' epistemic agency. Amy repeatedly mentioned how she would change the lessons to align with what students typically do. I would really like to revisit her class and see how she adapts and modifies, and how, if at all, this supports students’ epistemic agency.

Teachers must now manage digital distractions, while also trying to engage students in off-screen discussions. The digital environment may isolate students from the collaboration which frequently plays out in the epistemic agency literature. As such, perhaps we should adjust our methods to reflect the classrooms. If students are on screens all day, are we honoring the integrity of their learning by removing their familiar learning devices to look for our pre constructed notions of epistemic agency? As Amy demonstrated, students were capable and competent to engage with sensemaking and discussion with their devices out and were invited to refer to digital resources. Students' digital contributions may be one way. I saw a few studies which looked at students' discussion board posts to analyze both what students wrote and how they responded to each other, however I would be hesitant to describe that as epistemic agency; I have facilitated and participated in discussion boards enough to hear students' dislike of such formats, which to me imply that engagement and participation is more likely to be compulsory and "school like" not of the purposes of knowledge construction. However, like the LR-MEL activities which scaffold students' lateral reading across websites, I am interested in how students look for knowledge online as an indicator of epistemic agency. In this way, while they are not the authors of the knowledge, they determine, as Amy's students' did, which sources to use.

Professional Development

The collaborative planning I did with Amy throughout our interview and observation cycle was incredible—I believe for both of us. Hearing her insight was so valuable for me, and a great reminder that teachers are professionals. Amy demonstrated such deep care and commitment to her students. Had we not spent time planning, if our interviews were simply transactional, I may not have understood that.

I also would not have seen her decision making in allowing choice in their reading which was critical to my understanding the "typical" form of epistemic agency students enacted in her class. I entered that study with the intent of sharing my research ideas with her, to inform her teaching; I emerged as her sharing her practice with me, to inform my interviewing. I now cannot imagine conducting interviews any other way. That said, it was exhausting for both of us to meet so many times before and after class.

As a teacher, I am admittedly frustrated at continued reference to professional development for teachers, provided by researchers, in implications sections. As paper three demonstrated, teachers know their practice. This is their realm, and they are the masters. Therefore, I think now more than ever, that professional learning for teachers should be less about implementing change--be it curriculum or standards or practices--and more about working with the good practices they already have. In this way-instead of reinventing the wheel, teachers just learn new tricks to roll their own wheels more efficiently. For example, Amy and I discussed framing at length, and she increasingly recognized the impact of her language and framing moves to nudge students, such as her use of inclusive pronouns. In this way, she continued her successful practices, yet more metacognitively.

Next Steps

Looking for Differing Forms of Epistemic Agency

I am curious about expanding the collection of epistemic agency beyond discourse during discussion. As paper three demonstrated, students can act with epistemic agency with a) structure b) highly structured materials and c) when they do not determine the direction of learning. Therefore, I find it critical to look for forms or flavors of epistemic agency, and to identify multiple means of inviting students to enact these different forms in classrooms, so that teachers may address any mismatches when using highly structured materials. Professional development should be a mechanism to meet that need.

Other Means of Observing Epistemic Agency

Sensemaking discourse is the most common indicator of epistemic agency. In all of my years of teaching high school, I rarely had student driven, robust whole class discussions in which all students contributed. Small-group discussions were far more common and comfortable for students, even when I abandoned all curricular goals for the purposes of students launching experiments to space. More commonly, and what I saw in papers two and three, are a few students who contribute during whole class discussion while everyone else is silent. Even in small groups, a few students tend to take the lead. I was not a student who contributed my thoughts to discussions prior to college, and neither are my children. My husband and many of my friends are currently teachers, and they consistently cite the near impossibility of pushing students to engage in *any* sort of sensemaking, especially with technologic temptations. Students are more driven than ever to complete worksheets, and our curricular systems have provided. Somehow, we emerged from a Pandemic–which reminded us that there is more to school than grades–and doubled down on achievement metrics.

That said, I am interested in constructing a thorough discourse analysis for teachers' talk and interactions, and examining how that relates to epistemic agency. However, for issues I just cited, I am not entirely hopeful. Perhaps I will demonstrate that we need to abandon this as the default indicator. I would like to investigate the teachers' inflections, tone, and pronoun usage. I am also really interested in looking at other, non-verbal indicators of students' uptake of teachers' sensemaking framing bids. I am intrigued by the photography study used in the Zimmerman and Wieble (2018) article. The authors examined how students saw themselves as scientists as evidence of them acting with epistemic agency. Our digital natives have the tools to capture themselves, to annotate imagery, and they could construct any number of digital presentations or displays for their work, which could be used to characterize epistemic agency, sensemaking, and engagement with authentic science.

Supporting teachers

As Levin et al. (2012) described, suggesting an idea as a "foothold" can, over time with continued success, embed as a belief. If teachers are exposed--be it through curricular elements, peers or collaborative interviews like I had with Amy—to concepts such as framing moves, epistemic agency and use of tone and pronouns, all of which they use on a regular basis, they may become more attuned to their use and impact. Over time, they may, as I did, recognize elements of their practice which may create or eliminate space for students' epistemic agency. The point is that we do not need to design a weeklong PD to do this. Sitting in class with Amy and asking her about her pronoun use—the language she was already using—brought up an embedded commitment and allowed her to reflect on the meaning and impact, without any professional learning.

I am hesitant to over diagnose or describe epistemic agency; I do not wish to create a checklist or toolbox of strategies that ultimately deter the behaviors they were meant to elicit, however tempting it may be. I would like instead to work *alongside* teachers, like I did with Amy, to see what they are already doing, and instead of re-casting teachers' work for them, I would like to reframe their work for us (researchers). Working alongside teachers can also allow teachers to view their work as impactful and valuable, to enable them to be increasingly intentional about such moves going forward. In paper three, Amy demonstrated this perfectly when I pointed out her use of inclusive pronouns. Perhaps our work as researchers could be spent with district science specialists or professional learning coaches to assist them in understanding the construct of epistemic agency, so that they can in turn better support their teachers and students.

Epistemic Agency and Astronomy

Going back to the base of my mountain, I am now equipped and ready to look at astronomy education through the lens of framing and epistemic agency, as mechanisms for authentic science. I am collecting data to better understand and characterize teachers' use of student designed space experiments and similar activities. My goal is to establish a place for this work—which is nearly entirely led by individual teachers—into the corpus of literature on epistemic agency and authentic science practice. I am not interested in a curriculum, not that there is one, but how teachers launch student ideas, all pun intended, to space. These programs are most often led and sometimes designed by individual creative and innovative teachers. I foresee this work as epitomizing the spirit of NGSS and authentic science, and the construct of epistemic agency; I wish to work within this realm to further characterize the forms and indicators of epistemic agency, as well as grounding this work as NGSS-aligned authentic science, within the research corpus.

References

American Astronomical Society. (n.d.). *Education committee.* https://aas.org/comms/education-committee

Arnold, J. (2012). Addressing the balance of agency in science classrooms (PhD thesis). The University of Melbourne, Melbourne.

Arnold, J., & Clarke, D. J. (2014). What is ‘Agency’? Perspectives in Science Education Research. *International Journal of Science Education*, *36*(5), 735–754. https://doi.org/10.1080/09500693.2013.825066

Bailey, J. M., Willoughby, S., & Samie, B. (2023). An Initial Investigation of Students’ Understanding of Space Exploration. *Astronomy Education Journal*, *3*(1), Article 1. https://doi.org/10.32374/AEJ.2023.3.1.061aer

Bandura, A. (2006). Toward a Psychology of Human Agency. *Perspectives on Psychological Science*, *1*(2), 164–180. https://doi.org/10.1111/j.1745-6916.2006.00011.x

Barton, A. C., & Tan, E. (2010). We Be Burnin’! Agency, Identity, and Science Learning. *Journal of the Learning Sciences*, *19*(2), 187–229. https://doi.org/10.1080/10508400903530044

Basu, S. J. (2008). How students design and enact physics lessons: Five immigrant Caribbean youth and the cultivation of student voice. Journal of Research in Science Teaching, 45(8), 881–899.

Basu, S. J., Calabrese Barton, A., Clairmont, N., & Locke, D. (2009). Developing a framework for critical science agency through case study in a conceptual physics context. *Cultural Studies of Science Education*, *4*(2), 345–371. https://doi.org/10.1007/s11422-008-9135-8

Berland, L. K., Schwarz, C. V., Krist, C., Kenyon, L., Lo, A. S., & Reiser, B. J. (2016). Epistemologies in practice: Making scientific practices meaningful for students. *Journal of Research in Science Teaching*, *53*(7), 1082–1112. https://doi.org/10.1002/tea.21257

Calabrese Barton, A., & Tan, E. (2020). Beyond Equity as Inclusion: A Framework of "Rightful Presence" for Guiding Justice-Oriented Studies in Teaching and Learning. *Educational Researcher*, *49*(6), 433–440. https://doi.org/10.3102/0013189X20927363

Clarke, S. N., Howley, I., Resnick, L., & Penstein Rosé, C. (2016). Student agency to participate in dialogic science discussions. *Learning, Culture and Social Interaction*, *10*, 27–39. https://doi.org/10.1016/j.lcsi.2016.01.002

Fu, G., & Clarke, A. (2019). Moving beyond the agency-structure dialectic in pre-collegiate science education: Positionality, engagement, and emergence. *Studies in Science Education*, *55*(2), 215–256. https://doi.org/10.1080/03057267.2020.1735756

Ke, L., & Schwarz, C. V. (2021). Supporting students' meaningful engagement in scientific modeling through epistemological messages: A case study of contrasting teaching approaches. *Journal of Research in Science Teaching*, *58*(3), 335–365. https://doi.org/10.1002/tea.21662

Krist, C., Novak, M., Brody, L., & Tipton, K. (2016). Teacher's Toolkit: Cultivating a Next-Generation Classroom Culture. *Science Scope*, *039*(05). https://doi.org/10.2505/4/ss16_039_05_8

Lai, K.-W., & Campbell, M. (2018a). Developing secondary students' epistemic agency in a knowledge-building community. *Technology, Pedagogy and Education*, *27*(1), 69–83. https://doi.org/10.1080/1475939X.2017.1369150

Lai, K.-W., & Campbell, M. (2018b). Developing secondary students' epistemic agency in a knowledge-building community. *Technology, Pedagogy and Education*, *27*(1), 69–83. https://doi.org/10.1080/1475939X.2017.1369150

Limbere, A. M., Munakata, M., Klein, E. J., & Taylor, M. (2022). Exploring the tensions science teachers navigate as they enact their visions for science teaching: What their feedback can tell us. *International Journal of Science Education*, *44*(12), 1897–1915. https://doi.org/10.1080/09500693.2022.2105413

Penuel, W. R., Krumm, A. E., Pazera, C., Singleton, C., Allen, A.-R., & Deverel-Rico, C. (2024). Belonging in science classrooms: Investigating its relation to students' contributions and influence in knowledge building. *Journal of Research in Science Teaching*, *61*(1), 228–252. https://doi.org/10.1002/tea.21884

Pompea, S. M., & Russo, P. (2020). Astronomers Engaging with the Education Ecosystem: A Best-Evidence Synthesis. *Annual Review of Astronomy and Astrophysics*, *58*(1), 313–361. https://doi.org/10.1146/annurev-astro-032620-021943

Rodrigues, L., Meneses, A., Montenegro, M., & Cortés, C. (2024). Direct and Indirect Opportunities to Learn Astronomy Within the Chilean Science Curriculum. *International Journal of Science and Mathematics Education*. https://doi.org/10.1007/s10763-024-10459-1

Russ, R. S. (2018). Characterizing teacher attention to student thinking: A role for epistemological messages. *Journal of Research in Science Teaching*, *55*(1), 94–120. https://doi.org/10.1002/tea.21414

Salimpour, S., Fitzgerald, M., & Eriksson, U. (2024). *A descriptive overview of English-language publications in the field of Astronomy Education Research, 1898 to 2022*.

Singleton, C., Deverel-Rico, C., Penuel, W. R., Krumm, A. E., Allen, A.-R., & Pazera, C. (2024). The role of equitable classroom cultures for supporting interest in science. *Journal of Research in Science Teaching*, *61*(5), 998–1031. https://doi.org/10.1002/tea.21936

Windschitl, M., Thompson, J. J., & Braaten, M. L. (2020). *Ambitious science teaching* (1–1 online resource (viii, 304 pages) : illustrations). Harvard Education Press. https://public.ebookcentral.proquest.com/choice/PublicFullRecord.aspx?p=7263019