Affect, disciplinary conversations, and postqualitative research in STEM Education

A dissertation submitted by

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Dissertation Abstract

Over the last decade, STEM education research has reflected a turn towards framing disciplinary development in STEM as the repetition and stabilization of situated practices. In this dissertation, I turn further: towards *disciplinary relationships* as a potential focus of analysis. To centralize disciplinary relationships, I use a critical posthumanist approach towards material agency to conceptualize a conversation as an iterative cycle of attention and responsive action.

If listening is any type of direction of attention, and speech is any type of action; I consider an agent to be engaged in a conversation (with materials, theory, others, and self) exactly when they are iteratively speaking and listening. By characterizing *disciplinary conversations* as those conversations that are shaped by the discipline and contribute to shaping the discipline, I focus on how conversations both shape relationships and are shaped by relationships.

By considering disciplinary listening, I surface ways that iterative feedback and attention to one's embodiment can inhere in disciplinary practice. Considering disciplinary conversations, I find disciplinary continuity between students' material interactions, their shifting interpersonal relationships, their disciplinary identity, and their embodied sensations and affect. Reconceptualizing disciplinary practices as posthuman conversations also helps to describe the ways that listening carefully for emotional dynamics can be seen as an integral part of STEM rather than separate from STEM practices.

In chapter 2, I argue that relational turns such as this one require consideration of a material agency of methodology. I use a postqualitative approach to explore how the framework of disciplinary conversations changes the space of narratives of disciplinary behavior, and describe how relational ontology and postqualitative research impacted our design-based research. In chapter 3, I motivate this turn towards disciplinary relationships as a focus of analysis by making the argument that harm can often inhere in current embodiments of STEM. I describe our research team's emergent modes of inquiry and refinement of the concepts of *disciplinary listening* and *disciplinary speech* of more-than-

human agents. I operationalize the framework of disciplinary conversations by using postqualitative narrative inquiry to understand the development of one student's disciplinary relationships. I describe four emergent design principles of this relational perspective. In chapter 4, I use a diffractive approach to understand how the ways that mathematics involves a close relationship with our own and others' emotions.

Understanding how affect inheres in STEM is important for noticing and responding to the material and affective conditions of our students. Recognizing that affect inheres in STEM requires also questioning where harm may problematically inhere in STEM. To avoid and possibly repair such disciplinary malpractice, a relational turn in STEM education might instead reimagine disciplinary development as the growth of the many relationships that come to define the disciplines.

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Chapter 1:

Introduction; Relational perspectives for STEM

This chapter outlines the underlying motivation and approach of this dissertation. Enacting postqualitative inquiry in STEM Education, I join scholars working to bring STEM and STEM Education into better alignment with relational ontologies.

Overview: Reimagining relational perspectives for STEM

Themes of extraction, dominance, and control are commonly found in the disciplines of Science, Technology, Engineering, and Mathematics (STEM). Theory building is sometimes framed as an extraction of knowledge from observations. The predictive power of modeling is often used to build systems of control over objects and people. And reasoning is frequently used to perpetuate dominance over others through authoritative knowledge. Problematically, these themes resonate with the logics perpetuating White supremacy, settler colonialism and other oppressive cultural dynamics.

To resist these themes, a movement has been growing to bring STEM (Cajete, 2000; Hernandez, 2022; Kimmerer, 2013), fields of Science and Mathematics Education (Bang et al., 2012; R. Gutiérrez, 2017; Warren & Rosebery, 2011), and research in the Learning Sciences (Bang et al., 2016; Calabrese Barton & Tan, 2019; K. D. Gutiérrez & Jurow, 2016) into better alignment with relational ontology and forms of ethical reciprocity. During the 2021 annual conference of the International Society of the Learning Sciences (ISLS), Rishi Kristnamoorthy, Colin Hennessey Elliot, and Jasmine Ma organized a symposium (titled: “Learning to Center Relational Ontologies: Desettling Interaction Analsysis,” with discussants: Megan Bang and Ananda Marin) to “think with Indigenous Ways of Knowing (IWOK) to reinterpret the methodological commitments of interaction analysis” (Krishnamoorthy et al., 2021, p. 851).

In the symposium, the organizers shared a video clip from an ethnographic study of a youth robotics team. The clip showed “two different angles on unfolding action as multiple youth engage with

a large machine that bores holes and cuts metal parts as designed" (p. 854). The room of scholars then engaged in two rounds of viewing and reflection using two different guidelines "to surface the tensions between interaction analysis rooted in colonial ontology, and analysis emergent through a relational ontology rooted in [Indigenous ways of knowing]" (p. 856).

First Data Viewing	Second Data Viewing
Collective analysis of the video clip through traditional interaction analysis methods that center human participants in the unfolding interaction will use these guiding questions:	The authors and the audience, learning from and with the discussants, will engage in group analysis of the same video data, recognizing relations as the unit of analysis guided by the following questions:
• To what are human actors orienting across the material landscape? • What sense are human actors making of their worlds? • What resources support joint activity? • How do previous actions provide contexts for subsequent action?	• What kinds of human-MTH relations emerge in the data? • How does the metal piece contribute to the ongoing unfolding interaction? • How does the mill-human relation form part of a local ecosystem? • Where does the mill end and the human actor begin?

"Table 2: Two different viewing guidelines" (Krishnamoorthy et al., 2021, p. 857)

In their proposal, the organizers argue for continually revisiting our approaches towards established theory and methodology:

> Rather than adopting and decontextualizing IWOK to fit into what the method already is (de F & Emilia, 2013), we take what we see as a settler responsibility to interrogate how conventional interaction analysis is rooted in settler colonial logics and surface what needs to be reimagined.

These scholars, the discussants, and their ISLS reviewers viewed this work to "surface what needs to be reimagined" as a substantive research objective. Not only is it nontrivial to engage in the reimagining of relational perspectives for STEM, but beginning to develop a sense for what needs to be reimagined is itself a significant research goal.

This dissertation contributes towards surfacing and reimagining forms of ethical reciprocity in STEM. Alongside similar projects, I engage with the entanglement of ethics, ontology, epistemology and critique of representation surfaced by poststructuralism and Indigenous ways of knowing (Garroutte & Westcott, 2013; J. L. Rosiek & Snyder, 2020). I reimagine a relational framework for STEM around the

perspective that disciplinary practices can be understood as relation-building practices of disciplinary listening, disciplinary speech, and disciplinary conversations. And I use that framework to investigate a material agency of methodology in design research, a perspective of disciplinary development as a strengthening of relationships, and harmonic resonances of positive forms of affect in mathematics.

In this chapter, I introduce the underlying motivation and logical structure of my dissertation. Here in chapter 1:

- I discuss the need for daily reflective praxis for justice in STEM.
- And I lay out the logical structure of the dissertation.

In chapter 2, I investigate:

- ***How does a change in the framing of STEM also change the space of stories that are possible to tell about disciplinary development and pedagogy?***
    - I argue that the ontologies that support perspectives of material agency are not compatible with some of the common research methodologies in the Learning Sciences—and require postqualitative forms of inquiry (Murris, 2020).
    - To operationalize postqualitative research in STEM Education, I position an account of a classroom episode as an act of theory-building. I conclude with implications for postqualitative inquiry and relational ontology within design-based research.

In chapter 3, I ask:

- ***In what ways do disciplinary conversations build and sustain disciplinary relationships?***
    - I advocate for a turn towards relationships as a conceptual unit of disciplinary development. And I operationalize a framework of to explore how *disciplinary relationships* can be understood to develop through *disciplinary conversations*.

    - I use postqualitative forms of narrative inquiry (J. L. Rosiek & Snyder, 2020) and critical discourse analysis (Rogers, 2011) to better understand the many types of disciplinary relationships present in an undergraduate computational physics course.

In chapter 4, I explore the question:

- ***In what ways are noticing and responding to affect integral to mathematics?***
    - Motivated by a potential to support justice-oriented design approaches, I use a postqualitative approach of diffraction (Murris & Bozalek, 2019) to explore the agency of stories about disciplinary conversations.
    - The framework of conversations helps me understand ways that mathematics involves iterative attention and response to individual and cultural constructions of aesthetics, emotion, pleasure and interpersonal interaction, empathy, and development of meta-affect.

In chapter 5, I summarize the arguments of the previous chapters and discuss three remaining questions:

- What disciplinary conversations in STEM are there for us to notice?
- How do we rethink our learning environments to be more relational and dialogic?
- Can further investigation sustain relational narratives for STEM?

In an empirical context, chapter 2 is dedicated to unpacking the way I understand relational ontology, material agency, and postqualitative inquiry to be entangled. In that chapter, I operationalize postqualitative inquiry in STEM Education by surfacing forms of reciprocity in STEM. In chapter 3, I use more empirical data from the same design research project to reimagine how STEM can be brought into better alignment with relational ontologies. Chapter 4 is a theoretical chapter where I bring together a

set of eccentric texts to both surface and reimagine where affect inheres in mathematics. And chapter 5 is an epilogue where I discuss further implications.

Read in this suggested order, the dissertation supports an argument that,

- Justice-oriented learning environments (and research about them) should be aligned with relational ontology and performative approaches to knowledge. (Chapter 2)
- STEM can be (re)imagined in these ways. (Chapter 3)
- And noticing disciplinary harm is necessary for noticing disciplinary care. (Chapter 4)

Since the chapters are intended to be read independently, a different ordering would make them resonate differently with slightly different arguments—allowing slightly different meanings to flash up. For instance, chapter 4 is an outgrowth of my first qualifying paper, and chapter 3 is the heart of my second qualifying paper. Placing chapter 4 before chapters 2 and 3 supports a slightly different narrative:

- Visibilizing affect in STEM also visibilizes harm that currently inheres in STEM. (Chapter 4)
- The listening that inheres in STEM resonates with the relational listening that inheres in restorative justice. (Chapter 2)
- Reimagining STEM as collections of conversations is a coherent way to boost this resonance. (Chapter 3)

Placing chapter 3 before chapter 4 and ending with chapter 2 corresponds to another element in this family of narratives:

- The framework of disciplinary conversations is subtle shift with a lot of potential. A focus on disciplinary relationships is a better way to notice harm that inheres in STEM. And a focus on disciplinary conversations is a way to focus on disciplinary relationships. (Chapter 3)

- Both positive and negative affect inhere in Mathematics. Listening for disciplinary conversations is a way to find affect that can replace and repair disciplinary harm. (Chapter 4)
- Frameworks of material agency require performative understandings of knowledge—including knowledge developed through design-based research. Postqualitative inquiry is the appropriate research for bringing the Learning Sciences into better alignment with relational ontology. (Chapter 2)

And so on. The argument of the dissertation comes to matter (i.e., into being) through the unique combination of the words I have written, the reader, and the specific reading. Hopefully, reading this dissertation sparks something meaningful for you out of many possibilities.

My personal turn towards theory

Sarah Michaels pointed me towards a bell hooks quote from Teaching to Transgress (hooks, 1996):

> I came to theory because I was hurting—the pain within me was so intense that I could not go on living. I came to theory desperate, wanting to comprehend—to grasp what was happening around and within me. Most importantly, I wanted to make the hurt go away. I saw in theory then a location for healing. (p. 59)

My dissertation involves a lot of theory building, and so I've been thinking about how to make explicit the source of pain that has warranted my personal turn to theory.

Math hurts a lot of people. And it hurts some people quite a lot. I know from experience that even people that say they love math have had experiences with feeling incompetent, embarrassed, or scared. People that do not love math have also had these traumatic experiences. This would tragically imply that experiencing some degree of trauma is a more reliable outcome of traditional math education than any of the listed standards.

My understanding of the structure of this violence and pain is personal in that I have experienced shame, failure, lack of community, effects of privilege, and tedium in math. I have taught arithmetic and algebra to adults working through repeated trauma. As an instructor, I have also witnessed the privilege that math educators have available to distance themselves from others' trauma—distance even from empathy, as well as from responsibility. I have experienced privilege that comes from being "good" at math and moving through the world as a cisgender White man in STEM. As a young student, I did well in math class but could not imagine being passionate about math since its role seemed to be so tedious. My graduate research involved visualizing extremely non-intuitive geometric spaces and telling stories about their interesting features that sparked passion. But I also experienced enough pain to decide to drop out of a PhD program in mathematics after advancing to candidacy. With personal experiences of the many different characters of mathematics, I returned to graduate school (in Education) to understand students' trajectories of thinking, the trauma inflicted, and how we might differently shape what math is.

Individual traumas in math also converge with other forms of structural marginalization. For instance, standardized tests shape and are shaped by White supremacy (Knoester & Au, 2017) with ontological tools of "wrong answers" in mathematics (Cunningham, 2019)—a field that can often only be conceived as being about right/wrong answers (Muis, 2004). To resist this structural harm, we must work to rebuild mathematics as something less resonant with meritocracy or other harmful ideology (R. Gutiérrez, 2017). Because similar trauma reverberates across all STEM disciplines, behind all my work are the broader questions: *What is STEM doing to us? And what do we want STEM to do/be for us? How might we shape a refusal to resist the character of STEM that is causing harm (Martin, 2019)?*

Motivation: Daily reflective praxis for justice

> The issues that disproportionately and negatively impact Black, Indigenous, and Latinx youth in traditional public schools are clear. We must move beyond this knowledge toward justice as praxis in teaching and learning. (Everett, 2020, p. 102)

We need practices to notice students' material experiences such as affect and trauma. We need frameworks with capability to describe ways that moment-to-moment interactions reproduce structural injustices. And we need iterative attention to these dynamics. Part of the difficulty is that *any* framework of representation of STEM phenonema (described as practices, relationships, commodities, behavior, skills, *conversations*, standards, etc.) could be woven into social structures inflicting violence. Patterns of structural violence necessarily have a lot of dynamic stability to resist perturbations. Thus, any framework for representing STEM phenomena that does not *iteratively* attend to visibilizing, disrupting, and repairing harm will perpetuate existing stable patterns of violence. More than just innovative practices of representing STEM, we need practices of continually *re*-representing STEM to continually look for what knowledge is missing.

Listening as a daily practice of justice

One of the central concepts of restorative justice is to pay close attention to harm, needs, and finding ways to repair (Zehr, 2002). This leads to guiding questions for the restorative justice practitioner that include: *Who has been hurt? What are their needs?* Practicing restorative justice means "seeing the full humanity of others [and being] open to the possibility of not always being right but instead *making things right*" (Winn, 2018, p. 18).

I see something in common between the careful listening done by a restorative justice practitioner (paying close attention to the needs of their rightsholders), the careful listening done by a teacher (paying close attention to the thoughts and resources of their student), and the careful listening done by a scientist (paying close attention to the ways materials and theory push back on their understanding). Each of these moments involves close attention and care for others. Actions that are

not inside a context of listening to relational impacts—and working to make things right—could not be described as part of a restorative justice process. Considering that a scientist must listen carefully to others to do science, I would like to conceive of a definition of science that would exclude actions and practices as unscientific if they are outside of a context of listening to relational impacts.

Gloria Ladson-Billings (2015) argues that we need to attend to injustice by developing *practices* of justice—shifting from "justice as *theory* to justice as *practice*." Further, Sakeena Everett argues that "we need to adopt a paradigm that understands justice as a *daily* practice" (2020, p. 102, emphasis added). Restorative justice practices begin with careful listening for impacts and implications …similar to the daily practices of reflective scientists and attentive teachers. Drawing from Ladson-Billings (2015) and Winn (2018), Everett (2020) describes *justice as praxis* as "a daily theory-informed reflective practice—a theoretical and pedagogical paradigm committed to seeing the full humanity of others and making things right" (Everett, 2020, p. 102).

I claim that daily theory-informed reflective and relational STEM practices can be framed similarly: within a theoretical and pedagogical paradigm committed to seeing the full agency of more-than-human others and working to make things right. Developing such a paradigm is the goal of this dissertation. I develop the concept of *disciplinary listening* as a daily practice of scientists, teachers, and continuous with restorative justice practices. This makes equity questions become disciplinary: *Who is speaking? Who is listening? Who is being ignored? How can we help them be heard?* I also develop the concept of *disciplinary conversations* to explore how the iterative work of "making things right" can become disciplinary. We might then position disciplinary growth as the outcome of caring for students' interpersonal relationships, relationships to theory, and relationships to disciplinary identity and affect.

Approach: Ontology, agency, and postqualitative research

To shape a perspective of science as a collection of reflective and relational practices, I draw from several connected philosophical traditions. While the terminology is technical, the logical structure is easy to follow:

- To center relationships in STEM, I develop a framework (of *disciplinary conversations*) that is compatible with a *relational ontology*.
- A relational ontology requires frameworks of *material agency* and *posthumanism*.
- Relational ontologies are not compatible with *representationalist* methodologies, and require different approaches.
- Research that is compatible with relational ontologies, posthumanism, and a poststructural critique of representation is (sometimes) called *postqualitative*.
- Many *Indigenous ways of knowing and being* involve all of these things: relational ontology, material agencies, and research focused on "working out specific performative and ethical implications of agent ontologies on their own terms" (Rosiek et al., 2020, p. 336).

Thus, the approach of my dissertation is to use postqualitative research to develop a posthuman framework of disciplinary conversations in STEM that is justice-oriented through its compatibility with relational ontologies, and through its continuity with restorative justice practices. My intention is that it is also compatible with the relational ontologies of Indigenous ways of knowing and being, and I cite Indigenous scholars to the best of my ability. I will unpack these technical terms in much greater detail in subsequent chapters.

A relational ontology facilitates justice by establishing an "ethical imperative to acknowledge and honour the significance of the relationships we have with others" (Donald, 2012, p. 536), to listen for harm (Zehr, 2002), and find ways to "[make] things right" (Winn, 2018, p. 18). This type of relational approach is mindfully done with ethico-onto-epistemological frameworks of material agency,

posthumanism, and Indigenous ways of knowing (Barad, 2007; Donald, 2012; J. Rosiek et al., 2020). And the modes of inquiry that are compatible with this approach are called *postqualitative research* (Murris, 2020; Murris et al., 2021; St. Pierre, 2021). This dissertation develops a critical posthumanist framework of *disciplinary conversations* in STEM.

Discussion: Searching for disciplinary listening in STEM

To me, the shift this dissertation explores is one that feels simultaneously ambitious yet subtle. Why attempt to reframe STEM (which is an ambitious project)? How does reframing STEM as a collection of many different types of conversations (which may seem subtle) lead to a change in understanding or pedagogy? As a concluding example of the potential for a subtle reframing to have meaningful implications for justice, let us consider how visibilizing epistemic affect in STEM has implications for attending to harm.

Jaber and Hammer's (2016) perspective that "affect inheres in science" does more than just acknowledge that science is done by humans who are necessarily emotional beings. And their illumination of epistemic affect is not a discovery of what is the "most true" about science, or something simply gone previously unnoticed. The power of their analysis comes from carefully revisiblizing disciplinary entanglement that has been institutionally vanished (Vaught, 2019) by the onto-epistemology of STEM. The mythology of emotionless rigor in STEM meshes with structures of cisheteropatriachy, coloniality, and white supremacy to characterize marginalized voices as "too emotional for rational thought" (especially if their emotion comes from pain of violence, displacement, dispossession, disenfranchisement, etc.)

Experiencing and cultivating epistemic affect is part of learning science, being and becoming a scientist (Jaber & Hammer, 2016b, 2016a). That means that when students develop feelings, emotions, and affect (whether through intention or negligence) that are incompatible with the discipline; they are being disenfranchised from the discipline. A student developing math anxiety, for instance, has learned

something equally disciplinarily invalid as if they learned that $\pi = 3$. An example of math anxiety should be of incredibly less concern than the harm we know to be caused by the entanglement of STEM learning environments with interlocking systems of oppression (Hatfield et al., 2022; Lambert, 2015; Martin, 2019). Trauma experienced in STEM learning environments is more than just a series of unfortunate individual accidents. If we want to begin to decouple STEM from the systemic violence of its sexist, racist, colonialist history and present; we might start by viewing harm done in STEM learning environments as disciplinary malpractice.

Developing a relational ontology for STEM is not a trivial shift from the dominant framing of science. In this dissertation, I explore ways to see STEM as a collection of many developing relationships between more-than-human agents (leading to understanding, care, and reciprocity). From this standpoint, negligence for these relationships might (radically) be understood as anti-disciplinary. We may envision that if the practices of STEM are framed as expansive versions of speaking and listening, then the listening necessary to repair relationships (Winn, 2018) may become continuous with disciplinary practice.

Prior research has explored the educational implications of framing science as practices (Ford, 2015), implications of framing science as fundamentally dialogic (Ford & Wargo, 2012), and implications for framing teaching as fundamentally cultural (Nasir et al., 2006) and intercultural (Warren & Rosebery, 2011). *What educational implications may come from blending these framings with constructs of material agency, ethical relations, and epistemic affect?* I question: *What forms of listening exist within STEM?* To approach this, I develop a posthuman perspective of intra-, inter-, and extra-personal listening (and conversations). I then also ask: *How does a change in the framing of STEM also change the space of stories that are possible to tell about disciplinary development and pedagogy? In what ways do disciplinary conversations build and sustain disciplinary relationships? In what ways are noticing and responding to affect integral to mathematics?*

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Chapter 2:

The role of agency and ontological innovation in design experiments

Material agency is a concept that is steadily being explored in the Learning Sciences. Most commonly, either Indigenous knowledges or new materialist philosophy (or both) provide theoretical grounding for this work. However, the ontological commitments shared by these relational approaches are incompatible with some of the research assumptions and methodologies commonly found in the Learning Sciences. In this chapter, I operationalize a form of postqualitative inquiry in design-based research that can accommodate the critique of representationalism found in Indigenous and new materialist methodologies. I explore how the agency of methodology (as well as materials) can be incorporated into design-based research in the Learning Sciences.

Introduction

Agency is more than a simple matter of intention and will. We act in ways that are constrained and enabled by our environments. The concept of *material agency* (Barad, 2007; Pickering, 1993; J. Rosiek et al., 2020) is used to intentionally flatten the differences and hierarchy between how we understand both humans and non-humans to be in relation—with each other and within their environments. In both cases, we can say that humans and non-humans react within their environments in the ways that are available to them. Contrasting with a picture of passive objects awaiting interaction, each agent can be conceptualized as both determining and being determined by a unique and vibrant network of relations with others[1]. Not only are individual attributes the emergent products of dynamic

[1] A *relational ontology* involves either the idea that relationships are ontologically primitive to relata, or that they emerge together with neither being ontologically primitive to the other (Barad, 2003; J. Rosiek et al., 2020). In the way I will approach these terms, the concept of material agency necessitates a relational ontology: If agency is understood to emerge from relational systems (rather than as an inherent property of an individual), then neither relations nor agents are ontologically prior. A relational ontology also necessitates a conception of material agency: If agents can only be conceptualized within complex networks of interrelation, then agency is

contexts, but attributes are actively shaped by many agential relations. This perspective extends beyond agential relations among people and objects to also include the agency of concepts, stories, analyses, apparatuses of measurement, methodology, etc. (Garroutte & Westcott, 2013; J. L. Rosiek & Snyder, 2020)—implying that our responsibility to shape methodology includes care for how it shapes others, and how it reciprocally shapes us.

But why would we flatten differences between humans and non-humans—and how would it benefit the study of teaching and learning? In Education research, students are very commonly described as possessing dynamic attributes with contextually varying levels of intentionality, intelligence, sophistication, competence, development, literacy, disciplinary expertise, etc. And in the Learning Sciences, measuring, representing, and interpreting changes to these levels is common enough that no justification is required for why this would be meaningful or a sound research practice. This methodological justification of this representationalist approach is self-evident: By measuring and representing the changing attributes of our research subjects, we simply attempt to understand how our learning environments influence these changes.

From this perspective, there is a reasonable and inherent difficulty in trying to imagine any other way to examine how learning environments influence development. Whether quantitative or qualitative, what method could possibly reject or eschew the idea that we would find and describe something and then measure it? What science would there be in the Learning Sciences—if theory is not built and validated through measurements of student learning?

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impossible to attribute to an individual and must only emerge from these complex networks of relationships. I unpack these ideas further in the next subsection. For me, *relational ontology* and *material agency* are inseparable concepts.

Using our everyday experience, it can be difficult to problematize the idea that our seemingly inert representations could do anything other than passively represent the world (without actively changing it). *But just like every other agent, forms of knowledge also have an emergent agency that enables and constrains others (specifically, an agency that affects others' ways of knowing and being).* A theme of this chapter is that our relationships constrain and enable the actions of other agents, and I explore methodological implications for research in STEM Education.

Along with theories of material agency, learning scientists are already incorporating relational approaches, Indigenous ontologies, and new materialist philosophy into the design and analyses of their justice-oriented learning environments (Kayumova & Dou, 2022; Keune et al., 2021; Krishnamoorthy et al., 2021; Marin & Bang, 2015). While it is not always explicitly stated, these approaches engage with a poststructural critique of representationalism (Barad, 2003; J. Rosiek & Gleason, 2017) that leads to a shift in the set of compatible research methodologies (Garroutte & Westcott, 2013; Higgins & Kim, 2019; Murris, 2022). Some scholars have chosen to describe their research as *postqualitative* (Lather & St. Pierre, 2013; Murris, 2020) because of this incompatibility of poststructuralist philosophy with attempts to measure the world to build a passive representation of it.

Understandably, both concepts of "material agency" and "postqualitative inquiry" can leave many people feeling ungrounded. The idea of postqualitative inquiry can quickly sound like "everything is made up and anything goes." And the idea that materials have agency can sound like "everything is just like humans: sentient, intentional, emotional, etc." I will make the case (instead) that postqualitative inquiry involves *increased accountability* and that material agency is about *understanding the intricacies of our relationships* with the world and each other.

Extending the voices of previous scholarship (Barad, 2003, 2014; Donald, 2012; Hetherington & Wegerif, 2018; Higgins & Kim, 2019; Marin & Bang, 2015; Murris, 2020; Murris & Bozalek, 2019; J. L. Rosiek & Snyder, 2020; Simpson, 2017), I will argue that the ontologies that support perspectives of

material agency are not compatible with some of the common research methodologies in the Learning Sciences—and require postqualitative forms of inquiry (regardless of whether the term "postqualitative" is used). By suggesting that relational ontologies require postqualitative forms of inquiry, I will argue that postqualitative research (Lather & St. Pierre, 2013; Murris, 2020; Murris & Bozalek, 2019; St. Pierre, 2021a) is needed in the Learning Sciences. To operationalize postqualitative research in STEM Education, I share a performative (Barad, 2003; Butler, 1988) enactment of theory-building to investigate how a change in the framing of STEM might also change the space of stories that are possible to tell about disciplinary development and pedagogy. And I conclude with implications for postqualitative inquiry and relational ontology within design-based research.

Primer: Relational ontology and material agency

A significant portion of the contemporary scholarship developing conceptions of material agency has been through feminist, queer, and trans studies. Thus, two common names associated with this area of the research field are *new feminist materialism* and *new materialism*. New materialist scholars often also refer to their approaches as *"posthumanist"* (Barad, 2003; Braidotti, 2019; de Freitas, 2017; Jeong et al., 2021; Murris, 2020; Taylor, 2016) because of their commitment to de-center the human subject—in contrast to anthropocentric philosophy. New materialist frameworks of agency are also sometimes bundled together as *the ontological turn* (J. Rosiek & Gleason, 2017) due to the shift in ontological perspectives for what "agency" means, what "discourse" means, and what "reality" entails.

Ontology and epistemology are entangled

Now, epistemology and ontology are words that can substantially slow a reader down—even far beyond the first time one comes across them. I use the word *epistemology* to mean: the "how" of how we come to understand ideas, or the "knowing" of our *ways of knowing*. In addition to simple increases in knowledge, learning requires changes to epistemology: We develop practices of knowing that shape how we recognize that we have learned something and how we communicate ideas to others. I use the

word *ontology* to mean: the "what" of what there is to know, or the "being" of our *ways of being* in the world.

For instance, some sharks continue to actively swim when they sleep—in order to keep water moving over their gills. It would be a reckless assumption to presume that our human idea of a "moment" or snapshot of time is something ontologically possible for a shark like this. A shark's agency to conceptualize time as an infinite continuous stack of instantaneous moments might be completely constrained by its embodied experiences of constant movement (in addition to the many other differences between sharks and humans). From interpretations of everyday events to deep fundamental "facts" about our environment, one cannot blindly assume that an agent's ontology (such as that of a shark) would overlap in a commensurable way with another agent's way of being in the world. It is also a reckless assumption to presume that different ontologies of humans are all commensurable. This presumption underlies the narrative of Western Modern Science (WMS) as a universal and neutral system to represent reality—as opposed to a cultural way of knowing and being. The reckless assertion that Indigenous Knowledges need to be commensurable with WMS to be valid has indeed wrecked many lives (by legitimizing the erasure of Indigenous Knowledges and facilitating genocide).

The ways you understand yourself to *be* in the world implicitly shape your ways of *knowing* the world. The term *onto-epistemology* refers to this entanglement of *ways of knowing and being* (Warren et al., 2020). Learning involves changes to both epistemology and ontology because our ways of knowing and being shape what we see in the world, what relationships we are able to see, and how knowledge is developed and shared.

Relational ontology and material agency are inseparable concepts

A *relational ontology* treats relationships as irreducible units of reality—and involves an understanding *that analyzing an individual apart from their many relations is not possible*. In a more typical Western paradigm, objects are the irreducible units of reality. And each relationship is then

understood to be an emergent property of the *inter*actions of individual agents (Engeström, 2001). In a relational paradigm, each individual agent would instead be approached as an emergent, *intra*-active, performance[2] of their defining relations (Barad, 2003). One immediate methodological implication of this perspective is that a student's individual "level" of competence, expertise, literacy, etc. cannot be assessed or conceptualized as if it exists separately from the network of relationships that enabled and constrained their actions.

A relational ontology *necessitates* a conception of material agency because considering "humans as *inseparable* from the network of relations they are in" leads to the collapse of a few (typically taken for granted) dichotomies of thought. As mentioned previously, the most important implication of a relational ontology is that people cannot be separated from the network of relations that they are bound by. We do not only exist in relation to other humans—we are also in relation to many non-human agents. For instance, each species is the outcome of the many ecological relationships that have shaped its formation. Likewise, humans are shaped by their relations with their environment. This perspective of "agents being shaped/defined by their relations" leads to a breakdown of the dichotomy between agent and non-agent in the world: *The environment acts on agents, and agents act on the environment*. There are no non-agents (although there are different and unique agents). In this sense, the environment (or, each/any element of it, at any scale) is also an agent that acts and responds—just as a human acts and responds. Thus, the hierarchy between human and non-human has been flattened: *Each agent simply exists in/as a network of relations that is unique to them.*

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[2] For Karen Barad (2003, 2007), neither relata nor relationships pre-exist each other: "phenomena are ontologically primitive relations—relations without preexisting relata" (2003, p. 815), and relations and relata snap into being together in a performative enactment (that they call an *agential cut)*: "...a specific intra-action (involving a specific material configuration of the 'apparatus of observation') enacts an *agential cut* (in contrast to a Cartesian cut—an inherent distinction—between subject and object) effecting a separation between 'subject' and 'object'" (2003, p. 815).

Indigenous ways of knowing and being are established relational ontologies

Importantly, formulations of material agency and relational ontology are ideologically tied to *Indigenous ways of knowing and being* (Hokowhitu, 2020; Todd, 2016). While "there is no one 'Indigenous' cosmology or metaphysics," (Rosiek et al., 2020, p. 337) there are, however,

> repeated and consistent references to an understanding of the character of agency as something that emerges out of particular circumstances in such a way that its most salient features are missed if it is dealt with primarily as an abstraction. (Rosiek et al., 2020, p. 337)

For this reason, ethical engagement must proceed "in light of the history of colonization, displacement, and genocide" (Rosiek et al., 2020, p. 334). Eve Tuck writes: "There have been several 'turns,' including the ontological turn, the material turn, the spatial turn, each of which is actually a turn to where Indigenous people have always been" (2018, p. 15).

More pressingly, the dichotomy between human and non-human is also repeatedly used as justification for subjugation, harm, or death of those who are understood to be less-than-human. The term *more-than-human* (Bang et al., 2018; Krishnamoorthy, 2023) is used to emphasize that the non/human dichotomy is a construction of language with substantial ethical implications. Many Western formulations of material agency maintain this problematic distinction between human and non-human agents. For instance, in Andrew Pickering's *The Mangle of Practice* (1993); he describes breaking the semiotic symmetry between human and material realms by allowing human intentionality to have no material counterpart. Pickering describes material agency as "temporally emergent" to purposefully avoid the concept of non-human intentionality (1993, p. 564). However, redefining "agency in a manner that dissociates it from mind, will, and purpose…leads to a hierarchy of agencies" (Rosiek et al., 2020, p. 338).

Rather than recognizing the inherent ethical obligations that come from existing in a network of many types of relations, an anthropocentric hierarchy of agencies leaves space for problematic

justifications of unethical behavior. Historically, many people have enacted this justification for inflicting harm: “Non-living / non-human / non-White / etc. do not deserve the same level of respect or care as I need for myself and my kind.” In contrast, destabilizing all hierarchies of agencies is supportive of projects to iteratively search for reciprocal impacts and ethically maintain *all* interconnected relationships. There are no agents unworthy of respect. A relational ontology, then, recognizes an entanglement of ethical obligations with ways of knowing and being. The term *ethico-onto-epistemology* (Barad, 2007) refers to this further entanglement of ethics and onto-epistemology.

Indigenous relational ontologies and new materialist approaches share similar enactments of critiques of representationalism and anthropocentrism, similarly perform knowledge through iterative storytelling, and similarly investigate ethical implications of material agency (Hokowhitu, 2020; J. Rosiek et al., 2020). Yet coming from different traditions, scholars of Indigenous studies may not mention or choose to engage with poststructural lineages of thought—and are unlikely to self-describe their work as “posthumanist” or “new materialist.” Likewise, authors of posthumanist scholarship sometimes only narrowly cite Western philosophers, only “read Indigenous work extractively, for discovery” (Smith et al., 2018, p. 15), or are reluctant “to cite [Indigenous work] without significant mastery, or just avoidance of conflict altogether. This rationale for avoidance “is common and in turn can be seen as a performance of white privilege or white fragility” (Rosiek et al., 2020, p. 334).

Relational ontology is needed for justice

Restorative justice principles for repairing harm were also developed from the relational understanding that our actions exist within a web of relations and effects propagate through the system (Zehr, 2002). These reciprocal relations “imply mutual obligations and responsibilities” (Zehr, 2002, p. 20), and actions of harm come with inherent ethical obligations to repair. With a similar orientation,

Dwayne Donald (2012) describes *ethical relationality* as a philosophical ethical commitment inspired by Plains Cree[3] and Blackfoot[4] relational ontology:

> This concept of relationality instantiates an ethical imperative to acknowledge and honour the significance of the relationships we have with others, how our histories and experiences position us in relation to each other, and how our futures as people in the world are tied together. (p. 536)

Rosiek, Snyder, and Pratt (2020) also describe an entanglement of epistemology, ontology, and ethics within the relational ontology of multiple North American Indigenous communities:

> in seeking knowledge, a person becomes involved in a co-constituting relation with another agent or group of agents. These actions alter the ontology of the subject engaged in inquiry in so far as that subject is no longer constituted as a spectator or critical observer, but as a participant in ethical relationship with other agents. (p. 340)

Relational understandings of ethical reciprocity involve *ontology* because they involve understanding that *what it means to be in the world is to be connected to others*.

Ontological innovation and design experiments

In their paper, *Ontological innovation and the role of theory in design experiments*, Andrea diSessa and Paul Cobb (2004) explored how two long-term design-based research projects involved a particular type of theory development they call *ontological innovation*. The authors notice that the

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[3] "The Cree (Cree: néhinaw, néhiyaw, nihithaw, etc.; French: Cri) are a North American Indigenous people. They live primarily in Canada, where they form one of the country's largest First Nations." ("Cree," 2023)

[4] "The Blackfoot Confederacy, Niitsitapi, or Siksikaitsitapi (ᓀᐦᐃᓶᒡ, meaning 'the people' or 'Blackfoot-speaking real people'), is a historic collective name for linguistically related groups that make up the Blackfoot or Blackfeet people: the Siksika ('Blackfoot'), the Kainai or Blood ('Many Chiefs'), and two sections of the Peigan or Piikani ('Splotchy Robe') – the Northern Piikani (Aapátohsipikáni) and the Southern Piikani (Amskapi Piikani or Pikuni). Broader definitions include groups such as the Tsúùtínà (Sarcee) and A'aninin (Gros Ventre) who spoke quite different languages but allied with or joined the Blackfoot Confederacy." ("Blackfoot Confederacy," 2023)

categories and scientific terms that we craft to "cut nature at its joints" (p. 84) determine what distinctions matter and which are "inconsequential" (p. 84). They argue that,

> The process of creating [scientific terms and categories] is far more complicated than writing down a definition, or finding a relevant meaning in a dictionary. Instead, defining the technical terms of science is more like finding and validating a new category of existence in the world; hence we use the term ontological innovation. (diSessa & Cobb, 2004, p. 84)

The categories we define then come to "empower" (diSessa & Cobb, 2004, p. 84) what we can see in complex settings.

Using the language of material agency, these authors have noticed an agency of ontological innovations. Along with enabling what we can see and understand, ontology and epistemology can also constrain our ability to develop or understand other perspectives. Our agency constrains and enables the actions of others through our relations—and our actions and thoughts are constrained and enabled by other agents (including ontological innovations). If theory and methodology are seen as agents, then research might be understood as the building or strengthening of relations with these agents—and paying attention to how research relationships impact others.

Drawing from both new materialist philosophy and Indigenous studies scholarship, Rosiek and Snyder (2020) use the term *narrative inquiry* to refer to approaches that acknowledge the agency of methodology, results, analysis, ontological innovations, etc. An agent (such as an ontological innovation) is an emergent performance of its defining relations with other agents (including us). In that sense,

> An inquirer and the object of their study have already been shaped by one another by the time the inquiry is underway. The "objects" of our inquiry are partially constituted by the way we frame our questions and by the material features of our inquiry apparatuses. (J. L. Rosiek & Snyder, 2020, p. 1152)

Rosiek and Snyder describe narrative inquiry "as a process of reimagining the possibilities within experience that ontologically transforms a person's relation to his or her vocational activity" (2020, p. 1158).

In the first line of their article, diSessa and Cobb (2004) state that "the motivation for this article is our belief that theory is critically important but currently underplayed in design research studies" (p. 77). After describing different types of theory building, they propose that ontological innovation is a type of theory building that is well-suited for design-based research in the Learning Sciences. Extending their argument, the *agency* of each ontological innovation is also critically important but currently underplayed in design research studies. My goal in this chapter is to explore the agency of theory-building in the context of design-based research.

Study context

This chapter has been developed through unique people, places, and times. I am a White man in a STEM Education PhD program at a small liberal arts university in the Northeastern region of North America. I have been involved with a design research project (Cobb et al., 2003) funded by the National Science Foundation (NSF) to investigate how computational making projects could support flexible reconfigurings of students' relationships to tools, materials, and each other. Our broader project worked with middle and high school STEM teachers at local public schools. We implemented an 18-month, three-phase cycle to explore computation and making, integrate ideas about computation and making into their curriculum, and implement their designs in their classroom. When we initiated our project, we anticipated our methodology to be aligned with Interaction Analysis (Jordan & Henderson, 1995). Our research team videorecorded classroom activities throughout the oscillator project, wrote field notes, and interacted with students with in situ interviewing and rapport-building conversations. We also met regularly for iterative and collaborative review as we created and refined content logs, transcript, and analytical memos.

Between 2018 and 2023, we extended our project to include a portion of an undergraduate computational physics course taught by one of the Principal Investigators. One of the five projects of the course was to model the behavior of a physical construction made from everyday craft materials—string, magnets, wooden hoops, tape, dowels, and cardstock. With the materials on display at a communal table, the students were invited to "make an oscillator." After constructing and refining an assemblage of materials, the students collected video data and used image-tracking software to create a data set of position coordinates. The students then designed and coded a computational model of the system.

Noticing a "dialectic of resistance and accommodation" and "conversations with materials"

As a participant observer, I noticed that most students did something more than simply adjust their models to fit "the observed world" of their oscillator. The students also reciprocally adjusted their oscillators to be in better alignment with their computational model. I found this interesting because it was outside of the range of our expectations, and because it disrupts the narrative of scientific modeling as a process of approximating and representing the "real" world.

The dominant cultural narrative positions science as a method to find truth. In this narrative, the beliefs of scientists frequently become separated from the contexts they emerge from, stiffened into rigid facts, and sharpened into tools that enforce structural oppression. For example, the notion of blood quantum originates from the abstracted ideas that your phenotype is determined by your genotype, and that the essential character of your ethnicity can be fully represented by your genetic inheritance. Both of these ideas are abstractions that have useful applications in some contexts. But 'stiffened' into rigid facts, the contexts in which these "facts" may fail to be true become invisibilized. Your genotype is additionally determined by your environment, and your lived experiences and practices greatly influence your ethnic identity. We might say that these abstracted rigid facts have been further

'sharpened' into weapons of colonial violence in the form of blood quantum laws and the "one drop rule."[5]

By focusing on how our students built their computational model and oscillator *together*, I noticed reciprocity in a place where there is typically a narrative of dominance (over others through the authority of accuracy and truth) or control (of others through predictability). Exploring this interplay of materials and people in scientific relations, I happened to find my way first to the work of Andrew Pickering—who described this reciprocity as a "dialectic of resistance and accommodation" (Pickering, 1993, p. 559). In separate work, Bamberger and Schön noticed something similar, and they described their students as having "reflective conversations with materials" (1983, p. 68). We developed these ideas as we shaped our picture of what happened in the course. Our research group began to think about a framing of science as a collection of many different types of conversations with materials and others.

Asking new "disciplinary" questions after an ontological innovation

We began to consider actions as "speech", close attunement (Shotter, 2015) as "listening", and an agent to be "in conversation" if they engaged in an iterative cycle of speaking and listening. With this material-dialogic (Hetherington et al., 2018) framework, we asked: *What types of conversations are central to science? How do conversations build and sustain relationships (Gee, 2011)?* If we characterize *disciplinary conversations* as those conversations that are both shaped by the discipline and contribute to shaping the discipline, we can ask: *What disciplinary conversations are we facilitating through our*

[5] Blood quantum laws uphold White Supremacy in the United States by guaranteeing a diminishing population of descendants of "full-blooded" Native Americans that are eligible to claim the benefits that were negotiated by their ancestors in exchange for property rights. The legal principle of the "one drop rule" (anyone with only "one drop" of "black blood" is Black) upholds White Supremacy in the United States in an opposite way: by guaranteeing an expanding population of descendants who will be more severely affected by laws that deny rights to Black Americans.

designed learning environment? In our disciplinary context, who is speaking, who is listening, and who needs to be heard? We noticed that these questions (newly understood as disciplinary) are similar to the types of questions involved in a restorative justice process (Winn, 2018): *Who has been harmed, and how do we work to make it right?*

With this connection in mind, we began to search for a relational ontology for STEM by considering how conversations both emerge *from* existing relationships and contribute *to* the existence of relationships. Sakeena Everett (2020) describes *justice as praxis* as "a daily theory-informed reflective practice—a theoretical and pedagogical paradigm committed to seeing the full humanity of others and making things right" (Everett, 2020, p. 102). We began to investigate how daily theory-informed reflective and relational STEM practices could be framed similarly: within a theoretical and pedagogical paradigm committed to seeing the full agency of more-than-human others—and working to make things right.

Significance

There is injustice found in STEM (Avraamidou, 2020; Battey & Leyva, 2016; Camangian & Cariaga, 2021; Ibrahim & Johnson, 2019; Lambert, 2015; Leyva, 2017; Martin, 2003, 2019; Philip et al., 2019; Warren et al., 2020). The existence of this harm implies that whatever ways Science, Technology, Engineering, and Mathematics have existed and developed have not been adequate to prevent harm. So if we seek social justice in STEM, how would we shape the evolution of STEM to resist unjust cultural dynamics that cause harm?

Repeatedly, the assertion of neutrality of STEM (Andreotti et al., 2011; Avraamidou & Schwartz, 2021) is used to "objectively" justify the behavior of the oppressor (Warren et al., 2020, p. 279)—becoming a mechanism of structural oppression. No new set of "neutral" actions or practices will be sufficient to disrupt that mechanism, then. Each instance of meaning-making ignites the questions: *What understanding is constrained or excluded by the stories that our current frameworks support?*

What (new) frameworks might enable different stories, or enable pluralism among stories? Our current frameworks must also be currently enabling stories that we should *want* to constrain—for instance, the stories that are used to enable settler colonialism. *What frameworks might constrain stories such as those?*

In this chapter, I explore material and affective agencies within STEM with an intention to build/explore alignment between disciplinary practices in STEM, restorative justice principles, and relational ontologies (such as Indigenous ways of knowing and being). I argue that relational ontology requires a performative understanding of knowledge, and I position my account of a classroom episode as an act of theory-building.

Theoretical claim: Relational ontology requires postqualitative inquiry.

Among qualitative social scientists, a "new spirit of realism" (Rosiek, 2018, p. 1) is emerging from the poststructuralist critique of representationalism. This critique (and "spirit" of new materialism) rejects a "two-world ontology that assumes there is a real out there and then a representation of the real in a different ontological order" (St. Pierre, 2021, p. 6). And it has motivated scholars to develop postqualitative forms of inquiry (Ceder, 2015; Hetherington et al., 2019; Lather & St. Pierre, 2013; Murris, 2020; Murris & Bozalek, 2019; St. Pierre, 2021b). Jerry Rosiek writes,

> This [new materialist] realism is not a naive unitary realism that frames the social world as a passive object awaiting the one best methodological approach that will reveal its secret workings in a totalizing fashion. Nor is it a relativist nominalism that frames all claims of realism as self-deceived denials of the socially constructed nature of our understanding of our objects of inquiry. (2018, p. 1)

For both "scientific realists" and "social constructivists", scientific knowledge mediates our access to a passive material world: "where they differ is on the question of referent, whether scientific knowledge represents things in the world as they really are (i.e., 'Nature') or 'objects' that are the

product of social activities (i.e., 'Culture')" (Barad, 2003, p. 805). In contrast, relational ontologies of material agency frame reality as "constituted by the methodological and semiotic apparatuses we use to interpret the world *and* constituted by the activity of a world that is obdurately other than our interpretations of it" (Rosiek, 2018, p. 1). According to this view, "reality is what happens when the universe comes to 'meet us halfway' (Barad, 2007) in our inquiries; it emphasizes the way different, even incommensurable, realities can emerge from differently designed inquiries" (Rosiek, 2018, p. 1).

Representationalism involves the assumption that there are "two distinct and independent kinds of entities (representations and entities to be represented)" (Barad, 2003, p. 804). Relational ontology leads to a critique of representationalism because the "subject" to be represented comes into being through its emergent relations—including relations with the representor and the material performances of representation.

Consider a small example. The following complex sentence communicates an idea about material agency, and is rather long:

> The actions and agencies of both humans and materials emerge from the vibrant dynamics of the contexts, cultures, and environments that constrain and enable each type of behavior, thought, development, etc.

Perhaps that sentence sums up the previous primer on material agency, or perhaps the extended brea(d)th of that sentence induces you to skip over it rather than reread it. Now, consider how the materiality of an alternative formatting changes how you engage with its meaning:

> The actions
> and agencies
> of both humans and materials
> emerge from the vibrant dynamics of the
> contexts,
> cultures, and
> environments that
> constrain and enable each type of
> behavior,
> thought,
> development,
> etc.

Written in this way, a pause in your reading at each line break might be enabled by the formatting. On the other hand, perhaps there is no helpful formatting that could overcome the way the sentence structure constrains your sense of having properly understood the meaning. Perhaps (as often happens to me) both the block quote and the non-traditional formatting initiated a reflex to skip over the sentence entirely. In each scenario, your personal relationship to the meaning of the words is constrained and enabled by the specific material performance of the knowledge. Yet, the "meaning" of the words can still be understood to exist, and we can discuss each of our relationships with that meaning.

The issue here is subtly different than the question of whether we have begun to socially construct a meaning for these words. Yes, the "meaning" is built between the author and audience. But our construction of relations to this "meaning" instantaneously define it as a material entity that has now "come to matter"—and can thus be understood as agential because it will constrain and enable our thoughts and behavior. In this example, the performance of the sentence is a phenomenon that both separates and binds the representation (the words) and represented (the meaning)—because a relational ontology posits both the "representation" and the "represented" as defined by each of their specific collections of relations (thus existing of the same "ontological order").

This relational critique of representationalism implies that inquiry and meaning-making can no longer be understood as a project of building increasingly accurate representations of individual agents

and inter-actions. There is no non-agential representation that is separate from the relational act and agency of representing.

Rather than a project of developing representations, meaning-making can be understood as practices of iteratively shifting the stories of relationships to create understanding through the repetition of themes (Murris & Bozalek, 2019; J. L. Rosiek & Snyder, 2020; Simpson, 2017). Instead of leading to a universal avoidance of representation, the problem being raised is seen as an "irreducible element of social research for which we need to take responsibility" (Rosiek, 2018, p. 1). Poststructuralist ethnographers have redirected "their attention from how well their writing describe[s] cultural phenomena to a problematization of the idea that any single description could transcend the cultural contingency of the language in which it was expressed" (Rosiek, 2018, p. 5). Thus, postqualitative research involves both "deconstructing power-producing binaries" as well as "working with barriers and making new patterns of thought;" all while "not holding one text, theory, oeuvre, perspective as foundational" (Murris & Bozalek, 2019a, p. 1507). According to Anishinaabeg[6] traditions, stories too are considered "living agents that merit an ethical response themselves. The ontological view here is nuanced and resonant, though not isomorphic, with the themes of new materialist philosophy of science" (Rosiek et al., 2020, p. 341).

Knowledge as performance

[6] "The Anishinaabe (alternatively spelled Anishinabe, Anicinape, Nishnaabe, Neshnabé, Anishinaabeg, Anishinabek) are a group of culturally related Indigenous peoples present in the Great Lakes region of Canada and the United States. They include the Ojibwe (including Saulteaux and Oji-Cree), Odawa, Potawatomi, Mississaugas, Nipissing and Algonquin peoples. The Anishinaabe speak Anishinaabemowin, or Anishinaabe languages that belong to the Algonquian language family. ... ᐊᓂᔑᓇᐯ Anishinaabe has many different spellings. Different spelling systems may indicate vowel length or spell certain consonants differently (Anishinabe, Anicinape); meanwhile, variants ending in -eg/ek (Anishinaabeg, Anishinabek) come from an Algonquian plural, while those ending in an -e come from an Algonquian singular." ("Anishinaabe," 2023)

Postqualitative research and Indigenous methodologies involve taking up and re-turning to stories to understand them differently (Barad, 2014; Murris & Bozalek, 2019; Simpson, 2017). In this tradition, narrative inquiry searches for "modes of representation that include performative elements that draw attention to how the narrating process coconstitutes the writer, reader, and focus of study" (J. L. Rosiek & Snyder, 2020, p. 1157). Throughout my own writing, I often craft sentences that blend the beginning of my thought with a quote from another author. This can be off-putting to some readers. If a reader takes the perspective that my writing should represent my own new ideas, then it will seem as if I am not sufficiently synthesizing the work of others (into new abstract representations). For me, even my own "new" thoughts are agents that have been shaped by their relations with other readings—and I understand them to be a diffraction (Barad, 2014) of previous discourses echoing through the performance of my writing (Bakhtin, 1981). So, my writing style includes an intentional attempt to build a citational practice (Ahmed, 2013; Mott & Cockayne, 2017) that will not lose or mask the lineage of my ideas (as best as I can understand or remember). By noticing and citing the ideas that I take up and reconfigure, I am adding precision and history to my performance of knowledge.

I orient this chapter as narrative inquiry, and I am explicit about my postqualitative approach to keep the intra-action (Barad, 2003) of the framework with my meaning-making process at the forefront of my methods. Methodology that is compatible with relational ontologies and postqualitative research emphasizes tentativeness, noticing what is missing, historicizing, and innovative performances of knowledge as intentional moves. There are indeed many methodological moves of precision and tentativeness in all forms of quantitative and qualitative research. But moves to *settle* (Bang et al., 2012) meaning-making are not always understood as discursive constructions. Methodological moves to settle knowledge are often positioned as superior to discursive constructions—the deliverables are not "stories", they are "real results". However, the concept of "results" requires a number of material (often violent) and discursive (often stubborn) moves to uphold who has the power to determine what is

allowed to exist as "real" and what is not. For instance, Cash Ahenakew (2016) describes how institutions erase and delegitimize possibilities for Indigenous ways of knowing by dictating the terms of when incommensurable knowledge is welcome:

> Indigenous logics are only welcome when they do not effectively threaten to change the status quo, when it is made the 'same'. In this sense, Indigenous knowledges and methodologies can either be incorporated as a colourful (but insignificant) alternative to what is considered 'normal', which confirms the benevolence of the proponent of inclusion, or perceived as something that is already integral to the dominant logic and therefore also insignificant, given that it offers nothing new. (p. 336)

The violence initiated by settler colonial invasion is perpetuated through discursive constructions of which types of knowledge are taken seriously.

Ahenakew (2016) proposes three methodological sensibilities to notice and subvert ways that dominant knowledge production subsumes and erases other ways of knowing: (1) highlight "the absences of our modes of inquiry" and writing "tentatively about our data and findings," (2) "using metaphor and poetry to disrupt sense-making and prompt sense-sensing in the experience of readers," and (3) "historicizing the referents that circumscribe Western frameworks of reasoning so that we can recognize these referents in our researcher selves and in our writing" (p. 337). In this chapter, I (1) highlight the absence of materiality, affect, harm, and relationality in our current framings of STEM. And I use (2) the metaphor of STEM as a collection of more-than-human conversations to help disrupt (3) the cultural narrative of Western modern science as a universal neutral system for meaning-making (Andreotti et al., 2011; Bang et al., 2018)—which enacts colonial violence (Warren et al., 2020).

Leanne Betasamosake Simpson (2017) writes that as a principle in Nishnaabeg aesthetics, the concept of *abstraction* can sometimes be confused by Westerners with the concept of extraction. Extraction is a cornerstone of settler colonialism and capitalism. And abstraction is sometimes

characterized as an extraction of meaning and knowledge out of the contexts and "relationships that give it meaning" (p. 202). Akin to stealing (knowledge—from the place/people/agents/relationships that produce it), extraction causes harm. Simpson instead characterizes abstraction as "shifting the relationality to change meaning or to illuminate a different meaning" (p. 202). With this conceptual grounding in mind, my exploratory theory-building can be better understood as a type of abstraction. My exploration of disciplinary conversations does not fit a description of a project to extract a representation of authentic disciplinary practice. But it *is* a work of abstraction because I will be shifting the relationality between practice and observation of STEM to illuminate a different meaning and explore how our understandings of education and disciplinary culture might reciprocally change.

Operationalizing postqualitative inquiry

The following moment was selected by our research team as a representative example of one piece of our framework of disciplinary conversations: the concept of listening to internal embodied sensations, affect, and identity. One framing of restorative justice is "working to make things right"—whether or not repair is fully possible (Winn, 2018). This starts with understanding what has been wrong, who has been hurt, and *listening* to what they need. We ask, *What forms of listening exist within STEM?* Our research team sought to consider how "listening" could be seen as a disciplinary practice—in order to find and highlight commonalities between restorative justice practices and practices that inhere in STEM.

We chose this moment because of the complex disciplinary interplay we observed between students' embodied sensations and epistemic affect. Our field notes, video and audio recordings, and interpretations have been refined into an analytical memo. The accompanying analysis is theory focused, fine grained, and involves an open consideration of data. For these reasons, it could be seen as an example of a microgenetic learning analysis (Parnafes & Disessa, 2013), but it differs substantially with its orientation towards postqualitative research.

As an example of postqualitative inquiry, this piece was chosen because of its relevance to the theoretical framework and its shorter length as a vignette. The following is a written performative understanding of my perspective from the first day of the making project. It has been iteratively refined by our research team into the following account.

Vignette: From micro-adjustments to micro-noticings

Christopher holds a string with a magnet tied to the end, and Dex holds another that has been constructed identically. Christopher (he/him pronouns), Miriam (she/her pronouns), and Dex (he/him pronouns) have begun to work with two disk-shaped craft magnets each tied to a length of string. Christopher and Dex bring each magnet-pendulum closer to each other, trying to avoid touching—yet close enough for potential magnetic interaction. Dex's magnet hangs relatively still, and Christopher slowly brings his closer with each swing.

I was a participant researcher with these three students as we watched the magnets swing near each other. During a semi-structured interview after the project was over, Miriam recalled her thought process when choosing to work with magnets: "It just seemed like—I don't know.. Out of all the materials—I was just like, 'oh! magnets are fun. Let's play with the magnets.'"

The longer they watch the swinging interactions, the more Christopher smiles—until his mouth is wide, in an open grin. Dex and Miriam also watch intently. Dex is calmly fixated on the magnet hanging from its string. Miriam stares at the video she is recording on her phone. I transcribed their dialogue in this moment from the projects' video data:

MIRIAM; Wait, it's SO cool.

((After 10 seconds, Miriam looks up from her phone))

((Christopher laughs))

MIRIAM; ((whispering)) It keeps going! ((she turns her head to look towards the instructor, and waits for a moment to speak))

Screenshot 1: Christopher (left). Dex (middle). Miriam (right, back to camera). Christopher and Dex each hold a magnet-pendulum.

MIRIAM; Professor Atherton,

CHRISTOPHER; YEAH, yeah—wait, check this out!

MIRIAM; —look at this. ((looks back to the magnets))

INSTRUCTOR; oh my god!

MIRIAM; ((looks to the instructor, and then back to the magnets)) Look! It just keeps going.

INSTRUCTOR; Ohh, that's great!

MIRIAM; That one twists, and then that one ((unintelligible)).

INSTRUCTOR; That's amazing

MIRIAM; It's been going on for so long.

RESEARCHER; Thirty-seven seconds?!

MIRIAM; ((turns and nods))

MIRIAM; And it was going before that.

Screenshot 2: "I am, like, micro-adjusting the distance a little bit, but I'm not doing almost anything…and it just kind of continues"

CHRISTOPHER; But, honestly, like, I—I am, like—I am, like micro-adjusting the distance a little bit, but I'm not..doing almost anything…and it just kind of..continues to ((unintelligible))

At that point, I laugh and our audio data is distorted by my uncontrolled outburst—too close to the video camera. I remember their path of affect and wonderment at what might be happening—questioning how much or in what way the magnetic influence was affecting the swinging motion. They shared this wonder with each other, with the instructor, and the researchers. Christopher's statement was wonderful to me because he was starting to bring his initial curious noticings into sharper focus. The three of them were on a cresting wave of disciplinary curiosity—developing a subtle sense that the phenomenon they were experiencing was worth looking at very carefully. At the same time, Christopher's admission of "micro-adjusting" jumped at me as an adorable underestimate—since his hand (as well as any subconscious cognitive biases) were completely entangled with this system of investigating the extended duration of the magnets' motion. How could he possibly know whether it would continue indefinitely—when his mind and body were exactly part of the phenomenon he was investigating!

As I understand this moment, the beginning of Christopher's disciplinary noticing was separating itself from this entangled relational system of gravity, cognition, embodied sensation, magnets, and colleagues encouraging and observing him. For me as well, my complex emotions (of surprise, wonderment, and judgement) also initiated a separation of noticing. I noticed how Christopher's embodied experience was entangled with his disciplinary inquiry—which persisted throughout the project.

Christopher and Dex were not simply watching the interaction of the magnets. For each of them, the changing momentum of the magnet was transferred through the string to their hand to give them an embodied sensation of the magnet's movement. Their relationship to the magnet was shaped through these sensations. Each of them has a memory and experience of the sensation the swinging magnet produces when it is not near another magnet.

We can infer that Christopher was deeply attuned to these sensations because of the resolution with which he describes noticing the difference in the magnet's behavior. He said that he was paying close enough attention to verify claims about the magnet's behavior ("keeps going") despite the inevitable noise introduced by his unintentional hand movements. His claim was that he could filter his sensations into components of the magnets' influence and separate influences of gravity, hand position, momentum, etc. Regardless of whether he was correct, his statements are evidence of the close attention Christopher must have been giving to both the materiality of the system and the affective and sensorial experience he had.

Christopher's joy came from watching the magnets behave in unexpected ways, but his engagement was also sustained by his attempt to build an understanding of what to expect. The rest of the group's project—building an assemblage to repeat this behavior, refining the materials, building and refining a computational model, and developing graphs and diagrams—was an extension of this engagement to find joy in building and refining further understanding. Christopher's trajectory through

the project was shaped by which constructions, models, and theories were "interesting" to him and his groupmates. The scientific inquiry began with very small noticings of subtle behavior and micro-adjustments. Then, Christopher's listening to his embodied sensations was followed by noticing and sustaining a particular affective trajectory of curious interest and wonder. In a sense, the development of Christopher's scientific inquiry involved tuning the resonance of *this* larger entangled system of affect, materials, theory, and students into an assemblage that could become an oscillatory phenomenon:

affect
driving further listening
to materials
sparking affect
and theoretical questions
perpetuating disciplinary affect
in its becoming.

Discussion: Postqualitative research embodies knowledge as performance

The difference between this account and a structuralist qualitative account (built from grounded theory, for instance) is that this account explicitly and implicitly embodies the orientation of knowledge as performance. Although each of the following markers can often be found in postqualitative research, what makes the above account postqualitative research is not merely that I invented a new conception of *disciplinary listening*, nor solely that I included myself in the analysis, nor the simple inclusion of the poem at the end. The orientation of *knowledge as performance* "insists on understanding thinking, observing, and theorizing as practices of engagement with, and as part of, the world in which we have our being" (Murris, 2022, p. 46). Concepts are "entangled with theory, practice and methods" (Murris et al., 2021, p. xxiv). This implicates the researcher as an apparatus of measurement that is performatively mapping differences and resonances among multiple sources (Barad, 2014; Murris & Bozalek, 2019). New forms of knowledge are then found by encouraging "knowledge production to cross disciplinary boundaries, e.g. by diffracting quantum physics with poetry or fiction or queer theory" (Murris & Bozalek, 2019, p. 1513).

The above account of Christopher is a performative enactment of knowledge. For this account, I historicized the theme of listening as a mechanism for repairing harm—establishing an ethical motivation for inquiry since we know STEM to be implicated in ongoing harm. I both described and embodied the sensibility of closely noticing (listening) within the account of Christopher's relationship with the magnets, his embodied sensations, his emotions, his scientific inquiry, and my involvement in connecting these threads. I presented a performance of writing as an offering for the author(s) and reader(s) to share emotions of understanding. For the reader as well, "each reading is a performative engagement with the text that is always dynamic and that changes with every re-turning" (Murris et al., 2021, p. xxiv).

Specifically, the poem at the end of the vignette was an intentional design choice. I wrote it first as a run-on sentence—attempting to convey a feeling of unending momentum for the cycle of affect, materiality, and scientific inquiry. This entanglement was the focus of the vignette, and the run-on sentence is placed as the culminating description. It is intended to be intelligible to the reader by that point (after the previous careful description), yet simultaneously overwhelming in a gentle way (hoping to capture the reverberant ambient background of the resonating entanglements). Our research team made the additional choice to format it as a poem rather than one run-on sentence to further signal that the previous narrative structure was beginning to break down—hopefully "disrupt[ing] sense-making and prompt[ing] sense-sensing in the experience of readers" (Ahenakew, 2016, p. 337).

More than just the previous account of Christopher, it is important to recognize that this entire chapter should be viewed in this way as a performative enactment of knowledge. My primer on relational ontology and material agency, my description of the learning environment, my summary of the critique of representationalism, my characterization of Christopher's experience, etc. are all instances of performance intended to resonate with a reader's experience. In each case, I am hoping to spark constellations of thoughts and emotions that I wish to share with the reader through these

discursive moves. I would argue that structuralist qualitative analyses are also composed of discursive moves designed to spark particular emotions—ones that the researcher wishes to share with their audience—through their performative enactment of knowledge.

Research oriented towards finding or building representations often obscures what knowledge is lost or precluded—in favor of crafting a convincing story. Structuralist qualitative methods tend to prioritize the unique emotional state of feeling like you have arrived at a conclusion without being influenced by emotions—something categorically impossible. The serene feeling (Thurston, 1995) of "rational and emotionlessness thought" is itself an affective state. Quantitative methods often do the same: discursively present affective credentials of neutrality. My postqualitative stance is that a structuralist account (that builds a definitive certainty from its categories and codes to represent "what really happened" with "evidence" and argument) uses a discursive creation of "certainty" to support the methodology and conclusion. Literature reviews are often positioned as definitive summaries of what knowledge has already been represented. Data is often positioned as separate from analysis and theory. And analysis, interpretation, and implications are positioned as new representations of knowledge (rather than performative instantiations). Each of these actions of positioning exists within a particular web of relations—and effects propagate through the system.

Discursive moves are not categorically suspicious—as if they obscure an objective "truth". Nor are they categorically unsuspicious—as if they are equally "relative" in some system of truth or another. *A relational ontology recognizes that each discursive move shapes and creates relations*—with unique ethical consequences in each case. Like discursive moves to build "certainty", Ahenakew's call (2016) to "write tentatively about our data and findings" (p. 337) is also a discursive move that enacts particular ethical consequences. Writing tentatively is sometimes interpreted as an unintentional display of weakness. But as a methodological choice, future deconstructions (of what knowledge is currently excluded) are supported by intentionally crafting a sense of tentativeness—just as intentionally crafting

a sense of certainty will constrain future critique. Whether choosing to enact qualitative, quantitative, or postqualitative approaches; researchers "should not make choices without realizing that these will affect what their stories can *do*: those stories' ability to evoke realities and to illuminate possible lives" (Garroutte & Westcott, 2013, p. 76).

Relevance for design-based research: Student agency in networks of relations

There is a dominant narrative that frames STEM as a set of value-neutral practices for crafting representations of the world as it "really" is. Just like every narrative, this framing has enabled knowledge while also constraining other perspectives. In particular, this narrative is supportive of the agency (and hence, violence) of settler colonialism by "claiming the privilege of narrating what 'others' are while simultaneously denying other perspectives, histories, and subjectivities" (Warren et al., 2020, p. 279). Increasingly, a focus of design-based research includes disrupting this narrative and searching for design sensibilities (Bang et al., 2016; Warren et al., 2020) that also involve "reimagining the relationship between science learning, classroom teaching, and emerging understandings of grounding concepts in scientific fields—a process we call *desettling*" (Bang et al., 2012, p. 302).

Something that diSessa and Cobb explicitly note as a "key criterion" of ontological innovations is that they "do real design work in generating, selecting and validating design alternatives at the level at which they are consequential for learning" (2004, p. 77). I think diSessa and Cobb were trying to find a way to separate their argument from an implication that they wish to avoid: that any and every ontological innovation would be inherently worth sharing with the community. To me, it seems reasonable of them to separate their argument from that implication. I understand their statement to be a small part of a larger performance and presentation of their work.

But notice, also, how the discursive move they chose does work to invisibilize power dynamics. The following questions are left unexamined: Who determines what design work counts as "real"? Who decides which methods for validation will be accepted? Who will determine what design alternatives are

"consequential for learning"? Will it be the case that real design work is only valid—or only consequential for learning—in so far as it does not disrupt mechanisms that reproduce structural inequity? Whether or not they meant to, diSessa and Cobb's narrative of ontological innovation acted to both open and close avenues to investigate certain questions. In this chapter, I argued against presupposing that our representations *merely* "cut nature at its joints" (as if nature is something dead that we will dissect or consume). I have argued that crafting new narratives and investigating the ways our actions impact others are more sustainable research goals.

For our research team, reading literature on material agency and Indigenous approaches enabled our developing perspective of STEM practices as relational practices. Literature in these areas constrained our research team's thinking about the extent to which we can really trust representationalist approaches. I see material agency and relational ontology as complimentary ideas that belong together. Above, I argued that a relational ontology requires a performative approach towards knowledge and a relational perspective towards STEM practices. By framing methodology and ontological innovations as agential, I explored how design-based research can be(come) more compatible with material agency and relational ontology.

In our project to "make an oscillator", we came to see our students as having many conversations with different types of more-than-human agents (including their own embodied and affective states)—and building many different relationships. My own positive experiences in STEM enable me to consider how "disciplinary development" might be framed as a strengthening of the many relationships that come to define Science. Our design research emerged from this network of agential relations.

I historicized listening as a central practice of reciprocity (within Indigenous ways of knowing, restorative justice work, and new materialist ethico-onto-epistemology) that can also be (re)imagined as a disciplinary practice in STEM. In conversation with scholarship on ethico-onto-epistemological

frameworks, our research team explored ways to build narratives that might constrain (rather than enable) the agency of settler-colonialism in STEM. Our vignette of Christopher's "microadjustments" helped us develop a relational conception of disciplinary listening (as close attention to another agent that builds a disciplinary relationship). I operationalized postqualitative research in the Learning Sciences by offering a performative account of a moment of disciplinary importance in a computational physics classroom. Within that account, I initiated an exploration of a relational conception of disciplinary listening (as close attention to another agent that builds a disciplinary relationship). The concept was an ontological innovation in our design process because it affected how we understood the many actions and relationships of our students—and the ways that we perceived these actions "as consequential for learning" (diSessa & Cobb, 2004, p. 77) (or, consequential for developing strong disciplinary relationships). Because our concepts of *disciplinary listening, disciplinary conversations, and disciplinary relationships* further involved "theories, practices, and structures of values, ethics, and aesthetics...that shape current and possible meaning, meaning-making, positioning, and relations in cultural ecologies" (Bang et al., 2016, p. 28), these concepts were also "axiological innovations" for our work.

Agency in the oscillator project

Throughout this chapter, I have described some of the many agencies in relation that influenced our design research. I included in that network of relations a conception for agencies of narrative and theory (Garroutte & Westcott, 2013; J. L. Rosiek & Snyder, 2020). Our research team's perspective on material agency helped us to understand the agency of our students as ways that they could speak, listen, and have conversations that would build disciplinary relationships. And our exploratory retellings (i.e., postqualitative research) of how we understood the learning environment helped us shape that perspective and framework.

As we looked back on our project, the design of the oscillator project enabled a wide range of student agency that we felt was critical for enabling the development of our students' disciplinary

relationships. We introduced the students to a set of materials, we asked them to "make an oscillator", and we asked them to describe the behavior of their assemblage using their knowledge of physics and programming. Along with agency to iteratively build their oscillator and reconfigure their workgroups, the students also had agency to define a number of things for themselves: what the word "oscillator" would mean for their group, what behavior they would choose to model, what complications would be involved in their inquiry, what would constitute "a computational model", and what "success" would mean for them. We observed students determining (in ways that fit them): what to build, what to notice, what was interesting, what data to collect, how to interpret it, how to model it, how to craft interpersonal relationships, where to find support, how to construct or deconstruct leadership, and what performances of knowledge they would enact. Not only did the students have many disciplinary conversations (with materials, each other, and their embodied experiences)—the students had agency to pursue these conversations in ways that felt right to them.

The large field of student agency that we designed enabled rich disciplinary relationships. Building on previous work, our research team also developed a metamodel of knowledge production in computational physics (Phillips et al., 2023). This metamodel enabled how we understood our students to engage in practices, generate artifacts, and how their goals changed over time. We found that "students conducted essentially all the components of an act of scientific inquiry, as viewed through our metamodel" (p. 20). In particular, we saw "students engage in computation not only as a tool to use while doing physics but *as a core part of what it means to do physics"* (p. 20).

The students were enabled to negotiate relationships that worked for them—which then enabled their sustained and rich disciplinary conversations. During a semi-structured interview that I conducted at the end of the semester, two groupmates (Jacob and Edson) agreed with each other that the project structure compelled them to keep following up on the interesting things they noticed. The following transcript is from their interview (emphasis added):

EDSON; I think like I—I *usually*, like, take an active approach to my learning. You know, and it's like, this was something that...it was like, 'Well there is no other way.' ((nods)) um, which—Which is nice because I think, like, **there is a way that, like, when things get stressful or heavy, it's like, easy to default to, like, 'Okay, well this is just what is expected of me. Let me just do this, then. Yeah, whatever.**' and

EZRA; Yeah

EDSON; This [project] was something where, like—**that active approach, it was like—not only is it encouraged, but it's kind of the *only* way to get through** ..any of these [similarly structured projects in the course].

EZRA; Yeah

JACOB; Yeah I didn't think about that—that's really true. ..Even on some of the other projects, like, um, what was the one..right..so, the time..independent Schrödinger equation.

EDSON; Yeah.

JACOB; Um..I was doing a bunch of other crap, and I just wanted to get it done ((gestures)). So, it was sort of like, 'Let's get the minimum viable solution..on the page, and go.' And—you're right [Edson]—that, that was not possible for this project. **Because like..the minimum viable solution was whatever you determined it to be**..and, the way the project was structured..it was like, you wanted to have a model of what it was—The minimum viable, like, **it encouraged you to push that minimum viable solution as far as you could.**

EDSON; ((nods)) Right.

We also noticed the students iteratively searching to disrupt settled knowledge. With the agency we enabled, they followed what was interesting. And themes that were interesting were often desettlings of knowledge—rather than repeating or validating established narratives. In this sense, the structure of the project opened space for Physics practices to also be queering practices (Rands, 2019); the students ignored boundaries of established narratives to search for alternative performances of knowledge in Physics (Eng et al., 2005). Once the students had an initial story of "what" was happening, they almost always investigated queer complicating factors.

For instance, they further investigated: sensitivity to initial conditions and chaotic behavior; finding and tweaking parameters of the model (drag, energy dissipation, Reynolds number, coefficient of restitution, etc); or precision in measurement (capturing the data in the best way, calculating differences and error). The students were enabled by the designed learning environment to pile on complications—asking new questions—until their disciplinary conversations and relationships felt sufficiently engaging. One group reported that the reason they chose a double pendulum was specifically because the complicating factor of "chaos" was interesting to them. Their group's first assemblage essentially involved three independent simple harmonic oscillators, but they instead decided to build a double-pendulum system because it was "more interesting" and "chaotic." At the initial conditions they modeled, an idealized double-pendulum does not, in fact, exhibit sensitivity to initial conditions in the sense of chaos theory. But because of the double-pendulum system's connection to the development of chaos theory, this group wove the descriptor of "chaotic" into their narrative of the oscillator's behavior. Like Miriam's description of her affective pull to work with magnets, Emerson (a student in this pendulum group) described how their disciplinary growth was the result of following what they found to be interesting. Further, Emerson credits the learning environment for enabling their agency:

> And it's good because **I felt for the first time that I had agency** in what I was doing. So often I just do projects and everyone's like 'oh, this is horrible.' And I don't complain, because I'm like but it needs to get done. And I get it done, you know? But in this class, **you could actually have agency and do something cool** if you wanted to. So it makes it harder for everyone to be complaining, and also a lot easier for you to not want to complain. The concept of busy work and daily homework assignments that I've had in other classes, right? —they're just tedious. You don't actually learn a lot from them. **And in this class, I felt like so many kids—including myself—learned a whole new branch of ways to solve problems**. *(Emerson, workgroup interview, emphasis added)*

For Emerson's group, "chaotic" also meant strange—and therefore, interesting. And their disciplinary growth emerged from conversations between the agencies of their materials (their oscillator), theory (the idealized double-pendulum system, chaos theory, and programming techniques), affect (determining what they found to be interesting), and each other (working collaboratively). For our team engaged in design research, finding ways to weave relationality into our conception of STEM (through narrative, theory-building, observation, and postqualitative research) gives us hope for (re)making STEM to be a less harmful agent. And our research here has emerged from conversations between the agencies of prior scholarship, the learning environment we created with our students, and each other.

The design of our learning environment enabled the students' agency to redefine their disciplinary relationships in ways that fit them best. We found that our students engaged in "essentially all the components of an act of scientific inquiry" (Phillips et al., 2023, p. 20). Their successful disciplinary work included disciplinary practices that are relational and underplayed in disciplinary standards documents. Our students listened carefully to other agents (such as their embodied sensations, the materials, and each other) as they built disciplinary relationships. Our students pushed themselves to actively engage and develop rich disciplinary relationships with each other and with the

material—"not only is it encouraged, but it was kind of the only way to get through" (Edson, workgroup interview). And our students reported learning more by being able to "have agency and do something cool if you wanted to" (Emerson, workgroup interview).

Summary

> The stories produced by narrative inquiries earn our commitment, not by being the most accurate—although accuracy plays a role—but through the quality of their promise to ameliorative future relational activity for persons conducting the inquiry and their communities. (J. L. Rosiek & Snyder, 2020, p. 1158)

In our design experiment, there is evidence that our discursive framework of disciplinary conversations was consequential for learning. But disciplinary conversations are not representations of what "really" happened in our learning environment. Nor are they representations that we constructed primarily to understand something "better" (although that also happened). Evidence that this ontological innovation was consequential for learning exists in a different place.

We worked with a framework of disciplinary conversations to shift our context of computational physics into better alignment with relational ontology (J. Rosiek et al., 2020), ethical relationality (Donald, 2012), and justice as praxis (Everett, 2020). We understood our students to be engaged in authentic scientific inquiry that was both defined on their own terms and supportive of future scientific endeavors with others. We attempted to enable them to renegotiate their relationships. And narratives of disciplinary conversations enabled us to explore how computational modeling might begin to be decoupled from narratives of dominance and control.

I used a postqualitative approach to begin an investigation of how a change in the framing of STEM might also change the space of stories that are possible to tell about disciplinary development and pedagogy. This shift helped our research team craft different stories of relational disciplinary practices

(listening and speaking) and led us to explore a framing of disciplinary development as the growth of the many more-than-human relationships that come to define STEM.

Broader implications and limitations: *The space of accessible stories*

Different perspectives of what there is to know (i.e., ontology) lead to different practices of refining knowledge (i.e., epistemology). Some stories become easier or harder to tell in different onto-epistemic paradigms, and some stories are not possible to tell without the appropriate onto-epistemic context. Even for something as simple as the ontology of number, the story of what it means to "be" a number like one-half or one-third may involve a narrative involving an infinite sum in some paradigms and not in others. Written in base 10, the number one-third has a non-trivial repeating decimal and the number one-half does not. Written in base 3, the opposite is true.

The numbers we know as "the real number line" are the completion of the rational numbers with respect to the standard way to measure the "distance" between fractions. Somewhat shockingly, the completion of the rational numbers with respect to a range of other metrics is not a line—not even a little bit. These number systems have properties of closeness similar to the Cantor set: there are uncountably many points, convergent sequences also have limiting values in the space, yet there are no continuous mappings to or from sections of the familiar number line and this metric space.

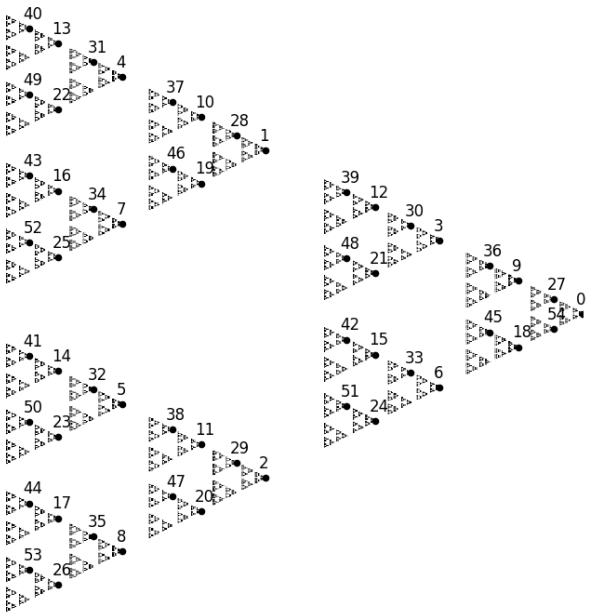

Figure 1: Not a number line. This is a visualization (RUser4512, 2020) of the fractal topology of the 3-adic numbers—the metric completion of the rational numbers using a particular and peculiar way of measuring distances. Some integers are marked because this space contains the rational numbers as a subset.

In these cases, the rational numbers still exist as a subset of the metric completion, but there are uncountably many "numbers" in this new set that have no description on the real number line. Likewise, the irrational numbers on the familiar number line do not have any description in these incommensurable spaces. The sequences that converge in one metric do not converge in some others—so they cannot correspond to any number.

Even for the simple question of "what is a number?", ontology shapes the space of stories that are easy, difficult, possible, or impossible to narrate. Rather than merely changing the contours of an imaginary space of all stories, ontology can drastically change the underlying topology of which stories are similar to each other or even knowable at all.

Vignette and discussion: Avalee's disciplinary relationships

How does relational ontology change the space of accessible stories *about a learning environment*? Based on the previous mathematical vignette, we should expect that the differences

could be incommensurable. The main body of the chapter explores relational narratives within an undergraduate physics course. And in this final example, I consider different lines of inquiry that are enabled by either a perspective of disciplinary practices or a perspective of disciplinary relationships.

Consider this vignette from our broader research project helping teachers to implement project-based curricula in middle and high school STEM classes. Two of our participant teachers had developed a project for a third grade class. After the class project was over, part of our data collection involved semi-structured interviews with students. I conducted one of the interviews with a Black girl named Avalee—who had been in a group with another girl and two boys. Part of our interview protocol was to ask about a time students felt proud or excited. I was surprised (and slightly confused) at Avalee's response (bold emphasisis added to bring out a streamlined version of this exchange):

EZRA; Can you tell me about a time—when you were working on the project—and you felt really proud or excited?

AVALEE; Uhm, one part that I felt really exciting and proud was when **our team** kind of.. was almost finished with the project...and **we were not**—really **having fights about what things should we decide on.**

EZRA; Can you say that again… you were really proud when you thought you were finished? ((By intentionally asking about the wrong piece of what was important about what she said, I hoped to be less of an influence on her story on her terms. This utterance was also edited for clarity.))

AVALEE; Yeah. And then when our group was not—like **really having a hard time** deciding what things we want **because all of us want different things.**

EZRA; What about that made you proud? You guys weren't working well together?

AVALEE; We worked well together, but like, **the two other boys really had some argument.** But after that, we tried—**me and my other friend that were in the group—we tried to make them..not really fight about anything.**

EZRA; Oh, yeah. What did they fight about?

AVALEE; **They fight about**, like..the other boys just trying to make—**trying to put *his* idea, and then the *other* boy is trying to make *his* idea happen**.

EZRA; Mm, did you say that you and Abby… found a way to not ..er, what did—what did you guys do? And did you talk about it beforehand? Or did you just... ((Again, I intentionally avoided succinctly revoicing her words as an attempt to capture her words without as much influence from me.))

AVALEE; Uhm..At first we didn't really do anything. **We just kind of waited, so—that they would figure it out by theirselves. Then after that, we** just kind of **made them separate.** We tried to umm.. **We both took one of the boys, and** put them—**make them sitted with us**. And **then we talk about their ideas**. Then we tried to put both of their ideas in the house. **So that one of them wouldn't get jealous.**

Along with the other girl in the group, Avalee's trajectory through the project involved managing the boys' disagreements. The moment where she was proud or excited was when the group was able to work without fighting.

Later in the interview, I came back to this question to try to understand more of her experience. When I asked her if there were other times she felt proud or excited, she said that there was one day when the boys were gone and the girls were more productive. When I asked if there were times where she felt frustrated, she noted a time where the boys were fighting and refusing to listen to her:

EZRA; Do you remember—So, way back..a question was about a time that you felt proud and excited. And you—I think you said, like, when everybody was kind of, like..working together. Do you remember what you were making—at the time?

AVALEE; Umm.. At that time we were making.. We were, like, um, deciding what part we want to put in the house.

EZRA; Um.. **Were there other times you felt proud.. or excited?**

AVALEE; Ummm.. **One part that I feel proud and excited was when ..me and Abby were—we were the, like—we were the only two that came.. And our other partners weren't here. So, we got to kind of figure things out by ourselves**. I thought we pxxx, that we..did a good job at it.

EZRA; Yeah. Yeah! That can feel really good. Were there any times when you guys, uh, felt—or when _you_.. felt like you were struggling? Or, challenged? Or felt frustrated?

AVALEE; Um, there was one time..that **I felt frustrated.** It was because, like, the boys were fighting—**and I was like, "Can somebody, like, make me talk too?" But they were like, "Lalala. Lalalaa."**

Disciplinary practices or disciplinary relationships?

With an ontology of STEM as a dynamic collection of cultural practices, the available lines of inquiry regarding Avalee's account are different from the lines of inquiry available within a relational ontology. Investigating the design of the learning environment within an ontology of disciplinary practices, we can most easily ask: Did Avalee's experience with the boys in her group disrupt her ability to engage in any of the disciplinary practices the learning environment was intended to enable? Were there ways that the learning environment supported the boys' behavior despite the impact on the girls? Using a structuralist qualitative methodology would likely involve (a) sufficient video and audio data of

the students interactions, (b) an analysis of what behavior was relevant to Avalee's account, and (c) a methodology to objectively represent Avalee's account as something that really happened and had real impacts on her learning. Through some sort of qualitative analysis, results from this type of inquiry might take some of these broad forms:

- Yes, Avalee's experience was real and there are reasons why it is undesirable.
- We now understand Avalee's experience better.
- We better understand how to design equitable learning environments by considering the ways that particular cultural dynamics interact with student experiences.

In contrast, to investigate the design of the learning environment within an ontology of disciplinary relationships, Avalee's account gives insight about the relationships within the learning environment. For Avalee, part of the work to sustain the project involved maintenance and repair of the boys' adversarial relationship. This is *disciplinary* work. Her most memorable moment of pride and/or excitement was her success with relationships—more memorable than other aspects of her group's disciplinary work. It could be argued that Avalee's grappling with this relational issue is substantial exercise that will support her growth in sustaining disciplinary relationships in the future.

While this may be true, it also seems to be exhausting for Avalee: her second most memorable moment of pride and/or excitement was her relief on the day when the boys were *not* present. Additionally, we can see that relational maintenance became the girls' responsibility—reifying the powered cultural dynamics of gender and race (even in a third grade classroom). What kind of support does Avalee need for this configuration of disciplinary relationships in STEM? Are there ways we can anticipate and care for the aspects of disciplinary relationships that may be exhausting or harmful? These are not questions about what social factors enable or constrain disciplinary practices—these are questions about how we want to continually embody STEM and how we want to craft the ontology of STEM. These are disciplinary questions that should be asked during the design of the learning

environment. In contrast, separating disciplinary practices from actions of care can enable harm to pass through disciplinary environments; from that framework, questions of harm or care can more easily be dismissed as distractions from "real" disciplinary work.

Speaking very broadly, a representationalist ontology most easily enables the questions: Did sexism happen? Can we find ways to stop unjust patterns from blocking disciplinary experiences? In contrast, a relational ontology creates a different space of accessible stories. This particular embodiment of STEM was made up of relationships that animated gender dynamics in a particular way. These unjust patterns didn't "block" disciplinary experiences*, they were inherent to the disciplinary experience*—although, we should search for ways to constrain that kind of performance of STEM. As a researcher on this project, Avalee's account is interesting to me as a way to understand the depth of how relational work inheres in STEM, how maintaining relationships can be just as hard and just as important as other disciplinary practices, and how the agents in relation constrain and enable what performances of knowledge emerge. These areas of inquiry are enabled by relational ontology.

Limitations and implications

The label "postqualitative" carries baggage—limiting the accessibility of this mode of inquiry. As I mentioned above, Indigenous scholars have good reasons to resent new "turns" to places "where Indigenous people have always been" (2018, p. 15). The prefix of post- is not meant to be an identifier for a superior class of scholars from the future. The post- is attached to the beginning of the word to signal a lineage with poststructuralism (Dixon et al., 2023). But poststructuralism is confusing(!) and can easily alienate people. Like the words "epistemology" and "ontology," *confused* is the appropriate way to feel about poststructuralism for significantly longer than it takes to first think you might understand it. Elizabeth St. Pierre has shared (2021a) that her main advice to students is to just keep reading, writing further (p. 7):

> I've learned I long for what Elliott Eisner (1996) called working "at the edge of incompetence" (p. 412) and what Patti Lather (1996) called working in "rigorous confusion" (p. 539). What's important here is that theory should be unsettling, disruptive, confusing, and perhaps that's why we resist it.

I have argued that relational ontology should carry an implication of a postqualitative orientation towards inquiry. While the label "postqualitative" may not fit everyone, frameworks of material agency and relational ontology belong with performative (rather than representationalist) understandings of knowledge. Specifically, the emergent agency of design-based research methodology constrains and enables ways of knowing and being—leading to an ethical responsibility of the researcher. To help stop performances of knowledge from erasing a plurality of ways of knowing; Ahenakew (2016) has proposed that an ethical approaches should include: (1) highlighting "the absences of our modes of inquiry" and writing "tentatively about our data and findings," (2) "using metaphor and poetry to disrupt sense-making and prompt sense-sensing in the experience of readers," and (3) "historicizing the referents that circumscribe Western frameworks of reasoning so that we can recognize these referents in our researcher selves and in our writing" (p. 337).

To put these arguments into practice, I operationalized postqualitative inquiry in the Learning Sciences by (1) highlighting the absence of materiality, affect, harm, and relationality in our current framings of STEM. And I used (2) the metaphor of STEM as a collection of more-than-human conversations to help disrupt (3) the cultural narrative of Western modern science as a universal neutral system for meaning-making (Andreotti et al., 2011; Bang et al., 2018)—which enacts colonial violence (Warren et al., 2020). With this inquiry, I began to shape a different space of accessible stories for STEM. I found that Christopher's development of physics and computational knowledge was anchored by his careful attention to his physical sensations, his surprise and wonderment, and his epistemic affect and pursuit of what was "interesting" (in a disciplinary sense). Considering Christopher's disciplinary listening

helped me recognize that iterative feedback and attention to one's embodiment can inhere in disciplinary practice. Considering the many types of agencies in the learning environment, I recognized how students worked to both settle and desettle knowledge during their rich scientific inquiries. And by considering the agency of narrative and theory, our research team contributed to the work of noticing and building narratives for STEM with promise for ameliorative futures.

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Chapter 3:

Disciplinary conversations as material-dialogic pedagogy

In this chapter, I expand the use of postqualitative inquiry in STEM Education to (1) theorize relational ontology as compatible with STEM (which is not widely attempted), (2) better theorize epistemic affect as relational (which lets us see some *harm* as undesirably disciplinary), and (3) theorize relational development as disciplinary development (which helps us also see *care* as disciplinary). In the setting of an undergraduate computational physics course, I develop a material-dialogic framework of *disciplinary conversations* and consider design principles that emerged from our inquiry.

Introduction: Turning from disciplinary practices to relationships

Over the last decade, disciplinary standards have begun to reflect a turn towards framing disciplinary growth in STEM as the repetition and stabilization of situated cultural practices (National Governors Association, 2010; NGSS Lead States, 2013). In this chapter, I turn further: towards *disciplinary relationships* as a potential focus of analysis (Krishnamoorthy et al., 2021). Blending previous approaches towards material agency (Bang et al., 2018; Barad, 2003; Dominguez, 2019; Hetherington & Wegerif, 2018; Pickering, 1993; J. Rosiek et al., 2020), I develop perspectives of intra-, inter-, and extra-personal listening, speech, and conversations. I explore reframings of STEM that are more compatible with relational ontologies. And I will trace emergent design principles identified by our research group.

Specifically, I investigate: *In what ways do disciplinary conversations build and sustain disciplinary relationships?* I consider the interview transcript of a student in a computational physics course. Blending critical discourse analysis (Rogers, 2011) and postqualitative narrative inquiry (J. L. Rosiek & Snyder, 2020), I look carefully for the disciplinary relationships that shaped their positive experience. To motivate this work, I start by sharing a vignette to illuminate how relationships both enable and constrain performances of disciplinary practices.

Analytical vignette: Emerson's account of relational impacts

Emerson was a student taking an undergraduate computational physics course at a private liberal arts university in the Northeastern United States during the spring semester of 2019. The course is one site of our ongoing design research project (Bell, 2004; Cobb et al., 2003) to investigate students' changing relationships to tools, materials, peers, instructors, and the discipline. Names for students and the teaching assistant are pseudonyms.

Near the end of the semester, the Principal Investigator (PI) met with Emerson and one of their group mates (Ashley) for a semi-structured interview that lasted just a few minutes over an hour. A theme of the interview was the close peer-to-peer relationship that developed between Emerson and Ashley. About twenty-seven minutes into the interview, Emerson jokingly mentioned their sensibility to avoid instructor interaction:

ASHLEY; I don't think that we went to Tim ((the instructor, a co-PI)) with that particular problem. I think I kept feeling like I was on the brink of figuring it out but just never got there, so then I went to Emerson and was like 'okay, I've been working on this. Do you wanna get some fresh eyes on this and see if you can figure something out?'

INTERVIEWER; So you used each other a lot?

ASHLEY; Yeah. And then Emerson got something running, so then I was like, 'oh, we've got something,' and I still don't know what was wrong with the first one. But we got something moving, so we moved on with that.

INTERVIEWER; But it works now

EMERSON; Yeah. See—this is why we're a good team. We don't need no teachers.

When Ashley clarified that the instructor had indeed been a resource for help at times, Emerson agreed.

ASHLEY; I think my instinct was to go to—

EMERSON; We do. ((regarding whether they need teachers))

ASHLEY; Emerson and [I] go to web resources, and if that had failed I think we would have gone to Tim.

INTERVIEWER; But you were able to sort of sort it out?

ASHLEY; Mm-hmm ((affirmative)).

But Emerson also then revealed that they were not merely joking—they have developed a mistrust for interactions with teaching assistants (TAs) and instructors.

EMERSON; In the Comp Sci department—because I'm a Comp Sci major, right, at heart— I know it's different in other departments, but in the Comp Sci department it's not exactly a great environment in terms of asking your teachers for help. They have lots of teaching assistants, such as Dani— One of our group members, Ava, reportedly asked for a lot of help from Dani— That's a very CS thing to do—is ask the TA for help, not the teacher.

I choose here to use gender non-specific they/them/their pronouns to refer to Emerson. On the first day of the course, they happened to be the last person to share with the class their name, major, and pronouns. While many of the students shared their preferred pronouns with some awkwardness, Emerson was the only student to decline to answer. Below is the transcript of what they shared:

Hello everyone, I'm [Emerson]. Um..I..am a senior, studying..Computer Science, English, and ((voice slightly shaky)) Applied Physics in the School of Engineering; uh …((pause)) yeah.

Rather than forgetfulness or inexperience, their pause appeared to our research team to come from carefully weighing their options and impressions, but purposefully declining to share with the class. I have chosen they/them/their pronouns for Emerson as an attempt to leave space for Emerson's identity—not to assume or impose an identity without their input. By the time of the interview at the end of the semester, they imply that they self-identify as queer.

During the interview, Emerson continued to specify the ways that "asking your teachers for help" has been "not exactly" great for them. Emerson revealed that their reluctance to seek help was not only a type of learned cultural practice in their field—but the result of previous harm they experienced:

INTERVIEWER; Got it. And you felt like this course operated like that? Or people treated it as though they were more comfortable from their home discipline or something like that? Did you go to Dani ((the TA)) much?

EMERSON; I've never gone to a TA before because I went once, and then they were discriminatory against queer people and I just was like 'well, f**k it. I'm done.'

INTERVIEWER; 'I'll do this on my own', yeah.

EMERSON; But that was ((gestures away)) in the CS department, and that TA was not TA-ing again, after. So it was just a one-experience thing ((gestures as if they're throwing something over their shoulder)). But it doesn't matter.

At the end of the interview (about 30 minutes later), the interviewer asked if they "had anything else to share." Emerson first notes their appreciation for the course's vibrant online discussion. Then Emerson described the feeling of being watched by the camera as potentially "a bit scary." They positioned their own bravery as the result of their perception of safety in expressing their identity, and their willingness to be seen by others.

EMERSON; Yeah. I think that having a camera being pointed at you in class can be a bit scary sometimes. But I don't think that it ever changed the way that I behaved in class. But that's largely because I'm very comfortable with myself and who I am, and I don't mind people seeing me for who I am.

INTERVIEWER; You can imagine it has different effects for other people.

EMERSON; For other people, correct.

Ashley then began to position this feeling of uncomfortableness with being seen by others as correlated to one's confidence with their work.

ASHLEY; Yeah. I also kind of forgot about the cameras in class. I was aware that they were there, but they didn't really bother me. But yeah, if someone's less confident about their work, that might be uncomfortable for them.

Emerson then repositioned the explanation of their bravery back to the issue of visibility of their identity. Rather than implying that this stability of identity is essential to an individual, this time they describe the bravery to be seen by others as something that is constrained and enabled by context and community.

EMERSON; And that feeling, also, is very dependent on the space I'm in. So, when Ashley's around I'm very comfortable. But if it was just me in a room with some of the straight, White, cis[gender] guys in the room; I probably would all of a sudden not have been speaking as much, and then the camera would make it worse. And I'd just be like 'well, this sucks.' So it just depends how much of a community you have in the class at certain times too.

Emerson imagined how their bravery to be seen by others would be impacted by having less community ("but if it was just me in the room") or by having less certainty of their safety from mistreatment ("with some of the straight, White, cis guys in the room"). Emerson imagined the impact on their disciplinary engagement to be: "I probably would all of a sudden been not speaking as much."

Emerson's ability to find guidance and mentorship to enact disciplinary practices is enabled and constrained by their many relationships. Emerson reported that their sense of community and safety influences who they feel comfortable asking for help and how much they talk or engage with group mates. They are wary of interacting with instructors because of previous harm caused by an authority

figure in a disciplinary space. And Emerson's self-assessment was that they speak less when they are not comfortable to be seen for who they are.

Disciplinary relationships: Enabling and constraining disciplinary practices

We can infer that any disciplinary practice involving interpersonal communication (such as, asking questions, constructing explanations, engaging in argument, communicating information) will be constrained and enabled in complex ways by the relationships within a student's learning environment. Rather than merely conclude that interpersonal relationships are critically supportive of established disciplinary practices, I want to question further: Is our understanding of disciplinary development constrained by the perspective that individualized actions and practices are canonical units of analysis? Is it possible to consider relationships as irreducible defining elements of STEM? Practices of harm and care impact relationships—perhaps a perspective of *disciplinary relationships* would lead to greater attunement to the balance between relational harm and care in disciplinary settings.

Emerson's relationship with their community mediated their performance of disciplinary engagement. Emerson's agency to refine their disciplinary practices was mediated in part by their relationships with the instructor and the TA: Emerson's previous relationships constrained their ability to ask the instructor and TAs for help. Emerson also reported that their relationship with Ashley mediated their progress through the project: Emerson says that feeling comfortable and part of a good team impacts how their engagement. We see here that Emerson's agency for the performance of their identity is not separate from their agency for performance of disciplinary practices—such as collaborative meaning-making or argumentation. Emerson's relationships are entangled with their practices.

Practices and relationships influence each other cyclically. Actions emerge from relationships, and relationships are shaped and changed by actions. Disciplinary growth is typically characterized by the stability of disciplinary practices that emerge in contexts, but this perspective makes it hard to

notice the disciplinarity of the relationships that enable those practices. Conceptualizing STEM as a collection of disciplinary practices frames relationships as incidental to disciplinary "content". But there is a case to be made that Emerson's relational engagements were not any less "disciplinary".

During their project, Emerson and Ashley used the Runge-Kutta algorithm to help them model a double-pendulum system. In the previous two projects, the instructor designed exercises for the students to encounter this algorithm and others (such as the Bashford-Adams algorithm). When considering an algorithm as disciplinary content, it is not provocative to say that any future engagement with computational physics will be supported by coming to understand these algorithms. Even if Emerson were to never again encounter the Runge-Kutta algorithm, Emerson's engagement with it will shape their future practice and their overall understanding of computational physics. While describing the Understanding the details of what knowledge will transfer to other contexts is quite difficult. But it is uncontroversial to say that Emerson's disciplinary knowledge is shaped by these encounters.

Now consider a relational version using the same logic: Emerson's engagement with Ashley will also shape their future practice of computational physics—just as their engagement with a discriminatory TA continues to shape their disciplinary engagements. Like other disciplinary practices, Emerson's productive relational practices of working with Ashley are important experiences that will support other future disciplinary engagements. I would argue that the type of relationship that Emerson had with Ashley seems at least as important of an experience (if not more important) compared to Emerson's engagement with the Runge-Kutta algorithm.

If we imagine a student missing the opportunity to develop a positive relationship with the Runge-Kutta algorithm, this seems incredibly easier to remedy in the future than missing opportunities to develop positive working relationships with colleagues like Ashley. For instance, a beginning graduate student without experience with Runge-Kutta would spend some time to catch up. But without experience feeling supported by these types of disciplinary relationships and experience sustaining

disciplinary relationships, it is difficult to imagine a student ever making it to a graduate program in STEM.

Perspective shift: practices of harm are relational and also (unfortunately) "disciplinary"

With a turn of perspective, these relationships are more than just mediating disciplinary growth. The collection of many types of relations—healthy and unhealthy—with theory, materials, affect, and others can be seen *as* the discipline. And the growth of these relationships might instead be understood as to *be* disciplinary development.

This would also mean that harm and structural marginalization enacted through the discipline are relational trauma that *inheres* in STEM. Like other disciplinary behavior, actions that perpetuate harm and impact relationships are also enactments that shape how we understand disciplinary boundaries (Leyva, 2022; Philip et al., 2018; Prescod-Weinstein, 2020; Vakil, 2020). Consider some of the structural harm that inheres in mathematics: The actual practices of professional mathematicians maintain a niche literary genre (Netz, 2003)—significantly driven by aesthetics (Silver & Metzger, 1989), emotion (Lakatos, 1976), and community trust (Steingart, 2012). While at the same time, White supremacy shapes and is shaped by standardized testing (Knoester & Au, 2017) with ontological tools of "wrong answers" (Cunningham, 2019)—in a field that can often only be conceived as being about right/wrong answers (Muis, 2004). The harm enacted by White supremacy is enabled by a deeply entwined disciplinary aesthetic of right/wrong answers. If this aesthetic is not even universally compatible with the practices of professional mathematicians, then the massive ongoing harm should trigger a massive reconsideration of the narrative of mathematics as a domain of pure and correct knowledge.

There are no current *disciplinary* guidelines for noticing or attending to harm perpetuated in STEM learning environments. Relational analyses of harm and care are left out of our calculations for determining which practices will be "disciplinary." If it the very act of leaving out these relational

analyses remains a common disciplinary practice, then STEM will continue to complicitly enact harm. Joining other scholars (Gutiérrez, 2017; Martin, 2019), I wish to consider: *how might we shape a refusal to resist the character of STEM that is causing harm?*

Emergent design principle

The first emergent design principle from this relational shift of perspective is an intention to: *Design for strengthening relationships.* Emerson's relationship with Ashley grew during their computational physics course, and their relationship facilitated their disciplinary work. Emerson had a relationship with their identity as a computer scientist. And Emerson had a relationship with their embodied emotions and reactions to the way others affected them. These positive relationships supported Emerson's relationships to the physical and theoretical material of the course. However, the intention to design for strengthening relationships requires better answers to two questions: *What disciplinary relationships inhere in STEM? And, how would we be able to say anything about whether disciplinary relationships are growing or strengthening?*

Exploring a relational perspective of disciplinary conversations

Tracking changes to relationships can appear to be a difficult and nebulous goal. Discourse both shapes relationships and is shaped by relationships. We can imagine conversations as emerging from relationships, and we can imagine relationships as the sedimentations of many accumulating conversations. In order to describe *disciplinary relationships*, I explore a framing of STEM as a collection of many *disciplinary conversations*. I use a critical posthumanist (Murris, 2020) approach towards discourse and material agency to expansively reconceptualize conversations, speech, and listening.

My own formative STEM experiences were through Mathematics—where exploring the interplay of definitions, redefinitions, and implications is simultaneously playful and substantive. So, let us consider the following definition, and then explore how it changes our understanding.

Definition: disciplinary conversations

> Aligned with other material-dialogic approaches (Hetherington et al., 2018), I will conceptualize a conversation as an iterative cycle of attention and responsive action. If listening is any type of direction of attention, and speech is any type of action; then I will consider an agent to be engaged "in a conversation" exactly when they are iteratively speaking and listening. I characterize disciplinary conversations as those conversations that are shaped by the discipline and contribute to shaping the discipline.

Continuing the discipline may be a goal of science education, but perpetuating harm enacted by STEM is what needs to be noticed and stopped. If we understand disciplinarity to be continually embodied and negotiated, then the practices and boundaries of STEM are always open to *re*negotiation—towards a less harmful future.

Significance

There are many practices that seem to inhere in STEM disciplines despite being unpalatable: deficit talk (Byun, 2021), epistemological dominance (Andreotti et al., 2011), White empiricism (Prescod-Weinstein, 2020), gender disparities (Leyva, 2017), and more. These practices emerge from the many relationships that come to define STEM. Perhaps honestly/pessimistically labeling these, too, as "disciplinary practices" would help us begin to *accountably* change the practices, change the kinds of relationships, and change the impact that STEM enacts in the world. Strengthening relationships involves paying attention to the impacts of your actions. It seems plausible that if we saw "disciplinary development" as the development of *relationships*, then it be more difficult to ignore the harm that often happens in disciplinary contexts. Because of the harm repeatedly enacted through STEM, this approach is worth investigating.

Emotional experiences (including harm) are both deeply personal as well as interpersonal. Affect and harm can be theorized as individually embodied experiences of mind and body. Yet mind and body

can also be theorized to include interpersonal interaction (de Freitas & Sinclair, 2014). To accommodate these two approaches, I choose to consider connections between mind, body, and affect as *intra*-personal relationships (within a person and themselves).

By theorizing these seemingly individual processes into a broader social framework of discourse, students' disciplinary development can be seen to be fully mediated through relationships. Sociopolitical perspectives have highlighted the fundamental entanglement of culture, discourse, and *inter*-personal relationships in cognition, learning, and development (Gutiérrez, 2013; ojalehto & Medin, 2015; Philip et al., 2018; Przybyla-Kuchek, 2021). Posthuman perspectives have highlighted the fundamental entanglement of material agency and *extra*-personal relationships (between people and their environment) (Millar et al., 2013) in STEM (Jackson, 2013; Lemieux, 2021; Pickering, 1993, 2006). Additionally, research on (intra-personal) embodiment and epistemic affect have highlighted the entangled nature of mind and body in cognitive systems (de Freitas & Sinclair, 2014; Hannula, 2012; Jaber & Hammer, 2016b, 2016a; Lambert, 2019). Using these perspectives, *Can disciplinary growth be seen as growth of disciplinary relationships? Can disciplinary relationships be understood to develop through disciplinary conversations?*

I will explore approaching STEM with a relational onto-epistemology (Barad, 2003) with the broader purpose of better noticing and attending to harm and marginalization. There is a long history of connection between material agency, respect for agents, and maintaining/repairing relationships—both in Indigenous knowledge systems, and feminist and queer theoretical formulations of material agency (Barad, 2011, 2015; Hokowhitu, 2020; J. Rosiek et al., 2020; Todd, 2016). In this chapter, I make small adjustments to the conventional definitions of speech and listening to highlight commonalities between human-to-human relationships and more-than-human relationships. I will next explore how this change affects the stories that can be told about disciplinary relationships. I will be investigating which

conversations (with materials, theory, peers, instructors, affect, and identity) appeared to inhere in Emerson's trajectory through a project in a computational physics course.

Author Positionality

The knowledge in this chapter has come together through specific people and places. I am a White man living in the Northeastern region of North America. Our research team collaborated with the participants in this study during the Spring of 2019. Funded by the National Science Foundation (NSF), our broader design research project investigated how computational making projects could support flexible reconfigurings of students' relationships to tools, materials, and each other. This chapter was written during the COVID-19 pandemic.

I explore this framework of disciplinary conversations with an intention of making space for ethical relationality (Donald, 2012), disciplinary reciprocity (Gutiérrez, 2017), and multiple ways of knowing (Andreotti et al., 2011; Warren et al., 2020) that is not counter-productive to other work of Indigenous scholars (Ahenakew, 2016; Ahenakew et al., 2014; Gutiérrez, 2017; Todd, 2016; Tuck & Yang, 2012). But the agency of my settler background may still have impacts that "reify the (neo-)colonial categories, concepts, and structures even as we labour against them" (Higgins & Kim, 2019, p. 113), and I put myself in a space to be corrected.

Study context

The disciplinary setting for this work is an undergraduate computational physics course taught at a small liberal arts university in the Northeastern region of North America. One of the five projects of the course was to model the behavior of a physical construction made from everyday craft materials—string, magnets, wooden hoops, tape, dowels, and cardstock.

Figure 3.3: Students at the materials table. Miriam waves a pipe cleaner back and forth as a (humorously easy to make) "oscillator."

With the materials on display at a communal table, the students were invited to "make an oscillator." After constructing and refining an assemblage of materials, the students collected video data and used tracking software to create a data set of position coordinates. The students then designed and coded a computational model of the system.

Emergent modes of inquiry

Students were encouraged to be playful and expansive in the ways their constructions could be seen as oscillators. Initiated by the instructor Tim (who is also a co-PI), students joked with each other about any object that wiggled qualifying as an oscillator: a pipe cleaner swayed back and forth, a swinging dowel, the clicking of a ballpoint pen, etc.

Design-based research and Interaction Analysis

As a part of a larger collaborative design-based research project (Cobb et al., 2003), our data was collected with a methodology of Interaction Analysis (Jordan & Henderson, 1995) in mind. Our research team videorecorded classroom activities throughout the oscillator project, wrote field notes, and interacted with students with rapport-building questions and in situ interviewing.

Listening to others as a disciplinary practice

As I watched the project unfold, I started to notice a repetitive them of students paying close attention to their materials as they searched for oscillatory behavior to refine and amplify. The students making oscillators seemed to follow this general trajectory: Students would pick up materials that were close to them or that they found interesting. Students would hold and move the materials—picking up new materials to connect and search for oscillatory behavior. While talking with others, students listened to the ways their materials spoke back to them and excitedly declared to the group behavior of their materials that seemed interesting.

This type of listening resonates with John Shotter's dialogical formulations of *withness* and *attunement*. A scholar of Bakhtin and Vygotsky, Shotter characterizes withness-thinking (as dialogical) in contrast to aboutness-thinking (which is monological) (Shotter, 2010). Aboutness-thinking happens when we think in familiar terms: "repetitions and regularities, bodies of systematically connected knowledge, etc. of a kind already known to us" (p. 10). But ongoing events happen only once and can never be finalized—initiating a "continual concern for the unique" (p. 10). Withness-thinking occurs in these moments of uniqueness "when we allow the 'otherness' of the other to enter us and make us other" (p. 10). Shotter identifies listening as an ethical piece of dialogically-structured exchanges that is often missed: "we must begin to distinguish between merely *hearing* what a person is saying, or has said, and truly *listening to what uniquely they are in fact trying to say*" (Shotter, 2015, p. 10). Shotter's formulation of attunement captures a similar idea:

> In such listening without attunement, we listen for what is said, the propositional content, and we seek to assimilate what is said to what is already familiar to us—we take another's words and make them ours. We fail to meet the other as who in fact they are. In attending to patterns of already spoken words (what is said), we tend to miss what is felt, the expressive movement of a person's words in their speaking. By contrast, attuned listening—listening in a way in which we are oriented wholly towards the otherness of the other—entails letting their speech flow through us, so to speak, to such an extent that it 'move' us," (p. 10)

Our prompt to "make an oscillator" intentionally left space for students to configure (and reconfigure) their own relationships to the physical and conceptual material. Reading Shotter's work made us consider how these types of dialogical practices involve "retraining ourselves in a whole new set of 'ontological skills' at being a *particular kind of listener*, a *particular kind of looker*, a *particular kind of care-taker,* and so on" (p. 11). Shotter was a psychologist. But it struck us that this particular kind of listening, attunement, or withness-thinking is also an ontological skill of careful scientists and empathetic teachers (as well as a skill of a good therapist).

One class of disciplinary relationships is developed through careful listening and attunement to other people. Another class of disciplinary relationships is developed through careful listening and attunement to materials and theory. And Shotter also argues that "our 'inner lives' function in essentially the same communicative terms as our ordinary, everyday transactions with other people out in the world" (Shotter, 1993, p. 379). A third class of disciplinary relationships is developed through careful listening and attunement to self, identity, emotion, and embodied sensations.

Relational ontology

Relational ontology involves the viewpoints that relationships are ontologically prior to relata and that actions of agents reverberate through vast networks of relationships among more-than-human agents. Making a relational turn by

- considering relationships as a unit of analysis;
- considering materials and self as relational and conversational agents;
- considering the entanglements of care, harm, and ethics

is inherently a turn towards relational ontology.

The key metaphor I use to form meaning for the somewhat intimidating phrase *relational ontology* is from Mathematics. One of the most basic mathematical moves is to imagine two points, and then draw a line segment between them (just like Euclid's axiom). In this picture, the points existed first—we will say they were *ontologically prior*. Our understanding of what constituted the universe (for this story) was first those two points, and then the line was created between them. Picture the line as the relationship between those two points. Here, the objects in relation—relata—are ontologically prior; and our object-ontology involves the ability to separate them from the relationship between them.

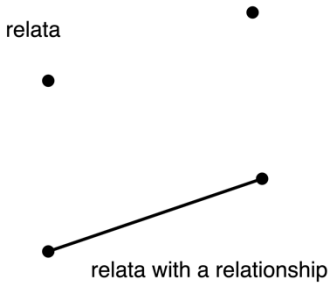
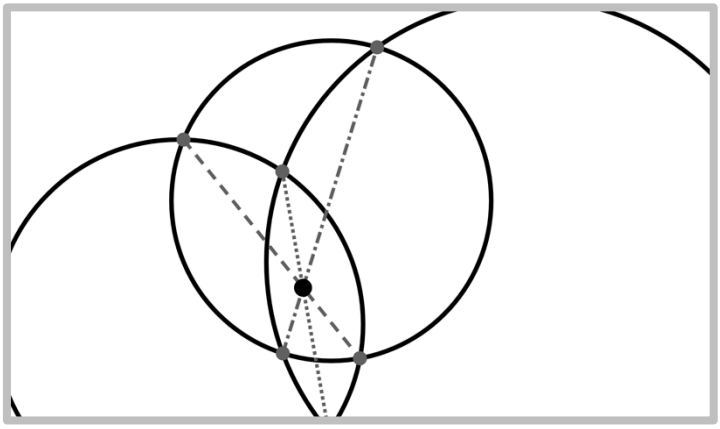


Figure 3.2

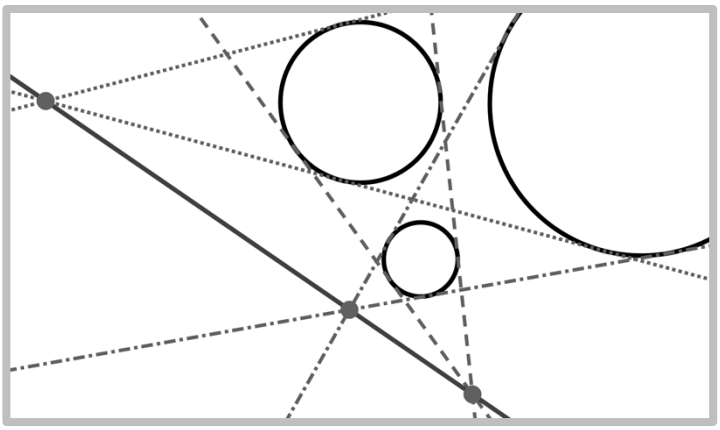


The common points between three circles determine three lines (one for each pair of circles) that surprisingly share a common point[1].

[1] To even understand what a sentence like this could mean, an important disciplinary practice is required: reading it over it *very* slowly while looking back at the picture…more than once…usually between 10 and 50 times. To understand if it is true or not is a different business. This particular statement is a theorem because it is difficult to determine whether or not it is true, but it is!

In the 19th century, mathematicians had a breakthrough, mind-expanding idea, about geometry. They realized that a surprising number of theorems[2] in geometry remained true if you swapped the words “points” and “lines”. They marveled that additionally swapping the ontological priority inherent in the definitions of points and lines created a duality between a geometry constructed from points and a geometry constructed from lines (as if they were complementary—or dual—realities). Using points as the ontological primitive, the common way to conceptualize a line (or, say, a circle) is as a particular collection of points (that lie on the line, or on the circle). But using lines as the ontological primitive, it is possible to conceptualize a point as the family of lines that pass through that point. If you playfully treat the *lines* as ontological primitives in this way, you can (surprisingly) formalize a precise duality between points/lines—which mathematicians first only noticed as a curiosity. A circle becomes a collection of tangent lines to the circle—rather than a collection of points on the circle. This kind of duality between theoretical spaces became a cornerstone of mathematics—underpinning the development of vectors, modern algebra, functional analysis, topology, mathematical physics, statistics, and more (for instance, the mathematics behind machine learning).

[2] Theorems are statements that give mathematicians disciplinary feelings of surprise to find out they are true. This perspective is part of what I unpack this perspective in more detail in chapter 4.



The common *lines* between three circles determine three *points* (one for each pair of circles) that surprisingly share a common *line*.

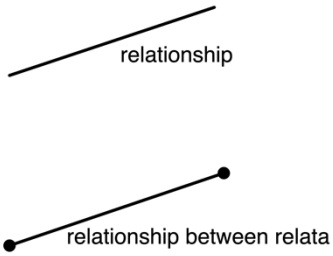


Figure 3.3

Consider this dual version of the mathematical move above: given a line segment, we can locate the two endpoints. In this version, it is the *line* (the relationship) that is ontologically prior to the points (relata). This is what *relational ontology* means to me at the most basic level: When we conceptualize the world and what it is composed of (ontology), the primitive elements are not objects (the relata) but relationships. As with the ambiguity between the ontological priority of points or lines when formulating geometry, there is an ambiguity between whether the relata or relationships must exist prior to the other. A point can either be conceptualized as an ontologically prior grain of sand, or conceptualized as (being "composed of" or "defined by") the family of lines that pass through it.

I notice that an ontology of a flat plane that is made up of all possible points makes it deceptively easy to pretend that I could simply separate one of those points—as if it were a grain of sand that could be removed. However, an ontology of the plane made up of all possible lines makes it harder for me to imagine how removing a point could even be possible. Every point (in this ontology) is fundamentally *defined* as an infinite family of connections to other points—and trying to separate that family of lines…would…what? lift the entire plane? It doesn't seem possible. But actually, this difficulty in imagining the separation is a key feature, not a sticking point. To build a better intuition for a relational ontology, I *want* to choose/remember that taking an individual away from their defining

relations is not possible. I *want* better control over when I slip into individualist thinking patterns. I *want* to develop a hesitation for conceptualizing an individual apart from their network of relationships that constrains and enables their behavior.

And this is how I see the idea of relationships as ontologically prior (i.e., *relational ontology*) to be implicitly linked to an *ethical responsibility* that comes from existing in a network of relations. If agents are ontologically determined as a collection of relations in a network, then they cannot be conceptualized, analyzed, or absolved separately from those relations. Meaning-making can no longer be understood as a project of building *accurate* representations of individualized agents and interactions. There is no non-agential representation that is separate from the relational act and agency of representing. Instead, meaning-making can be understood as practices of iteratively shifting the stories of relationships to create understanding through the repetition of themes (Murris & Bozalek, 2019; J. L. Rosiek & Snyder, 2020; Simpson, 2017).

As I have described it, the ambiguity between the ontological primitiveness of relationships or relata is similar to Karen Barad's (2003) description of *agential realism* as a formulation of *relational ontology*. This is worth noting because Karen Barad's work is influential within my grounding of literature.

For Barad, neither relata nor relationships pre-exist each other—they snap into being together with (what Barad calls) an *agential cut*:

> phenomena are ontologically primitive relations—relations without preexisting relata. ...a specific intra-action (involving a specific material configuration of the "apparatus of observation") enacts an *agential cut* (in contrast to a Cartesian cut—an inherent distinction—between subject and object) effecting a separation between 'subject' and 'object.' (2003, p. 815)

Barad describes agential realism's relational ontology as extending the relational implications of Judith Butler's (1988, 1990, 1993) theory of performativity to include material phenomena "without the anthropocentric limitations" (Barad, 2003, p. 822).

As our research team shaped the framework of disciplinary conversations, we followed this lead of Barad and Butler. Discursive practices are inherently relational, and agency emerges from phenomena and systems.

Indigenous Knowledges

Importantly, formulations of material agency and relational ontology are ideologically tied to *Indigenous ways of knowing and being* (Hokowhitu, 2020; Todd, 2016). While "there is no one 'Indigenous' cosmology or metaphysics," (Rosiek et al., 2020, p. 337) there are, however,

> repeated and consistent references to an understanding of the character of agency as something that emerges out of particular circumstances in such a way that its most salient features are missed if it is dealt with primarily as an abstraction. (Rosiek et al., 2020, p. 337)

For this reason, ethical engagement must proceed "in light of the history of colonization, displacement, and genocide" (Rosiek et al., 2020, p. 334). Eve Tuck writes: "There have been several 'turns,' including the ontological turn, the material turn, the spatial turn, each of which is actually a turn to where Indigenous people have always been" (2018, p. 15).

Indigenous relational ontologies and new materialist approaches share similar enactments of critiques of representationalism and anthropocentrism, similarly perform knowledge through iterative storytelling, and similarly investigate ethical implications of material agency (Hokowhitu, 2020; J. Rosiek et al., 2020). Yet coming from different traditions, scholars of Indigenous studies may not mention or choose to engage with poststructural lineages of thought—and are unlikely to self-describe their work as "posthumanist" or "new materialist." Likewise, authors of posthumanist scholarship sometimes only narrowly cite Western philosophers, only "read Indigenous work extractively, for discovery" (Smith et

al., 2018, p. 15), or are reluctant "to cite [Indigenous work] without significant mastery, or just avoidance of conflict altogether. This rationale for avoidance "is common and in turn can be seen as a performance of white privilege or white fragility" (Rosiek et al., 2020, p. 334).

Postqualitative research

Research in science education has begun incorporating relational approaches, Indigenous ontologies, and new materialist philosophy into the design and analyses of their justice-oriented learning environments (Kayumova & Dou, 2022; Keune et al., 2021; Krishnamoorthy et al., 2021; Marin & Bang, 2015). While it is not always explicitly stated, these approaches engage with a poststructural critique of representationalism (Barad, 2003; J. Rosiek & Gleason, 2017).

The incompatibility of poststructuralist philosophy with some common research methodologies (that are grounded in positivist or structuralist philosophy) is the reason why some scholars have chosen to describe their research as *postqualitative* (Lather & St. Pierre, 2013; Murris, 2020). Elizabeth St. Pierre (2021a) clarifies:

> following Derrida, deconstruction does not reject what it deconstructs. Rather, it overturns and displaces a structure to make room for something different. So *post qualitative inquiry is not a rejection of qualitative inquiry* or any other preexisting social science research methodology. (p. 5, emphasis added)

Relational ontology leads to a critique of representationalist methodologies because the "subject" to be represented comes into being through its emergent relations—including relations with the representor and the material performances of representation. Qualitative methodology that assumes a non-agential representation of knowledge can be extracted or constructed from data is not compatible with relational ontology (Garroutte & Westcott, 2013; Higgins & Kim, 2019; Murris, 2022).

Narratives defining STEM

Later in the project, we noticed that the students were building their computational models in iterative and discursive ways. Not only did they fit their computational models to match the behavior of their oscillators—they also modified their oscillators to better align with their computational models. While not completely surprising, this was interesting to us because of the ways it subverts a narrative about STEM.

Scientific modeling practices tend to be either framed as discoveries of increasingly better 'models of' the world or as the constructions of cognitive agents that build 'models for' particular epistemic purposes (Gouvea & Passmore, 2017). Both of these approaches treat scientific models as existing as representations separate from the world they represent. The presumed inertness of the representations and neutrality of the representation process can then dangerously be used to legitimize the actions of those wielding the representation. While plenty of scientific knowledge is *not* weaponized in problematic ways, the narrative of Western Modern Science as a universal neutral frame of reference is repeatedly used to enact colonial violence (Warren et al., 2020).

Modeling is sometimes framed as a process of accurately controlling the environment or dominating others with authoritative knowledge. But we also noticed that our students' disciplinary work could be seen through a lens of reciprocity, care, and dialogicality. The students were both listening and responding to their materials and physical theories. The students were building relationships with their materials, each other, and themselves and crafting narratives about the ways the materials and theory were related. This perspective was interesting to us because it is better aligned with performative understandings of knowledge, frameworks of material agency, and relational ontology. Conceptualizing relationships (rather than relata) as irreducible elements of reality is a defining feature of relational ontology—but not a straightforward idea to square with some of the foundational narratives of STEM (such as modeling as either the discovery or construction of objective knowledge).

Narrative inquiry

Drawing from both new materialist philosophy and Indigenous studies scholarship, Rosiek and Snyder (2020) use the term *narrative inquiry* to refer to approaches that acknowledge the agency of methodology, results, analysis, ontological innovations, etc. In these relational frameworks, an agent is an emergent performance of its defining relations with other agents (including us). In that sense,

> An inquirer and the object of their study have already been shaped by one another by the time the inquiry is underway. The "objects" of our inquiry are partially constituted by the way we frame our questions and by the material features of our inquiry apparatuses. (J. L. Rosiek & Snyder, 2020, p. 1152)

Rosiek and Snyder describe narrative inquiry "as a process of reimagining the possibilities within experience that ontologically transforms a person's relation to his or her vocational activity" (2020, p. 1158). Narrative inquiry searches for "modes of representation that include performative elements that draw attention to how the narrating process coconstitutes the writer, reader, and focus of study" (J. L. Rosiek & Snyder, 2020, p. 1157).

As our research group began to consider disciplinary listening as a description of our students' behavior, we also began to question how narratives that uphold the ontology of STEM intertwine with other oppressive cultural dynamics. While themes of extraction, dominance, and control are interwoven through STEM; we noticed that themes of reciprocity, attunement, and care are (or could) also be woven through narratives of STEM. We began an inquiry to re/write (Roth, 2012) a narrative of STEM that was more compatible with relational ontologies.

Emergent design principle

A second design principle emerges from this shift in perspective towards relational ontology, postqualitative research, and narrative inquiry: *Identify harmful narratives of STEM, and seek ways to subvert or supplant these narratives.* Cash Ahenakew (2016) argues for "historicizing the referents that

circumscribe Western frameworks of reasoning so that we can recognize these referents in our researcher selves and in our writing" (p. 337). In our design-research project, we noticed themes of Western supremacy within some enactments of computational modeling.

Leanne Betasamosake Simpson (2017) has also problematized typical enactments of the concept of *abstraction*—a defining element of computational thinking (Weintrop et al., 2016; Wing, 2011). Abstraction is sometimes characterized as an extraction of meaning and knowledge out of the contexts and "relationships that give it meaning" (p. 202). Extraction of resources from the people and places that create them a theme at the heart of settler colonialism and capitalism. When enacted as an extraction of meaning from the relationships that produce knowledge, abstraction is reified as another instance of Western supremacist logics. Simpson writes that as a concept in Nishnaabeg aesthetics, abstraction can instead be characterized as "shifting the relationality to change meaning or to illuminate a different meaning" (p. 202).

In our design-research study, we began to think of computational modeling in these relational terms: a process to look carefully at the world and use physical theories and algorithmic technology to craft new narratives of the relationships between agents.

Limitations

Here it is important to explicitly note three ways that this work should *not* be interpreted. (1) Consistent with critiques of representationalism, the narratives in this chapter are *not* presentations of "evidence." The inquiry is a reformulation of a narrative of Emerson's disciplinary relationships using the framework of disciplinary conversations. (2) While the framework of disciplinary conversations is intended to be compatible with relational ontologies, it is *not* a universal framework. Even relational frameworks hold the possibility of enacting harm or being complicit in larger patterns of violence. More importantly, similarities between the framework of disciplinary conversations and Indigenous ways of

knowing and being are intended as respectful engagement with Indigenous studies literature (Hokowhitu, 2020; J. Rosiek et al., 2020; Todd, 2016) but critique is welcomed.

Crucially, (3) postqualitative research involves iteratively re-turning to narratives to seek perspectives that have been missed or invisibilized. While the goal of postqualitative work is "experimentation and the creation of the new, which is very difficult" (St. Pierre, 2021, p. 6), new narratives are *not* final narratives. Jack Halberstam writes that "dominant history teems with the remnants of alternative possibilities, and the job of the subversive intellectual is *to trace the lines of the worlds they conjured and left behind*" (2011, p.19, emphasis added). Like Halberstam's formulation of low theory, narrative inquiry involves an *iterative* drive to "untrain ourselves so that we can read the struggles and debates back into questions that seem settled and resolved" (2011, p. 11). One instance of narrative inquiry—or any type of postqualitative research—should never be assumed to have accounted for everything.

Critical discourse analysis

I orient this chapter as narrative inquiry, and I am explicit about my postqualitative approach to keep the intra-action (Barad, 2003) of the framework with my meaning-making process at the forefront of my methods. But throughout our data collection and review, our strengthening perspective of the centrality of discourse in shaping disciplinary relationships also heightened our attention towards scholarship in critical discourse analysis (Rogers, 2011).

We began to inquire which agents were in conversation with students throughout the computational making and modeling process. We began to take seriously the actions of the materials as the speech of agents and the listening of our students as an important disciplinary practice, and sought out relevant literature (Gourlay, 2015; Rowe, 2011). Noticing that the students often playfully talked to their materials (or talked back to them), I experimented with transcribing the action of materials as speech.

One such experiment involved a different group of students (Christopher, Miriam, and Dex) and their explorations with materials on the first day of the making project. Their interactions with their materials, each other, and their emotions felt to me to be foundational elements of their further work (to build a more refined oscillator and computational model). But it was difficult for me to explain (to myself or others) why I would feel that way using only transcript of their speech. I experimented with supplementing the transcript with descriptions of their actions, and experimented with positioning the materials as agents with which the students were building disciplinary relationships (subscripts and brackets indicate instances of overlapping talk):

[00:00:14.07]

CHRISTOPHER; ((Holds the magnet in his right hand and the string in his left. His hands are about 12 in apart, and he's holding the string taut. He's looking at the Magnet throughout.))

Screenshot 3.1, [00:00:14.07]: Christopher (left). Dex (middle). Miriam (right, back to camera). Christopher holds the magnet-pendulum.

CHRISTOPHER; ((lets go of the magnet))

MAGNET; ((swings like a pendulum for two periods))

[00:00:15.23]

CHRISTOPHER; Alright, we got a swinger.

Screenshot 3.2, [00:00:16.12]: The Magnet swings like a pendulum for two periods.

[00:00:16.26]

DEX; ((turns around and looks))

[00:00:17.12]

MIRIAM; ((turns her head and looks))

[00:00:18.08]

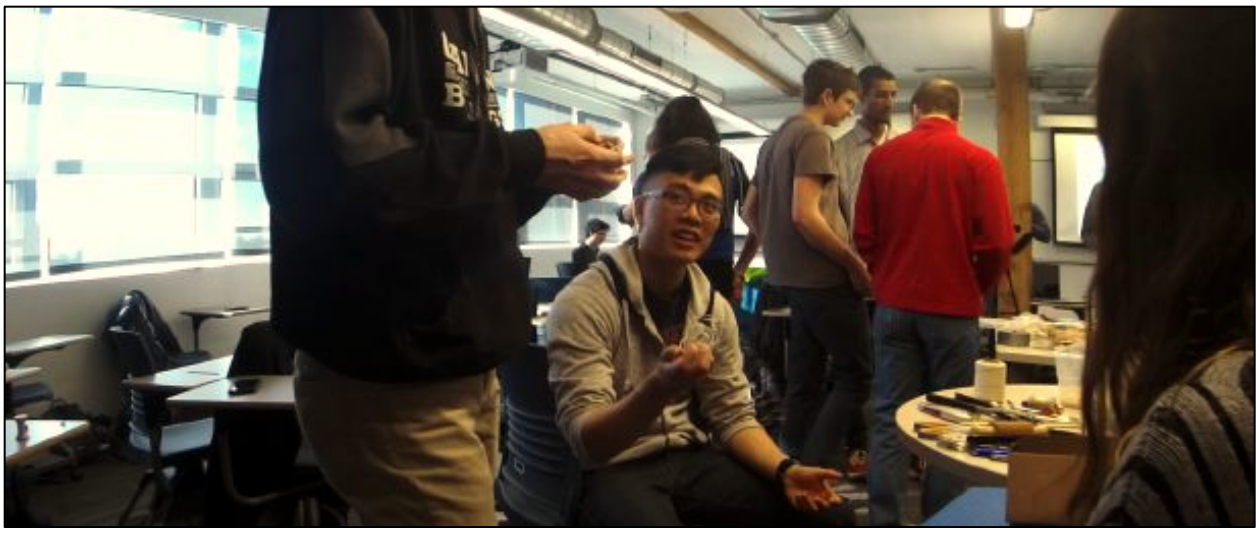
MIRIAM; woo[1]ooo!

CHRISTOPHER; [1]an oscillator, let's say [2][((laughs))

DEX; ((looks to his left, and then back at the string-magnet pair))

MIRIAM; [2]an oscillator.

MIRIAM; Yeah, that counts. [3]We've got [4]SO many [5]oscillators.



Screenshot 3.3, [00:00:23.11]. Dex holding the Spring.

[00:00:23.11]

DEX; [3][((lifts the coil of wire he's been holding—now shaped like a SPRING))

[4][((mouth opens))

[5][((He lets it fall. He swings it in a circle.))

INTERRUPTING STUDENT; Can I get a cutting board?

MIRIAM; Sorry. Yeah.

CHRISTOPHER; ((Is already standing. Reaches to the table, and hands a cutting board to him.))

[00:00:32.27]

DEX; And we have this too. ((He pulls apart the coil of wire to let it spring.))

SPRING; ((springs))

MIRIAM; Perfect!

After transcribing, I wrote the following analytical memo:

As the students create new material participants with their dialogue, they introduce the newcomers to the rest of the group. The students watch both new oscillators behave. The students'

reactions of paying attention to the newcomers could be interpreted as welcoming the material participants to the group.

The students have been playfully making and finding materials that can exhibit oscillatory behavior. As Christopher finishes a separate utterance on the border between a joke and advice (prior to the transcription), his hands finish attaching a magnet to a length of string. The magnet swings, and Christopher does not interrupt it to speak until it has swung twice. He then says playfully, “Alright, we got a swinger.” His introduction is met with enthusiasm. Both Miriam and Dex look over, and Miriam says, “wooooo!” in repsonse. Christopher’s gaze drifts from his magnet to Miriam and the string that she is tying to a different magnet. His gaze pauses between Dex and Miriam, and then he looks at his swinging magnet again as he purses his lips to one side and smiles. He appears to be thinking of what to say next as well as continuing to watch the magnet’s behavior. Christopher’s eyebrows raise high when he interjects, “An oscillator, let’s say.”

The students built momentum for the work they were starting by listening to each other’s laughter and by mixing playfulness with other aspects of disciplinary content. Christopher shares a joke that simultaneously shares some disciplinary wisdom as well as humor. By looking and laughing, Miriam shows that she is listening and bonding. The magnet swings at the end of its string. Christopher continues with a playful description of the pendulum as a “swinger.” Miriam responds positively again. Christopher reframes his description to include the language introduced by the instructor (an “oscillator”). Miriam amplifies this language. And adds to their dialogue in the same way that one would amplify or extend a joke. She says, “We’ve got SO many oscillators.”

Dex attempts to add to this momentum, but he chooses to not talk over Miriam. He listens for when an appropriate point of entry might arise. He starts to speak, but he waits. After Miriam has finished and the interruption from the other student has passed, Alex introduces another material for consideration. He builds on Miriam’s playful utterance of “SO many” by framing the material he has

been holding as yet another ["*And* we have this *too*." (emphasis added)] in their growing list of oscillators. To some extent, this list of oscillators also acts as evidence that they are making good progress. He then primes the coil of wire to perform in a particular way. The coil of wire responds in a similar way to how one might behave when prompted to introduce yourself. Miriam addresses both Dex and the coil of wire positively: "Perfect!"

Moments such as this one shaped my thinking about disciplinary conversations and disciplinary relationships. I began to wonder if all disciplinary practices could be framed as different types of conversations with many more-than-human agents. This line of inquiry was interesting to me because of the different types of narratives that shape enactments of STEM. A framework of disciplinary conversations seemed better aligned with relational ontology, better at making space for practices of listening and the creation of new narratives, and better at framing practices to notice and repair harm as disciplinary.

Emerson and Ashley's interview

After Emerson and Ashley's interview was conducted, our research team was surprised by how many relational moments had surfaced. We chose to use this interview as a site for deeper analysis. Our research team wondered if we could consider Emerson's experience to be prototypical of the disciplinary growth we might hope a learning environment would facilitate. To shape meaning for the idea of "strengthening one's disciplinary relationships," Emerson's developing relationship to computational physics appeared to our research team to exemplify what we would wish to characterize as positive disciplinary growth.

Before this course, Emerson had coded video games and posted them to their personal website as well as github. During the course, they were easy-going, charming, and confident in their physics and programming knowledge. They frequently carried a Rubik's cube, and at the time of the course sold custom parts and cases for various sizes of Rubik's cubes through their online shop. Throughout this

project, Emerson's charisma, facility with coding, and experience with Physics helped position them as a leader in the group. However, we also noticed that they sometimes deemphasized their authority and distributed power across the group. They worked hard, and their projects grew more sophisticated throughout the course. In the view of the instructor and research team, their experience and growth in the course was as positive as we might hope.

We ask: Does it make sense to consider "developing a stronger disciplinary relationship" to be the instructional goal of a course? If that were to become our goal, how should we think about what it means to strengthen a disciplinary relationship? If we *assume* that Emerson's relationship to computational physics grew through the course, a way to understand that growth might be to look for the many disciplinary conversations that Emerson was part of.

Methodological orientation

I first came to the interview transcript with our framework and the methodology of critical discourse analysis in mind. Consistent with both critical discourse analysis and Interaction Analysis, I engaged with our data iteratively and collaboratively to reflect on moments in the transcript that represented different kinds of speech and listening. Through repeated viewing of the video while reading the transcript, I generated memos in between lines of dialogue. The moments were reviewed, sorted thematically, and repeatedly refined collaboratively with our research team. I then wrote broader analytical memos that summarized Emerson's disciplinary conversations that could be inferred from the interview data.

The memos have been iteratively refined by the research team into accounts of Emerson's disciplinary conversations. I have theorized three scales of relational engagement: extra-personal conversations and relationships with materials and theory, inter-personal conversations and relationships with other peers and instructors, and intra-personal conversations and relationships with embodiment and identity.

The moments were interpreted through underlying assumptions that are shared by both Interaction Analysis and critical discourse analysis: “knowledge and action are fundamentally social in origin, organization, and use, and are situated in particular social and material ecologies” (Jordan & Henderson, 1995, p. 41), and “language-in-use is always part and parcel of, and partially constitutive of, specific social practices, and that social practices always have implications for inherently political things” (Gee, 2011, p. 28). My research question: “In what ways do disciplinary conversations build and sustain disciplinary relationships?” intentionally echoes Gee’s (2011) question of “how language builds and sustains relationships” (one of “seven building tasks” (p. 30) of language).

However, the perspective of disciplinary conversations should be understood as a critical posthumanist (Murris et al., 2021) framework explored through the postqualitative approach of narrative inquiry (J. L. Rosiek & Snyder, 2020). In this chapter, I am asking: *What forms of listening exist within STEM? What disciplinary conversations do we notice? How do disciplinary conversations build and sustain disciplinary relationships?* At this time, these questions do not make sense as attempts to represent a model of reality. Evidence cannot be produced to validate a representation of a student’s “relationship to the discipline” from within an ontology of (ontologically primitive) disciplinary actions and interactions. Instead, my exploratory relational redefinitions of “speech” and “listening” are designed to holistically describe something about the slippery category of “relationships”—just as quantitative test scores are designed to holistically describe something about the slippery category of “knowledge” (within an ontology that conceptualizes “knowledge” as an object that you “have”). Rather than constructing or verifying a representation, my goal in this chapter is to explore and create other narratives of STEM that are less resonant with the logics of Western supremacy.

I wish to “shift the relationality” of Emerson’s development “to illuminate a different meaning” (Simpson, 2017, p. 202) of how Emerson strengthened their relationship to disciplinary practices in physics. Taking Emerson’s experience as an example of positive disciplinary development, I will consider

how Emerson's disciplinary conversations might be framed as evidence of disciplinary relational growth. *What might it look like to frame disciplinary development as relational growth, and relational growth as the accumulation of disciplinary conversations?* This question is about re-turning to Emerson's story and building a new narrative—which requires postqualitative inquiry.

Specialized research

I will be exploring conceptions of *disciplinary speech, listening,* and *conversations* with more-than-human agents. The concept of disciplinary "listening" is similar to Higinio Dominguez's relational theorization of reciprocal noticing (Dominguez, 2019, 2021). And the concept of "speech" among more-than-human agents is consistent with a material-dialogic approach (Hetherington et al., 2018; Hetherington & Wegerif, 2018) to STEM Education. To help relate this chapter to other contemporary research, I will summarize these two research streams.

Material-dialogic pedagogy: Akin to disciplinary speech and conversations

Hetherington, Hardman, Noakes, and Wegerif (2018) notice that established theoretical grounding for "dialogic pedagogy" can already "account for how pupils engaging in science learning will be simultaneously talking and thinking as well as using their bodies to sense and manipulate their environment" (p. 143). However, Hetherington and Wegerif (2018) note that "the idea that materials might enter into dialogic learning is not obvious and requires a new theory if it is to make sense" (p. 29). The authors draw from Barad's agential realist formulation of relational ontology and material-discursive practices to extend dialogic pedagogy to include material agency: as *material-dialogic pedagogy*.

Bakhtinian concepts (originating in the field of literary criticism) have enriched scholarly discourse in many disciplines, including education (Ball et al., 2004; Matusov, 2007) and the learning sciences (Greene et al., 2016; Hsu & Roth, 2014; Kubli, 2005; Rosebery et al., 2010; Roth, 2009). From a Bakhtinian perspective, speech "is always cast in the form of an utterance belonging to a particular

speaking subject, and outside this form it cannot exist" (Bakhtin, 1986, p. 71). With this orientation, verbal and nonverbal communication (like a mathematical proof, a scientific journal article, the code for a human-computer interface, an algorithm, a verbal explanation, or any representational artifact) are types of utterances between author and audience that exist in a larger, living, dynamic conversation with previous and subsequent utterances—and capable of containing multiple overtones of meaning. Futhermore, "knowledge is a phenomenon that emerges through dialogic interactions" (Hetherington & Wegerif, 2018, p. 28).

In *Making the case for a material-dialogic approach to science education* (Hetherington et al., 2018), the authors argue that "dialogic pedagogy has a relational ontology" (p. 160) and offer a "diffractive reading of Bakhtinian theory and Agential Realism [to raise] questions of pedagogy" (p. 167). A diffractive reading is a postqualitative approach of "rethinking issues by reading theorists or different theories and data through each other" (Bozalek et al., 2016, p. 2). They modify concepts from dialogic pedagogy (such as 'dialogic space' and 'dialogic switching') to remedy an under-theorization of "the role of the material in science education" (Hetherington et al., 2018, p. 169):

> In the same way that dialogic pedagogy prompts specific ways of working that foster exploratory talk (using collaborative activity, avoiding an 'initiation-response-feedback' (IRF) pattern of teacher talk, or using question prompts for example), a material-dialogic pedagogy builds on these but deliberately draws in the material. Teachers employing a material-dialogic pedagogy would purposefully break away from a linear sequence of practical work, observation, discussion and conclusion and instead consider other lesson structures. (p. 168)

In *Developing a material-dialogic approach to pedagogy to guide science teacher education*, Hetherington and Wegerif (2018) report on an international design-based research study "to explore theory-driven science education pedagogies" (p. 31). They found that teachers can find dialogic pedagogy difficult—needing further support through pedagogical framing and personal guidance. They

also found that teachers did not spontaneously consider materials being part of the dialogue (regardless of whether they were thinking about dialogic pedagogy). The results of their large-scale survey highlighted "the role of material resources in science education" (p. 32). Their interview findings also showed that dialogue was valued by teachers and played a role in enactments of learning. However, they found "little evidence of clear pedagogical thinking about the role of these materials in the dialogue" (p. 35). They also found that

> although teachers value pupil discussion in science and link this to teaching the nature of science, there is not always a strong sense that those experienced teachers who are involved in teaching student teachers are confident in using dialogic pedagogy even in a school involved in practice-based research in this area. (p. 40)

They argue that a material-dialogic approach could support a justice-oriented dialogic approach, emphasize the role of materials, and lead science teachers to "consider how their choices of materials and communication tools intra-act in dialogue with themselves and their pupils in generating emergent learning" (p. 40). Exploring a framework of disciplinary conversations, I extend material-dialogic pedagogy into the specific contexts of a making project and a computational physics course.

Reciprocal noticing: Akin to disciplinary listening

Higinio Dominguez historicizes teacher noticing (Dindyal et al., 2021) as a type of relational care, and develops a framework to shift the relationality of meaning-making interactions using relational ideas from Indigenous Knowledges and agential realism (2019, 2021). Dominguez describes his framework emerging from "an elaboration on what might be the most generative and interactive dimension of noticing: attracting, enlisting, or drawing others to attend to what one is currently noticing" (2021, p. 46). For Dominguez, "to reciprocate is to assume *reversible roles* as knowers in relationships, aware of and responsible for each others' learning" (2019, p. 77); and he theorizes

reciprocal noticing as "a relational practice through which teachers and students exchange roles as knowers by reciprocating each other's noticing as they study mathematics concepts" (2019, p. 75).

Dominguez outlines a methodology for reciprocal noticing that includes three steps: "occasioning of moments of reciprocal noticing" (2019, p. 78) to intentionally promote the "emergence of reciprocity in noticing" (2019, p. 78), "making sense of those moments" (2019, p. 78) by "selecting and transcribing moments that were rich in relationships" (2019, p. 78), and "following the mobility of a concept" (p. 78) by analyzing "how references to past and future understanding mobilize a concept along with participants' relationship to that concept (2019, p. 78). Dominguez finds that "focusing on the reciprocity in noticing reveals images of teachers and students engaged in something that is relevant for both: mathematical concepts" (2019, p. 87) and that this perspective decenters the human, relationally mobilizes mathematical concepts, and reacquaints sensing and making-sense in ways that cognitive approaches to noticing do not (2021). He positions this perspective of reciprocal noticing as located "not in the minds of individual teachers or students, but in the space and time that these vibrant bodies cocreate with other vibrant nonhuman bodies" (2021, p. 53).

Dominguez (2019, 2021) frames *reciprocal noticing* as supportive of culturally sustaining pedagogy (Paris & Alim, 2014): "when student's cultural ways of understanding are reciprocated, different ways of knowing create unity in the learning of diverse students and teachers" (Dominguez, 2019, p. 77). I see something in common between the careful listening done by a restorative justice practitioner (paying close attention to the needs of their rightsholders), the careful listening done by a teacher (paying close attention to the thoughts and resources of their student), and the careful listening done by a scientist (paying close attention to the ways materials and theory push back on their understanding). With similar intention and theoretical background as Dominguez, I frame disciplinary listening as a practice of paying attention, noticing, and trying to understand an agent more deeply.

Operationalizing disciplinary conversations

To investigate my research question (In what ways do disciplinary conversations build and sustain disciplinary relationships?), I present an account of the disciplinary relationships that we can infer that Emerson developed. At the scales of extra-, inter-, and intra-personal conversations, I ask: *What disciplinary relationships did Emerson cultivate through the oscillator project? What disciplinary conversations can we infer Emerson engaged in? And can we see any evidence of strengthening disciplinary relationships?*

Emergent design principle

Another emergent design principle from this inquiry is the intention to: Iteratively inquire about which disciplinary conversations are being facilitated in a learning environment. Which conversations are being constrained? What disciplinary conversations would be desirable? And which agents' voices are still missing?

Emerson's extra-personal conversations: Tools, materials, and theories

- What relationships to tools, materials, and theory did Emerson cultivate through the oscillator project?
- What extra-personal conversations can we infer Emerson engaged in?
- And can we see any evidence of strengthening disciplinary relationships?

The design of the oscillator project put Emerson and Ashley in close contact with materials. Their first assemblage essentially involved multiple simple harmonic oscillators. When they presented what they had made to the rest of the class, Emerson joked that their goal "was to make the most oscillators out of one device as possible." Later, they decided to construct a new oscillator. They said that they made something that might act like a double-pendulum system because it was "chaotic" and "more interesting." At the initial conditions they modeled, an idealized double-pendulum does not, in fact, exhibit sensitivity to initial conditions in the sense of chaos theory. But because of the double-pendulum system's connection to the development of chaos theory, Emerson and Ashley wove the

descriptor of “chaotic” into the identity of their oscillator. For them, “chaotic” also meant strange, interesting, and worth getting to know better. Not unlike chatting with multiple acquaintances, Emerson and Ashley listened to each system to see what it had to say. Their choice to work with the double-pendulum involved considerations of how it spoke back to them and the potential they saw in a future engaging relationship.

The students’ unique material circumstances were inseparable from their experience building and modeling their oscillator. Hence, Emerson’s disciplinary conversations were uniquely personal and impact their relationship to theory and practice in uniquely personal ways. Consider the following section of interview transcript concerning Emerson’s entangled interactions with (1) the physical system they created (the double pendulum), (2) idiosyncrasies of their filming setup (glare), (3) the motion capture software (called Tracker), (4) equations governing the behavior of a double-pendulum, (5) the computational method of the Runge-Kutta algorithm, (6) grammar of programming languages (Python and C), and (7) the specifics of Emerson’s computer hardware:

ASHLEY; I mentioned this before, but I got really stuck on the Runge-Kutta implementation ((a short-hand name for a computational algorithm)), ... And then I sent all my code to Emerson and I was like ‘I’m not seeing what’s wrong with this. Can you take a look at it and see what you can figure out?’.

EMERSON; And then I changed it from Python to C, and got it working. And then it was illegible in python because it was C code, but we put it back into Python for submission. So—but either way—the Runge-Kutta was a big thing. For me personally, the most frustrating thing was the tracking—like I said, I spent seven hours in the first thing of data. I also was the one who got the tracking data that we finally used for the double pendulum. And that also took five, six hours.

INTERVIEWER; So you said in the first [iteration] it was a lot to do with the frame of reference, and wiggle. Same problems with the double pendulum or—?

EMERSON; In this one we didn't really have many of those problems. It was just that as the pendulum swings, light would glint off of it in a different way.

INTERVIEWER; So it would throw the tracking sensor off.

EMERSON; So three times per revolution, I would have to manually re-click on it. And not only did I have to manually re-click on it, I also had to do a bunch of labor to remove data points that I had incorrectly labeled.

INTERVIEWER; Because of the glare or whatever?

EMERSON; Yes. And since the software is so janky, and my computer is not very fast, every click takes about a minute.

Emerson's disciplinary development is entangled in these specifics of their disciplinary conversations. As the pendulum swung back and forth, light would "glint off of it in a different way" and throw the tracking sensor "off". As Emerson was filming and examining the video, they listened by watching carefully—tuning their sense of how they expected the software to respond compared to how it did respond. Emerson "took five, six hours" to reply to all of the software's misspeech: they manually recentered the focal point of the software's tracking algorithm. Emerson carefully cleaned the data by iteratively looking (Emerson's listening) for data points to remove or recalculate (Emerson's speech). Throughout this process, Emerson was also in conversation with the limitations of their "janky" computer. All of these modes of listening and responding wore pathways of connection between Emerson and the material components of this system—which produced an important disciplinary component of their work (the dataset).

Their work emerged from these many entangled interactions, so the momentum of their work depended on how well the disciplinary conversations flowed and felt engaging to Emerson and Ashley.

Ashley was initially in charge of the computational model (for the equations of motion). Emerson carefully read over Ashley's Python code to listen to what it was saying. Emerson chose to work with another programming language (C); so, we can infer that Emerson must not have been clear on how to respond directly to this type of speech. Because of this emergent agency of the code, Emerson's careful listening (to Ashley's Python code and the equations of motion and computational algorithm) led to speaking back through their own computational model (this time coded in C). Emerson and Ashley decided that this computational model was a better representation for their system, and then translated this code back into Python (the default submission format was a Jupyter Notebook, and Python the default presumption).

Emerson's work involved conversations with material specificities of their oscillator (the Tracker software, and their computer) and theoretical specificities of the equations of motion, computational algorithm, and programming language. Due to these disciplinary conversations with materials, Emerson reported a positive shift in their identity as a maker. When asked if this course had changed the way Emerson thinks about themselves as a student, Emerson at first suggested that they "know it did, but I just don't really think that I can put it into words." With an invitation to articulate more, they shared that the oscillator project "kind of sparked this thing in me—where all I wanted to do was build." They continued, "I started viewing myself as learning as 'a mechanical engineering kind of individual.' And I started hanging out in mechanical engineering spaces a lot."

Emerson's inter-personal conversations: Ashley and others

- What relationships with other group members and instructors did Emerson cultivate through the oscillator project?
- What inter-personal conversations can we infer Emerson engaged in?
- And can we see any evidence of strengthening disciplinary relationships?

It was clear throughout the interview that Emerson's robust philosophy of relationships must have begun its development before this project began. We could see this in the way they talked about their past experiences:

EMERSON; ... You share a collective head space. When I worked at [Company], the Slack channel was always [crashing]—and that was the company that I got crazy tons of work done. And a lot of it was just because I pinged a question—someone would answer it immediately. I didn't necessarily know who this person was, but we all just were sharing information we knew.

We can infer that the relational philosophy Emerson brought to the course would have continued to be practiced and exercised through the group work built in to our course design. Emerson articulated passionate viewpoints about the importance of developing and maintaining disciplinary relationships:

EMERSON; So that kind of communication is what I'm talking about. That's what makes things fast.

ASHLEY; So we were actually doing—individually—things we hadn't done as much before. In the first project Emerson and I worked together in, Emerson did the Runge-Kutta, and I did some more visualization, and we kind of switched. But then supported each other.

INTERVIEWER; ... Did you feel like your ideas mattered when you were working with your partners?

ASHLEY; Yes.

EMERSON; Always. Yeah, no, that's one of the most important things. I always think that if anybody on a team that I'm on thinks that their ideas don't matter, it's code red, I shut down everything. And I just get that back on track. That's how I deal

> even with my [significant other]. If they ever say something to me that's in a dejected voice or showing their wasn't enough respect given to an idea, I just shut everything down and I'm like 'okay, we're going to bring back that respect for your idea, because it was your idea and it needs to be talked about'.

In the interview, both Emerson and Ashley spoke extensively of relying on each other for different parts of the project. They both spoke of balancing each other's knowledge. Emerson also identified Ashley as complementary in the sense of helping them "focus" and helping them tame their "chaotic energy."

At the beginning of the chapter, I drew attention to how Emerson's inter-personal conversations and relationships can be seen to inhere in their disciplinary experience. Emerson's understanding of what made their disciplinary work in computational physics successful included becoming attuned to what factors contributed to their successful interpersonal relationships. Emerson noticed that robust team support[3] and close complementary relationships[4] where everyone's ideas are appreciated were some of the "most important things" for disciplinary work. Emerson would prefer to "shut down everything" to repair the relationships that facilitate "crazy tons of work."

We saw evidence of this relational maintenance when discussing other group members. Emerson and Ashley were group mates on this project along with two other students: Ava and Terry. Emerson and Ashley worked together closely, but Ava and Terry were less connected to the project. Ashley shared that Ava and Terry

> were doing a little bit more of their own pieces of the project. We tried to break out in class, different chunks of the project that everyone would work on. And I think the two of us relied on each other more so.

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[3] Connected through a Slack channel, for example.
[4] With a colleague like Ashley, for example.

Ashley also shared that they lost communication with Ava at some point and never received her code. In each case, Emerson protected Ava and Terry from the narrative that their engagement was unacceptable. When Emerson conferred that "the reason why we relied on each other is mainly, we did the bulk of the work that was presented as well," they also emphasized that Terry worked on visualizations on his own that were interesting and appreciated. Emerson shared, "And he didn't need help. He just got it done." Emerson also clarified that Ava was busy applying for a job with a successful company leading to a job offer she accepted: "So we don't blame Ava. Good for Ava."

Emerson's relationship with the instructor also developed through the course:

EMERSON; It vastly changed my perspective on what a professor is.

INTERVIEWER; Really?

EMERSON; Yeah. I view professors as spoon-feeding machines that are just trying to get stuff done. And they don't actually care if you learn, they just care if they can give you a grade at the end. Tim is very much the opposite of that. He doesn't tell you anything, right ... Or he does, he does. He says "here's a project description, go ahead".

Their experience shifted the set of possibilities that Emerson can now envision for disciplinary relationships with professors. And Emerson noticed that the instructor's performance of care for their disciplinary learning involved extended agency for students to "go ahead" and to then come for help when needed[5].

Emerson's intra-personal conversations: Embodiment and identity

[5] In transcript shared in the vignette, Ashley says their plan would have been to go to Tim for help if their other resources were not sufficient.

- What relationships within themselves did Emerson cultivate throughout the oscillator project?
- What intra-personal conversations can we infer Emerson engaged in?
- And can we see any evidence of strengthening disciplinary relationships?

With the extended agency enabled by the course design and instructor, Emerson appreciated the freedom to work on what they found themselves to be interested in. Emerson clarified his statement (previously) that the instructor "doesn't tell you anything" (emphasis added here for clarity):

EMERSON; Yeah. It was a compliment, yeah. And it's good because **I felt for the first time that I had agency** in what I was doing. So often I just do projects and everyone's like 'oh, this is horrible.' And I don't complain, because I'm like, 'but it needs to get done.' And I get it done, you know? But in this class, **you could actually have agency and do something cool if you wanted to**. ((utterance continued below))

Acquiring a taste for what is interesting is a process of refinement of one's interpretation of your embodied experience. To feel that something is interesting, you must interpret your configuration of emotion (as an embodied state) as the state associated with that description. To articulate that you have found something interesting, you must have been paying attention to your embodied reactions. And finally, to say that you have made decisions to pursue an interesting idea, you must have iteratively noticed what was interesting and chosen actions to maintain aspects of the embodied configuration you recognize as "interesting."

Paying attention to one's embodied configuration of affect might be seen as *listening* to oneself. And taking actions to maintain a particular embodied configuration can be seen as *speaking* to this aspect of your emotions (considered temporarily as an agent). In this way, iteratively paying attention to what is interesting, and intentionally acting to pursue that interest, can be seen as an *intra-personal conversation*. Our agency constrains and enables the actions of other agents through our relations; and

(symmetrically) our actions and thoughts are constrained and enabled by other agents. If our affect, embodied sensations, and identity are seen as agents (that we are in relation with), then our relationships with these agents might also be seen as developing through iterative listening and response (i.e., conversations).

Jaber and Hammer (2016a, 2016b) argue that "affect and motivation are not just part of the dynamic of students' learning material; they are part of the material to learn" (2016a, p. 186). They argue that certain emotions are "entangled with the ways of knowing science" (2016b, p. 197) in the sense that they often "instigate and stabilize disciplinary behavior" (2016a, p. 189). Emerson's experiences of "pleasure in studying phenomena" (Jaber & Hammer, 2016a, p. 193) and their noticing of "affective signals of ideas and questions" (p. 193) were disciplinary practices that initiated and sustained their further disciplinary investigations. Emerson was paying close attention to their affective sensations. And this can be characterized as *listening* to their emotions. Emerson sustained their engagement with their embodied reactions by responding with agency (i.e., *speaking*) to follow and refine their sense of what (in computational physics) is "cool." Considering Emerson's intra-personal conversations with their emotions, these conversations (and relationships) can be seen to inhere in disciplinary practice when "affect and emotion are inherent in scientific inquiry." Emerson's disciplinary conversations with their embodied reactions shaped and was shaped by their disciplinary relationship with their self.

For Emerson, their agency to follow what they found interesting (and develop a disciplinary sense of what generates and sustains interest) led to extended disciplinary learning. Following the previous transcript, Emerson continued:

EMERSON; ((from the same speaking turn as the previous transcript)) So it makes it harder for everyone to be complaining, and also a lot easier for you to not want to complain. The concept of busy work and daily homework assignments that I've

> had in other classes, right? —they're just tedious. You don't actually learn a lot from them. And in this class, I felt like so many kids—including myself—**learned a whole new branch of ways to solve problems**.

Agency (that the instructor and learning environment enabled) was an essential ingredient for Emerson to engage in intra-personal conversations that sustained disciplinary work and led to disciplinary development (i.e. learning "a whole new branch of ways to solve problems").

Another way that Emerson listened and responded to their self can seen be through Emerson and Ashley's description of constructing and tuning their oscillator. They described tuning its behavior to better "act like a [double-]pendulum." Why would they do this, though? The class activity was to first build whatever they build, and then to engage in modeling activity to describe however the "oscillator" happens move. There was no requirement for its behavior to act in any pre-defined way—such as, "like a pendulum." Consider, also: how exactly does one *decide* if something is properly acting like something else or not? You must listen to and compare the feelings produced by watching the two different objects. In this case, Emerson and Ashley watched an animation of an idealized double-pendulum system, and they watched the movement of their assemblage of parts for their oscillator project. As Ashley described the story of their group's choice to model a double-pendulum system, she said that they formed a set of expectations of behavior they were hoping to emulate. She said, "We looked up on the internet what some [double-pendulum systems] looked like. ... We went through a number of iterations of trying to get the joints right...so that we were seeing similar behavior." Both she and Emerson described a process of adjusting the arms of the pendulum, the hinge between segments, and whether (or not) weights added in certain spots helped the behavior more closely mimic the animations they were using for reference. In the end, Emerson said they decided to remove the weights they had added because it appeared to "[magnify] the imperfections in their pivot point...and never act like a pendulum."

Emerson and Ashley iteratively modified their contraption and listened to how their embodied reaction to their oscillator's movement compared to the reaction evoked by the double-pendulum animation—until they felt the two reactions were sufficiently close. This comparative process can be seen as an intra-personal conversation of Emerson's because they were iteratively listening to the emergent reactions of their body after each action of Emerson's. This is a disciplinary conversation because it also helped to solidify Emerson's embodied understanding of what a double-pendulum system "acts like"—which is one aspect of developing a disciplinary relationship with the material/theoretical form of "the double-pendulum system."

Their disciplinary growth can also be seen in the shifts of their disciplinary identity. Emerson's agency and experience with a "whole new branch of problems" led to a change in how they thought about themselves. Their conception of having disciplinary expertise in STEM shifted.

> EMERSON; ... because I didn't calculate tolerances right, because I'm a fake mechanical engineer. But I did change my mind about myself because I started learning so much mechanical engineering things. ...

In earlier transcript, Emerson had also reported that they began to find themselves "want[ing] to build" in ways they had not experienced before or expected. Here, they describe part of their disciplinary identity in STEM as less "fake" than it had been. Emerson is describing multiple noticings, changes in emergent feelings, and iterative attunement to their dynamic disciplinary identity. By looking for evidence of intra-personal disciplinary conversations, I see growth of Emerson's disciplinary sense of agency, affect, and identity.

Summary: Noticing disciplinary conversations alongside disciplinary growth

With respect to (external) materials and theory, Emerson listened and responded to many agencies to better understand the interplay of the physical phenomenon, the equations of motion of a double-pendulum system, and an implementation of the Runge-Kutta algorithm. They had disciplinary

conversations with these material and theoretical entities during their disciplinary work. As Emerson described them, they experienced these extra-personal conversations as fun and rewarding—contributing to their account of an identity shift.

Emerson also listened and spoke to their peers as an integral part of their (interpersonal) disciplinary work. Emerson explicitly stated that attunement to other members' wellbeing is a necessary condition for disciplinary work, and that disciplinary work is enhanced by group communication. Emerson and Ashley described trading tasks, sharing intermediate progress, and finding complimentary niches. Emerson's reported that their relationship to the concept of a professor also changed as a result of the interactions they observed and experienced with the instructor. Emerson's relationships with Ashley and other group members were practices of disciplinary experience that strengthened their relationship to the discipline.

Finally, Emerson developed a deeper intra-personal disciplinary embodied sense of the double-pendulum system. While simply noticing what does or does not "act like a pendulum" may appear somewhat inconsequential, it represents an integral piece of embodied disciplinary knowledge (that also exists alongside many other pieces). Engaging with the material form of their oscillator allowed Emerson and Ashley to refine their embodied understanding for the behavior of an "ideal" double-pendulum—along with other features of the double-pendulum system that describe its emergent agency in different ways (such as the equations of motion, code for the numerical simulation, and description of chaotic behavior). Coming to know the double-pendulum system involves seeing and listening to it in many ways. Coming to know someone well by attending a weekly meeting with them would involve the development of an analogous embodied sense and memory for what they look like, sound like, and act like. Emerson and Ashley paid iterative attention to (listened and spoke to, i.e. were in conversation with) their internal embodied reactions to their oscillator, the double-pendulum animations, and their code and visualizations.

Noticing Emerson's conversations with these agents is a way to understand Emerson's deepening relationship to disciplinary ideas and practices. They strengthened their relationships

- with the ideal physical system of a double-pendulum,
- with computational practices like the Runge-Kutta algorithm as well as specifics of coding in C and Python,
- with the system of equations of motion,
- with peers and mentors,
- with epistemic affect,
- and with their disciplinary identity.

Taken together, I see (in these many types of conversations) Emerson's strengthening relationship to computational physics and STEM practices.

Emergent design principle

In retrospect, we designed the learning environment to investigate students changing relationships to tools, materials, each other, and instructors; and this gave the students agency to renegotiate these relationships in ways that fit them best. The students had agency to decide what materials they chose to develop closer relationships with, to decide what phenomena they chose to model, to decide what "oscillator" would come to mean for their group, to decide what "computational model" would come to mean for their group, to decide what theoretical and material relationships they would develop, to decide what interpersonal relationships they would develop, and to decide how their disciplinary conversations would unfold.

In Emerson's case, it appears that the strengthening of their disciplinary relationships was enabled by the structure of the project. The students had agency to follow what phenomena they found interesting, and Emerson connected this extended agency with their sustained engagement and

ultimately learning "a whole new branch of ways to solve problems." This leads to a final emergent design principle: *Support student agency to reconfigure relationships in ways that fit them best.*

Discussion and conclusion: *Asking different questions*

A theorization of the material world's agency as passive and separated from meaning-making in science is steadily being problematized in STEM Education (Krishnamoorthy, 2023; Sheridan et al., 2020). So far, I have engaged with the question of how meaning-making can be framed relationally to capture the many reciprocal relationships that inhere in STEM. I used a postqualitative approach to investigate how a change in the framing of STEM might also change the space of stories that are possible to tell about disciplinary development and pedagogy.

Alongside inter-personal reciprocity, I examined the close attention to materiality and affect that inheres in science. Consistent with the concept of *reciprocal noticing* (Dominguez, 2019, 2021), I positioned the close attention required for ethical reciprocity (Donald, 2012; J. Rosiek et al., 2020) as akin to "listening." Consistent with *material-dialogic pedagogy* (Hetherington et al., 2018; Hetherington & Wegerif, 2018), I positioned material agency as akin to "speech." I then framed STEM as a collection of *disciplinary conversations* involving iterative speech and listening to consider how ethical reciprocity might be woven directly into the onto-epistemology (Warren et al., 2020) of disciplinary practices and pedagogy.

Implications: Emergent design principles

Considering Emerson's disciplinary conversations, I see disciplinary continuity between their material interactions, their shifting interpersonal relationships, their disciplinary identity, and their embodied sensations and affect. By considering disciplinary relationships, we can (1) better understand varying ways and degrees that actions can be disciplinary, (2) understand disciplinary growth from a relational perspective that is less compatible with individualism, and (3) recognize a continuity between

the listening practices that inhere in science and the listening practices that propel restorative justice practices.

Throughout the chapter, I paused a number of times to consider design sensibilities that were emerging from this line of inquiry and narrative of Emerson's disciplinary relationships. Returning to collect these emergent design principles, I have developed intentions to:

- Design for strengthening relationships.
- Identify harmful narratives of STEM and seek ways to subvert or supplant these narratives.
- Iteratively inquire about which disciplinary conversations are being facilitated in a learning environment. Which conversations are being constrained? What disciplinary conversations would be desirable? And which agents' voices are still missing?
- Support student agency to reconfigure relationships in ways that fit them best.

One way to attempt to meet these design goals would be to design for a plurality of disciplinary conversations with materials, theory, others, and self.

Conclusion

> In the science classroom, a material-dialogic framework tunes us in to thinking of teachers, pupils, practical materials, classroom tools, models and artefacts as entangled intra-acting phenomena that are continuously produced within a material-dialogic educational space. (Hetherington et al., 2018, p. 167)
>
> Tying these various meanings of reciprocity are relationships: an agent related to another agent, a speaker related to another speaker, a fraction or a function related to another fraction or a function. (Dominguez, 2019, p. 76)

Listening can be understood as a first necessary step towards (re)making STEM relationships and finding restorative forms of disciplinary learning. I positioned listening as a disciplinary practice by

examining scientific practices as discursive practices that reify relationships. A conception of STEM practices as collections of many material-dialogic conversations invites pedagogical questions that could help reframe practices away from individualistic descriptions of scientific actions. For instance: Which (physical, internal, and external) agents are speaking? How can we better listen to them? What knowledge can we build together? Disciplinary questions that centralize restorative justice principles and practices (Winn, 2018) could be 1) built into the design of the learning environment, and 2) incorporated into the onto-epistemology of scientific practice.

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Chapter 4:

Epistemic affect and disciplinary conversations in mathematics

Mathematics is often characterized as a sterile, solitary, emotionless, straightforward discipline. In this chapter, I conceptualize action and response as "speech," conceptualizing noticing as "listening," and considering iterative speech and listening as a "conversation." This perspective helps reframe mathematics as something that emerges from networks of relations—among many (more-than-human) agents engaged in dialogic conversations. In particular, this perspective changes how we ask the question of "What conversations with affect are integral to mathematical practice?"

Introduction: Violence and other harmonics that inhere in mathematics

One of the most elaborate computing machines of the pre-digital era was a large mechanical assemblage of gears and weights. Operating the computer involved setting many hand-cranked dials to correspond to the initial input values corresponding to measurements of temperature, pressure, water depths, and times. The computer's output represented the solution to a particular system of differential equations that modeled the complicated tidal cycle of our oceans. Modeling the changes of ocean tides is a very difficult problem, and generations of mathematicians spent time developing new mathematical methods and theory. The current mathematical approach took centuries to mature. Developing each different mechanical design (for the very few machines that were built) took years of time and required extensive governmental funding. To do this work, mathematicians refined their practice of separating aspects of the problem into different abstractions that could be approached in new ways—leading to vibrant mathematics such as harmonic analysis and the study of infinite dimensional vector spaces. Throughout this process, the continued interest and funding for the research was for the benefit of imperial naval forces and projects of conquest. Knowing when your military boat will be safe from running aground is very important for defending or invading coastal territory—important enough to help support centuries of state level educational and research projects.

As with the theory of harmonic analysis and the prediction of tides, colonial projects help drive the momentum of many mathematical developments. Joy, discovery, connection, respect, social trust, and reciprocity can also inhere in mathematics. But as it is stands today, violence inheres in mathematics. And the violence and harm that is perpetuated through mathematics cannot be stopped if it is continually ignored.

One way that violence inheres in mathematics is through disciplinary practices that facilitate or invisibilize the impacts of harm. Abstraction inheres in mathematics. It seems difficult to imagine harmonic analysis being developed without a mathematical epistemology of separating knowledge away from the contexts that use it. But this disciplinary value for abstraction also supports colonial violence by making it easier for mathematicians to ignore any damage caused by the unchecked reentry of their abstractions back into real world contexts. On one hand, it is easy to find mathematicians that would correlate the "purity" of their mathematical work with the length of the work's lineage of abstractions—with increased purity corresponding to a more distant relation from real world consequences. On the other hand, mathematical development is often driven by funding for projects that perpetuate structural violence. For example, the mathematics of predicting tides enabled settler-colonialism—as did the mathematics behind lens technology for lighthouses (Levitt, 2014). Among many performances of mathematics, there seems to be a resonance with the idea that abstraction (and mathematics) involves ignoring the impacts of your actions.

Harmonic analysis is a branch of mathematics dedicated to understanding the deep details of how to consider a wave as an infinite sum of many other simpler waves. Generally, waves combine by amplifying each other and cancelling each other out in different places. And the emergent constructive and destructive interference combines to form a resultant wave. Any wave can be understood to be made up of many simpler harmonic components that inhere in the resultant combination. Changing the component values changes the resultant wave. For sound waves, the difference in timbre between

different instruments performing the same note can be understood as a difference in the component values of harmonics of each resultant wave.

While many different harmonics of mathematics
inhere in each performance of mathematics,
we have an opportunity
—with our ongoing embodiment of mathematics—
to boost or enable certain harmonic characteristics
that inhere in the discipline
while constraining or eliminating others
that we recognize as undesirable.

The sentence above has a meaning. And the formatting offers suggestions for how it may be read. The meaning then comes into existence as a network of relations. The materiality of the "meaning" is created by relations with the specific sentence structure, the performance of the formatting, what meanings are possible in the English language, the unique resonances created within the reader, and so on.

Within the performance, some lines start at the same distance of indentation. The phrases with matching indentation cohere as a sentence within the larger sentence. The impact of the full sentence, the explicit meaning of the smaller harmonic, and implicit resonances with other external ideas is fully dependent on the cadence invoked in reader, patience of the reader, and whichever emotions and thoughts are sparked as they read it. The meanings of both the larger sentence and any harmonic overtones each depend on how I crafted the specific performance of the words and how the meaning is coconstituted in each reader.

All resonant meanings
of the larger (or constituent sentences)
can be brought out or buried
in the mix
by the specific way that the reader is
constrained or
enabled to engage
with the performance of knowledge.

Each coconstitution of meaning is an opportunity for different harmonics to be read differently—just as a musical performance in a different setting would amplify different configurations of pleasing or displeasing overtones. To say that harm inheres in mathematics is not to say that every performance of mathematics carries overtones of harm—but many do. To say that overtones of colonialism inhere in mathematics is not to deny that many other overtones exist simultaneously. But the impacts of our actions—that performatively embody the discipline—should not be ignored.

Harmful affect *inheres* in mathematics

There are harmonics of affect and emotion that our performances of mathematics can either bring out or bury. Can we learn what to look for? Can we learn how to coconstitute mathematics in ways that disrupt harm rather than perpetuate it? Both positive and negative types of affect can be said to inhere in the ongoing embodied performances of the discipline. What negative affect do we wish to constrain? *What positive types of affect are conceivable to boost?*

The primary inquiry of this chapter will be a search for *desirable* harmonics of mathematics by using a critical posthumanist (Murris, 2020) approach of diffraction (Barad, 2014; Ceder, 2015; Murris & Bozalek, 2019a; J. Rosiek & Adkins-Cartee, 2023). But the ethical motivation for this work is the recognition that *undesirable* harmonics currently inhere in mathematics. These undesirable harmonics are not separate from the main signal of mathematics—they are inherent components of how mathematics currently propagates. Trauma and harm often inhere in many performances of mathematics—in a superposition with other disciplinary harmonics.

Imagine a sixth grade boy in a mathematics classroom. The teacher has asked the class to think about the problem posed on the white board, and she has asked if anyone has an idea. The boy's hand rises, and then nervously comes down part way. As the teacher asks him to share, his hand rises again and he says his answer—already suspecting he is wrong. The teacher asks him to come to the board and "point and show us what you're looking at." She asks other students to explain what he is thinking

about. She does not call his answer wrong. She correctly notices what he was thinking about and how it led him to answer in the way he did. She asks that the other students consider the context where he is right.

Not only is it easy to imagine this type of interaction happening in many classrooms—this story emerged from a video of a well-respected teacher educator posted to the internet[1]. This teacher educator is a renowned expert in supporting student ideas, noticing student thinking, and emphasizing contextual correctness. I speculate that the video is posted as a positive example of a teacher noticing a student's thinking (Dindyal et al., 2021). I would agree that the teacher's noticing of the student's mathematical thinking inheres in this moment. A harmonic of the teacher's support and grace for the student also inheres in this moment.

Taking seriously the negative affect that inheres in mathematics

But watching this clip, I also see a negative harmonic of mathematics that inheres in this interaction. The student at the center of this clip is a dark-skinned Black boy in an American classroom, and the teacher is a White woman. Although the instructor explicitly says his answer is "right," she also signals that his answer does not have equal standing. The instructor speaks repeatedly to the rest of the class about him in the third person. Of his 2 minutes in front of the class; 75% of his time is spent waiting. The boy is only able to speak twice for more than 3 seconds without being interrupted. He answers three questions with one only word. And he is interrupted three times in less than 90 seconds.

[1] My account does not constitute human-subject research because I am not analyzing private information. Additionally, my scholarly commentary is permissible under the fair use doctrine of the U.S. copyright statute. My critique is that what happened *appears* problematic through a lens of affect, and that it is easy to speculate that similar problematic episodes are common. I am not making claims about whether what happened was problematic in a measurable sense. I am not making the argument that any positive interpretations of this interaction are wrong. And I do not wish to bring undue scrutiny to the team that collected and has analyzed this data. My argument is that *both problematic and positive harmonics exist in simultaneity* within this clip. For these reasons, I have chosen to omit the reference to the public web page.

He waits silently for 60 seconds as she leads the class in a discussion about "what did he do?" As the instructor asks this, she turns away from him for the first time since she began speaking to him. He immediately slumps his shoulders and looks down at the floor. The instructor does not interrupt the next student in the same way. This student happens to be a White girl. After being allowed to sit back down, the boy is instructed to "pay attention" to the next student's explanation.

Even in an example of how to notice and attend to student thinking, we see what appears to be harmonics of negative emotions of embarrassment, community disconnection, and judgement. The fundamental character of mathematical inquiry could be centered around the feelings of working to understand other people's thoughts and building collaborative stories of how different mathematical ideas affect each other. But mathematics is difficult to conceptualize without the ideas that knowledge is either right or wrong, and that authority figures hold the answers (Muis, 2004). Mathematics as a realm of truths, mistakes, and raw intelligence underpins standardized testing—which helps uphold White supremacy (Knoester & Au, 2017) and leads to epistemological erasure (Cunningham, 2019).

Instead of collaboration and reciprocity, students often learn that conclusions will be imposed on them by mathematics. Students learn that imposing conclusions on others can be justified by using mathematics. And students learn that mathematics is inherently about the epistemological dominance (Andreotti et al., 2011) of constraining what others can do, say, or think.

Would we be able to recognize an inquiry as mathematical
if it lacked potential to make someone feel wrong or stupid?

To what extent do mathematical ways of being involve
argument styles *meant* to bully and silence others?

Would we notice how
sharing emotions and thoughts
inheres in mathematics,
if we boosted harmonics of relationality?

Could mathematics support justice rather than coloniality?

I've formatted these four questions so that two other "harmonics" are visibilized by grouping the lines that share matching indentation: To what extent do mathematical ways of being involve sharing emotions and thoughts? If it lacked potential to make someone feel wrong or stupid, would we notice how—if we boosted harmonics of relationality—could mathematics support justice (rather than coloniality)? Many overtones of meaning can inhere in performances of knowledge. In this example, the initial four questions may have resonated with you (on first reading) in a way that made my explicit reiteration of these harmonic overtones feel redundant. The harmonics inhered within the previous wording of the questions—and were (in some sense) already "really" there. Yet the specific performance of the four questions involved calling attention to these particular harmonic meanings through formatting, and then further through repetition of text. So (in another sense), the harmonics would not have been visible or "real" in the same way if they had not been brought into existence through this particular extended performance of the ideas.

Similar to this example, this chapter is crafted to simultaneously
1) look for what positive affect already exists in mathematics, and
2) look in a way that may bring new versions of mathematics into existence.

The well-respected teacher educator in this clip does not have a reputation for being insensitive—far from it. It would be reasonable of you to counter that we have too little evidence to tell if this student was "really" embarrassed. But it is not a stretch to imagine that there are many students—experiencing similar situations—that would come to understand the emotional timbre of

mathematics to resonate with the sickening feeling of people ignoring your signals of discomfort and vulnerability. Why does "ignoring others' emotions" seem to inhere in mathematics, and can we change that?

You might also counter that his embarrassment is small, and a necessary part of learning. But the magnitude of embarrassment becomes irrelevant if we acknowledge that episodes of disconnection can compound—exacerbating wounds formed through repeated trauma, or resonating with other types of microaggressions. And the necessity of these types of negative emotions is exactly what should be problematized. The belief that negative feelings of embarrassment could be necessary for learning is to believe that there is no version of mathematics that could exist without these harmonics of negative emotions. That a cynical position that I propose we reject.

You may instead counter that there are plenty of contexts where playful teasing is not traumatic. But to argue that there are appropriate forms of playfulness, teasing, or emotional dynamics are part of mathematics is to exactly argue that *disciplinary practices should include close attention to the impacts of our actions*. Maintaining appropriate and supportive disciplinary environments requires disciplinary practices of close attention to emotion. Mathematics involves affect. Mathematics involves sharing ideas and emotions of understanding. Mathematics teaching and communication involves either relational care or relational indifference—and indifference leads to harm.

We can look again at this boy's reaction: he slumped his shoulders and looked at the floor as soon as the teacher looked away from him. I would not say he seems like he was enjoying the connection of a joke shared with the teacher. I would not say he felt seen by the teacher who "noticed his thinking". I would not say he was enabled to share the story of his understanding on his own terms. I would not say that the teacher saying his answer was "also right" was quite enough to fully disrupt the harmonics of judgement inherent to his experience of mathematics. But what types of positive affect could we then find to work towards the full disruption of violence that inheres in mathematics?

Searching for harmonics of positive affect in mathematics

Embodied movements and affective states are integral to the practice of science (DeBellis & Goldin, 2006; Hannula, 2012; Jaber & Hammer, 2016b, 2016a; Zan et al., 2006). In this chapter, I explore how being in touch with others' and one's own disciplinary affect is an important component of mathematical practice. Where other work has made this argument using an expansion of the concept of "body" to include the social (de Freitas & Sinclair, 2014); I will, instead, explore a complementary approach: I will explore how a posthumanist (Barad, 2003) conception of "social" expands concepts of speech and listening to include individual's embodied configurations of emotion and affect as agents in discursive entanglements.

Our embodied systems of affect and emotion are related to perception, and considering the effects of affect on a cognitive system is a subdomain of the study of the cognitive influences of embodied actions (Hannula, 2012). However, there are also important social implications of exploring how one's "capacity to affect and be affected" (Ehret & Hollett, 2016; Massumi, 2015; Mulcahy, 2019) sustains disciplinary relationships. An important pedagogical corollary of both perspectives is that if there are affective components of mathematical expertise, then disciplinary development depends on students learning to listen and respond to their own and others' affective responses.

Research questions

As we make sense of what we are looking at (in a learning environment, for instance), we build stories of what happened for ourselves and each other. The frameworks we draw from can both enable and constrain these stories of what we understand to be happening. Rather than expecting to build a robust framework that leaves nothing out, one approach to this problem is to iteratively return to these stories to explore how changes to our narratives can differently constrain and enable our actions and interpretations. Leanne Betasamosake Simpson (2017) writes that as a principle in Nishnaabeg aesthetics, the concept of *abstraction* can sometimes be confused by Westerners with the concept of

extraction. Extraction of resources is a cornerstone of settler colonialism and capitalism. And abstraction is sometimes characterized as an extraction of meaning and knowledge out of the contexts and "relationships that give it meaning" (p. 202). Akin to stealing knowledge from the place/people/agents/relationships that produce it, extraction causes harm. Simpson instead characterizes abstraction as "shifting the relationality to change meaning or to illuminate a different meaning" (p. 202).

In what ways
are noticing and responding to affect
integral to mathematical practice?

Contrary to dominant framings of mathematics, I will argue that mathematical practices involve iterative attention and response to individual and cultural constructions of aesthetics, emotion, pleasure and interpersonal interaction, empathy, and development of meta-affect. None of these disciplinary practices are found in current educational standards Next Generation Science Standards or the Common Core Standards in Mathematics (National Governors Association, 2010; NGSS Lead States, 2013). Thus, uncovering these practices is an important contribution towards (1) developing mathematical pedagogy that is better aligned with those practices of mathematicians that are worth preserving, and (2) continually crafting a futurity for mathematics education that refuses and resists recurring harm (Camangian & Cariaga, 2021; Gutiérrez, 2017; Lambert, 2015; Leyva, 2017; Martin, 2019; Philip et al., 2019).

What new ways of being
in mathematics learning environments
are constrained or enabled
by stories of disciplinary conversations?

I will examine epistemic affect (Jaber & Hammer, 2016b, 2016a) in mathematics using a relational framework of disciplinary conversations. Consistent with other relational approaches (Murris, 2020; J. Rosiek et al., 2020; J. Rosiek & Adkins-Cartee, 2023), I orient this work as postqualitative

research (Murris, 2020; St. Pierre, 2021)—specifically drawing from enactments of *diffraction* (Barad, 2014; Bozalek & Zembylas, 2017; Ceder, 2015; Haraway, 1992; Murris & Bozalek, 2019a), *low theory* (Halberstam, 2011), and *re/writing the subject* (Roth, 2012).

Posthumanist philosophy and postqualitative research is ideologically tied to Indigenous ways of knowing and being (J. Rosiek et al., 2020). In particular, the enactment of diffraction and low theory in this chapter has also been shaped by Dwayne Donald's formulation of *Indigenous Métissage* (Donald, 2012); by Leanne Betasamosake Simpson's description of Indigenous aesthetic practices of "repetition, duality, multidimensionality, and abstraction" (Simpson, 2017, p. 200) as well as "layering" (p. 202); and by Cash Ahenakew's call "to disrupt sense-making and prompt sense-sensing in the experience of readers" (Ahenakew, 2016, p. 337) through breaks in the form and language of scholarship (such as through metaphor and poetry). This enactment of re/writing the subject of mathematics by describing disciplinary conversations is also shaped by Rosiek and Snyder's description of *Narrative Inquiry* (J. L. Rosiek & Snyder, 2020) and Garroute and Westcott's emphasis of the agency of stories (Garroutte & Westcott, 2013).

Framework for inquiry: Disciplinary conversations

In this chapter,

> I will conceptualize action and response as "speech,"
> close attention as "listening," and
> iterative speech and listening as a "conversation."

This material-dialogic (Hetherington et al., 2018) approach transforms the previous research question (In what ways are noticing and responding to affect integral to mathematical practice?) into a different form:

> What conversations with affect
> are integral to mathematical practice?

This new form of the question leads to a different orientation towards the design of learning environments:

- What kinds of conversations do we want to facilitate?
- What kinds of conversations are being supported by the design?
- Whose voices are present, or not present?
- How can we help them be heard?

This shift is substantive because these questions for the design of learning environments share many similarities with the questions used to repair relations using a restorative justice approach (Winn, 2018). Questions to response-ably (Barad, 2007) design learning environments become the same questions to design for substantive mathematical practice.

By considering speech and listening as the actions, agencies, and attunement that inhere in disciplinary practices; I characterize mathematics (and STEM) as a collection of many types of *disciplinary conversations*. Motivated by a potential to support justice-oriented design approaches, I will be exploring the agency of stories about *disciplinary conversations*.

What new understanding and meaning
can be illuminated through shifting the relationality
of how and where we see emotion and affect in mathematics?

Mode of inquiry: Postqualitative research and diffraction

If you were to drop two rocks in a still pond, the interaction of the two waves will produce a pattern of constructive and destructive interference as the crests and troughs of the waves combine and cancel each other's oscillations.

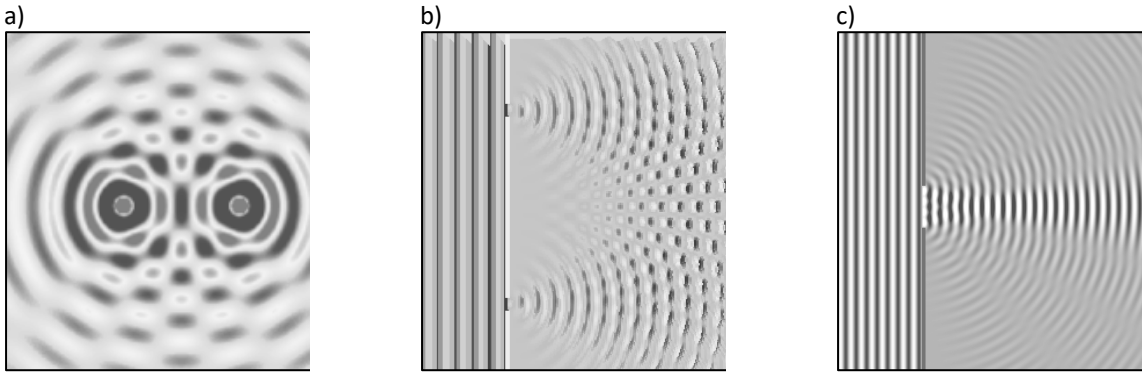

Figure 4.1: Images of numerical models for (a) "Interference of waves from two point sources." (Wave Interference - Wikipedia, n.d.), (b) "Two-slit diffraction pattern by a plane wave." (Double-Slit Experiment - Wikipedia, n.d.), and (c) "diffraction pattern from a slit of width four wavelengths with an incident plane wave. The main central beam, nulls, and phase reversals are apparent." (Diffraction - Wikipedia, n.d.).

The initial waves will create an interference pattern with the diffraction of surface waves moving through each other. Light waves passing through two small slits will also create an interference pattern on a distant screen as the light from different slits combine and cancel as pass through each other. In this way, a diffraction pattern is not a picture of a subject (as a reflection is), but a picture of a *relationship*—the emergent pattern of an interaction between a wave and an edge, or a wave and another wave.

> When emergent patterns are the object of study
> (such as, disciplinary practices, cultural norms, powered relationships,
> performances/practices of knowledge or identity, etc.);
> it is a methodological choice to remember
> that the analysis is a type of interference pattern of a *relationship*
> —rather than a reflection of a subject or object.

In education research, diffraction has been taken up by interdisciplinary critical posthumanist scholars (Murris, 2020) as a form of postqualitative research.

Poststructuralism, feminist methodology, and postqualitative inquiry

Poststructural approaches emphasize that objects cannot be cleanly separated from the relationships they are tethered to (Gutiérrez, 2013): knowledge and power, representations and the represented, subjects and discourses about subjects. Poststructural critiques of representationalism reject the "two-world ontology that assumes there is a real out there and then a representation of the

real *in a different ontological order*" (St. Pierre, 2021, p. 6, emphasis added). This critique has motivated some scholars to describe their work as *postqualitative:*

> The robust critique of representation in postructuralism is crucial in post qualitative inquiry because so much effort in preexisting social science research methodologies focuses on how to represent the real, authentic lived experiences of human beings. Representation is not the goal of post qualitative inquiry. Its goal is, instead, experimentation and the creation of the new, which is very difficult. (St. Pierre, 2021, p. 6)

Donna Haraway noticed that the optical phenomenon of diffraction fits better with this postructural critique of representation, since

> Diffraction does not produce "the same" displaced, as reflection and refraction do. Diffraction is a mapping of interference, not of replication, reflection, or reproduction. A diffraction pattern does not map where differences appear, but rather maps where the effects of difference appear. (1992, p. 300)

Karen Barad built on this work extensively (2003, 2007, 2014, 2017a, 2017b), and described that diffraction as a methodology emerged through many voices and ideas coming together—especially at the University of California at Santa Cruz during the late 1980s, and including Trinh Minh-ha and Gloría Anzaldúa (Barad, 2014). Diffraction as a mode of inquiry has steadily grown since then as an "alternative vocabulary and different technology for critical inquiries" (Kaiser & Thiele, 2014, p. 166).

Diffraction as a mode of inquiry has also been steadily developed in Education (Bozalek & Zembylas, 2017; Ceder, 2015; Gough, 1994; Moxnes & Osgood, 2018; Murris, 2022; Murris & Bozalek, 2019a, 2019b) as a "relational, feminist form of academic engagement" (Murris, 2022, p. 75). As Ceder (2015) describes diffraction, a "close reading is about reading one text together with and through another, making different transdisciplinary practices talk to each other" (p. 3).

Diffraction as an approach to investigating disciplinary harmonics

I wish to understand the relationship between affect and mathematics.

This invites me to use diffraction as a mode of inquiry.
While I wish to build theory that constructively
interferes with the affective dimensions of mathematics,
I am not searching for a definitive description of mathematics.
This aim, also, fits best
with poststructural approaches and postqualitative inquiry.

Wolff-Michael Roth (2012) writes that "every text that writes mathematics education, in writing it again (rewriting) and thereby writing it anew, also erases (a bit of) mathematics education" (Roth, 2012, p. 452). Constraining the violence that inheres in mathematics requires re-turning to our narratives of mathematics, shifting the relationality of how we understand mathematics, and continually re/writing bits of the narrative to constrain and eliminate undesirable disciplinary harmonics.

Affect in mathematical practice is typically invisibilized by the (destructive interference of the) narrative of mathematics as a realm of universal objectivity. In this sense, I am exactly searching for "theoretical knowledge that works at many levels at once" (Halberstam, 2011, p. 15) that is built by "untrain[ing] ourselves so that we can read the struggles and debates back into questions that seem settled and resolved" (Halberstam, 2011, p. 11). My poststructural approach aligns with the way Halberstam describes low theory:

> a kind of theoretical model that flies below the radar, that is assembled from eccentric texts and examples and that refuses to confirm the hierarchies of knowing that maintain the high in high theory. (Halberstam, 2011, p. 16)

In this chapter, my inquiry involves assembling "eccentric texts" (Halberstam, 2011) to do close readings of conversations with affect—diffracting mathematics practices through a posthuman relational approach towards discourse. I explore the agency of stories (Garroutte & Westcott, 2013; J. L. Rosiek & Snyder, 2020) of disciplinary conversations by re/writing (Roth, 2012) the emotional and affective dimensions of mathematics. As I share each close reading of a piece of mathematics, I also

share questions about how this type of re/write could impact the teaching and learning of mathematics. I conclude by examining how this perspective has influenced my own teaching practice.

Mathematics emerges from conversations involving affect

Mathematical theorems are typically positioned within a realm of knowledge that is purely dependent on fixed definitions. But in his book, *Proofs and Refutations*, Imre Lakatos (1976) illuminates a reciprocal dependence of a definition upon a particular theorem that a community of mathematicians decide *deserves* to be true. That is, the affective feeling of truth can evolve *at the same time* alongside the "objective" truth of the theorem. Lakatos explores this through an investigation of the historical development of a topological invariant called the *Euler characteristic*. In a sense, Leonard Euler started a conversation with an intriguing spark of a statement (in the form of a theorem) that he built into a fiery story (in the form of its clever proof). Rather than let it burn out (once they realized the "mistake" in the proof), mathematicians kept the conversation smouldering (over generations)—affecting themselves and each other—while they worked on ways to satisfyingly preserve the fire started by Euler's voice and wit.

The particular theorem in *Proofs and Refutations* (Lakatos, 1976) involves geometric shapes called polyhedra that can be visualized in 3-dimensional space—as well as the question, "What counts as a polyhedron?" And the conversation spanned centuries! A cube—as an example—has 8 vertices, 12 edges, and 6 faces; and it happens that 8 – 12 + 6 = 2. Choosing to let V represent the number of vertices, E represent the number of edges, and F represent the number of faces; it turns out that (V – E + F) remains 2 for a surprising number of configurations of shapes (a pyramid, a tetrahedron, a soccer ball, and many more). This result is now known as Euler's Theorem. An elegant proof was laid out by Leonard Euler for the invariance of the calculation (V – E + F), but eventually other mathematicians found many classes of counterexamples where (V – E + F) does not equal 2. Rather than rejecting the theorem and proof, these exceptions were labelled with highly emotional connotations: lamentable (p. 19), monsters

(p. 22), non-genuine (p. 17). As arranged by Lakatos (1976), the historical objections to these examples show that mathematicians sometimes shape their theorems and definitions together—to affect each other. The proof of Euler's theorem affected them in ways they wanted to save and pass down to others—surprise, cleverness, joy, confusion, etc.

The emotionally unsettling examples they found drove them to investigate the phrasing of the theorem and to very carefully define and redefine their initial notions of *shape, edges, faces*, etc. All this was done in order to preserve the "truth" of Euler's theorem; and to preserve the satisfying cleverness of Euler's original proof. The mathematicians listened to the way theorem and original proof affected them, and their responses refined the definitions and proof in a way that preserved their affective experience. In this instance, mathematicians engaged in conversations—with theoretical elements, with each other, and with their emotions—about what it would take for a theorem to feel right.

What kinds of classroom experiences could support students and teachers together investigating the interplay of definitions and theorems? The emotions of mathematics include the satisfying feeling of theorems and definitions fitting together tightly—as if they were built for each other, which they are! Given certain definitions, axioms, and methods; the fixedness of implications and theorems produce a meaningful feeling of objectivity and inevitability that feels very good. Unfortunately, a claim of supposed objectivity often "enacts colonial violence by claiming the privilege of narrating what 'others' are while simultaneously denying other perspectives, histories, and subjectivities" (Warren et al., 2020, p. 279).

- Are there ways to emphasize the satisfying stories of these relations rather than the satisfying "truth" of theorems?
- Are there ways to constrain the narrative of the objectivity in mathematics while emphasizing the satisfying *relation* between definitions and theorems?

Mathematical development involves listening to affective responses

Silver and Metzger (1989) interviewed five mathematics professors and three graduate students. Each participant was interviewed twice. At each interview, each of them solved two math problems and answered questions designed by the authors to help build a framework for possibly interpreting their problem-solving behavior. Each interview started with 20 minutes to work on a problem while the interviewer observed. Participants were asked to think aloud, and prompted to verbalize whenever there was a long period of silence. At the end of the 20-minute interval, the interviewer asked follow-up questions about the participant's behavior, some general questions about their background, and beliefs about mathematics. The second half of the interview consisted of another 20-minute period for a second problem, with time again afterwards for follow-up questions. Interview data consisted of audiotaped interview protocols, the interviewer's notes, and the participant's written work.

Although their investigation was not aimed at studying affective responses to the problems or solutions, Silver and Metzger (1989) report that examples of aesthetic factors emerged as extremely important influences on the problem-solving behavior they observed. They identified aesthetic monitoring behavior in every participant, and most extensively in the problem-solving protocols generated by three of the professors. They use excerpts from the protocols of each of these three professors to illustrate two different functional roles for aesthetics that they interpret from their data: appreciation of elegance of a problem before or after its solution, and to act as a guide for decision making during the course of problem solving.

Silver and Metzger (1989) conclude that their data supports the idea that "mathematical problem solving expertise is a function of taste as well as competence" (p. 69). This is important to them because "aesthetic monitoring is not strictly cognitive but appears to have a strong affective component" (p. 70). Silver and Metzger write,

> If mathematical aesthetics is an important component of the culture of mathematical thinking, we need to explore both the wisdom and feasibility of transmitting some of the aesthetic aspects of that culture to students at an earlier point in their mathematical education, especially through experiences that allow them to appreciate and reflect upon fundamental aesthetic principles. (1989, p. 72)

- Are there ways that a learning environment could enable students to develop their own aesthetic taste as well as join in cultural traditions of mathematical elegance?
- Could the delivery of solutions (proofs, explanations, diagrams, presentations, etc.) be seen as performances of knowledge that shape and embody the discipline?

Emotion and the communication of emotion are integral to mathematics

In a video recording of a department seminar, Benson Farb (2014) presents his mathematical research and humorously muses that experiencing certain affective states are necessary requirements for a career in mathematics. Transcript [conventions of Conversation Analysis (Ayaß, 2015)]:

> So THAT was amazing theorem number one. ((pause))
>
> So…. This is also a test. Basically, if you want to know if you'd be interested in geometry or topology, if you don't like any of these theorems… ((Farb's voice trails off, then speaking loudly))
>
> IT'S like, "the math test": ((pause)) If you don't like Cantor's proof that the Reals are uncountable, ((Farb shrugs with his hands raised and head tilted.)) the rest of math... ((pause))
>
> It doesn't get THAT much better. ((Farb's voice trails off again as he erases the board. The audience releases unforced laughter.))
>
> I MEAN! math is amazing. It gets much deeper, right? But, like, do you know anybody who—If you're not, like, completely blown away, ((Farb pauses, then bobs his head)) then you definitely shouldn't do math. ((pause))
>
> I—I'd be that definitive about that. ((nodding))

Farb's dry humor pinpoints an affective experience that he claims is unique and necessary for life as a mathematician. The idea that whatever it takes to be a mathematician is something that he knows and has authority to judge has overtones of gatekeeping; and phrasing it that way could discourage a student from further study. Without apologizing for his error, Farb was speaking to a room of professional mathematicians and graduate students. I also think his intention was to make dryly humorous statement somewhat like, "if you don't like spicy food, then you might not have a good time at the hot sauce convention."

In any case, notice that rather than saying that the content or truth of the theorem itself evokes particular emotions for mathematicians, he claims the origin of these feelings is in the *communication* of the theorem. By suggesting that this emotional experience is not only a common experience but could even be considered a defining characteristic of a mathematician, Farb implies that being affected and affecting others is just as essential to mathematical practice as the proof and the result. For mathematicians, theorems are associated with proofs—and proofs are associated with emotions. Mathematical proofs are communicative presentations, and Farb used his opinion of the ubiquity of the emotional experiences evoked by mathematical presentations to joke about the importance of his own theorem. Along the way, he played with the idea that *a disciplinarily-appropriate, embodied sense of joy is an important determining factor in one's decision to become a mathematician*. His implicit assumption is that mathematicians are in conversation with their affective states (by listening and responding to them).

For many, it is difficult or impossible to conceive of mathematics as anything other than an expedition for right and wrong answers (Muis, 2004). Other genres of performance are understood to communicate emotion—especially comedy, tragedy, etc. Mathematics (and all disciplines) should be understood as knowledge performed with intention to affect others. Farb implies that a delivery of

Cantor's proof (of the uncountability of the Real numbers) from one mathematician to another should ideally transmit the feeling of being "completely blown away."

- How does a perspective of knowledge as affect-inducing performance change the way we evaluate the effectiveness of learning environments?
- The dominant narrative of mathematics positions it as a discipline of Platonic forms and statements that humans have discovered. How does this narrative constrain the perspective of mathematics as a way to share particular thoughts and feelings?

Affect inheres in disciplinary practice

Jaber and Hammer (2016a, 2016b) argue that emotional experiences in science are not simply motivating of scientific inquiry—but initiate, sustain, and shape epistemic practices. Disciplinary inquiry involves more than learning discipline specific techniques, facts, and styles of argument. Disciplinary ways of knowing (Warren et al., 2020) emerge from ways of *being*: to be a scientist involves experiencing the emotions of the discipline, appropriately affecting others, and becoming appropriately affected by others—enough to engage in and sustain disciplinary practices. Before considering case studies of elementary school students, Jaber and Hammer (2016a, 2016b) examine how affect is evident in the practice of professionals.

Jaber and Hammer (2016a, 2016b) identify five themes of epistemic affect: the pleasure in studying phenomena, the feelings involved in scholarly interactions, empathy with the object of study, affective signals of cognition, and meta-affect. The *pleasure in studying phenomena* in math has been documented. In a TED talk recounting his invention of the proof that earned him the 2010 Fields Medal, Cedric Villani describes his experience as a mathematician (2016):

> What is it that we find so sexy in math? After all, it seems to be dull and abstract…just numbers…and computations…and rules…to apply. Mathematics may be abstract—but it's not dull, and it's not about computing. It is about reasoning, and proving—[which is] our core

> activity. It is about imagination—the talent which we most praise. …There's nothing like the feeling which invades you…when after months of hard thinking, you finally understand the right reasoning to solve your problem. The great mathematician, André Weil, likened this—no kidding—to sexual pleasure. But noted that this feeling can last for hours, or even days. (0:57)

Villani describes the drive for discovery being fueled by the anticipation of an affective state. He associates pleasure with the *finding* of a path of reasoning, and he describes listening to his affective states ("hard thinking") as well as responding by using his "talent" as a mathematician ("imagination"). He does use language that resonates with the idea that there is *one* right path of reasoning. But Villani identifies "imagination that leads to rewarding joy" as a mathematical activity that is at least as important to the discipline as his "reasoning." Neither imagination nor joy are typically understood to be crucial to mathematical reasoning.

- Could we recognize an absence of passion in learning environments as counter-productive to disciplinary learning?
- Could imagination, passion, and joy be framed as essential ingredients of authentic mathematical inquiry?

Jaber and Hammer (2016b) describe both productive interpersonal collaborations and productive rivalries as producing *feelings involved with scholarly interactions*. In mathematical practice, the unit of discovery is proof, which we may consider as a type of utterance in a conversation (in a cultural context, and within a network of relationships). A proof is an explanation within a conversation (Latour, 2008; Netz, 2003; Steingart, 2012, 2015). As we noticed above, proofs sometimes emerge in tandem with mathematical definitions to tell a particular mathematical story (through iterative speech and listening) that feels to mathematicians like a story worth telling (Lakatos, 1976).

- How might we emphasize that vibrant interaction and sustaining restorative relationships are purposes of mathematical inquiry?

The third theme the authors identify is *empathy with the object of study*. Jaber and Hammer point to accounts of scientists imagining themselves in place of their subjects and identify with their subjects' thinking, feeling, and histories. They also tell of physicists "putting themselves in the place of the electron, a metaphoric connection that evidently helped them make sense of and reason about mechanism by imagining what the electron was 'trying' to do" (2016b, p. 193). The mathematician and Fields Medalist, William Thurston, wrote of "spatial structures that encompass us and that we move around in" (1995, p. 4). Thurston's pioneering mathematics in the field of 3-manifold topology was based on intuitions built from immersing himself within his imagination in the theoretical spaces he studied and listening to his embodied experiences.

- Are there ways to frame engagements with theoretical constructs as episodes of closely listening for the purpose of developing intimate understanding and attunement (Shotter, 2015)?

Thurston described some of his process in iterative terms, "absorbing each of these concepts as something new and interesting, and spending a good deal of mental time and effort digesting and practicing with each, reconciling it with the others" (1995, p. 3). He mentions personalized affective states accompanying a mathematical definition: "one person's clear mental image is another person's intimidation" (p. 4). And he describes his state of mind for mathematical work in a way that seems congruous with a calm and serene affective state: "Personally, I put a lot of effort into 'listening' to my intuitions and associations, and building them into metaphors and connections. This involves a kind of simultaneous quieting and focusing of my mind" (p. 5). Jaber and Hammer (2016b) similarly notice that *disciplinary ideas and questions sometimes come to represent affective signals* to scientists. Thurston seems to indicate that investigating a problem involves noticing and following a feeling of serenity. Jaber and Hammer describe scientists iteratively following a "feeling of direction," feeling a "focusing of intellect and emotions," and "feelings that are associated with knowing" (p. 194).

Some of the important emotions that inhere in mathematics seem like calm and serene flows of emotional waters. But there is a difference between the calm waters of a lake and an empty lake. The narrative of mathematics usually includes a description of an empty lake of emotions—yet this is categorically impossible for living humans.

- How did we construct the cultural narrative of mathematics as an emotionless discipline? Could it be that the disciplinary emotions of deep sincerity and serenity are misinterpreted and misrepresented as unemotional?
- What pedagogical changes may come from positioning mathematics as dense with vibrant emotions of sincerity rather than dead and unfeeling?

The final theme of epistemic affect that Jaber and Hammer identify is *meta-affect and affective regulation*. They characterize the awareness and management of the experience of feelings as an important part of science.

> Scientists often articulate such meta-affective dispositions, for instance, perceiving confusion as motivating, associating puzzles and uncertainties with pleasure rather than intimidation, and perceiving inconsistencies as simultaneously bothersome and stimulating rather than menacing. (2016b, p. 194)

Debellis and Goldin (2006) make the important point that

> [c]areful consideration of meta-affect suggests to us that the most important affective goals in mathematics are *not* to eliminate frustration, remove fear and anxiety, or make mathematical activity consistently easy and fun. Rather they are to develop meta-affect where the emotional feelings *about* the emotions associated with impasse or difficulty are *productive* of learning and accomplishment. ...For example, frustration *could* and *should* indicate that a mathematical problem is nonroutine and interesting. ...A supportive classroom culture provides a sense of *safety* in being 'stuck'. (p. 137)

Mathematicians develop culturally specialized ways of interpreting how they are affected. Development as a mathematician partially involves learning to interpret signals from our bodies, and these interpretations are part of what comes to define disciplinary practice.

- Are there ways to frame connection to oneself as a disciplinary strength?
- What learning environments could we design to enable these affective facets of mathematical inquiry?

Conclusion

The mathematics educational system has a violent history of supporting relations of dominance and oppression (Lambert, 2015; Leyva, 2017; Martin, 2019). Conversations both shape relationships and are shaped by relationships. So, attuning to disciplinary conversations could be a productive way to sustain and repair relationships. In this chapter, conceptualizing mathematics practices as posthuman conversations helps us to describe the ways affect inheres in the discipline—so that we may attune to the material and affective conditions of our students.

The framework of disciplinary conversations helps me to see the questions, "Who is speaking? Who is listening? What conversations are the students engaged in?" as deeply disciplinary—and exciting origin points for pedagogy and design. Jaber and Hammer's (2016) conclusion that "affect inheres in science" does more than just acknowledge that science is done by humans who are necessarily emotional beings. And their illumination of epistemic affect is not a discovery of what is the "most true" about science, or something simply gone previously unnoticed. The power of their analysis comes from carefully revisiblizing disciplinary entanglement that has been institutionally vanished (Vaught, 2019) by the onto-epistemology of STEM. Trauma experienced in STEM learning environments is more than just a series of unfortunate individual accidents. If we want to begin to decouple STEM from the systemic violence of its sexist, racist, colonialist history and present; we might start by viewing harm done in STEM learning environments as disciplinary (affective) malpractice.

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Chapter 5:

Epilogue; Future noticing, designing, and narrating

I have used a critical posthumanist approach to put forth three arguments. In chapter 2, I argued that considering the agency of methodology is important for design-based research. In chapter 3, I argued for a relational turn in STEM Education. And in chapter 4, I argued that mathematics involves a close relationship with our own and others' emotions. In this epilogue, I discuss three broader questions that deserve explicit attention: How do we train ourselves to see disciplinary conversations in STEM? How do we rethink our learning environments to be more relational and dialogic? What types of further investigation will sustain relational narratives for STEM?

Summary

Science, Technology, Engineering, and especially Mathematics are historicized as realms of material facts of the universe extracted and captured by the best representations we can come up with. This approach to knowledge dovetails with other Eurocentric narratives that support White supremacy and colonialism. But even for people actively working to disrupt these cultural structures of violence, making STEM compatible with relational ontologies is far from straightforward.

As I have argued, a straightforward approach is not what is needed to bring STEM into alignment with relational ontologies—since many contemporary performances of STEM are not compatible and should not be legitimized. Narratives of control, domination, extraction, and judgement should be noticed, constrained, and ideally eliminated. Work is needed to notice where narratives of reciprocity, attunement, and pluralism can be enabled and boosted. Fortunately, there are many people engaged in this work.

In this dissertation, I have used a critical posthumanist approach to put forth three arguments. In chapter 2, I argued that considering the agency of methodology is important for design-based research. In chapter 3, I argued for a relational turn in STEM Education. And in chapter 4, I argued that

mathematics involves a close relationship with our own and others' emotions. We need to understand the relations that come to shape what is understood to be straightforward. Queer theory was developed for that purpose. We need to look again at the relations STEM creates and maintains, and question whether we can improve these relations. Building right relations is a grounding principle in many Indigenous Knowledge systems. And we need to better understand the entanglement of ethico-onto-epistemology as it applies to both learning and doing Science. New materialist philosophy is becoming a language and approach for exactly types of investigations. By carefully bringing together elements from queer theory, Indigenous approaches to reciprocity, and new materialist perspectives on agency; I have approached the problem in a new way.

Here in this epilogue, I will discuss three broader questions that deserve explicit answers:

- What disciplinary conversations in STEM are there for us to notice?
- Are there small ways to rethink our learning environments to be more relational, dialogic, and amenable to disciplinary conversations?
- Can further investigation sustain relational narratives for STEM?

Noticing disciplinary conversations

- What disciplinary conversations in STEM are there for us to notice?

Noticing disciplinary conversations in STEM is both a way to understand STEM differently, and to continually turn over our understanding and re/write our narratives of disciplinary relationships. In chapters 2 and 3, I used examples of undergraduate students in a computational physics course to explore what a framing of disciplinary conversations might look like. But given any existing narrative of STEM, what disciplinary conversations are there for us to notice? In this section, I use the narrative of the origin of Chaos Theory as an example of looking continuously for disciplinary conversations. This example also shows that re-turning to a narrative to notice the network of disciplinary relationships can both change the story and help uncover knowledge that has been lost.

Re/writing disciplinary listening and material speech into Chaos Theory2

Sometime before 1961, Edward Lorenz was using a system of 12 differential equations and an early computer to numerically simulate weather patterns. He describes deciding reexamine the machine's output:

> I stopped the computer, typed in a line of numbers that it had printed out a while earlier, and set it running again. I went down the hall for a cup of coffee and returned after about an hour, during which time the computer had simulated about two months of weather. (Lorenz, 1993, p. 134)

The new numbers were wildly different from the old numbers, and Lorenz initially suspected a faulty vacuum tube or some other problem with the machine he was using—an LGP-30 "desk computer" (Lorenz, 1963a). Investigating further, Lorenz found that, "the new values at first repeated the old ones, but soon afterward…more or less steadily doubled in size every four days or so [of simulated data], until all resemblance with the original output disappeared" (E. N. Lorenz, 1993).

The computer used six digits of precision, but its readout only showed three. So his re-entry of data from the readout introduced a small perturbation to the trajectory of the simulation. Lorenz realized that he was seeing the round-off errors steadily being amplified to create significantly new patterns of behavior. In a way, the computer was speaking back to him in an unexpected way, and he chose to listen and engage.

After this preliminary discovery and further work, Lorenz followed a suggestion from Barry Saltzman to study a simplified system (1963a) with only three nonlinear differential equations that exhibited similar sensitivity to initial conditions. Lorenz continued his conversation by iteratively listening to the ways different systems of differential equations spoke back to him through the computer's output. He settled on a system of three equations that he felt captured the same essence of behavior as the previous twelve. He was investigating a new kind of middle ground between order and

randomness that eventually helped define a new field of study. Mathematicians have a history of often labeling their constructions with words that carry ironic or emotional connotations[1]—and by 1975, this new emergent middle ground was coined chaos (Li & Yorke, 1975).

Writing in Transactions of the New York Academy of Sciences, he ends his conference paper humorously with this dry paragraph:

> When the instability of a uniform flow with respect to infinitesimal perturbations was first suggested as an explanation for the presence of cyclones and anticyclones in the atmosphere, the idea was not universally accepted. One meteorologist remarked that if the theory were correct, one flap of a sea gull's wings would be enough to alter the course of the weather forever. The controversy has not yet been settled, but the most recent evidence seems to favor the sea gulls. (Lorenz, 1963b, p. 431)

Eventually, this metaphor evolved into what is called the butterfly effect. Lorenz's presentation at the 139th meeting for the American Association for the Advancement of Science (1972) was famously titled, *Predictability; Does the Flap of a Butterfly's Wings in Brazil Set Off a Tornado in Texas?*

Re/writing to further shift how we understand disciplinary relationships

Lorenz could not have done this work without the computer present. His exploration depended on being able to hear what his simulation had to say to him. And in this case, the output of the simulated computational model was the voice that directed the conversation into new and generative territory.

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[1] In number theory, there are rational and irrational numbers, complex numbers, and transcendental numbers. In the field of algebra, there are exceptional groups and superreal numbers. In the field of topology, there are pathological objects and perfect sets. put it mildly: there are many more examples, as well.

A Bakhtinian (Bakhtin, 1986) analysis of what Lorenz took away from his interaction with the computer would (at the very least) consider the computer's speech as a kind of distorted echo of his own programming. With a perspective of the social and distributed aspects of that cognitive system (Hutchins, 1995), we can also conceptualize the computer as a refined artifact of multiple human conversations and understanding. The computer was carefully designed, built, tested, adjusted, and shipped to speak in a particular way. The computer represents the cultivated outcome of many accumulated voices in cultural conversations.

When the computer spoke to Lorenz in a way he didn't expect, its voice emanated from a sedimentation of culture—much as the way our real voices (and all utterances) come from internal echoes of cultural practices within our own minds (Wertsch, 1991). Lorenz's scientific contributions emerged as the product of a conversational context. As Ford and Wargo have noticed (2012), we see here that the knowledge that seeded the field of Chaos Theory is fundamentally a product of dialogue.

This re/write of history gives an example of the agency of both the material world and the theoretical world Lorenz was working in (Pickering, 1993, 1995). He attuned his listening (with the help of the computer) to what different equations and systems of equations would say to him. And he followed and guided the change of the system of equations into a "simplified" system that had fewer equations.

Noticing places to re/write even more disciplinary relationships

Using disciplinary conversations to tell the story, we can also revisibilize important disciplinary relationships. Not only did Lorenz's work emerge from disciplinary attunement to materials and theory; but also close attention to how he was being affected, as well as disciplinary relationships with colleagues typically left out of the story.

Without an embodied, disciplinary sense of affective attunement; Lorenz would not have been able to notice what was worthy of more investigation—nor would he have been able to choose a

simplified system that exhibited similarly strange behavior. Lorenz's refined sense of how interesting paths of inquiry *felt* were integral to his decisions to stop when something felt strange, look again, keep trying to understand what seemed strange, and choose a smaller system of equations that was simpler yet retained the same *feeling* of strangeness. Dynamic systems exhibiting these characteristics are called strange attractors—retaining this emotion within their label. Learning chaos theory not only involves feelings of surprise, but also learning when and why you should be surprised.

Not only is the behavior important to understand, but the specific feelings of surprise and wonderment that flash up are essential pieces of teaching and learning in many areas of STEM. More than just chaos theory, similar constructions of 'becoming appropriately affected' are built into the teaching and learning of relativity theory, quantum theory, set theory, topology, and epigenetics (among surely more). Because cultural dynamics shape the distribution of privileges for who can show or feel emotion, these cultural dynamics implicitly shape who is allowed access affective aspects of disciplinary development. Recognizing and purposefully reshaping the emergent politics of disciplinary identity, therefore, requires recognizing ways that affect inheres in mathematics.

Additionally, the contributions of two women have been left out of narratives of Lorenz's discovery. Margaret Hamilton and Ellen Fetter worked (consecutively) as technical assistants that would have been coauthors by today's contemporary publication norms (Sokol, 2019). Hamilton and Fetter "still speak of Lorenz's humility and mentorship in glowing terms" (Sokol, 2019), but James Gleick (1987) and other chroniclers left them out.

Writing for Quanta Magazine, Joshua Sokol interviewed both Hamilton and Fetter to revisbilize their entanglement with Lorenz's work. Hamilton came to work with Lorenz at MIT in 1959—just as Lorenz had taught himself to use the LGP-30. Sokol (2019) quotes Hamilton as saying, "He loved that computer. And he made me feel the same way about it." Hamilton programmed the LGP-30 with Lorenz during these "formative years" of hers. Sokol relays anecdotes from Hamilton:

> She recalls being out at a party at three or four a.m., realizing that the LGP-30 wasn't set to produce results by the next morning, and rushing over with a few friends to start it up. Another time, frustrated by all the things that had to be done to make another run after fixing an error, she devised a way to bypass the computer's clunky debugging process. To Lorenz's delight, Hamilton would take the paper tape that fed the machine, roll it out the length of the hallway, and edit the binary code with a sharp pencil. 'I'd poke holes for ones, and I'd cover up with Scotch tape the others,' she said. 'He just got a kick out of it.'

Lorenz first mentioned the sensitivity to initial conditions of their weather model at a conference talk in November of 1960—meaning that Hamilton would have been running the calculations where this piece of chaos theory was first noticed. Hamilton's disciplinary relationships with the LGP-30, the model, the code, the paper tape, and the beginnings of Chaos Theory must have been just as strong as Lorenz's disciplinary relationships.

Hamilton moved to another project in the summer of 1961, and trained Fetter as her replacement. Hamilton eventually led the team for the onboard flight software for the Apollo project, coined the term "software engineering", and led the team that wrote software for the first US space station (Sokol, 2019). Fetter worked with Lorenz as they investigated the simplified system of equations, and plotted the trajectories of points to visualize the Lorenz attractor for the first time. Fetter, too, would have been running the calculations that further developed this idea of sensitivity to initial conditions. In addition to Lorenz's disciplinary relations, Fetter's relationships with the computer, the theory, the model, the programming, the strange feeling of the phenomenon, and the description they were building were also defining relationships for the beginnings of Chaos Theory.

After the Lorenz's 1963 papers were published, Fetter moved with her husband as his academic positions changed. Eventually, she left her programming job to raise children. Fetter says she considered returning to programming in the 1980s, but she says she "got sort of put off by a couple job interviews, I

said forget it. They went with young techy guys." By then, the demographics of women in computing related jobs began a decline that continues today.

Every moment is a re/write

Relational ontologies bring a type of built-in sense of infinity to our conception of agents, phenomena, and narratives. An idea, object, story, idea, etc. is like an intersection point of infinitely many relationships. No one finite representation can fully represent it, and different representations may not be commensurable or comparable. This sense of infinity is a feature—enabling multiplicity (Warren et al., 2020), pluralism (Andreotti et al., 2011), and continual deconstruction and re/writing (Roth, 2012). Noticing disciplinary conversations involves continually looking again for how relationships are built and sustained.

Everyday designs for disciplinary conversations

- Are there small ways to rethink our learning environments to be more relational, dialogic, and amenable to disciplinary conversations?

It can seem like a difficult problem to conceive of mathematics as dialogic, rather than a system to find truth and correct interpretations. The educational and professional institutions of mathematics (and all of STEM) are also very stably established. How do we rethink our learning environments? And what outcomes could we expect—when we cannot retie all the tangled knots of mathematics all at once?

As it relates to the design and assessment of learning environments, I think three holistic principles are necessary:

1. Acknowledge that learning is taking place from within a system where structural harm is not being actively addressed.
2. Determine the minimum amount of buy-in to the system that is required. And meet that standard.

3. Make intentional design decisions that should help desettle some of the harmful onto-epistemology present in dominant performances of the discipline.

In my own classroom, I acknowledge that students often have a lifetime of trauma that sits with them. A formative moment for me happened when I was tutoring a student: As I asked questions, gently explained a problem, and led her to answer; she cried tears of pain when she got the answer right. I asked why, and she said that finally seeing how to do it had made it seem easy—and that she felt stupid for not understanding it earlier. Even in the safety of a moment where she had the best chance to experience the satisfying snap of her understanding locking into place (possibly the one thing in mathematics that makes it worthwhile), the judgement that inheres in mathematics still reached through to hurt her.

Decoupling STEM from the many overtones of settler-colonialism, may not be an attainable goal—especially when designing a lesson or grading scheme. Students will need to take standardized tests. Students will encounter themes of dominance and control in other STEM environments. Students will need to move past the designed experience into a learning environment that hurts them.

A common approach of justice-oriented design-research in STEM has been to build literacy in STEM by investigating political dimensions of contemporary problems like climate-change, housing reform, energy sustainability, voting rights, algorithmic bias, etc. This is important work. But a complimentary approach is also important: noticing where ideological themes exist in STEM, and then deciding how some themes could be eliminated and others might be boosted. In chapter 2, I argued that representationalism supports zero-point epistemology, and that STEM can also create narratives of dominance and control of the world through our scientific models and theory. I also noticed that close attention to others exists as a theme in STEM. And I suggested that boosting the disciplinarity of listening could bring STEM practices into closer alignment with restorative justice practices. In chapter 3, I argued relationships define STEM in an analogous way to how we typically understand practices to

define STEM. I argued that a relational turn would help notice how harm and care inhere in STEM, so that we may constrain and enable them in more purposeful ways. In chapter 4, I argued that overtones of harm inhere in STEM, and that searching for overtones of other positive affect is necessary to decide which types of affect we coconstitute as inherent to mathematics.

In this dissertation, I have made these arguments at broad scales and used specific examples. But in my own teaching, I blend these themes into my daily praxis. I have four design intentions as I design my lessons and grading schemes:

1. Facilitate the students' conversations with each other, the material, and themselves.
2. Support an environment where the students are accountable to each other and the material.
3. Remain minimally and sustainable accountable to larger structural systems despite their harmful nature—and without carceral logics of punishments or inability to repair relationships.
4. Build opportunities and assessments where the students can build and rearrange their disciplinary relationships in ways that fit them best.

Chapters 2 and 3 have explored ways that our research design for an open-ended project to "make an oscillator and build a computational model" was a substantive way to facilitate the students' negotiations of their relationships to tools, material, each other, and themselves.

Building further narratives

- Can further investigation sustain relational narratives for STEM?

Further investigation can build more relational narratives for STEM. Throughout this dissertation, I have emphasized that disciplinary conversations are not more "real" than other descriptions of learning and doing STEM. But there are strong connections to other theory and scholarship that made this work worth developing.

We know that the cognitive practices of science are integrally entangled with our embodied movements and affective states (DeBellis & Goldin, 2006; Ehret & Hollett, 2016; Hannula, 2012; Jaber & Hammer, 2016b, 2016a; Zan et al., 2006). An important pedagogical implication is that if there are affective components of scientific expertise, then a central piece of what we are teaching and learning in Science classes is a particular way of listening and responding to affect.

Beyond just noticing and reproducing previous ways of attending to affect, this gives us an opportunity to question what ways of listening and responding to affect we *want* to be characteristic of STEM. The entanglement of affect and STEM has been noticed. Entanglements of STEM with misogyny, colonialism, heteronormativity, and racism have also been noticed. But these entanglements have been under theorized. The ethical motivation for understanding affect in STEM has been scarce. And ways forward are far from obvious.

Narratives of disciplinary relationships and disciplinary conversations do this work in three important ways. By theorizing disciplinary practices as performative relational practices (rather than actions of individuals), we can talk about affect as it emerges and how it propels inquiry in STEM—without having to fix a representation for which emotions as disciplinary or epistemic and which are not. By motivating an account of harm perpetuated through STEM, an ethico-onto-epistemology for STEM that theorizes relational care becomes necessary. By shifting the focus to material-dialogic relationship building, the framework of disciplinary conversations changes the narrative of STEM practices.

Rather than individual actions that
perpetuate the current (often
harmful) directions and momentum of STEM,
searching for deep understanding about
possibilities for future intra-relationships
could become the benchmark for whether inquiries are
considered scientific or
trash.

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