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A pedagogical reasoning framework for teaching and mentoring STEM research

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Abstract

Pre-tertiary students conducting authentic scientific research is an internationally occurring phenomenon, but it is currently poorly reported and understood in the literature. Consequently, how science teachers may best support students in their learning during authentic inquiry is functionally still opaque and not well-developed, and this paints a bleak image of in-service teachers being unimportant to the development of authentic scientist capacity. In this paper, we propose a pedagogical framework to navigate the uncertainty involved in mentoring high school students in STEM research. Five teachers from the Philippines mentoring students in authentic projects in the computational, life, and physical sciences critically investigated their empirical teaching episodes. Using the language of inferentialism, a novel interpretation we pursued as method for pedagogical reasoning, this paper proposes pragmatic steps that teachers may follow to be more intentional and explicit in their pedagogical decision-making as they navigate the uncertainties of scientific research. These findings may not only be directly helpful to "teacher scientists," but also could scaffold future work in the teaching of STEM research to students at the secondary level and beyond.

Keywords Authentic science, Inferentialism, Scientist education, STEM, Self-study

1 Introduction

Despite our discipline's evolving visions for scientific literacy as a key feature of the general population (see [37, 43]), the formation of future scientists remains a main goal of science education. If we broadly define scientists as individuals who contribute to scientific knowledge through research in STEM (from the recognition approach, see [24]), the Philippines is one example where this is made explicit in post-elementary curricula. In the two education systems in the country, namely the Department of Education (DepEd) and the Philippine Science High School (PSHS), secondary students pursuing the STEM strand are expected to complete a novel scientific project prior to graduation. This process includes a project proposal, its implementation, and a final defense, not unlike typical research projects done by students in disciplinary STEM education. These projects allow students to mirror what scientists do, and in the process potentially contribute

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to scientific knowledge or solve problems and develop science identities. The quality of these projects in the Philippines are not homogenous across students and school contexts, although research outputs have occasionally led to international competition winnings, publications in peer-reviewed journals, or intellectual property protection. The STEM research sequence in the Philippines is typically a capstone requirement for students aged 16 upward, although research teaching may start as early as age 12, as in Table 1.

Pre-tertiary participation in scientific research is not unique to the Philippines as it occurs in multiple countries and contexts, but it is unstandardized and therefore poorly understood [1]. Regardless, it is an internationally active endeavor. Since 1950, pre-tertiary scientific research from across the globe compete in the annual International Science and Education Fair (ISEF) in the United States. Consequently, DepEd conducts science fairs at the division, regional, and national levels to screen for the country's participants to ISEF. As an educational activity, students conducting projects as scientists appears to be theoretically sound, applying long-standing ideas of authenticity in learning [12, 21], see also authentic science e.g. [33], and supported by results in both problem- and project-based learning (e.g. [35]).

An issue that arises from conceptualizing some aspect of science education as the formation of scientists is that science teachers, who serve as frontline implementers, are not trained as scientists. Therefore, we do not expect them to be prepared to mentor students to succeed in authentic scientific inquiry, and some involvement of external scientists appears mandatory. In the Filipino context for example, science teacher education programs may be science content-heavy, but there is no provision for STEM inquiry experiences. The only adjacent research preparation pre-service teachers receive is action research [19] and an undergraduate education thesis, but both operate under vastly different norms as disciplinary STEM work.

Unfortunately, there are no systematized scientist-school partnerships when it comes to Filipino research teaching. When the government expects scientist education beginning at the secondary level, or when there is pressure for Filipino schools to succeed in competitions such as ISEF, significant professional development must be implemented to scaffold teacher capacity in research. For example, recent work in the UK on students and teachers (e.g. [3, 7]) showed significant gains in teacher profiles when they participated in ongoing research. Still, teacher development in STEM research is difficult as there is a lack of a rich knowledge base to inform it. For one, there is no shared language

Table 1 Research in Filipino secondary curricula [22, 23, 38]

	Grade (age group)	DepEd curriculum		PSHS curriculum
Junior High School	Grade 7 (12–13)	Research 1*		
	Grade 8 (13–14)	Research 2*		
	Grade 9 (14–15)	Research 3*		
	Grade 10 (15–16)	Research 4*		STEM Research I
Senior High School	Grade 11 (16–17)	Practical Research I		STEM Research II
	Grade 12 (17–18)	Practical Research II	Inquiries, Investigations, and Immersion	STEM Research III
			Research Project	

*Additional courses only in special STEM public schools

toward these experiences. They manifest as research experiences (like course-based undergraduate research experiences or CUREs, see [30]), investigatory projects [41], innovation, inquiry, or authentic science, among other terms. For another, understanding better how STEM disciplines conduct research does not necessarily address *how* those could be taught to students, or *how* teachers could incorporate those in their professional practice.

We are a collective of Filipino STEM research educators, and in the process of attempting to improve our research teaching practice, saw firsthand the lack of literature that could guide us toward our development. We resolved that fundamental theoretical work would be the most appropriate way to guide our shared development, and hence we turned to self-study, a key methodology in teacher education that allows the theorizing of how teachers learn [31, pp. 818–819].

The STARTLES group, which stands for the "Systematic Theorizing of Authentic Research Teaching and Learning Experiences in STEM," is composed of Filipino teachers from multiple cities and in various teaching contexts, and sought to generate theoretical work that not only would be pedagogically useful, but also empirically generative for future inquiry in STEM research education. In our collaborative self-study, we supported and investigated each other's research teaching practice to articulate epistemologically and methodologically rich perspectives that could not only immediately improve our own teaching, but also guide STEM research teacher education in the Philippines and beyond.

Our initial goal was to conduct rigorous examination on our actual teaching episodes to tease out new professional knowledge for our various content domains. However, in our research meetings, we frequently encountered pedagogical dilemmas that were highly contextual and somewhat detached from the scientific processes themselves. Instead of discussing issues with using a spectrometer, or interpreting a statistical test, for example, we mostly navigated class disruptions, late delivery of learning materials, or natural disasters, among others. All these interfered with our teaching of STEM research and the potential learning of our students. As "teacher scientists" [44], we had a commitment to not only upholding the standards of the STEM discipline we were conducting research in, but also to ensuring that our students were *learning*. It is a common talking point among learners in the Philippines that some research teachers don't actually *teach*, instead leaving students to their own devices, and so the students develop negative attitudes toward research because of this poorly conceptualized pedagogical decision. We wanted to avoid this.

When discussing those contextual non-science dilemmas that impacted the research learning process, we could not reasonably offer definitive practical advice to each other. It would have been disingenuous to instruct someone what to do granted we were not the ones navigating the specific contextual nuances, but that also meant we could not pinpoint how to best move forward. In making pedagogical decisions in those episodes, we individually tapped onto our rich banks of professional knowledge, particularly the construct framed in the teacher education literature as contextual knowledge (CxK or XK, see [11] for a recent review), but unfortunately the available models and findings in PCK or TPACK were mostly descriptive and not inherently applicable to our decision-making. Additionally, the pragmatic research teaching papers we found (e.g. [52]) were not directly transferrable to our own issues due to the specificity of our contextual

problems. This paper documents our work as we redirected to a new research question: How could science teachers navigate contextual problems during STEM research teaching and mentoring? Our ultimate goal in this article is to offer a pragmatic framework for potential but immediate adoption, so that research teachers could be more intentional in mentoring their students' STEM projects.

2 Theoretical perspectives

2.1 Self-study as methodology

Self-study is recognized as an important methodological approach in teacher education, and it is "intimate scholarship" that embraces subjectivity and vulnerability, developing knowledge through dialogue with oneself, the literature, past experiences, and colleagues [14]. Self-study researchers, which in this case are teachers, focus on their own professional practice and aim to understand and improve it.

Self-study research frequently employs exemplars and narratives as core components for articulating findings and advancing knowledge [31, p. 818]. Exemplars refer to documented instances of "normal practice" within a community [36] that, by nature of being what happens in real contexts, collectively represent trustworthy concepts and methods for addressing professional challenges, thus serving as a foundation for knowledge growth in the field. Narratives, as a form of autobiographical writing, are vital in self-study because they are targeted stories with a beginning, middle, and end [39, p. 142], allowing researchers to explore individual moments within their broader professional history and reflect on their personal beliefs and identities. Self-study recognizes that teacher knowledge is often more narrative and contextual than absolute, and teacher storytelling is therefore an attractive way to capture the complexity of teaching and learning [31, p. 823]. Accommodating beyond positivist research perspectives, the goal of self-study is to provoke, challenge and illuminate rather than merely confirm and settle, and narratives serve this purpose by providing rich, lived experiences for others to draw upon.

This article therefore pursues a stylistic choice that weaves personal narratives and scholarship. The use of narrative forms, including personal stories and journal entries, captures the immediacy and intimacy of teachers' lives, intermingling description, commentary, introspection and analysis to enable deeper reflection and transformation [14]. While some traditional research forms may prioritize a distanced or objective voice, self-study explicitly embraces subjectivity and acknowledges the influence of personal histories and emotions [6, 14].

We hence briefly tackle the rich discussion on the validity of this methodology. Self-study research is characterized by its self-initiated and self-focused nature, with the researcher, situated in relation to students, acting as both the subject and author of the study [13]. This distinct ontological and epistemological stance inherently justifies smaller "sample sizes" in positivist language, as the focus is on intimate inquiry into one's own practice, or a collaborative exploration among a small group of educators. The reason for our pursuit of self-study lies in its core characteristics: it is improvement-aimed, interactive, and utilizes multiple, primarily qualitative methods [31, pp. 849–852].

So, in self-study research, validity is redefined as trustworthiness [14], which emphasizes the degree to which other practitioners or researchers find the reported observations, interpretations, and generalizations reliable enough to use as a basis for their own

theorizing, research, or practice. The inherent personal and contextual nature of self-study means that knowledge generated is approximate and suggestive rather than absolute truth, which means it employees different standards of rigor [31, p. 821].

As collated by Butler and Horton's [14] assessment of self-studies published in Studying Teacher Education, trustworthiness in self-study is achieved through various strategies, such as: exemplar-based validation through extant frameworks and papers, external evaluation through critical friends or reviewers, detailed data collection and analysis, triangulation, iterative questioning/analysis, member checking or reviewing interpretations with participants, and thick description or providing comprehensive, detailed accounts of context and research outcomes to facilitate readers in assessing applicability. While not all measures are obligatory, their purposeful integration fortifies the assessment of trustworthiness by reviewers.

2.2 Pedagogical reasoning

Conceptualizing scientific research as something that can be *taught* requires reconciling the professional identities of "scientist" (who contributes to scientific knowledge) and "teacher" (who makes pedagogical decisions). We frame this study through the latter so that we can understand how teachers in general might navigate the uncertainty involved while implementing STEM research.

As teachers already making reasoned-out pedagogical decisions in our students' research projects, we manifest a specific sort of *knowledge in teaching*, although we are typically unable to examine it closely due to the whirls of our daily duties [32]. The components of our knowledge in teaching are implicit and personal, but they could be understood through *pedagogical reasoning*. In the book generated from the Second Pedagogical Content Knowledge Summit in 2016, pedagogical reasoning formed the core of what became termed as a teacher's enacted pedagogical content knowledge [15, p. 107], or the specific manifestation of PCK in real teaching episodes. Shulman [47] argued that pedagogical reasoning is the form of teacher cognition that motivates pedagogical actions, and is therefore a vital emphasis when assessing teacher quality. An effective teacher, or one with high PCK, demonstrates high levels of pedagogical reasoning and can articulate how specific teaching actions meet pedagogical *ends*, and why those *means* were selected in the first place. This value placed on pedagogical reasoning prompted the summit to recommend its inclusion in measures of teachers' PCK [17, p. 262].

As Loughran [32] argued, pedagogical reasoning is the manner to explicate the sophisticated sorts of teacher knowledge in actual practice, in contrast to scholarly moves of just observing teaching episodes as events that happened. We briefly review here common pedagogical reasoning models and how they might apply to STEM research teaching or mentoring.

Shulman's model for pedagogical reasoning, named the Model of Pedagogical Reasoning and Action (MPR&A), involves six major steps: comprehension, transformation, instruction, evaluation, reflection, and new comprehension. Shulman posited that pedagogical reasoning is dynamic (and not discrete) movement between these steps. A fundamental assumption that Shulman held in this model is that the teacher begins with a reference text or teaching material of some form, and the teacher is responsible for making sure students learn the contents of that reference text. To quote, the teacher "is

presented with the challenge of taking what he or she already understands and making it ready for effective instruction" [47]. The MPR&A appears reasonably influential and has been adapted into more contextual models such as Starkey's [49] Model of Pedagogical Reasoning and Action for the Digital Age, and Smart's [48] Technological Pedagogical Reasoning, both of which contain similar fundamental steps as Shulman's.

Trevisan and colleagues [50] argued that teachers' pedagogical reasoning and decisions involve not only cognitive processes but also their skills, practices, values, and orientations. To capture this complexity, they proposed using the Epistemic Frame Theory (EFT) as a model for understanding pedagogical reasoning. According to Shaffer's [45] formulation of EFT, individuals in groups develop epistemic frames, which are structured sets of skills, knowledge, values, and identities, that influence their actions. Within teaching, these frames shape how teachers approach pedagogical decisions by connecting individual reasoning to broader professional practices and group or cultural dynamics. By considering the interplay of cognitive and non-cognitive factors, EFT broadens the conceptualization of pedagogical reasoning beyond a purely cognitive phenomenon, situating it within the social and professional contexts of teaching.

For pedagogical reasoning among STEM professionals, Andrews-Larson and colleagues [2] provided a model centered on mathematicians (primarily university professors), demonstrating how engagement with students' mathematical reasoning influences instructional decision-making. Their study highlighted that rich pedagogical reasoning emerges from iterative interactions, where mathematicians first engage deeply with mathematical content themselves before interpreting and responding to students' reasoning. This dynamic process builds a feedback loop between professional expertise and instructional adaptation. Despite mathematicians' expertise as "doers" of mathematics, the study found that pedagogical reasoning, as "teachers" of mathematics, was often less developed and hindered by limited emphasis on inquiry-oriented and student-centered practices. Some emphasis on the instructional goals of a pedagogical dilemma may be helpful for experts. Gotwalt's [27] study on literacy-focused classrooms within a job-embedded, practice-based professional development setting revealed that teachers engaged more effectively in pedagogical reasoning when they explicitly identified and valued the instructional purposes underlying specific pedagogical challenges.

The previously mentioned models are explanatory in that they allow a theoretical description of pedagogical reasoning (i.e., allowing researchers to develop an explanatory frame for how teachers make decisions) but they may not necessarily be pragmatic or adaptable for direct application *by* teachers (or knowledge *for* practice). We needed a framework that we could sit down with and help us decide *what* to do during our practice, as STEM research is highly messy and uncertain. Another issue across the above pedagogical reasoning models that hindered us from immediately applying them is that they usually assume a defined learning end, and that pedagogical reasoning merely describes the steps or means to get to that end. In other words, there is a correct answer to be learned, or a clear outcome to be worked toward. For example, there is a "right" answer in a photosynthesis lesson, and hence a teacher through pedagogical reasoning can justify the steps taken to get to the student's learning of the right answer. This is functionally problematic in our current conceptualization of STEM research experiences because authentic scientific work is inherently uncertain, and there is no assurance that the teacher is working toward the correct thing in research.

A simple reformulation to address this issue may be to consider that research experiences work toward the answering of a research question, and therefore pedagogical reasoning in it would lead to that outcome, yet this manifests further issues. Firstly, this is a potentially intangible learning outcome with moving goal posts, and the pedagogical decisions a teacher scientist must make to get to that outcome (i.e. for learning) become functionally more opaque and difficult to conceptualize. Some research questions may never be answered, but learning and progress will happen regardless. Secondly, any larger educational program that seeks to teach potential scientists would likely recognize that solving research questions is an incomplete picture of what needs to be considered in forming potential scientists (see e.g. [51], where the most common reason surveyed scientists pursued science is because of interest). For this study, we leave the pedagogical goal open, as it may be too amorphous to generalize for STEM research. Instead, we characterize pedagogical reasoning in STEM research to revolve around the contextual problem solving a teacher/mentor may encounter that is still beneficial for the growth of the learner.

2.3 Inferentialism

Due to the inappropriateness of extant pedagogical reasoning models, we sought out a robust and more fundamental theoretical package to guide our reasoning. We chose Robert Brandom's *inferentialism*, a comprehensive philosophical approach that understands rationality as the giving and taking of reasons.

Brandom [9, p. 11] posited that what makes us rational is our ability to participate in inferential articulation. For simplicity, we can conceptualize an inference as an if/then statement, such as "*If* Fae is a cat *then* Fae is a mammal." Here, if one were to utter that "Fae was a mammal," they could justify their claim by their *commitment* to the idea that Fae was a cat. Their reasoning will further be supported by additional statements they hold true in their mind, such as "Fae has four legs and whiskers" and "All cats are mammals." These statements (or *judgments*, [10, p. 34]) are only meaningful because they can serve either as *premises* (X) or *conclusions* (Y) in an inference (if X then Y, or $X \rightarrow Y$; e.g. Fae is a cat $\rightarrow$ Fae is a mammal). Any utterance or action, such as a pedagogical decision, can therefore be explained as the conclusion from a *web of reasons* that are inferentially linked, logically consistent, and leading to that outcome. In other words, a web of reasons *is* pedagogical reasoning, and therefore inferentialism presents itself to be an attractive language for teacher education in attempting to chart out why teachers do what they do.

Inferentialism has already been introduced to education research on several occasions. For science education Causton [16] proposed inferentialism as an alternative to constructivism. Causton characterizes inferentialism as an epistemology, arguing that it can avoid several risks in constructivism such as a child's meaning-making given equal status as scientific language, or that students "learning" science would be about them making mental representations of scientific concepts instead of understanding how scientific concepts are used in reasoning. In a special math education issue dedicated to inferentialism, Bakker and colleagues [4] used inferentialism in an empirical project to unpack an intern's statistical reasoning, essentially spelling out in natural language the complicated connections of premises and conclusions that led the subject to *choose* actions to pursue while working through statistical information.

Because of its conceptual breadth and depth, inferentialism is appealing when it comes to research questions pertaining to cognition, and hence we felt it was appropriate to explore further for teacher education. Whereas the Epistemic Frame Theory approach for pedagogical reasoning (as summarized in [50]) would explain teacher action as the fruit of interactions of a teacher's knowledge, skills, orientations, and community, Brandom's inferentialism also explains all of these aspects yet through a philosophically robust package spanning several books. We chose inferentialism over EFT as Brandom's package offers an explanatory frame for cognition and action, as well as a deep exposition of how Kantian and Hegelian ideas would explain reasoning in the context of an individual's community, history, and personhood, and therefore we could then theorize for teacher learning as consistent with the goals of self-study methodology. A full exposition of inferentialism is not included here, but other aspects of Brandom's framework are included in the findings when relevant to the discussion.

The chief frame of using inferentialism as a guiding framework, therefore, is to make explicit what is implicit in the web of reasons, such as what judgments or beliefs an individual holds true, and what norms of the community the individual obeys. Utilizing inferentialism as our explanatory vehicle allows us to take all of these interacting factors, and unlike EFT, connect them more explicitly either upstream or downstream within a web of reasons. Hence, this possibility to sequence reasoning and interpret some as more fundamental than others could help us theorize pragmatic steps to scaffold teacher reasoning during STEM research mentoring.

3 Methods

This paper, and self-study as methodology more broadly [28], present as a recursive process between data collection, analysis and interpretation, and therefore it becomes difficult to disentangle these steps as separate during this project. However, as validity in self-studies presents as trustworthiness, we attempt to clarify these interwoven steps in the method prior to them being merged during the findings.

3.1 Context, participants, and data collection

The STARTLES members who participated in this piece are the five people displayed in Table 2, and data were collected and analyzed recursively over 5 months. Each participant was actively involved in STEM research teaching/mentoring, although contexts,

Table 2 Participant profiles

Participant	Experience	Current research teaching context
Computational sciences		
Bench	Three years of formal STEM research teaching	Public STEM high school teacher, teaching Grade 7 research
Le	Four years of formal STEM research teaching	Former PSHS teacher, mentoring a statistics research project remotely to a graduate student
Life sciences		
Wilbert	Four years of formal STEM research teaching	Public high school teacher, teaching Grade 10 research
Physical sciences		
Ariel	Three years of formal STEM research teaching	Public science high school teacher, teaching Grade 7 research, and mentored Grade 12 students for a research competition
Femi	Seven years of formal STEM research teaching	Public school teacher, teaching Grades 11 and 12 research

experiences, and disciplines were highly variable. Regardless, this diversity served as further motivation to capture these narratives through a collaborative self-study.

As a collaborative self-study, we largely adapted the methods from McCaw and colleagues [34]. We adapted their multi-phase design, yet instead of proceeding with it linearly as the authors, we went in between phases recursively as we proceeded to conduct our practice, interpret our experiences, and improve upon them. The self-study's moments are summarized in Table 3. We call these as moments instead of "phases" as originally done by McCaw and colleagues [34] to better describe how our study did not occur in a linear sequence.

3.1.1 Individual reflections

Each individual maintained electronic reflection journals detailing their experiences during this period, and the narratives in these journals formed the major corpus for this study. Journals were open-ended but reflective, and the content of the entries were up to full the discretion of the researcher. Entries, however, were dated to track changes or developments across time, and were focused on relevant experiences and ideas about being STEM research teachers.

3.1.2 Synchronous critical friend dialogues

Acting as a critical friend (a "trusted person who asks provocative questions, provides data to be examined through another lens," [20, p. 50]), each participant participated in synchronous research meetings once a month per content group (Computational, Life, and Physical Science) where we discussed our own practice and the circumstances we were navigating, which may or may not necessarily have been documented in the individual reflection journals. These meetings were also avenues to offer each other support as we navigated difficult and uncertain episodes in our practice. The meetings were held on Zoom, recorded, and transcribed. By default we spoke in English, but some would use Filipino if it would have improved the authenticity or accuracy of what they had to say. The meeting transcripts were included as research data.

3.1.3 Asynchronous critical friend dialogues

In Month 4, each participant per content group reviewed the journal entries of the other member in the group and left annotations and comments to elicit further reflection and dig deeper into emergent issues. These were also recorded as data.

Table 3 Self-study research process (adapted from [34])

Moment	Notes	Timing
Individual reflections	Researchers maintained electronic reflection journals pertaining to their STEM research mentoring	Months 1–4
Synchronous critical friend dialogues	Researchers participated in monthly critical friend meetings to discuss their practice, and to solicit and offer support	Months 1–4
Asynchronous critical friend dialogues	Researchers read and commented on other members' journals to elicit further reflection and action	Month 4
Individual synthesis	Researchers responded to asynchronous comments as well as developed webs of reasons for further reflection	Months 4–5
Development of the manuscript	Researchers processed the data, synthesized a consensus theoretical perspective, and developed the manuscript	Months 1–5 and beyond

3.1.4 Individual synthesis

Every individual was given opportunities to respond to the annotations in their journals in Month 5, as this would have been helpful for reflection and therefore for further theorizing. As a final reflection tool, each participant, in dialogue with the self-study assemblage, identified one key contextual problem they had brought up in the meetings or journals and developed a web of reasons diagram (adapting [4]) to illustrate their pedagogical reasoning.

A web of reasons, in the diagrammatic presentation of Bakker and colleagues [4] for math education, was a deliberate sequencing of premises and conclusions (i.e. inferences) an individual may have had to explain a decision the individual made. In their study, the premises and conclusions to reasons were identified by the researchers through interview data, and for validity, competing explanations were negotiated between them until there was agreement. In cases when the premises and conclusions were doubtful, member checking was done with the participant, or additional data was collected. The sequences were then visualized in diagrams by the researchers.

We approached mostly the same steps but with modifications. For our pedagogical problem under investigation, all of us generated diagrams directly instead of providing lists of reasons first. This was pursued to elicit reflection: as each researcher reflected on their problem and ultimate pedagogical action, each of us worked backward by asking why each action or belief was true to us, uncovering the implicit "in-between" reasons until we reached fundamental premises we could not go deeper from. In a sense, this reflection activity was a pragmatic and novel implementation of inferentialism, being able to make explicit the aspects of our reasoning that were never mentioned or said out loud, which were what we needed to theorize how to do pedagogical reasoning in STEM research mentoring. This backward process of reflecting on ideas that served as premises to the pedagogical action (or any intermediary reason within the web of reasons), allowed us to generate our diagrams for our webs of reasons.

Once each individual was able to generate a web of reasons, the diagrams were externally evaluated by other members in a synchronous meeting to assess their soundness, triangulated with the journal entries and meeting recordings to double check consistency with prior data, and refined afterwards to clarify contentious aspects. The validity status of these diagrams, being reflection artifacts, are comparable to the journals, but since there was external involvement in the crafting of these diagrams that impacted the validity, final member checking was done with the respective owners of the diagrams to verify that the diagrams still accurately represented the landscape of reasoning they maintained during decision-making.

3.2 Data analysis

The main analytic approach of this article is crystallization, a methodology to respect multiple rich perspectives in narrative research without having to privilege a few [25]. It was first introduced in Richardson's [42] influential work on writing as a way of knowing, and used in a recent self-study report [26]. Crystallization utilizes multiple modes of data, contrasting ways of knowing, and deep, thick description of a phenomenon or group [25]. As our intent in this article is a foundational examination, not to settle it once and for all, but to offer pragmatic language that could be helpful for teachers to not only work but construct knowledge, we echo Ellingson's crystallization in that we

wish to understand the phenomena not through traditional positivist approaches, but in lived, subjective, and open exploratory work. The openness and diagrammatic format of the webs of reasons, for example, lends it to be a creative, alternative way for teachers to make sense of their lived experience.

In terms of method, we used crystallization to repackage our closed coding of data, inductive immersion/crystallization, and philosophical writing-as-knowing into a unified narrative. By the end of the project, we had collected and analyzed complex multimodal data in the forms of 28 pages of peer-annotated reflection journals, 162 pages of meeting transcripts, and five web of reasons diagrams.

3.2.1 Closed coding

To systematically note the types of contextual issues that emerged from the data and track how they developed or resolved across the 5 months, meeting transcripts and journal entries were coded by a STARTLES member that was not part of the five participants, following Brianza and colleagues' [11] code scheme for contextual aspects. The choice to have an external rater was chosen to limit further subjective interferences into this preliminary positivist-reminiscent step, as the rest of the crystallization efforts were highly subjective. For this coding step, any contextual issue raised by a research teacher was coded a unique label or name before being assigned at least one *level* (immediate, proximal, or distal) and *dimension* (social, epistemic, or resource). An immediate context refers to the direct teaching/learning (classroom) context, whereas a proximal context refers to a wider scope up to the participant's region, and distal beyond those (at least inter-region, or national). A social context pertains to people, while an epistemic context refers to information and messages, and a resource context refers to a physical, infrastructure, process, or practical aspect.

3.2.2 Immersion/crystallization

With the closed coding, we were able to understand the general landscape of contextual concerns we were navigating, and therefore allowed us to be aware of *what* we could talk about in terms of theorizing, and *how* we were similar despite our diverse lived experiences. Fundamentally, data was always interpreted during the fact, mirroring the recursive nature of self-study methodology [28], and this section details how the complex set of data was analyzed in an ongoing manner. The inductive approach used to analyze the data was immersion/*crystallization*, which is distinct from Ellingson's [25] crystallization above that does not merely approach data inductively. Immersion/*crystallization* is composed of immersion, *crystallization*, creative synthesis, corroboration, arriving at final interpretations, and reporting [8].

Immersion [40] was led by the first author, who coordinated the project and was present in the meetings of all groups, and therefore was the most immersed in the data. He continuously engaged with, read, watched, or listened to the various data sources generated in real-time across the initial 5-month self-study period. Other members also immersed in the data in differing degrees. Then, *crystallization* involved "temporarily suspending the process of examining the data (immersion) in order to reflect on the analysis experience and attempt to identify and articulate patterns or themes noticed" [8]. The first author would frequently raise or inquire about perceived trends across the data and across participant groups during synchronous critical friend meetings, fueling

the groups to process ideas for data interpretation, recommend different courses of future action, or "facilitate improvements in data collection" [8] by asking members to reflect on particular aspects. During the self-study, we generated tentative themes that we engaged with on how we navigated our decision-making following Brandom's framework, which eventually formed the major sections in the findings.

3.2.3 Writing-as-knowing

The latter steps of the immersion/*crystallization* process were more integrated with Ellingson's characterization of crystallization, in a sense that we pursued more creative, multimodal, and narrative approaches. In creative synthesis, we moved beyond the themes we generated and attempted to abstract them to get the bigger picture. We attempted to find patterns that were less explicit in our texts and webs of reasons by attempting to write as a form of inquiry. Richardson [42] characterized the act of writing as the construction of knowledge, and therefore our ongoing reflections attempted to explore what we have *crystallized*. Also, we began to construct the draft of this article, attempting to make sense using narrative approaches and philosophy to generate a pedagogical reasoning framework. During this, we utilized open argumentation and philosophizing to help understand our data, conducting abduction instead of traditional induction in order to find possible explanations to the issues in the data that we encountered. We exchanged drafts or ideas in between each other to improve how the knowledge was synthesized, weaving in our individual narratives and experiences. In corroboration, we then returned to the literature, finding alternative explanations or support and discussing them closely, or rereading or rechecking against Brandom's writings on inferentialism. We repeated these steps iteratively until we arrived at the final pedagogical reasoning framework, which is reported in this article.

Because of this highly fluid, abstract, and theoretical process, we improved trustworthiness by pursuing external evaluation. Two STARTLES members who were not part of the five participants in Table 2 assisted in reviewing the narrative generated from immersion/crystallization. The findings presented in this article were then generated only after careful discussion and consensus of all participants, not to mimic positivist positions, but to ensure that it did not override the diverse narratives of the self-study assemblage as a final form of member checking. Of course, we recognize the highly positional nature of this work, and we wish to reiterate to readers that this does not seek to offer positivist-like "truths" about STEM research teaching, but to begin discussions as we move toward a shared comfort to pursue further research questions about it.

4 Findings

Our collective theorizing was shaped by our frequent encounters of contextual issues as summarized in Table 4. Non-contextual issues raised in the data (i.e. those that pertain to the science research process itself) were not included unless they had a specific contextual component. Based on the results, participants most frequently discussed immediate contextual concerns, particularly with respect to resources such as time, finances, or equipment. In terms of dimension, epistemic contextual concerns were the least frequently occurring dimension across the data. In terms of level, distal contextual concerns were the least reported level, with resource issues from the Department of Education being the most expressed concern in that level.

Table 4 Frequency of contextual issues raised in the journals and meetings

Code	Frequency (%)*	Examples
Immediate level		
Social	11 (100%)	Students' interests for research projects and teacher's expertise do not match (Ariel)
Epistemic	13 (83%)	Dealing with multiple types of STEM projects is cognitively demanding (Femi)
Resource	20 (100%)	The time zones of the mentor and mentee are 12 h apart (Le)
Proximal level		
Social	11 (83%)	Newer teachers are assigned relatively heavy workload, interfering with research teaching responsibilities (Ariel)
Epistemic	8 (50%)	Students could not secure a scientist's mentorship in their project (Wilbert)
Resource	11 (83%)	Multiple typhoons reduced the time to implement the research curriculum (Bench)
Distal level		
Social	1 (17%)	Certain system-level instructions were to be implemented without thorough consultations with teachers in their contexts (Ariel)
Epistemic	1 (17%)	There were no appropriate prescribed curriculum materials for the Science, Technology and Engineering program (Femi)
Resource	6 (50%)	There is no national format or process in preparing research manuscripts (Ariel)

*Frequency is in terms of unique instances, while percentage is occurrence of at least one instance across all participants. One unique instance may be assigned multiple codes

Table 5 Pedagogical decisions investigated in the study

Participant	Contextual issue	Pedagogical action
Computational sciences		
Bench	Multiple typhoons and school events led to class disruptions, but students still needed to complete a research poster	Merge topics to make them more comprehensive, and focus on improving the class experience
Le	Massive time zone difference and competing responsibilities made close mentoring of the student impossible, leading to student possibly making mistakes or feeling lost	Allow the student to explore and fulfill tasks independently, but make sure to be available as soon as possible whenever an issue came up
Life sciences		
Wilbert	Scientist originally contacted to guide students in a mitosis project became unavailable to mentor them further	Learn the methods personally by training under a biologist during free time
Physical sciences		
Ariel	Competing work responsibilities could not allow closer involvement in refining the research project to be sent out to the science fair	Make time to accompany students when possible, but focus on guiding through the paper output submission
Femi	Recent assignment as the officer-in-charge assistant principal made close mentoring of research students difficult to implement	Outsource the day-to-day mentoring to co-teachers, but still be actively involved through checking logbooks and offering advice

The contextual episodes that were particularly meaningful to us and became the sources for our webs of reasons are presented in Table 5. Unique among these cases is Wilbert's, as it was the only contextual issue in our data where science content knowledge was foregrounded, which is why we felt it was important to include and analyze more closely. All other issues were not chiefly concerned with knowledge about science/STEM. Across all cases, although our decided pedagogical actions happened during normal practice, we couldn't really explain yet *why* we ended up with those decisions over a full landscape of alternatives, or *how* we arrived to them. This explains why we wished to look into them more deeply, in order to be able to be more ready to find ways to decide

on actions in the future. In doing this, we wish to emphasize that we do not claim that these were the best decisions a teacher could have made in those contextual issues.

Across all these cases, the pedagogical dilemma involved some generation of a scientific research product. For the most part, the cases revolved around a traditional research project where methods were supposed to be implemented toward the generation of novel results, except for Bench, who was teaching Grade 7 students (12–13 years old) and was only expected to have students generate a poster for a project they conceptualized. Examples of the webs of reasons that served as the scaffolds for our analysis are presented in Fig. 1. For clarity, any node to the left of an arrowhead is a premise, and any node to the right is a conclusion. For example, in Femi's final reasons leading up to the pedagogical action, the inference contains two premises and one conclusion:

If I will have to outsource some of the mentorship I usually provide,

and I can still track the progress of my students despite not being able to supervise

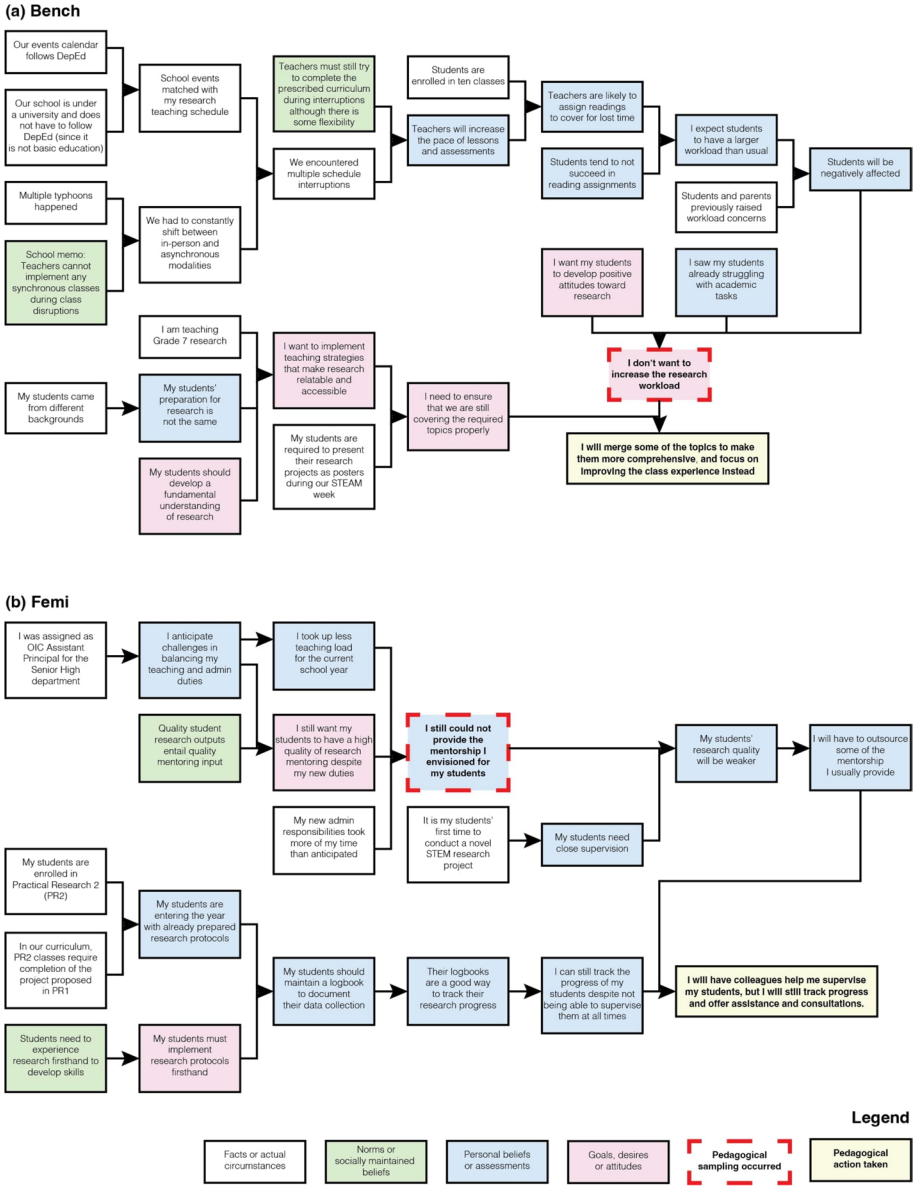


Fig. 1 Webs of reasons in classroom (Bench, top) and mentorship (Femi, bottom) contexts

them at all times,
then I will have colleagues help me supervise my students, but I will still track progress and offer assistance and consultations.

Each of these two premises also served as conclusions in a backward chain of inferences, using more fundamental premises.

In the subsequent sections, we use excerpts from the relevant data summarized here to develop the theoretical narrative leading to the answer to our research question. As such, all the subsequent text is already interpretive commentary, and the empirical excerpts themselves are annotated or pre-processed to support this commentary.

4.1 Establishing the constraints and non-negotiables

If we wished for a framework to help teachers understand how to reason during STEM research mentoring, we needed to establish what fundamental units of information a teacher will be working with so that they could start reasoning. We recognized this to be highly contextual and individual, inappropriate to be synthesized as a singular absolute phenomenon, so we approached this more broadly. Inferentialism's if/then structure allowed us to decode our pedagogical actions as conclusions from a complicated chain of inferences, which allowed us to explicate our reasoning by working backward: we looked at an action or belief in our reasoning and asked *why* it was the case. This section details the foundational sorts of constructs that we as research teachers *started with* that ultimately led us to justify our pedagogical actions.

All our reasoning could be traced back to two main aspects, which are represented in white in Fig. 1. The first major aspect that shaped our decision-making was the acceptance that there were some things beyond our control, and we could only navigate around them:

> *(Explaining faculty discussions on how to navigate the typhoon interruptions)*
> *Bench: Based on our faculty meeting [...] it's not our goal for the meantime to finish what's planned on our coursework. Whatever will be taught, then* let it be*. [...]*
> *Le (reiterating): ...when the students are in person, you do your best. But because of these interruptions, and because it's online [and] asynchronous you sort of* release control of a lot of things*. (Month 4 Computational Group meeting)*

When talking about how other teachers reasoned out how to navigate the typhoons, Bench alluded to potentially just accepting things as they were, and adjusting expectations for learning outcomes as a consequence. These "things beyond our control" were our *constraints* [18, p. 257], and we had to accept them and build our inferences with these as the most fundamental nodes. They were never conclusions in inferences where we applied our own knowledge (our beliefs represented instead as blue in Fig. 1), as constraints were external to our control and could only play as premises.

Constraints involved objective empirical events such as past or current happenings, but they also included the *norms* we had to observe as research teachers (which we represented as green for clarity), such as instructions or shared social beliefs that were not within our control. Norms in teaching gave us ideas on which personal beliefs and actions could be evaluated by other teachers as better than other options. Normativity plays a large role in Brandom's philosophy, as communities (such as teachers or

scientists) must share norms to be able to recognize and understand each other as members of the same community.

Bench had to wrestle with the constraint of the class disruptions, although he had another constraint to ensure his students were still prepared to present during the school's STEAM week, so he couldn't just "let it be" like what was discussed during the faculty meeting. Constraints appeared to interact with each other and further complicate decision-making.

The first step in mapping pedagogical actions in contextual dilemmas is therefore to acknowledge our constraints. For some instances, however, our constraints were highly implicit, and instead of acknowledging the events or norms that ground every subsequent conclusion in our web of reasons, we were rooted in fundamental beliefs we treated as *non-negotiable*:

> *(Writing about the consultation process held for students)*
> *My students come to me with their ideas—some well-thought-out, others half-formed—and it's my job to help them refine these ideas into workable experiments. [...]* I always ask for their sources *- of their methods, protocol, etc. We discuss their hypotheses, tweak their methodologies, and anticipate the challenges they might encounter [...] (Femi's journal)*

In Femi's reflections, he acknowledged a non-negotiable personal imperative in how he handles students, and this influences the inferences he makes when dealing with students. Femi's non-negotiable could actually be decomposed further into past empirical experiences (constraints), or norms about science research or science teaching, but Femi did not acknowledge those explicitly anymore.

Our non-negotiables such as this occurred frequently as beliefs, goals or desires in our webs of reasons, and they elicited a strong commitment from us, asking from us to integrate them in our pedagogical reasoning. However, it was not always clear to outline *why* we had some of our orientations or beliefs, even if they played major roles in our pedagogy. Hence, being able to recognize the norms or objective experiences for some of our personal positions were not necessarily done during our reasoning, but we implicitly applied those fundamental constraints in mapping out our possible actions anyway. Some of these more fundamental reasons were only clarified as the webs of reasons were generated. Regardless, these aspects allowed us to infer some of the beliefs we had during our reasoning, which allowed us to use them as new premises to build other inferences.

4.2 Establishing the anticipateds

Mapping out constraints and non-negotiables implies some form of looking backward, or identifying the fundamental starting points for teacher cognition, yet our inferences also frequently established some form of looking forward, even before we decided on our pedagogical action. A next step in developing a pragmatic framework for practice is to understand what to do with those fundamental starting points for teacher cognition. This section details this sort of wondering about the future:

> *(Writing about the degree of autonomy given to research mentees)*
> *When I was mentoring student research in the past, I do feel like I like having control. I would think that I knew the right steps to take more so than my students, so*

> *I am curious if that's a good position to have. [...] At what stage can I feel that the person I'm mentoring has enough competence, and that I shouldn't override their assessment? (Le's journal)*

Le's reflection on his past experiences highlighted an inference reliant on forward thinking: *If* he knew more than his students, *and* his students took charge instead of him, *then* his students were more likely to run into problems. Regardless of the correctness of beliefs such as these, we did frequently conduct forethought [5] to generate an anticipated outcome when reasoning out our decisions. Forethought provides an individual the hypothetical outcomes of particular actions they may pursue. The nature of what we call our *anticipateds* were not limited to the impacts our decisions would have on our students. Anticipateds manifest in whatever dimension, such as impacts to our own practice:

> *(Examining the choice to take on more work and learn mitosis research methods when the scientist contact was lost)*
> *Wilbert: ...this current study is having difficulties. For another research [project in mitosis], the procedure will be the same. [...] At least for the incoming research students, if someone will develop a study from this previous idea, I will already have an idea [how to navigate the methods]. (Month 4 Life Group meeting; translated from Filipino)*

Wilbert later clarified that his own interests in biology and his past contact of experts to train him supported this decision, although in this excerpt Wilbert's main justification is an anticipated, even with no assurance. The students could not work directly with those contacts due to logistical reasons. Wilbert generated several anticipateds for his pedagogical decision in this vignette, namely, *if* he learned mitosis research methods himself, *then*:

- he could support his current research students in their project
- he could prepare for future mitosis research projects
- his students could generate a completed mitosis research project
    - then, future students might also be influenced to pursue a mitosis research project

The first anticipated is the exact pedagogical reason Wilbert held as his students' research mentor, and the other two were projections that supported this decision. His third anticipated contained a chain of inferences. Regardless, all these anticipateds were not immediately clear to the group or even to Wilbert during our discussions, and these remained up in the air until we carefully disentangled our reasoning during the generation of the webs of reasons. Particularly, reiterating Loughran's [32] idea that we typically are too busy to think about our own thinking, these anticipateds can often be left implicit and possibly never articulated, which makes recommending for pedagogical reasoning difficult to do.

This implicit and unarticulated nature of anticipateds does not appear to be as explicit and intentional as Bandura's [5] forethought under self-efficacy, or Killion and Todnem's [29] reflection-for-action, although making it explicit would definitely have been beneficial for personal decision-making. This is why we commit to the word "anticipated" instead of "forethought" or "reflection-for-action" because our forward thinking was not

always certain or intentional. It appears that teachers often carry tentative or evolving ideas about future outcomes: ones they neither fully endorse nor necessarily act upon despite informing their decisions.

As an overall endeavor, pedagogical reasoning intends to articulate how an action would lead to students' learning. Therefore, the pedagogical goal is the ultimate anticipated from the pedagogical action one decides on. In our project, we had multiple explicit pedagogical goals, such as developing a researcher identity, or succeeding in a research competition, but we also occasionally held pedagogical goals implicitly such as in Femi's case (as the contextual problems were foregrounded). This diversity of goals, although relevant to make explicit, echo our initial unease with working with current pedagogical reasoning models.

Regardless, we were able to carefully reflect on our experiences to settle that when one begins with constraints and non-negotiables, what happens next in their mind is both explicit and implicit estimations of what might happen next. Some of these estimations are desirable, some not, and some a person may be indifferent to. Regardless of us teachers doing these anticipating routines intentionally or explicitly, we begin to populate our pedagogical reasoning landscapes with alternatives of what might happen to us, to our students, or to whomever.

4.3 Pedagogical sampling as rationalizing

Although not all constraints, norms, and anticipateds would necessarily be made explicit during reasoning, which means teachers wouldn't necessarily be able to immediately explain why they do the things they do, all these implicit ideas would still integrate into the web of reasons for a pedagogical decision and therefore need to be analyzed. Particularly, if from the previous section we've settled that teachers populate their mental landscapes with anticipateds, how does the teacher know which anticipated to work toward? This section details how constraints, norms, and anticipateds could be applied to reduce the pedagogical options one may potentially pursue. Here, we attempt to fill this question from our empirical data by theorizing with inferentialism.

Some actions a teacher could pursue will evidently be unhelpful for the student's learning and therefore are immediately removed by the teacher from consideration. This non-random process of identifying the appropriate pedagogical action from a broad set of possible moves could be called pedagogical sampling (adapting [46]). If a teacher could either move the deadline or cancel the assignment, maybe the latter was never an option at all. So, what happened that made the second option immediately dropped from consideration?

Brandom's overall package for inferentialism can allow us to explain why some aspects did not need to be made explicit for them to be integrated into our pedagogical reasoning. Brandom conceptualized people as rational beings "that *ought* to have reasons for what they do, and *ought* to act as they have reason to," [10, p. 3] and so individuals are a multiplicity of non-contradictory commitments. Whole sets of these mental commitments, influenced by norms, past experiences, and others, synthesize and form into a *self*, and we are endowed responsibilities in maintaining our selves by being rational [10, pp. 35–40]. For example, knowing that "I am Filipino" makes one responsible in weeding out commitments that contradict this (e.g. "I have no racial identity"), in understanding what inferences arise from this (e.g. "I am Asian"), and ultimately for applying this

commitment in any future utterance or action (e.g. checking "Asian" in a form asking for ethnicity).

Overall, rational people are complicated constellations of complimentary commitments, and therefore they would not contradict their commitments in their words and deeds. Because these commitments are complimentary, not everything has to be spelled out whenever someone does reasoning, as other less fundamental commitments are inferences from those fundamental commitments. Therefore, those things left implicit have already been incorporated.

This is an important but confusing idea, so we will present a hypothetical example. If a teacher's web of reasons contains a fundamental non-negotiable "I do not want to mentor anything that involves engineering," then the teacher doesn't always have to use this as a justification in their reasons and actions, instead relying on the downstream conclusions that arise complementary to this. A teacher might reason to a student wanting to incorporate some engineering in a project that "You will have a hard time looking for support" or "We will not have enough time to finish that project" even if, fundamentally, one of the root sources of these reasons is the teacher's non-negotiable belief "I do not want to mentor anything that involves engineering." Those two former reasons can be the ones made explicit during pedagogical reasoning, but they could come from more implicit, fundamental sources that are never said out loud. The teacher may not even realize that their preference against engineering in projects impact their overall decision-making. Regardless, what's left unsaid in the web of reasons is still applied to the eventual pedagogical action, because these all complement and form the teacher's sense of self.

So, if an anticipated leads to a hypothetical future that violates the complementary set of mental commitments a teacher has, then a teacher does pedagogical sampling automatically and drops those moves from consideration. To return to the above example, a teacher maybe doesn't have to think about it to know that cancelling an assignment is not something to even consider. Everything else in their mind complements and leads to a set of options where this pedagogical move is inconsistent with them.

To reiterate, everything that teachers do complement the whole set of commitments that they hold. However, we frequently encounter in the literature how teachers are "living contradictions" [53] because despite believing in X, teachers do the contradictory Y, and might therefore run contrary to Brandom's framework.

> *(Writing about requesting additional support from colleagues)*
> *The arrangement with my colleagues to help with tasks isn't working out as I hoped. They're swamped with their own responsibilities, and I feel guilty even thinking of adding to their load—this is my job, after all. I have to huddle with my students for now. I need to make sure I have the time for them. (Femi's journal)*

In Femi's reflections, he recognized the *norms* that guide good research teaching, that he has to take full responsibility for his own students. Despite feeling that his lack of time will make his own mentorship insufficient, Femi had to contradict this belief because he had to navigate this constraint. From this excerpt, Femi may be interpreted by some as a living contradiction, but in the process of choosing to be with his students, Femi stayed committed to his other fundamental beliefs and did not contradict his constellation of commitments. If Femi still insisted on having his students be completely under

the guidance of other teachers despite knowing it would not have worked, then he would have been *irrational*, in Brandom's language. Being irrational in one instance is fine, especially if the context demands it from us, as long as we continue to update our web of commitments in the process (which is the "living"-ness of the *living* contradiction), but if we continue to do nothing about that contradiction, then we regress to being irrational, or being bad teachers. Living contradictions do not appear to violate Brandom's inferentialist framework.

Again, we introduce these philosophical aspects because we found them important in understanding how we were able to rationalize picking some pedagogical decisions over others. Some participants explicitly identified certain decisions to be completely incompatible with their commitments, and doing those would have been irrational. For example, Ariel knew that he *had* to be there for his research students *despite* it not being a comfortable experience:

> *(Writing about the pressures to succeed in science fairs despite various circumstances)*
> *Ariel (journal entry): Despite the storm we are here in school finalizing our display boards for the science fair tomorrow.*
> *Femi (annotation): During Typhoon Kristine, we were also at school doing the forms required for the RSTMF [Regional Science, Technology, and Mathematics Fair]. Although it was not raining that hard anymore. I just feel that as research teachers who go into competitions, we are taking so many sacrifices [...]*

Ariel's commitments immediately eliminated several possible actions, such as expecting students to finish their work remotely, or dropping everything completely, because the anticipateds of those would have been irrational under the constraints he was navigating. It appears that in pedagogical sampling, the most fundamental filter is rationality, or obeying one's commitments, instead of affect or emotion which may filter inferences further down the web. Pedagogical actions deemed irrational are immediately removed from consideration.

The above form of pedagogical sampling was automatic, immediate, and perhaps not even considered (and therefore never made explicit). During our reflections, we were able to identify key stages in our webs of reasons where we clearly and deliberately eliminated some alternatives (represented as dashed red borders in Fig. 1). This explicit pedagogical sampling arises from justifying or constructing inferences from ones' commitments. Returning to Wilbert's choice to take on more work when other research teachers would likely just have told students to start over with a new study, Wilbert justified his decision by arguing that he would want students to remain motivated to do research. He believed scrapping the mitosis project the students themselves proposed would be detrimental to that goal, as in the top portion of Fig. 2.

Wilbert did also mention that students expressed that they were learning more under his closer involvement in their projects, and that if he *had* to, he would have offered a new study for his students. Downstream the web, when he had to choose between learning mitosis by himself or under someone else's guidance, he anticipated and reasoned out that learning by himself might lead him (and therefore his students) to some incorrect information. Across all our experiences, it became apparent that the heuristic we implemented to choose which pedagogical action to pursue was still the rational

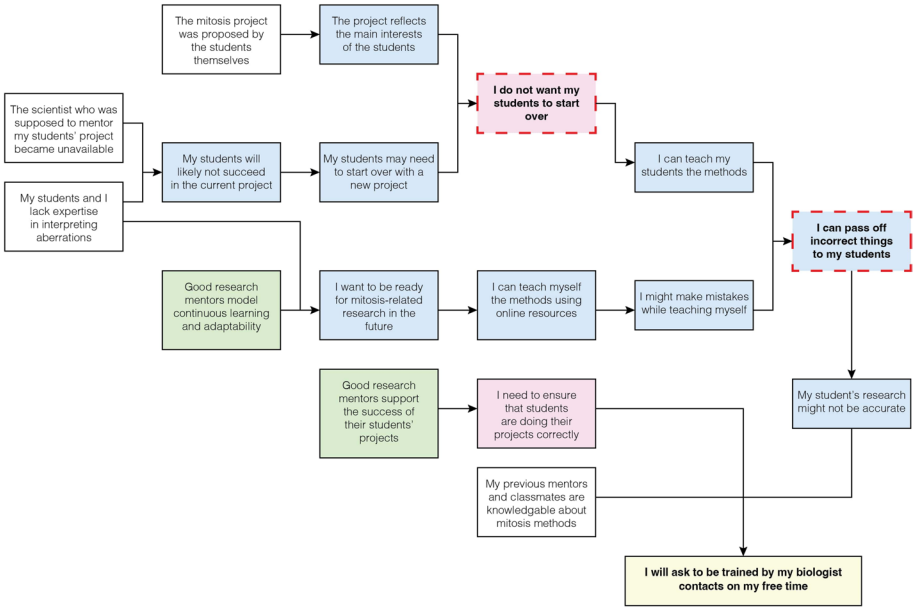


Fig. 2 Wilbert's web of reasons

approach. We justified reasoning by being consistent with the information and commitments we already had.

4.4 Developing a pragmatic framework

Careful qualitative analysis and philosophizing across all our empirical data has allowed us to pinpoint some key concepts that were important to our pedagogical reasoning. The story so far is summarized in Table 6. As we navigated our reasoning, our constraints typically fed into the premises of our inferences, while the anticipateds were conclusions. Some of these inferences, in the process of reasoning through our commitments, allowed us to perform pedagogical sampling by discarding inadequate options. Since our focus is on STEM research, we wish to emphasize that science plays closely into these components, as we saw with Wilbert's reasoning about his biology methods knowledge. Still, science mostly presented itself in its normative aspects. In our reasoning, we mostly tackled science through its rules or heuristics, such as validity or ethics, keeping them as constraints we had to navigate around as we did our pedagogical sampling.

From our own episodes of research teaching, we now propose our framework in Fig. 3 to guide pedagogical reasoning during contextual issues in research teaching. When planning out potential pedagogical actions, teachers do not have to sketch out full complicated webs of reasons, but the logic inherent to them are helpful to understand. We reiterate that the overall goal of this framework is to make explicit a teacher's internal logic in order for them to be more intentional and deliberate in identifying how to best move forward. Specifically, we hope that this framework can support deliberate reasoning and discourse about what to do as teachers to make pedagogical moves during STEM research mentoring.

- Step 0: Identify the pedagogical goal: Whenever the dilemma presents itself as something that could be an explicit teaching moment, reflect and clarify first what it is that you aim for your students to learn in the situation. This becomes a non-

Table 6 Key components in our pedagogical reasoning

Construct	Description	Examples from journal entries
Constraints	Fundamental ideas that are typically external to the reasoning of the teacher, but are relevant when making decisions; typically includes empirical knowledge of context or students	"Due to the Matatag Curriculum implementation my schedule was very loaded to the point where I can not even get a quick break." (Ariel)
Norms	Socially maintained ideas that would dictate the rationality of actions as interpreted by other members of the community; includes shared beliefs, instructions by the school, etc	"[A]s a research teacher, my role extends beyond guiding them; it includes continually growing alongside them." (Wilbert)
Non-negotiables	Commitments that are explicitly maintained throughout reasoning; could themselves be further decomposed into more fundamental constraints	"I still don't want to see myself as *just* a supervisor. After all, it is my project and I am fully responsible for it." (Le)
Anticipateds	Projections of what might happen granted an event will occur	"…while I have high hopes for our students, I can't help but feel they could give more if only we had more time to prepare." (Femi)
Pedagogical sampling	Reduction of possible actions to only a few that are valid for teaching/learning; could be trivial based on a teacher's commitments, or deliberately reasoned out	"I am always in [the] quest of the best, appropriate, and most effective way to teach research to my students who are young and playful. I need to find where I bridge the gap to where they can relate it to their daily and personal lives." (Bench, an example of a commitment that trivially excluded several possible actions)

Underlines indicate some direct and relevant illustrations for the particular constructs

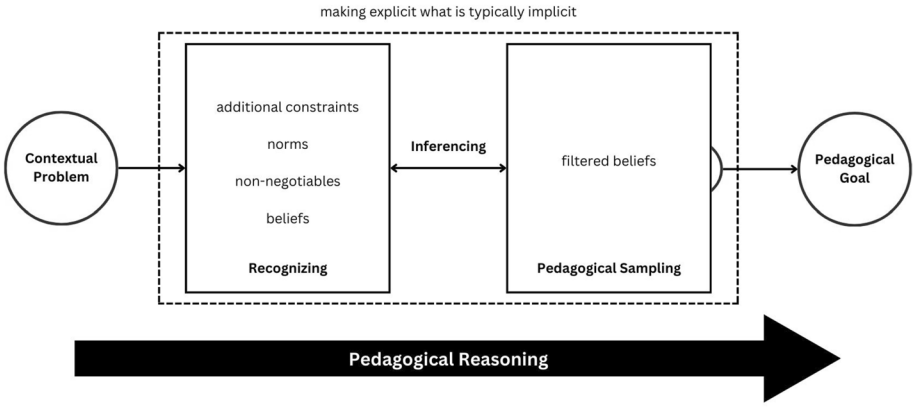


Fig. 3 Pedagogical reasoning during contextual problems in STEM research

negotiable. Some other dilemmas may be convoluted, and the pedagogical goal becomes muddled and difficult to untangle. In that case, the overall goal will just be to resolve the problem.

- Step 1: Specify the problem: Articulate the contextual issue that you need to navigate. If you identified a Step 0, remind yourself that the solution to the problem must ultimately anticipate the pedagogical goal.
- Step 2: Recognize the constraints, norms, and non-negotiables: Identify the factors that influence the decision-making landscape. List some things that immediately strike as non-negotiable to you, as you will have to work around those. Make sure that you will not violate the norms of the STEM discipline that you are operating under.

- Step 3: Reflect on what Step 2 and your beliefs entail and do not entail: Attempt to process everything you know and believe in so far, so you can immediately eliminate some potential actions because they contradict your circumstances. Focus instead on what you have enumerated in Step 2 and imagine several potential actions you can pursue. If you could not imagine anything within the context or your own experience to possibly move forward, review socially held norms, or ask fellow teachers or scientists to enrich the constraints you can reason around.
- Step 4: Refine the chosen action: Through reasoning, one pedagogical decision will seem most appealing to pursue. Prior to deciding on it, review if it (1) is consistent with your beliefs and the constraints you are working with, and (2) if applicable, would logically cause you to anticipate the pedagogical goal after you implemented the action.

By clarifying goals, systematically identifying constraints and non-negotiables, and engaging in deliberate pedagogical sampling through this framework, research teachers can respond more intentionally when factors beyond their control inevitably arise in their practice. With research being intimately uncertain, there is no assurance that the framework will improve pedagogical outcomes, but it does explicitly support intentional decision-making, a matter frequently taken for granted during science teacher education. After all, if the educational prospect of in-school research experiences is the formation of future scientists (itself potentially a non-negotiable to some individuals), then teacher reasoning must be sufficiently scaffolded to better align actions to these overall goals, despite contextual episodes being too complicated and nuanced to formally prepare for. We even imagine the framework to be pragmatically helpful for disciplinary STEM training in tertiary spaces or laboratories, as pedagogical goals, or the learning of apprentice scientists, may be completely overshadowed by the STEM research outcomes those spaces are working toward.

In terms of the STARTLES group, we have begun applying this framework whenever we navigated our contextual concerns, and moving forward we are now able to carefully untangle the other specific sorts of disciplinary knowledge that push our practice, and the outcomes of our students' learning in research, forward. Our present work is only preliminary in a sense that it aims to offer a language to talk about how to do pedagogical reasoning in these episodes, but it may not necessarily complete a full satisfactory picture for the matter yet. Still, we believe this framework offers compelling language to scaffold the professional development or teacher education of STEM research mentors, particularly in the Philippines which does not have that yet prior to service. Alternatively, we believe the language is helpful in the design of teacher education coursework or curricula to better help science teachers view STEM as a body of reasoning instead of facts, allowing future STEM research teachers to be scaffolded in thinking about how to handle the inherent uncertainty in STEM.

5 Contributions to the pedagogical reasoning debate

As Loughran wrote, plenty of extant literature on teacher knowledge has not been done with supporting teachers' practice in mind, saying "[m]any of the arguments have been driven more by the ways in which academics have sought to theorise the work of practitioners rather than being described or critiqued by teachers themselves" [32]. In a sense, our current paper responds to this call as we are STEM research teachers doing

actual STEM research teaching, and we needed the knowledge *for* practice instead of the frequently descriptive, inductive, and third-person scholarship that could not help us unravel the real work that we already do. Regardless of Loughran calling for education research to champion the reporting of pedagogical reasoning by actual pedagogues, not much has happened since 2019 in terms of pedagogue voices informing education scholarship. We wish that through this paper, educators conducting teaching and mentorship in STEM research would become motivated to also formalize their knowledge for the benefit of all who could utilize the resources to scaffold their practice. Again, as Ahmad et al. [1] wrote about, the pre-tertiary pursuit of novel STEM research projects happens all across the world but is not standardized, and therefore whatever knowledge is out there in terms of excellent teaching and mentoring of STEM research projects is also not available nor accessible to many, such as those across the Philippines, already doing the work in the frontlines.

6 Conclusion

In this paper, we critically investigated our own teaching practice to identify pragmatic steps that inform how STEM research teachers navigate decisions in highly contextual pedagogical dilemmas. Considering our pedagogical decisions not as static objects of inquiry but as theoretically rich teaching moves allowed us to condense our experiences into a framework that could help guide other research teachers as they mentor their students in authentic scientific research. Our major finding unraveled that a pedagogical reasoning framework, grounded in inferentialism, could explicitly articulate the complex chains of inferences and decisions teachers make when navigating contextual problems during STEM research teaching and mentoring, enabling more intentional and deliberate pedagogical actions through reflection.

We believe this preliminary work is practically helpful not only in the Philippines but also across the world, as science teachers may inevitably see themselves navigating uncertain inquiry situations. Additionally, our framework potentially contributes to making the teaching of scientists as a theoretically robust research agenda in science education. Aside from empirical work on teachers applying this framework, additional work may also be interested in the student outcomes which our methodology could not account for.

7 Limitations

Our inquiry into actual teaching episodes of Filipino research teachers, while theoretically insightful, may not generalize across all types of STEM research teaching/mentoring experiences (such as in post-secondary, or in international contexts). The experiences detailed here again not be necessarily representative of all Filipino research teachers, due to only investigating five stories. Regardless, we reiterate that this study is not positivist, and we disagree that there is an absolute "truth" to this phenomenon to be found. The value of the findings is to offer theoretical and value-based perspectives that can not only be practically useful for decision-making or teacher training, but also inform future work in the conceptualization of how teacher education programs can better develop mentors in authentic scientific inquiry. We hope that this work sparks enough confidence that we can collectively work toward a better landscape for STEM research teachers and mentors to understand their practice.

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Author contributions
L.D. conceptualized the project, wrote the main manuscript text, generated the figures, and led data analysis. L.D., W.J., B.F., E.A. and A.M. all contributed data and assisted with data analysis and interpretation. E.N. and V.A. assisted with data analysis and interpretation. All authors reviewed the manuscript.

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Data availability
Data, particularly reflections and meeting transcripts, contain unredacted and potentially identifiable information beyond the authors and thus have not been uploaded to a repository. However, the data that support the theoretical findings of this study can be redacted and made available from the corresponding author, L.D., upon reasonable request.

Declarations

Ethics approval and consent to participate
As theoretical/philosophical reflective work on our personal teaching practices (i.e. only the co-authors were involved), and with no systematic investigation on other individuals' data (e.g. student records), our work does not qualify as human subjects research and therefore is exempt from IRB review. As only the co-authors served as the data sources for self-study methodology, we confirm that the equivalent for informed consent (Consent to Participate and Consent to Publish) were obtained from all co-authors and affirmed during the manuscript editorial process.

Consent for publication
All authors give consent to publish. Authors give consent for the paper to be submitted, reviewed and published. The paper is not under review with any other journal.

Competing interests
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