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Article

Exploring Adaptations of the VisChem Approach: Advancements and Anchors toward Particle-Level Explanations

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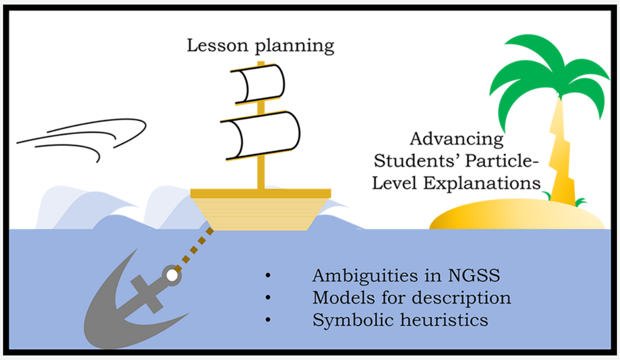

ABSTRACT: The Next Generation Science Standards (NGSS) have been imperative for informing many facets of the chemistry education research field, one of which includes the professional development (PD) of high school teachers. While many researchers and practitioners have responded to the NGSS' calls for reform by attending to internal factors that influence the PD's design, resources, and facilitation, there is less attention on extant factors that may negatively affect PD uptake and fidelity. Such factors encompass traditions of teaching chemistry or chemistry-related imprecisions within the NGSS themselves. If left unaddressed, these factors can act as anchors preventing advancements toward students' particle-level explanations and their chemistry conceptual understanding. In this article, we investigate the uptake and fidelity of our own PD program known as the VisChem Institute. The data are comprised of PD participants' learning designs (i.e., lesson plans) collected from the 2020 cohort ($N = 20$) and the 2021 cohort ($N = 15$). Results show that, although there was uptake in terms of the particulate level among participants' learning designs, more detail was ascribed to the description of molecular-level species rather than the explanation of relevant processes. Furthermore, an ontological analysis revealed that interpretations of evidence and models for description as well as symbolic heuristics for explanation may account for the VisChem approach's distortion in its translation to participants' learning designs. Implications and recommendations for chemistry instruction and research at both secondary and undergraduate levels are discussed.

KEYWORDS: *High School/Introductory Chemistry, Chemistry Education Research, Multimedia-Based Learning, Professional Development*

■ INTRODUCTION

In response to standards having been presented as long lists of disconnected and detailed facts, the Next Generation Science Standards provide new guidelines to inform how learners' minds, engagement in inquiry, and scientific reasoning should be cultivated.[1] While there are eight practices in total that are deemed essential, we select *Practice Six: Constructing Explanations* to be noteworthy for chemistry contexts. As elaborated by the National Research Council (ref 2, p 52, emphasis added), students must construct "logical coherent **explanations** of phenomena that incorporate their current understanding of science, or a **model** that represents it, and are consistent with available **evidence**". Supported by multiple NGSS-motivated studies, attending to evidence and models can improve the quality of explanations and advance chemistry conceptual understanding.[3−5]

Accordingly, our professional development (PD) program—known as the VisChem Institute (VCI)—is designed with *Practice Six: Constructing Explanations* as one of the main focal points. The VCI stresses the VisChem approach, a pedagogy that promotes evidence- and model-based explanations using dynamic, molecular-level animations and storyboards (i.e., drawings with explanations).[6] The VisChem approach aims to support learners in the challenging feat of integrating macroscopic phenomena, molecular-level structures and processes, and the related chemistry symbols.[7] As PD designers and facilitators, we are interested in the VisChem approach's uptake and fidelity among our in-service high school chemistry teacher participants in conjunction with the underlying features that influence these processes.

Many aspects affect teacher learning in PD, including the subject matter content,[8] the accessibility of provided resources,[9] and the nature of the facilitation.[10] We furthermore recognize that factors external to the PD itself, such as school science and policy documents, contribute to the mangled negotiations of

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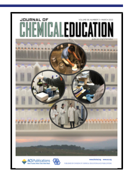

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instructional practice.[11] Leden and colleagues[12] show that the convention of teaching facts can override the given curriculum, resulting in fewer connections to the nature of science and possibilities for student discussion. McNeill and colleagues[13] report similar findings: even when provided with a NGSS-aligned curriculum, teachers make instructional choices and modifications that revert to traditional, teacher-centered instruction. The variation of teachers' contextual interpretations and the divergence from those of policy makers are thus important considerations for PD design and facilitation as well as the study of such PD programs and their outcomes.[14]

The NGSS may contribute to the mangle of instructional practice. Talanquer and Sevian[15] indicate that the NGSS do not fully represent the nature and power of chemical knowledge. Concepts like energy transfer/dispersal in a system, the socially relevant facet of chemistry, and well-outlined learning progressions for topics like kinetics remain absent. Miller and colleagues[16] also demonstrate a contradiction within the NGSS. They argue that encouraging students to do science leads to mimicking practices and learning content others have considered foundational, thereby obviating students' epistemic agencies.

While the NGSS are immensely beneficial, there are nevertheless detectable instances of imprecision that are more pronounced when examining the standards from a chemistry discipline vantage.[17] Such missing information, contradictions, and ambiguities further complicate the negotiations teachers must already do. This calls for coherence across multiple components entrenched in complex educational systems undergoing contemporary large-scale reforms.[18,19] Especially for *Practice Six: Constructing Explanations*, the ontological nature of **explanations**, **evidence**, and **models** determined vis-à-vis the situating literature, pedagogical norms, and teachers' own interpretations must be further unpacked to support implementation of reform-based instructional strategies. Thus, we have investigated the VisChem approach's[6] uptake and fidelity among VCI participants within the purview of explanations, evidence, and models.

■ TEACHING CHEMISTRY WITH EXPLANATIONS, EVIDENCE, AND MODELS: A BRIEF REVIEW

We interpret explanations, evidence, and models (EEM) being interconnected when conceptualizing scientific inquiry. Students are expected to justify their explanatory claims with evidence, typically stemming from the analysis of laboratory results[20] and/or engagement with hands-on activities.[21] Students' mechanistic reasoning that explains how and why something occurs can also be better supported with model-based teaching and learning.[22] Similar to Duschl's evidence−explanation model,[23] teachers must design opportunities for students to select or generate data to become evidence, use evidence to identify patterns in models, and use models to produce cause−effect mechanisms. In concordance with prior literature, EEM are essential for advancing students' conceptual understanding.[24,25]

Despite research supporting the efficacy of EEM in chemistry teaching and learning, the reality belies our field's recommendations. According to Smith's *Obstacles to and Progress Toward the Vision of the NGSS*,[26] students are not engaged in explanatory practices related to evidence and models. Fewer than a quarter of secondary science classes had students evaluate the credibility of scientific information, identify a model's limitation, and discuss the strengths/weaknesses of competing scientific explanations at least once a week. Although the work to facilitate NGSS-aligned instruction through the designing and offering of curricula has been tremendous,[27,28] we fear that more deeply rooted issues may continue to complicate how chemistry teachers plan and enact instruction.

Teachers' ontologies of evidence and models may also contribute to the mangle of instructional planning. For example, multiple studies in chemistry education typically refer to evidence as analyzed, empirical results from an experiment.[29,30] Although evidence encompasses data, prior knowledge, and/or lived experiences analyzed within a specific conceptual frame,[31] the nature of traditional science instruction may reappropriate data as unconditional answers to inquiry questions.[32] Duncan and colleagues[33] state that, even in the NGSS, quality and strength of evidence are underspecified and undifferentiated, resulting in a perfunctory implementation of evidence-based practices. In addition, teachers may be unfamiliar with developing and using generative models[34] and with the nature of models regarding revision, evaluation, and mechanism.[35,36] Models may then be construed as physical representations rather than tools for predicting and explaining phenomena.[37,38]

Given the many challenges associated with evidence and models for explanations, determining the efficacy of instruction is not fruitful until we first characterize how teachers interpret the nature of EEM within chemistry. Especially in settings where teacher learning of both discipline-specific content and pedagogy is essential,[39] clarifying these ambiguous ontologies can inform more effective PD efforts and reforms per what the NGSS recommend. To better understand teachers' realities of EEM, we require a methodological tool to investigate how EEM is situated in chemistry instruction.

■ UNDERSTANDING EXPLANATIONS, EVIDENCE, AND MODELS THROUGH LESSON PLANNING

One strategy to trace teachers' EEM ontologies is through their instructional planning. Jamali Nasari and Heidari[40] typify a lesson plan to be written description of the materials, methods, time, and place of education. Lesson planning is a core aspect of teaching that profoundly influences the types of learning opportunities.[41] Freiberg and Driscoll[42] have aptly called lesson planning the thread that weaves the *what* of teaching with the *how* of teaching. Recent studies have reported the challenges teachers experience in designing instruction, some of which include teachers' preconceptions of overly simplified teaching and learning[43] in addition to emergent uncertainties on students' prior knowledge, content, and authority.[44] Starting with the development of a lesson plan can thus be productive for characterizing and assembling the many components (e.g., teachers' realities of EEM) that eventually culminate into negotiated instructional strategies.

■ PEDAGOGICAL CHEMISTRY SENSEMAKING: A THEORETICAL LENS TO ANALYZE LESSON PLANS

The refined consensus model (RCM) of pedagogical content knowledge contributes to the rationale for investigating lesson plans. Hume and colleagues[45] assert instructional planning as one of three principal pedagogical reasoning processes in which teachers connect numerous layers of knowledge and experience. Building upon the RCM, we use the conceptual framework *Pedagogical Chemistry Sensemaking* (PedChemSense). Detailed in another publication,[46] PedChemSense articulates mechanisms of lesson planning to promote particulate-level explan-

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ations. PedChemSense provides greater analytical resolution by positing that lesson planning is the transformation of subject matter knowledge into pedagogical content knowledge.[47] Lesson plans thus become windows to view how teachers may understand EEM in the learning and teaching of chemistry. There are three PedChemSense constructs that we connect to EEM to inform our analysis of lesson plans.

The first is sensemaking, defined as figuring out complex and confusing incongruities that conflict with current mental schemas.[48,49] Sensemaking consists of using scientific ideas and past experiences to resolve uncertainties, enabling the development of more cohesive knowledge structures.[50] This purposeful interpretation of ideas and experiences requires a particular conceptual frame, thereby converting information as stimuli into evidence generated within the learner's mind.[31] To authentically catalyze student sensemaking, teachers must carefully plan for problems students will encounter, the decisions that may arise, and ways to warrant the knowledge that is to be ascertained.[51] Teachers themselves must undergo sensemaking of chemistry content, identifying the ways in which salient evidence can be purposed for explanations.

The second is Johnstone's triangle, an accessible way to promote sensemaking with chemistry phenomena. The macroscopic, symbolic, and submicroscopic (particulate or molecular) levels comprise the triangle's vertices.[52] Comprehensive chemistry understanding requires seamless transitioning among all three.[53] One example to facilitate these connections is the VisChem approach.[6] Students first experience a macroscopic phenomenon and afterward explain their observations by representing what they conceptualize occurring at the molecular level through storyboards and engaging in molecular-level animations. Because we operationalize explanation as the cause−effect mechanism derived from atomic/molecular behavior,[54] Johnstone's triangle is useful for generating uncertainties and warranting knowledge. PedChemSense encourages teachers' sensemaking of one representational level to another for engaging students in using atomic/molecular properties and interactions to explain macroscopic experiences,[55] simplifying particulate mechanisms via symbolic shorthand,[56] and developing appropriate epistemologies and ontologies of the representational levels themselves.[57]

The final construct is the models *for* perspective, a stance that evaluates the quality of a model's explanatory function.[58] We recognize that Johnstone's triangle is essentially a composite of models that are abstracted representations of features within a scientific concept or phenomenon.[59] Ascertaining a model's sensitivity to context is important to realize its utility.[60] Gouvea and Passmore[58] thus use the models *for* perspective to position learners as epistemic agents who must determine the ways that (and extent to which) a model corresponds to and explains a phenomenon. Teachers undergoing PedChemSense must accordingly plan for activities that encourage the generative and evaluative practices associated with the models *for* perspective to stimulate conceptual learning.[61]

In summary, PedChemSense is a theory that guides the incorporation of the macroscopic, symbolic, and particulate levels in teachers' lesson planning. Rather than connection as the primary goal of Johnstone's triangle, PedChemSense also supports leveraging the uncertainty of one representational level to warrant the explanatory function of another. Contextualized within the NGSS, PedChemSense consists of designing activities in which students generate particulate-level **explanations** from processes of conceptualizing **evidence** and identifying the limitations/utility of chemistry **models**. First, the Johnstone's triangle component of PedChemSense is a useful analytical tool. We use Johnstone's triangle to ascertain the uptake of the VisChem approach[6] by determining the extent to which the representational levels are incorporated. Using the sensemaking and models *for* components, we also investigate fidelity by exploring how teachers' EEM ontologies shape their authoring of the VisChem approach.[6] As such, the lesson plan analysis (referred to as *learning design analysis* hereafter) is guided by these research questions:

1. How do participants incorporate Johnstone's triangle in their learning design planning?
2. How do participants interpret the ontological nature of EEM in their learning designs?

■ SETTING

The VCI is a remotely delivered, intensive PD program in which participants learn about chemistry and pedagogy. One of the key practices of the VCI is the VisChem approach[6] that broadly includes (1) experiencing a macroscopic-level phenomenon that would prime the perception filter, (2) representing their ideas about what is happening at the molecular level via a pre-storyboard, (3) viewing VisChem animations in a manner that reduces cognitive load, (4) creating their post-storyboards, and (5) linking new ideas to prior knowledge through a related but different chemical phenomenon. VCI participants first undergo multiple rounds of the VisChem approach as students. To effectively translate PD content to their teaching, participants later read salient literature about student misconceptions and the cognitive learning model,[6] engage in discussion and reflection, and generate their own learning designs that use the VisChem approach.

Data were gathered from the first two iterations of the VCI in July 2020 and 2021. The 2020 VCI consisted of four full days, while the 2021 iteration consisted of seven half days. Each cohort experienced a total of 28 PD hours with required work outside of the VCI. There were 20 participants in the 2020 VCI and 16 participants in the 2021 VCI, all of whom were in-service high school chemistry teachers sampled from across the United States. Applicants had initially filled out a survey whose questions concerned their classrooms, years of teaching experience, pedagogical practices, and PD expectations. After the forms had been submitted, the research team developed a weighted ranking system that prioritized applicants who described more student-centered practices, taught at schools with higher percentages of students who qualified for the federal reduced/free lunch programs, and possessed 2−20 years of teaching experience (enough to understand chemistry content but early enough in their careers for the PD to have a longer impact on students). Information regarding our setting and sampling process is described in greater detail in a previous article.[62]

■ METHODS

Data Collection

The primary data source is participants' learning designs. On day 2 of the 2020 VCI and day 3 of the 2021 VCI, participants were assigned to complete a classroom-ready learning design using their PD experience gained thus far. The target chemistry phenomenon for planning the learning design was silver chloride precipitation. All participants were provided with the same

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resources including a suite of VisChem animations and storyboard templates. However, a learning design template was not provided so as to create an opportunity for teachers to authentically adapt the VisChem approach to their unique classroom contexts. Accordingly, the collected learning designs were quite varied. After the initial submission, participants were given an opportunity to present and discuss their learning designs with peers for insights, feedback, and recommendations. Revised learning designs were then collected on day 3 of the 2020 VCI ($N = 20$) and on day 5 of the 2021 VCI ($N = 15$). The pre−post peer discussion changes are not central to addressing the research questions. As such, we analyzed the revised learning designs from both cohorts. All methods of data collection, analysis, and reporting have been reviewed and approved by the PD-hosting university's institutional review board.

Data Analysis

Qualitatively determining uptake of the VisChem approach was both deductive and inductive in nature. The initial coding was deductive in that some of our codes were derived from the three representational levels of Johnstone's triangle: macroscopic, symbolic, and particulate. Given the context of the VCI, PedChemSense, and the NGSS, the particulate level was further divided into two subcategories: particulate-description and particulate-explanation. Other features such as components of the VisChem approach (e.g., particulate-description: *Animation*) and ideas inherent in VisChem animations (e.g., particulate-explanation: *Rapid Ion Pair Formation*) were also established as codes from the onset.

Coding took an inductive turn as the research team identified scientifically accurate and inaccurate themes that emerged from the learning designs. A flowchart of our analysis is shown in Figure 1. The learning designs were first parsed into analytical units deemed as *planned segments*. How one segment was delineated from another was determined by the nature of the activity, the role of the actors, and/or the extent to which it was student-/teacher-centered. Following Charmaz's[63] recommendations, we had iteratively identified initial codes. We employed the constant comparative method such that we looked for tacit assumptions, explicated implicit meanings, and explored possibilities suggested by the data. Initial codes were then raised to focused codes through axial coding and repeated discussions in which the research team systematically attended to the analytical connections of our codes to each other and our theoretical constructs. Our finalized code book can be found in the Supporting Information (see Table S1).

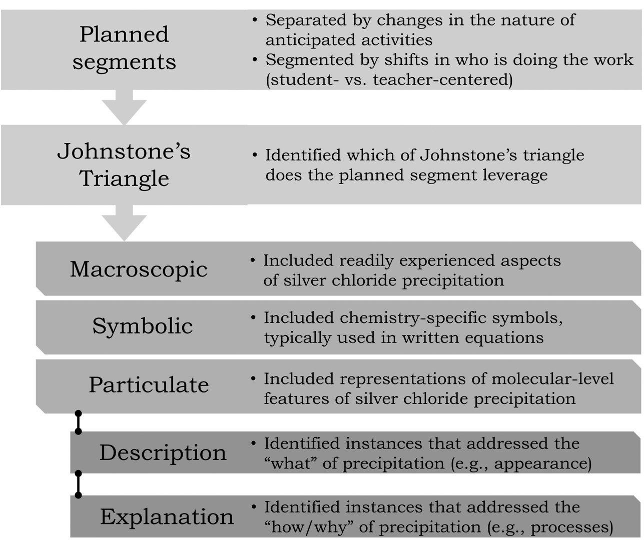

Figure 1. Flowchart of the learning design coding procedure. Planned segments were first identified and then coded for features of Johnstone's triangle. The particulate level was further divided into particulate-description and particulate-explanation.

To understand reasons that affect the fidelity of the VisChem approach,[6] we analyzed participants' EEM ontologies using multiple case studies.[64] We defined a case as a single participant's learning design. We purposefully sampled three learning designs because they exemplify the various ways participants would interpret and purpose EEM in their planned segments. Our multiple case study analysis furthermore aims to uncover how the NGSS and other factors external to the PD may contribute to the mangled nature of planning for chemistry instruction.

To maximize our findings' trustworthiness, we followed Lincoln and Guba's evaluative criteria.[65] To ensure our credibility, the first and second authors met weekly to discuss and refine the codes. The first author also worked with an undergraduate researcher, coding collaboratively for calibration purposes. Any emergent discrepancies were addressed and resolved, resulting in a mutually agreed upon code book. At this stage, both the first author and undergraduate researcher independently coded 10% of the remaining data, a comparison that resulted in an inter-rater agreement of 98%. To enable the transferability of our work, we have grounded our analytical rationale based on the suggestions and findings of prior literature as well as Geertz's[66] recommendation of a thick description via our analysis. To strengthen our dependability, our finalized categories were determined to be saturated; they comprehensively accounted for all salient patterns and variations both within and between themselves.

Finally, on confirmability, we acknowledge our roles as both PD facilitators and researchers. Both authors had contributed to the design of the 2020 VCI and its redesign for 2021. During the VCIs, the second author was one of the lead PD facilitators, while the first author's role alternated between facilitating and troubleshooting. In terms of background, the second author brings a wealth of experience working with in-service high school chemistry teachers, designing, implementing, and studying PD, and enacting pedagogy using VisChem animations. The first author has a comprehensive understanding of science education, teacher education, and their overlap with chemistry education. Although we may be interested in investigating explanations, evidence, and models due to alignment with the VCI, we justify our approach given their emphatic roles within the NGSS and scientific enterprises. Coupled with our familiarity with high school chemistry teacher populations, related literature, and major policy documents and norms propagated by the schools/districts, we view our subjectivities as a strength to more effectively investigate and explicate the nuances of participants' learning designs.

RESULTS AND DISCUSSION

Research Question 1: How Do Participants Incorporate Johnstone's Triangle in Their Learning Design Planning?

Determining uptake required identifying how participants leveraged Johnstone's triangle. Table 1 reports each code's frequencies categorized by the four representational levels. First, the two most frequent macroscopic level codes are *Connection* (37) and *Everyday Life* (30). This is likely explained by one of

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Table 1. Frequencies of Representational Level Codes

Level	Code	Freq.	Level	Code	Freq.
Macroscopic			Symbolic	Noting Chemistry Symbols	**146**
	Connection	**37**		Writing Chemistry Symbols	**72**
	Everyday Life	**30**		States of Matter	**57**
	Video	**26**		Reactants and Products	**41**
	Experiment	**19**		Double Replacement Reaction	**28**
	Demo	**14**		Balancing and Stoichiometry	**23**
	Images	**12**		Connection	**22**
	Physical/Chemical Change	**10**		Net Ionic Equations	**13**
				Spectator/Non-Spectator	**7**
Particulate-Description	Noting Relevant Chemical Species	**88**	Particulate-Explanation	Motion	**44**
	Representing Relevant Features	**84**		Interactions	**40**
	Animation	**60**		Lattice	**26**
	Representing Features	**47**		Hydrated Spectator	**25**
	Orientation of H_2O	**47**		Charge	**18**
	Number of H_2O	**47**		Transient Interactions	**7**
	Ratios	**21**		Rapid Ion Pair Formation	**5**

the emergent practices from the cognitive learning model underpinning the VisChem approach:[6] linking new ideas with prior knowledge. Participants had accordingly planned segments for their students to adapt and transfer their understanding of precipitation. While some opted for additional precipitation reactions that used formal chemistry language (e.g., precipitation of lead(II) iodide), others related precipitation to more familiar examples such as hard water deposits, water filtration, or kidney stones.

The presence of *Physical/Chemical Change* (10) is also noteworthy despite being less frequent. We note that the delineation between physical and/or chemical changes was not presented during the VCI. Nevertheless, questions about whether the changes were physical or chemical emerged in various ways: a segue from a previous lesson, a bell-ringer (warm-up) activity, or guiding prompts during storyboarding. These plans to encourage students' identifying one classification of change from another may instead reference the looming influence of a teacher's curriculum. Echoing Penuel and colleagues'[14] findings, there is evidence that local features such as prescribed curricula or district goals shape the renegotiation of the VisChem approach.

The two most frequent codes for the symbolic level are *Noting Chemistry Symbols* (146) and *Writing Chemistry Symbols* (72). Due to the broad curricular scope of precipitation reactions, participants had incorporated other concepts that use symbolic notations such as *States of Matter* (57) and *Reactants and Products* (41). The presence of *Double Replacement Reaction* (28) is also fascinating considering the VCI's deliberate avoidance of this term. Its inclusion in the learning designs suggests a high enough relevance among participants for their lesson planning. We interpret its frequency to be concerning, especially when juxtaposed with topics like *Balancing and Stoichiometry* (23) and *Connection* (22) that are less frequently occurring in the learning designs.

For the particulate-description and particulate-explanation levels, *Noting Relevant Chemical Species* (88) and *Representing Relevant Features* (84) are most frequent for the former, while *Motion* (44) and *Interactions* (40) are most frequent for the latter. The prevalence of storyboards and dynamic visualizations likely accounts for the distribution in frequencies. All participants had incorporated opportunities for students to represent the phenomenon at the molecular level and view VisChem animations that showed molecular-level species moving and interacting in their planned segments. Because these essential features of storyboarding and facilitating animation viewing are present in the learning designs, we determine that there is uptake of the VisChem approach's[6] core strategies.

Our analysis, however, detects two issues regarding the role of the particulate level in the learning designs. The first is the frequency of *Representing Features* (47) when compared to those of canonical concepts like *Orientation of H_2O* (47) and *Ratios* (21). Because some participants created their own storyboard templates, the instructions teachers provided did not consistently communicate a level of scientific accuracy or specificity similar to that of VCI storyboards. In many instances, no instructions were provided that prompted students to consider the relative sizes of atoms (or ions) or how polyatomic ions should not be depicted as a single sphere. Designing the pre—post storyboarding activities in such a manner, especially without intentions to co-construct a scientifically acceptable consensus model afterward, may reinforce students' alternative conceptions. Second, particulate-explanation codes are much

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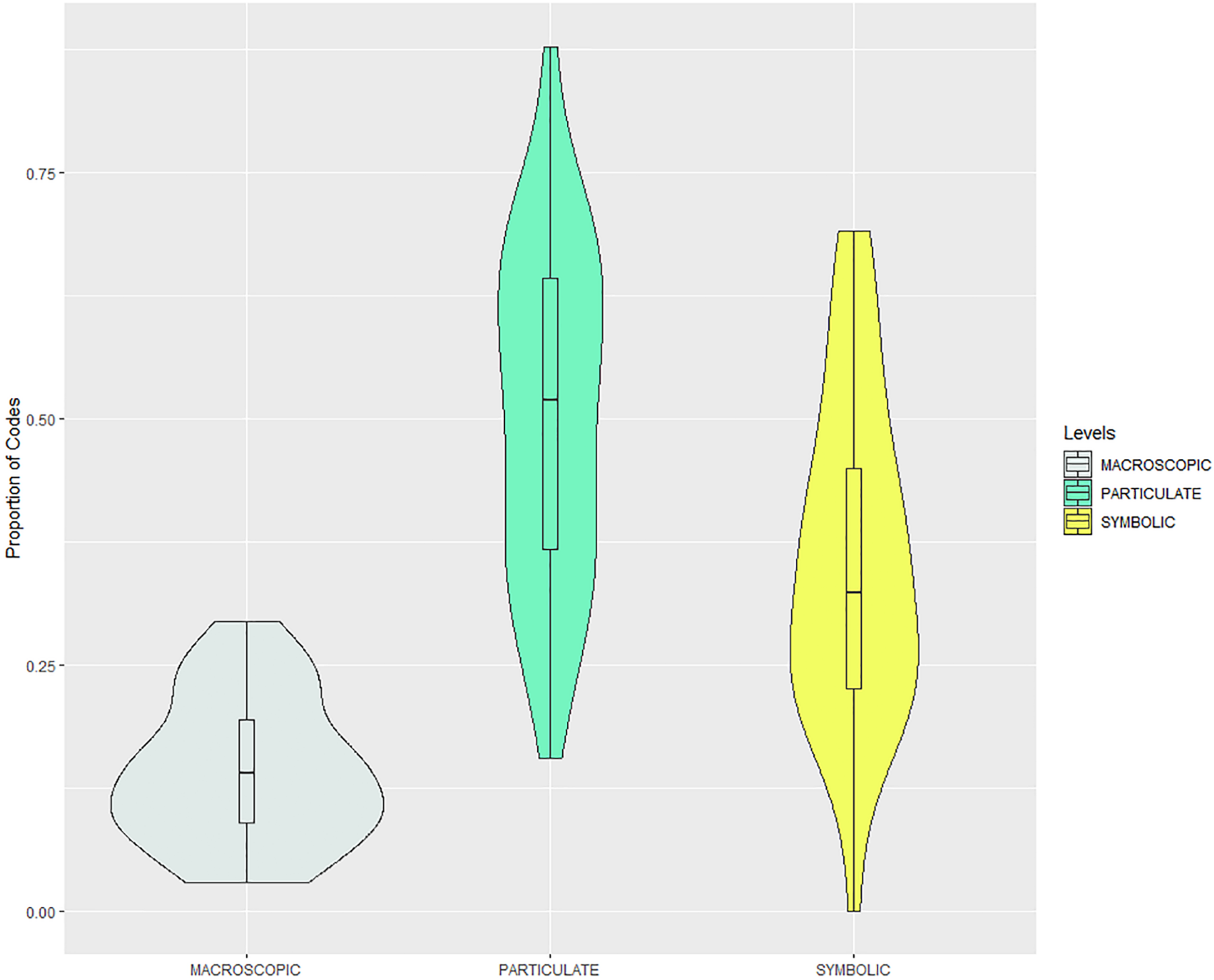

Figure 2. Violin plots showing the distributions of macroscopic, particulate, and symbolic level codes.

fewer than expected, despite the VCI's emphasis of moving past description and toward explanation. We posit that particulate-explanation may be less accessible than particulate-description during participants' lesson planning, requiring additional analysis to reveal potential barriers.

To examine the coded data corpus, Figure 2 shows violin plots of macroscopic, particulate, and symbolic level codes (along the *x*-axis) for the 2020 and 2021 VCI aggregates. Because learning designs vary in detail, values on the *y*-axis are calculated on a per participant basis. The number of codes for a single representational level was divided by a participant's total number of codes to identify the proportion of codes for each level within the learning design. A thick region in one violin plot thus indicates more participants with similar proportions of that representational level in their respective learning designs. As denoted by the embedded box plots, the median values describe the proportion of codes by level, specifically 0.14, 0.52, and 0.32 for macroscopic, particulate, and symbolic, respectively. Participants' learning designs thus contain planned segments that are mostly particulate, followed by symbolic and macroscopic.

Considering the VisChem approach's[6] design and reliance on molecular interactions, the particulate level having the highest median value is expected. The thick regions of the macroscopic and symbolic violin plots are also below their respective median values, indicating that more participants are underemphasizing these levels in their learning designs. These findings overall support the success of our attempts to curb the over-representation of symbolic and macroscopic levels in high school classroom settings. The incorporation of all three representational levels also suggests alignment with recommendations from the chemistry education literature. With plans to leverage the particulate level and the macroscopic and symbolic levels serving as ancillary support, students can better engage in their triadic connection for advancing chemistry conceptual understanding.[53,67]

Although the particulate violin plot had the highest median value, its thinness indicates more variability in the proportions of particulate level codes across teachers' learning designs. The particulate level was then separated into particulate-description and particulate-explanation, shown in Figure 3, with median values of 0.35 and 0.12, respectively. The explication, rather than the explanation, of chemistry phenomena appears to be more salient to participants. This is further evidenced by the particulate-explanation violin plot's thickness near the bottom, with more participants having no codes and fewer having some. Furthermore, where the particulate-explanation violin plot is

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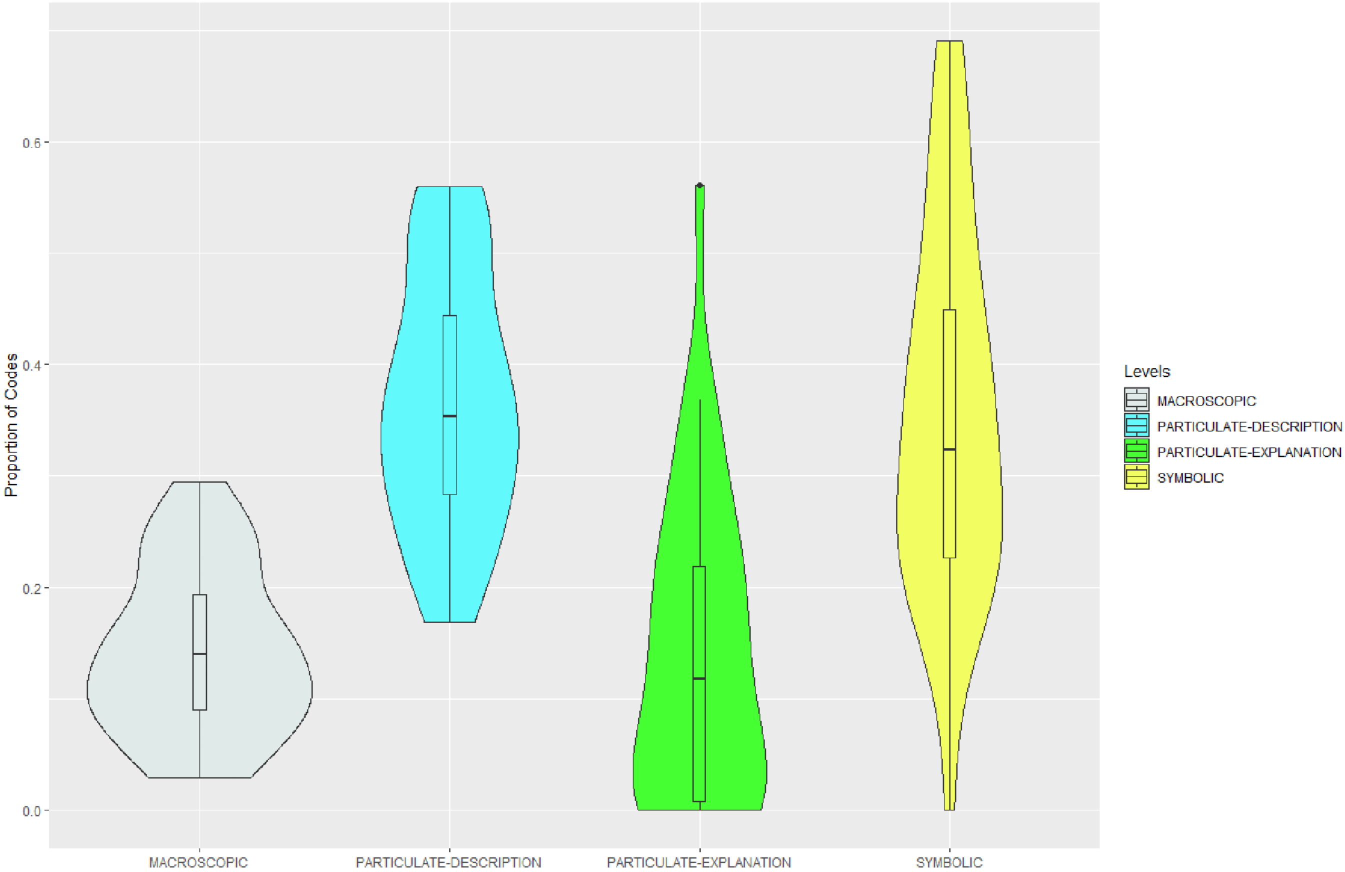

Figure 3. Violin plots showing the distributions of macroscopic, particulate-description, particulate-explanation, and symbolic level codes.

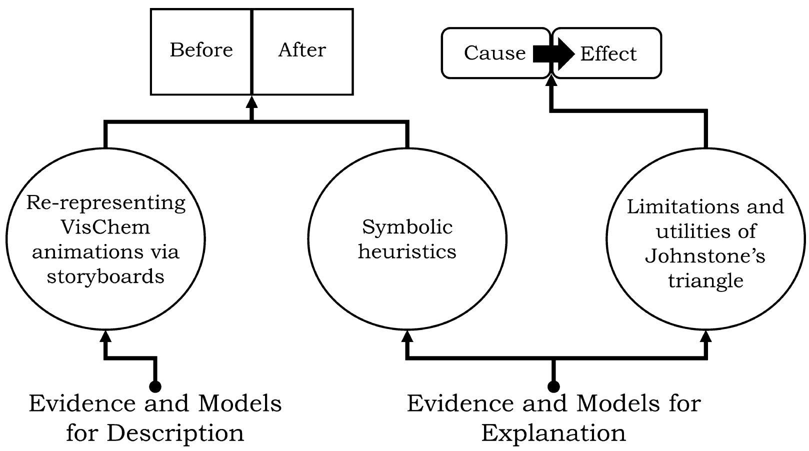

Figure 4. Pathways within lessons using the VisChem approach[6] due to differences in EEM ontologies.

narrow at the top, both the particulate-description and symbolic violin plots are wider. The width comparison of these three violin plots suggests that description may not be the only factor that supersedes explanation. Emphasis on symbolic planned segments seemingly appears at the expense of particle-level explanations. A more in-depth analysis is needed to unpack the mangle among particulate-description, particulate-explanation, and symbolic.

Research Question 2: How Do Participants Interpret the Ontological Nature of EEM in Their Learning Designs?

We unpack ontology to be a participant's interpretation of EEM at that moment of revising the learning design. Unlike epistemology that is associated with how students should learn with EEM, ontologies deal with the understood nature of EEM. Put more simply, we investigate how participants identify what classifies as EEM based on the inferred teaching and learning functions throughout learning designs. We begin with an exemplary case of EEM ontologies as intended by PedChem-Sense. We then transition to cases representative of more divergent teacher authoring due to variations in EEM ontologies.

Summarized in Figure 4, how participants purpose EEM in their learning designs led to different outcomes of the VisChem approach.[6] Contextualized by the NGSS,[1] we understand a chemistry explanation to be a cause−effect mechanism driven by

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molecular-level behavior. When evidence and models are for *explanations*, there is a pathway in which limitations/utilities of Johnstone's triangle support students' explanations. We also recognize a second outcome: a before−after characterization that lacks the explanatory power of cause−effect. If evidence and models were used primarily for *description*, storyboards become a re-representation of the animation without explicit plans to consider explanatory power. We also identify an alternative route in which participants may use symbols for "explaining", creating a divergent pathway that leads back to before−after. While both outcomes (e.g., before−after and cause−effect) are useful throughout the learning process, we prioritize the cause−effect pathway given what the NGSS recommend and our focus on pedagogy advancing explanations grounded in atomic/molecular behavior. We now present Teachers 111, 213, and 206 who demonstrate these three outcomes, respectively.

Shown in Box 1, Teacher 111 intends to "point out the tug of war" depicted in the VisChem animation. This cuing of the

Box 1. Teacher 111's Plans with VisChem Animations and Storyboards

Watch the actual precipitation visualization − 3× (silently, chunked to draw attention to ions as they appear, try to point out the tug of war, and then all the way through again)

- Would you say this one is more or less dynamic? Is that easier or harder to represent in a static picture? (discuss limitations of our model) So what could we add to our descriptions to improve our static models?

competition for electrons suggests that Teacher 111's ontology of explanation is likely situated in relative attractions among species. Watching the visualization multiple times and chunking information also supports Teacher 111's ontology of evidence as the VisChem animation itself. Meticulously directing students' attention can establish the conceptual frame needed to convert visual information into evidence for particle-level explanations.[31] Finally, we notice Teacher 111's focus on the storyboard's limitations via asking students to make sense of how storyboards are "more or less dynamic" and what descriptions could be added to "improve [their] static models". Although storyboards are static, Teacher 111 recognizes that this can be compensated by representing particle-level dynamism through words. Generating storyboards becomes less about copying what the VisChem animation shows but purposefully discerning what *can* be better depicted and *how*.

Shown in Box 2, Teacher 111 plans to ask students "what is really meant" with a symbolic equation. Teacher 111 hints at

Box 2. Teacher 111 Making Visible the Symbolic Level's Limitations

"When we write this equation, what is really meant by $AgNO_3(aq)$? $NaCl(aq)$? $NaNO_3$? What might be a better way to represent this equation?" (indirectly gets us to complete ionic equations a whole unit early − bonus)

how symbolic conventions do not fully communicate information, thereby drawing attention to uncertainty intrinsic to this representational level. By asking, "what might be a better way to represent this equation", Teacher 111 likely warrants the particle level (e.g., storyboards and VisChem animations) for more comprehensive understanding. The simultaneous attention to the symbolic and particulate levels reinforces Teacher 111's ontology of models being contextually functional representations. The mentioning of how this activity is a bonus because it can "indirectly get [them] to complete ionic equations a whole unit early" is also intriguing. This acknowledgment parallels with what Dolfing and colleagues[68] describe as teacher accommodation. Teacher 111 is not only expanding current practice but also identifying ways of fitting the VisChem approach[6] into extant curriculum. The word "bonus", although seemingly innocuous, supports the role of the prescribed curriculum as an undercurrent that guides how PD content may be translated into participants' classroom settings.

Teacher 111's learning design conveys EEM ontologies that lead to a cause−effect mechanism using atomic/molecular behavior (see Figure 4). Twelve other participants had similarly planned segments that drew students' attention to the limitations of models or the particulate level as evidence for explaining silver chloride precipitation. However, Teacher 111 was the only participant whose synthesis of EEM most directly aligned with PedChemSense and NGSS. Plans to compare the limitations of the storyboards and the VisChem animations encompass both descriptive and explanatory functions. Symbols in the written equation are also problematized, thereby warranting both connection to and sensemaking with the particulate level. These planned segments thus employ both Johnstone's triangle and the models *for* perspective as an invitation for students to generate particulate-level explanations of silver chloride precipitation.

Our analysis also detected ontologies of evidence and models that diverged from what PedChemSense recommends. Shown in Figure 5, Teacher 213 includes a storyboard template that has

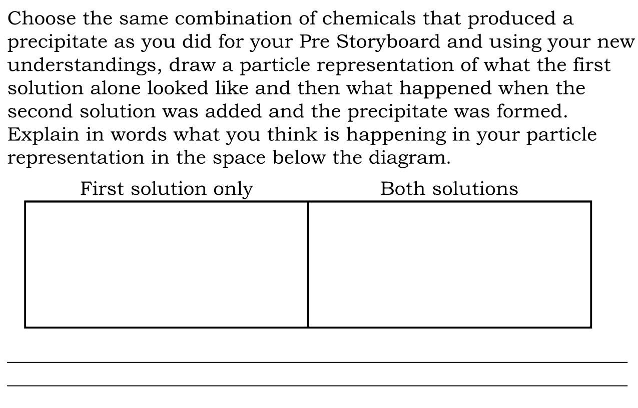

Figure 5. Teacher 213's redesigned storyboard template for description.

two boxes for drawing and lines for writing. This storyboard typifies many of the templates participants had redesigned. At a glance, it appears similar to a VCI storyboard. However, the instructions to "draw a particle representation of what the first solution alone looked like and then what happened" imply a preference for description. We also draw attention to the last sentence of the instructions. Although the word "explain" is present, in context with the other instructional components, it is more precisely asking for a description. Explaining in words *what* one thinks is happening obligates a different activity wherein students may not as strongly attend to *how* or *why*. As a result, teachers may have greater difficulties probing their students' ideas about the cause−effect mechanisms driving precipitation.

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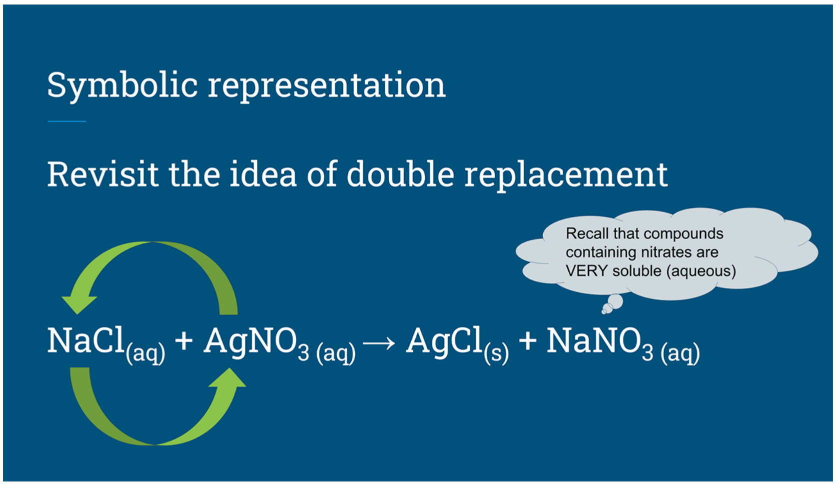

Figure 6. Teacher 206's use of a double replacement reaction to explain precipitation.

Similar to previous findings, Teacher 213 appears to possess ontologies of models as representations, occluding explanatory details like chemical bonds and intermolecular forces.[69] This phenomenon is akin to what Dolfing and colleagues[68] refer to as toleration. VCI participants have seemingly accepted features of the VisChem approach in terms of its processes and conditions without explicitly attending to the substantive aspects. We interpret participants are planning to go through the motions of the VisChem approach, repurposing the storyboards for conveying precipitation without making sense of the extent the storyboards can explain precipitation.

The imprecision in the NGSS' definition of models may also be increasing this ontological misalignment. Defined by the NRC (ref 2, p 56):

> *Conceptual models, the focus of this section, are, in contrast, explicit representations that are in some ways analogous to the phenomenon they represent. [. . .] Although they do not correspond exactly to the more complicated entity being modeled, they do bring certain features into focus while minimizing or obscuring others.*

Based on words like, "represent", "analogous", and "correspond", the NGSS present models as limited representations of phenomena. Although scientifically acceptable, how the NGSS associate the model's limitations is insufficient when recontextualized in chemistry. A model's constraints are mostly expressed in terms of the appearance, not the explanatory utility. Teachers who attend to the NGSS may consequently focus on the descriptive qualities of a model when planning classroom activities.

Similar to Teacher 213, there were 23 other participants whose VisChem approach[6] plans were primarily descriptive. Coupled with the NGSS' imprecision when defining a model's limitations, participants appear to associate evidence with VisChem animations (similar to Teacher 111) but with a different purpose. These learning designs feature instructions for students to transfer details on the chemical species' appearance gleaned from the animation onto their storyboards (see Figure S2). Students are encouraged to observe and record what happens, an epistemology similar to engagement with a macroscopic demonstration or laboratory experiment. Because students' first instinct when viewing animations is often accepting what they see as correct,[70] the design of this planned segment may dissuade the evaluation of presented features of the animation. Furthermore, when evidence and models serve a descriptive purpose, storyboarding becomes emulating specific frames of an animation (typically the first and the last). Participants thus transform the VisChem approach[6] into describing the "before and after" instead of explaining the "cause and effect" (see Figure 4).

Our analysis also revealed a different treatment of explanation that does not correspond with the NGSS or PedChemSense. Shown in Figure 6, we highlight Teacher 206 whose learning design indicates a different ontology of explanation. Students are first oriented to precipitation as "double replacement". Symbol swapping is further denoted by the green arrows that direct Ag^+ and Na^+ to switch places. We note that this type of symbolic manipulation is detrimental to students' learning when encountering precipitation reactions that are not 1:1 molar ratios. In addition, the depiction of $NaNO_3$(aq) contradicts the scientific model of hydrated ions. Suggesting that $NaNO_3$(aq) exist as a formula unit may hinder students' understanding of aqueous chemistry.[71] The written equation—due to the inherent limitations of the symbolic level—effaces the role of bulk water, making it ill-fitting for explaining precipitation.

Teacher 206 is among 13 participants who situate silver chloride precipitation as a double replacement reaction. Instances when students would view VisChem animations and storyboard the phenomenon would be planned concurrently with these heuristics of symbol manipulation. Solubility rules are additional heuristics participants would feature in their learning designs. Oftentimes, participants would present these symbolic algorithms as the de facto rationale of why precipitates form (see Figure S3). We interpret these learning designs to be deliberately facilitating symbolic level connections when learning precipitation. We stress that this manner of prioritizing the symbolic level, though laudable, may detract students' attention away from other, more essential processes at the particulate level. In other words, although symbolic heuristics are useful, they become detrimental to conceptual understanding when taught as an explanation.

Our analyses indicate that participants like Teacher 206 likely possess a different ontology of explanation that is not grounded in atomic/molecular behavior, a phenomenon that can be explained by the NGSS. According to the NRC (ref 2, p 67):

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Scientific explanations are accounts that link scientific theory with specific observations or phenomena—for example, they explain observed relationships between variables and describe the mechanisms that support cause and effect inferences about them.

Although scientific theory is absent in Teacher 206's learning design, this reappropriation of chemistry symbols still coincides with what the NGSS define as an explanation. The observed relationship between two cations (as symbolic variables) swapping to form products is technically a working, albeit superficial, mechanism. Shown in Figure 4, participants like Teacher 206 likely possess evidence and model ontologies congruent with PedChemSense. The principal difference is that symbols—instead of particles—are treated for explanation, culminating to an alternative ontology of explanation. These symbolic heuristics and their lack of particulate-level detail result in an outcome similar to Teacher 213's learning design: plans to implement the VisChem approach[6] address the before−after of precipitation more so than the cause−effect.

Similar to Kennedy's[72] findings, we surmise that factors external to the VCI may have influenced participants' sensemaking and led to unanticipated plans for instructional changes. Our findings underscore how factors in the mangle are relatively underexplored (e.g., NGSS). In addition, high school chemistry textbooks may also exacerbate matters because they typically re-represent oxidation−reduction reactions as single replacement, synthesis, and decomposition reactions.[73] These conventions, like double replacement, may have veered learning designs away from PedChemSense's recommendations. Symbolic algorithms have a rightful place in teaching and learning of chemistry, but they should not supersede particle-level understanding; the latter must first be developed to rationalize the former as shorthand approaches.

■ SUMMARY OF RESULTS

Addressing uptake, the 2020 and 2021 VCI's learning designs feature the particulate level most prominently, followed by the symbolic and macroscopic levels. However, there were more particulate-description codes than those of particulate-explanation. Particulate-explanation may be less accessible for various reasons, necessitating a more in-depth ontological analysis with PedChemSense. On fidelity, Figure 4 portrays branching pathways of the VisChem approach[6] due to differences in EEM ontologies. When aligned with PedChemSense (in Teacher 111's learning design), there are sensemaking opportunities to support students' chemistry conceptual understanding. However, when the ontologies of evidence and models are more descriptive in function (in Teacher 213's learning design), we detect instances in which representing appearance may override attending to atomic/molecular behavior. There is intriguingly an additional pathway (in Teacher 206's learning design) that reappropriates symbol manipulation for "explaining". These symbolic heuristics deviate from what PedChemSense recommends, again leading to a before−after outcome that may further displace plans for students to generate particle-level explanations.

■ IMPLICATIONS AND RECOMMENDATIONS

This study demonstrates the value in using lesson plans as a window to better understand teachers' ideas about and plans for teaching chemistry. While other studies have evaluated, compared, and investigated lesson plans in various ways,[74−76] lesson plans are more auxiliary relative to other teacher artifacts when characterizing teachers' professional knowledge bases.[77−79] This study showcases how lesson plan analysis can not only determine the uptake of Johnstone's triangle but also amplify underexplored teacher characteristics that affect fidelity. For the last 25 years, researchers have tried resolving the incongruity between what teachers report in surveys and the quality of interactions between teachers and students.[80] Using PedChemSense to triangulate the analyses of lesson plans and other teacher artifacts can help close this gap, improving our understanding of how teachers intend to translate their chemistry knowledge into enacted pedagogical content knowledge. The versatility of lesson plan analysis should be explored further in future research endeavors.

Our findings indicate complications in lesson planning that are deeply rooted in other factors not typically addressed in chemistry education research. Specifically, we call for researchers to further unpack the NGSS. While previous studies have promoted alignment such that the standards are more closely followed,[17,81] the potentially muddled overlaps between chemistry and NGSS should not be ignored. We focus on *Practice Six: Constructing Explanations* and the natures of EEM because of their compatibility with the VCI. However, there are many more components of the NGSS—components that may similarly need additional contextualization to be informative and pragmatic for chemistry teaching and learning.[15] We urge researchers to pursue an in-depth ontological analysis of the NGSS and to problematize terms that may often be taken for granted or are fuzzy in nature.[31] Using PedChemSense to evaluate the inherent utility/limitation of a particular NGSS concept and how in-service teachers understand said concept is one way to coordinate reform efforts and chemistry instruction.

Attending to external factors like the NGSS is also vital for fellow teacher educators. Carefully following recommendations on appropriate design, content, and resources[8−10] when planning the VCI has largely enabled the observed successes. Nevertheless, our efforts as professional developers may continually be stymied if such external factors are not actively incorporated into teachers' PD experiences. We urge fellow teacher educators to clarify and specify the interconnections between chemistry and the NGSS during PD activities. Articulating EEM ontologies via PedChemSense upfront may productively segue into planning and enacting related epistemological practices. Teachers who remain unaware of what constitutes as chemistry-specific EEM may transform their PD experiences in unexpected ways, just as how VCI participants reappropriated the storyboards, VisChem animations, and symbolic notations. Kang[82] states that solely making professional materials available is insufficient to support effective lesson planning. By supporting in-service teachers' actual use of high-quality resources, we can move away from toleration and more toward teacher accommodation.[68]

Finally, both practitioners and researchers should work in-tandem when considering other external factors like extant curricula and their associated pedagogical traditions. Both the tendency to treat models as descriptive tools and the reappropriation of symbol heuristics to explain precipitation disincentivize understanding particle-level processes. Students have been shown to rely heavily on the instructor for explanations insofar that slight alterations to facilitation can lead to significant changes in learner behaviors.[83] Both practitioners and researchers at the high school and undergraduate levels should thus be cautious. These reappropriations,

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when repeated over time, may become detrimental to students' chemistry understanding. Similar to Allen and Penuel's[84] implications, we recommend that practitioners, researchers, administrators, and policy makers should collaborate to confront and work through these pedagogical uncertainties unique to chemistry. We should collectively consider how an educator portrays EEM ontologies and the ways chemistry learning is nurtured or deterred. This endeavor also requires characterizing other problematic traditions related to our discipline's pedagogy, bringing into focus ingrained features that may be hindering our progress toward reform-based teaching.

LIMITATIONS

The learning design is a messy artifact of teacher knowledge. Early analysis had uncovered a paradox with how participants plan their lessons. The absence of a feature could mean it was not relevant or worthwhile to the teacher. Simultaneously, the absence of a feature could signify the opposite: It was so obvious to the teacher that it simply was not necessary to write down. The ambiguous nature of the learning designs also meant that they at times could not be discretely organized into the archetypes represented by Participants 111, 213, and 206. Many learning designs were thus designated with more than one archetype due to their overlapping characteristics. We rationalize that, given the instructions of the VCI learning design assignment and how participants had explicitly included details regarding the VisChem approach,[6] plans to facilitate students' evidence- and model-based explanations should be equally visible. This expectation also aligns with the VCI's learning outcomes and facilitation. We posit that these components are salient for proactive lesson planning and can support participants' learning of both chemistry and pedagogy.

We also acknowledge contextual dependency and possible lack of transferability as another limitation. Our claims are emergent from a small subset of in-service high school chemistry teachers with uniquely lived experiences from various parts of the US. In addition, the 2021 cohort had experienced a modified VCI based on feedback that we had received in 2020. Given these contextual differences, we opted to not make any comparative claims. We instead aggregated the cohorts, aiming to reveal more deeply rooted challenges, as they may continually problematize PD efficacy regardless of changes to design, content, and/or facilitation. We also note that, because our findings take an ontological stance, our claims can resonate with both high school and undergraduate-level chemistry instructors. Although our findings may not be directly transferable, our results can nevertheless spur productive discussions toward improved teaching practices for introductory chemistry at the secondary and tertiary levels.

CONCLUSION

Because explanations, evidence, and models are crucial for chemistry teaching and learning, our first research question addresses the extent to which Johnstone's triangle is incorporated in VCI participants' learning designs. Our analysis suggests that, while the learning designs have prominently incorporated the particulate level, planned segments more frequently encourage description rather than explanation. Our second research question thus aims to clarify these unexpected results via VCI participants' EEM ontologies. Adaptations of the VisChem approach[6] may be due to reappropriations of EEM reinforced by evidence and models for description, symbolic heuristics, and imprecisions within the NGSS themselves.

Teaching and learning are thus complicated, a mangle of various factors.[12] Lesson planning requires negotiating with internal and external demands idiosyncratic to teachers' classrooms. More facets emerge when teaching is situated in chemistry. While literature that supports chemistry-specific pedagogy is abundant, the number of studies that draw attention to the uncertainties between teaching and the chemistry discipline itself pale in comparison. If left unattended, these deeply rooted challenges may act as anchors unlike the ones that ground students' understanding and connect the familiar with the unfamiliar. These anchors instead are more pedagogical in nature, impeding and hindering uptake of reform-based instruction toward particle-level explanations. We as a chemistry education community should reflect on how chemistry is repackaged for instruction, identifying ways of upheaving these anchors and advancing conceptual understanding and the associated practices for teachers and students alike.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c01275.

Table showing a code book for learning design analysis, excerpt from Teacher 120's learning design, and excerpt from Teacher 101's learning design (PDF)

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Notes

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