Chemistry Education Research and Practice

Secondary Chemistry Teacher Learning: Precursors of and Mechanisms for Pedagogical Conceptual Change

Journal:	*Chemistry Education Research and Practice*
Manuscript ID	RP-ART-06-2022-000160.R1
Article Type:	Paper
Date Submitted by the Author:	15-Aug-2022
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Secondary Chemistry Teacher Learning: Precursors of and Mechanisms for Pedagogical Conceptual Change

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

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Despite years of research and practice inspired by chemistry education research, a recent report shows that US secondary instruction are not aligned with current national reform-based efforts. One means to mitigate this discrepancy is focusing on pedagogical conceptual change, its precursors (higher self-efficacy and pedagogical discontentment), and the subtleties of its mechanisms (assimilation and accommodation). In this study, we investigate the final reflections of participants (*N* = 35) who completed our professional development program known as the VisChem Institute (VCI). Our results show that Johnstone's triangle as well as evidence, explanations, and models can be conducive for stimulating pedagogical discontentment among VCI teachers who exhibit higher self-efficacy. In addition, how VCI teachers assimilate and/or accommodate reform-based chemistry teaching ideas problematizes conventional assumptions, broadens application of novel theories, and is germane to introductory chemistry learning environments across the world. Implications and recommendations for chemistry instruction and research at both secondary and tertiary levels are discussed

Introduction

The *Next Generation Science Standards* (NGSS) are prevalent drivers for chemistry education research in US secondary instruction. For example, Hike and Hughes-Phelan (2020) have created a laboratory report rubric that adheres to the Science and Engineering Practices of the NGSS. Stowe *et al.* (2019) have examined their NGSS-aligned chemistry curriculum's efficacy for supporting students' understanding of atomic/molecular behavior. Professional developers for in-service secondary chemistry teachers have also incorporated the NGSS as principles informing both program design and facilitation (Wu and Yezierski, 2022a). However, the *National Survey of Science of Science & Mathematics Education* (NSSME) reports that classroom time dedicated to certain scientific practices (e.g., evaluating the strengths and weaknesses of scientific explanations) is still low (Smith, 2020). Teacher beliefs remain only partially aligned with what is known about how students learn science (Banilower, 2019). We note the less-than-desirable uptake of reform-based instruction despite our communal efforts is akin to what Woodbury and Gess-Newsome (2002) call "change without difference."

Attending to instructors' chemistry teaching ideas (CTIs) could elucidate ways to more meaningfully effect change in secondary classrooms. Prior literature has established robust interconnections among teachers' thinking, their knowledge and beliefs, and their propensity to teach differently (Cohen and Ball, 1990; Shulman 1987). One strategy for better understanding CTIs' reformation is using the conceptual change model (Strike and Posner, 1992). There are two variants of conceptual change: 1. Assimilation of a new concept that is understood using one's mental scheme; 2. Accommodation of a new concept that requires replacing and/or reorganizing one's mental scheme (Taber, 2019). For accommodation to occur, there must be dissatisfaction with an existing conception while the new conception must also be intelligible, plausible, and fruitful (Posner *et al.*, 1982). Leveraging the conceptual change model to improve uptake of reform-based science instruction, Gess-Newsome *et al.* (2003, p. 762) spotlight pedagogical discontentment, defined as the unease when one discerns "the mismatch between stated teaching beliefs, goals, instructional practices, and student learning outcomes."

In the past decade, pedagogical discontentment has been used in various ways. Southerland *et al.* (2011b) have identified common areas of discontentment among in-service science teachers' practices. Later development of the Science Teacher Pedagogical Discontentment (STPD) scale enabled quantification of pedagogical discontentment (Southerland et al., 2012). More recently, interactions between teacher discontentment and the NGSS have been analyzed using the STPD scale and teacher reflections (Castronova and Chernobilsky, 2020). These cumulative works help legitimize pedagogical discontentment as an intrinsic factor for instructional reform. Traditionally, self-efficacy has been the prevailing metric for gauging both pre- and in-service teacher progress (e.g., Akin and Uzuntiryaki-Kondakci, 2018; Blonder *et al*., 2013; Menon, 2020; Zimmermann *et al*., 2021). Southerland *et al.* (2011a) instead insist that both pedagogical discontentment and high self-efficacy are prerequisites or precursors for teacher change.

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Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/x0xx00000x

Building from these studies, we recognize two directions for advancing the novelty and relevance for chemistry education research. First, the STPD scale comprises of items centered around *science* teachers' instruction. The STPD scale, although referencing students' understanding, inquiry, abilities, and knowledge multiple times, does not address those that are particular to chemistry: the various levels of representation, the related modeling practices, and sensemaking processes for creating particle-level mechanisms. Considering how specificity improves predictive ability of self-efficacy (Naibert *et al.* 2021), pedagogical discontentment's generalizability may actually limit its function concerning CTIs. Adjusting pedagogical discontentment for chemistry contexts is necessary for effectively prompting teacher change.

Second, although pedagogical discontentment originates from the conceptual change model, there is scant literature describing teachers' assimilation and/or accommodation of CTIs. Research has largely foregrounded pre-service teachers' learning of chemistry concepts (e.g., Kaya *et al*., 2022) or teachers' sensemaking of policy documents (Spillane *et al.* 2002), rather than ideas about chemistry teaching per se. Just as how knowing the *precursors* is important for catalyzing reform, understanding the *mechanisms* of change is also vital. Insights about how CTIs are assimilated and/or accommodated can help expand the conceptual change model and provide feedback for the design and implementation of professional development (PD). Thus, our study focuses on characterizing the *precursors* (i.e., pedagogical discontentment and high self-efficacy) and the *mechanisms* (i.e., assimilation and accommodation) related to in-service secondary chemistry teachers' pedagogical conceptual change.

Conceptual Framework

Precursors for Change

Pedagogical discontentment (PedDis) is a force for stimulating engagement with new pedagogies and conceptions (Gregoire, 2003; Southerland *et al.*, 2011a). Unlike contextual discontentment, which may be related to administrative support, classroom materials, or standardized assessments, PedDis is dissatisfaction directly associated with pedagogy (Southerland *et al.* 2011b). Delineation between PedDis and self-efficacy entails knowing their respective temporal orientations. On one hand, researchers have operationalized PedDis as a reflective assessment of current and past teaching practices (Castronova and Chernobilsky, 2020; Enderle *et al.*, 2014; Southerland *et al*., 2011a). On the other, teacher self-efficacy is associated with the future, that is, the belief that is one is capable of successfully facilitating activities to increase learning (Southerland *et al.* 2011). Balgopal (2020, p. 778) notes that self-efficacy, in the context of teacher agency to initiate and implement curricular reform, depends on "being willing to try new approaches." As *precursors* for change, PedDis functions as the trigger for teachers to thoroughly contemplate new pedagogical practices while self-efficacy determines the feasibility of the new practices' implementation.

Table 1 Summary of PD outcomes based on vignettes of chemistry instructors who have pedagogical (dis)contentment and high/low self-efficacy.

	High Self-Efficacy	***Low Self-Efficacy***
Pedagogical CONtentment	*Instructor A* No change	*Instructor C* No Change
Pedagogical DIScontentment	*Instructor B* Change	*Instructor D* Possible Change

Coupling PedDis with self-efficacy is productive for investigating PD's influence on teacher learning and later classroom practice (Southerland *et al*., 2016). Previous literature has problematized the overly simplified interpretation of self-efficacy and its role in the teacher education community (Pajares, 1997; Settlage *et al*., 2009; Wheatley, 2002). The insular emphasis of high self-efficacy may be problematic, insofar that teachers are resistant to seeking change (Kahveci *et al*., 2018; Granger *et al*., 2018). Portrayed as a summary of vignettes, Instructor A perceives oneself as a teacher who employs student-centered, model-based instruction (Table 1). When experiencing reform-based PD that also endorses model-based inquiry (e.g., Dass *et al.*, 2015), Instructor A recognizes the affinity with past/current teaching practices and is pedagogically content. As Instructor A's confidence in maintaining the pedagogical status quo is affirmed, receptivity to PD messages and inclination to reflect decreases. We note that Instructor A's high self-efficacy, in isolation, may not instigate reform. If the perceived need to change is missing via pedagogical contentment, the impetus for change cannot be realized. Such an affective state would "not be conducive to openness, receptivity, or strong engagement with professional development messages" (Southerland *et al.*, 2011, p. 308).

Teacher reform is theorized to occur when both PedDis and high self-efficacy are present (Southerland *et al.* 2011a). For example, Instructor B is one who primarily relies on teacher-centered practices (Table 1). Instructor B also problematically presents chemistry models as simplified copies of reality (Grosslight *et al*. 1991). Instructor B is subsequently taken aback by student processes of model generation and evaluation afforded by reform-based instruction (Edwards and Head, 2016). When reflecting, Instructor B acknowledges gaps in past/current teaching practices. Instructor B now experiences PedDis and is inspired to brainstorm the logistics needed to enhance teaching. Plans for lecturing are now being re-conceptualized with opportunities for discussing scale, usage, accuracy, parsimony, and other characteristics of chemistry-specific models (Lazenby *et al*., 2020). Combined with high self-efficacy in implementing these new instructional strategies for the future, Instructor B is now poised to change.

Additional combinations of pedagogical (dis)contentment and high/low self-efficacy are also theoretically possible. Instructor C can be so contextually discontent that self-efficacy can also be affected (Table 1). Teacher uncertainty may arise due to conflicting district-level demands, incoherent resources,

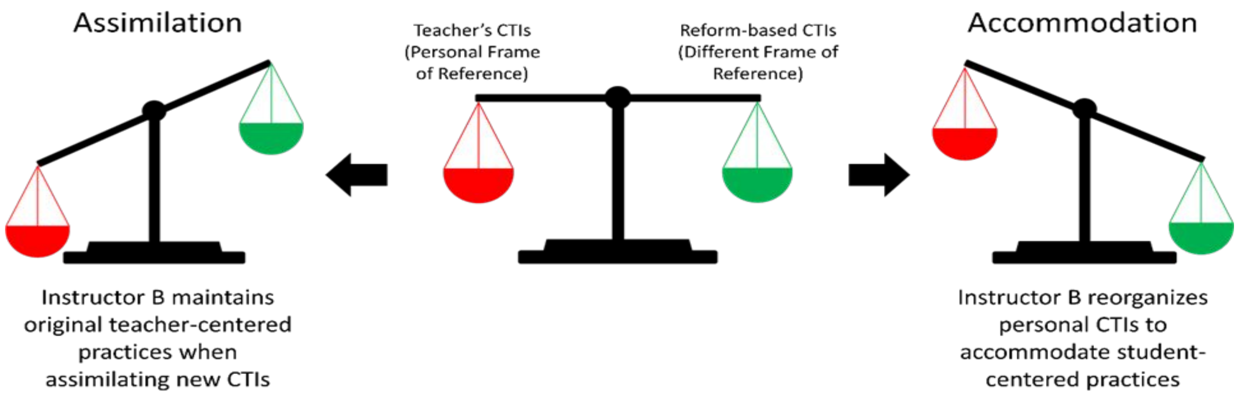

Fig. 1 Differences in pedagogical conceptual change wherein personal chemistry teaching ideas are prioritized for assimilation while reform-based chemistry teaching ideas are prioritized for accommodation.

and/or limited time (Allen and Penuel, 2015). Unfortunately, teachers who view their students in a deficit manner may believe that any future instruction would be ineffective due to the lack of students' capabilities (Southerland *et al*., 2011) These contextual features can exacerbate low self-efficacy such that, when paired with pedagogical contentment, possibilities for reform are obstructed. Instructor D exemplifies the last permutation where both PedDis and low self-efficacy are present (Table 1). Previous studies show that high school teachers may have chemistry misconceptions (Cheung *et al.*, 2009) and lack familiarity with using chemistry concepts to sequence their lessons (Nixon *et al*., 2016). Within this vein, Instructor D could be a novice teacher who acknowledges not only the ways teaching could be better but also the absence of conceptual and curricular tools required for improvement. Change is possible but more difficult to achieve.

Mechanisms of Change

When defining pedagogical conceptual change (PCC), we leverage aspects of both the conceptual change model (Posner *et al*., 1982) and the *Search for Meaning of Reforms* framework (Luttenberg *et al.*, 2013) due to inherent differences and similarities. The former deals with mental schema in which extensive perturbations emulate a scientific community undergoing a paradigm shift (Kuhn, 2012) or a change in research program (Lakatos, 1970). The latter relates to teachers' negotiation of state and national reforms and is relatively more appropriate for our assumptions about teacher learning. However, the *Search for Meaning of Reforms* framework does not clearly articulate conditions that engender change. We hence posit that the prerequisites forwarded by the conceptual change model and its adaptations in Southerland *et al.*'s (2011a) work, specifically pedagogical discontentment and high self-efficacy, precede the mechanisms of PCC.

The *Search for Meaning of Reforms* framework parallels the conceptual change model in that they share underpinning processes. A personal frame of reference—defined as a teacher's chemistry teaching ideas (CTIs) in our study—may experience a conservative or radical change when presented with a different frame of reference (Coburn, 2004; Spillane *et al.*, 2002). In terms of encoding stimuli in existing knowledge structures (Flavell, 1963), Luttenberg *et al.* (2013, p. 294) define assimilation as the "adaptation of the perceived frame of reference […] to fit into one's own frame of reference" wherein the latter is "serving as the guideline and thus predominating." Grounding this description in a familiar example, we revisit Instructor B having PedDis and high self-efficacy (Table 1). After the PD, assimilation could involve Instructor B using chemistry models but maintaining personal CTIs. Teacher B opts to lecture about a chemistry model's characteristics and disseminate particle-level explanations. In other words, Teacher B resumes a teacher-centered frame of reference by merely appending new CTIs about models to preexisting instructional routines.

For major restructuring of existing knowledge (Piaget, 1972), Luttenberg *et al*. (2013, p. 294) define accommodation as the "adaptation of one's own frame of reference to fit into the perceived frame of reference" to the extent that the teacher "transforms his or her own manner of thinking and acting" (p. 294). One instance of Instructor B's accommodation could be a substantial switch from teacher-centered to student-centered practices (Fig. 1). Instructor B understands that cogently integrating chemistry models demands transforming discourse with students, expectations of chemistry understanding, and/or undergirding epistemic practices (Ryu *et al.*, 2018). More importantly, Instructor B's accommodation of this new frame of reference may lead to the "possible loss of some important characteristics of his or her own manner of thinking and acting" (Luttenberg *et al*., 2013, p. 294). After the PD, Instructor B's personal CTIs would change to synergize with those more aligned with reform-based instruction.

Previous studies demonstrating the relationships among teacher beliefs, agency, PD, and reform efforts have applied ideas related to the *Search for Meaning of Reforms* (Belo *et al.*, 2014; Imants and Van der Wal, 2020; Ketelaar *et al*., 2014). Recently, Dolfing *et al.* (2020) has characterized secondary science teachers' pathways from assimilation to accommodation using the *Search for Meaning of Reforms* framework. The research context of their study (e.g., multiple data collection points and different teacher artifacts) enabled consideration of two additional teacher sensemaking processes described by Luttenberg *et al.* (2013) as toleration and distantiation. They define toleration as "putting up with the perceived frame of reference […] at the cost of one's own frame of reference" and distantiation as "the rejection of a perceived frame of reference […] in favor of one's own frame of reference" (p. 294). Our study excludes these processes (see Methods for details). Because we pursue teacher reform, we primarily investigate the *precursors* (PedDis and high self-efficacy) for and *mechanisms* (assimilation and accommodation) of PCC. We accordingly present the following research questions:

1. When prompted to describe their CTIs and reflect on instructional change, in what ways do teachers with higher self-efficacy describe pedagogical discontentment?
2. In what ways are assimilation and accommodation evidenced in teachers' CTIs?

Research Setting

Our PD program is known as the VisChem Institute (VCI). One of our core CTIs is the VisChem Approach that combines storyboarding, molecular-level animations, and discussion framed by a cognitive learning model (Tasker & Dalton, 2006). This modeling-based practice involves (1) experiencing a macroscopic-level phenomenon that primes the perception filter, (2) representing ideas about molecular level events on a pre-storyboard (i.e., drawing with written explanations), (3) viewing VisChem animations in a manner that minimizes cognitive load, (4) revising and creating post-storyboards, and (5) connecting new ideas to prior knowledge with an unfamiliar but related chemical phenomenon. The VCI fosters the learning of chemistry and pedagogy such that participants would experience the VisChem Approach themselves as students and then plan its design and implementations as instructors. A timeline of PD activities is provided (Appendix 1). As such, we define teacher change to be the uptake and improved understanding of the VisChem Approach. The VCI's learning outcomes will be discussed in further detail in Data Collection.

The VCI was remotely delivered in July 2020 and 2021. While the 2020 VCI was four full days, the 2021 VCI was seven half days. Both iterations consisted of 28 face-to-face PD hours with additional time for completing asynchronous work. In the 2020 and 2021 VCI, there were 20 and 16 participants, respectively. All participants were in-service secondary teachers from across the United States. Sampling consisted of an initial survey in which applicants responded to questions about their classrooms, years of teaching experience, instructional practices, and PD expectations. Afterwards, the research team created a ranking system that prioritized teachers from schools with higher minority populations and higher percentages of students who qualified for the federal reduced/free lunch program. Other characteristics that were weighted more heavily included 2-20 years of teaching experience (late enough to understand chemistry instructional repertoire but early enough career-wise for the VCI to have more longstanding effects on students) and disposition towards student-centered practices (greater likelihood of reform uptake). Additional information regarding VCI design and our sampling process are elaborated in a previous article (Wu *et al.*, 2021) and in a forthcoming paper.

Methods

Data Collection

Our data comprise of VCI participants' final reflections, collected on Day 4 of VCI 2020 (N = 19) and Day 7 of VCI 2021 (N = 16). The instructions for this assignment prescribed both teacher cohorts to identify their change throughout the VCI and give specific examples of what was and/or what needs to be further improved. The reflection itself consisted of four components (Appendix 2). In Part A, teachers described their growth with respect to VCI learning outcomes (A1-A9 in Fig. 2) that function as CTIs comprising the VisChem Approach. In Part B, teachers compared how the VCI and the VisChem Approach align with certain NGSS components. Finally, for Part C and D, teachers were asked to describe additional learning outcomes beyond what was previously listed as well as anything else they wish to do and/or learn. Because instructions were about growth, teachers may have felt less obligated to describe reluctance and/or outright disapproval of VCI CTIs. We therefore omitted toleration and distantiation due to our elicitation task being incompatible with these processes. All methods of data collection, analyses, and reporting have been reviewed and approved by the PD-hosting university's institutional review board.

Data Analysis

Reflection is a practice that has been endorsed for teacher PD (Butler *et al*., 2004; Russell, 2005). Studies have used teacher reflections to document advancements in their science teaching and learning (Bismack *et al*., 2022; Chen and Mensah, 2022; Danielowich, 2017). Frykholm (2004) notes teachers often experience dissatisfaction with their instructional strategies when reflecting. The practice of introspection itself can influence teacher actions and/or beliefs as the two are interactive (Richardson, 1996). These scholars collectively support our decision to analyze the VCI final reflections for pedagogical conceptual change (PCC). We turn our attention to Parts A1-A9 and Part C of the final reflection (Fig. 2) as these components offer the richest descriptions of VCI teachers' past, current, and future instructional practices. Below, we describe our two-phase coding process.

Phase One—Coding for Precursors

The initial analysis phase involved deductively coding for *precursors* (Fig. 3). Although PCC is theorized to partly consist of high self-efficacy, we recognized that distinguishing teachers as having high/low self-efficacy is inappropriate because we did not use any validated measures as other studies have done (e.g., Herrington *et al.*, 2016). We used the term *higher self-efficacy* (HSE hereafter) to denote VCI teachers' beliefs in their capability to enact CTIs that are positively related to student learning (Southerland et al., 2011).

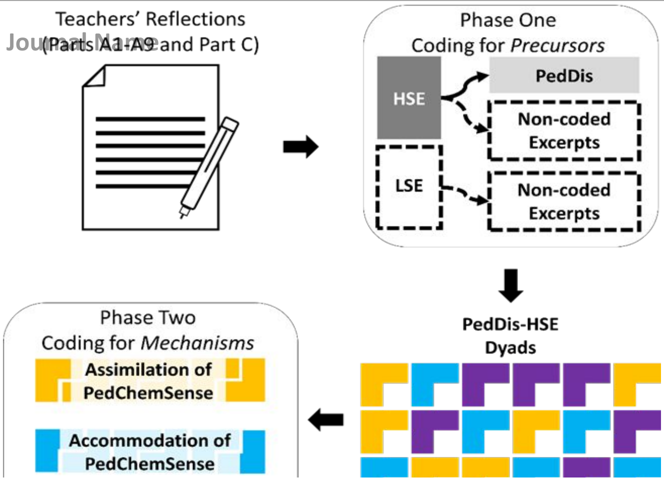

Fig. 3 Flowchart of data being reduced to Pedagogical Discontentment and Higher Self-Efficacy dyads (phase one) and then analysed for assimilation or accommodation of Pedagogical Chemistry Sensemaking (phase two).

Within each teacher response per Parts A1-A9 and Part C, we identified phrases/sentences that indicate a greater willingness to implement new CTIs for the future. Our coding guidelines were informed by the precedence established by prior studies that have measured teacher self-efficacy. Blonder *et al*. (2013, p. 278, emphasis added) identified chemistry teachers' phrases such as, "I understood that I *can* do, I *plan* to continue to learn and to improve, I *want* to produce a product" as having high self-efficacy. Zimmermann *et al*. (2021)'s 31-item self-efficacy questionnaire for pre-service chemistry teachers incorporated the "I can" stem 19 times. Finally, popular instruments as the Teaching of Science as Inquiry (ITB, Smolleck, Zembal-Saul, & Yoder, 2006) and the Science Teaching Efficacy Belief Instrument Form A (STEBI, Riggs, & Enochs, 1990) further shape our coding. The ITB includes the "I will" stem 45 times out of their 69 items, indicating that plans to improve CTIs can be related to positive self-efficacy. While the STEBI is not designed with repeating stems, the items nevertheless suggest that high teacher self-efficacy, similar to what Southerland *et al.* (2011) claim, can be detected in statements about beliefs in fruitfully enacting CTIs beneficial for their students' learning.

Once these portions of each VCI final reflection were flagged for HSE, another round of deductive coding occurred where we characterized phrases or sentences that indicated discontentment with past and/or current CTIs. We attended to HSE-coded excerpts first because as professional developers, we prioritized teachers' willingness to change per VCI learning outcomes. Assembling dyads with already identified HSE-coded components was more pragmatic because self-efficacy, not discontentment with past pedagogical practice, is the lynchpin for future change. Thus, responses that conveyed lower self-efficacy (LSE) or had HSE but pedagogical contentment were consequently not coded.

Our analytical decisions were motivated by the theoretical postulation that HSE and PedDis conditions lead to teacher change. We also decided to code excerpts per instructional prompt instead of holistically examining the entire reflection. Logistically, coding per Parts A1-A9 and Part C bounded each teacher's report of CTIs and afforded more feasible calibration among raters and management of the dataset. Given our coding criteria, the first pass had reduced the data representing CTIs from 35 VCI teachers to 32. Only three teacher reflections were not coded for either PedDis or HSE. The remaining 32 teachers had at least one instance of HSE or HSE with PedDis. A codebook with our HSE and PedDis criteria, teacher reflection exemplars, and non-coded examples is provided (Appendix 3).

After aggregating the PedDis-HSE dyads for each teacher, we noticed that six teachers only had HSE-coded excerpts (without any indicators for PedDis). These six reflections comprised of statements that suggested a willingness to enact reform-based CTIs but did not reference personal dissatisfaction with past/current pedagogy. Because the second phase necessitates investigating the dyads, our data were further reduced from 32 to 26 teachers, with a total of nine teachers who were ineligible for our analysis of PCC mechanisms.

Phase Two – Coding for *Mechanisms*

Tailoring the *Search for Meaning of Reforms* framework for chemistry-specific contexts, we established *Pedagogical Chemistry Sensemaking* (PedChemSense) as the other frame of reference (Fig. 3). Previously described as a conceptual framework for guiding model-based lesson planning (Wu and Yezierski, 2022b), we used PedChemSense as an analytical framework for several reasons. First, PedChemSense consists of representing chemistry at various levels (Johnstone, 1982; Taber, 2013; Seethaler *et al*., 2018), discussing the explanatory utilities and limitations of chemistry representations (Gouvea and Passmore, 2017; Krajcik and Merritt, 2012; Xue and Stains, 2020), and promoting students' sensemaking with molecular-level visualizations (Dewey, 1997; Mayer, 1997; Tasker and Dalton, 2006). PedChemSense's embedded constructs thus strongly resonate with our learning outcomes. Second, we selected PedChemSense because the pedagogy it informs resembles evaluating the strengths and weaknesses of scientific explanations: a practice that is under-reported in US secondary classrooms (Smith, 2020). Finally, because PedChemSense re-adapts Johnstone's triangle for both reasoning (e.g., connection of the macroscopic-particulate levels) and sensemaking (e.g., explanation of how the particulate level addresses limitations of the symbolic level), these guidelines lead to implementation of the VisChem Approach in its highest fidelity. We theorize that VCI teachers' accommodation of PedChemSense would result in more dramatic shifts in their CTIs and, consequently, be more easily detected within the data.

Coding for *mechanisms* was both inductive and deductive (last segment of Fig. 3). We followed Charmaz's (2014) recommendation for creating initial codes via open coding.

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Final VisChem Institute Reflection Instructions	
Part A: Describe how you have grown in the VCI with respect to the learning outcomes.	A teacher who successfully completes the VisChem Institute should be able to: A1. Use the particulate level to explain core chemistry concepts; relate these explanations to macroscopic phenomena, symbolic representations (formulas, equations), and mathematical relationships (e.g., concentration as a crowding of particles in a given volume of solution represented as $c = n/V$). A2. Identify the limitations of dynamic molecular models generally (and specifically VisChem animations) and recognize how limitations influence student thinking and generate inaccurate ideas. A3. Use VCI tools (e.g., frames from animations, static models, sample drawings, and graphics) and strategies (e.g., peer discussion, storyboarding, attention focusing, segmenting) with students to effectively reduce the cognitive load associated with visualizations. A teacher who successfully completes the VisChem Institute should have strategies planned to: A4. Diagnose students' alternative conceptions from drawings and descriptions in storyboards. A5. Challenge students to notice key features of animations, to make sense of phenomena while also ignoring contextual visual information (e.g., uninvolved water molecules in the background). A6. Generate questions that encourage students to rationalize macroscopic observations with their own molecular-level drawings and explanations, and express these using conventional symbolism. A7. Facilitate class discussions that motivate students to imagine molecular processes as a narrative, and improve their storyboards, explanations, and quality of evidence. A8. Help students to identify generalizable molecular behavior (e.g., competing attractions, effective and ineffective collisions) that enables them to transfer understanding to new chemical systems. A9. Construct appropriate assessment items that evaluate students' explanations of phenomena at the three thinking levels for chemistry and aligned with NGSS' 3D learning.
Part C: Describe any ADDITIONAL learning outcomes you've gained from the VCI.	

Fig. 2 Part A and Part C as the foci of VisChem Institute teacher reflection analysis

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Initial codes are tentative, in-vivo labels that segment the data into components and explicate what the data suggests. We iteratively examined PedDis-HSE dyads regarding commonalities, variation, relationships, tacit assumptions, and implicit meanings (Corbin and Strauss, 1990; Saldaña, 2013). Using axial coding, we entered a more focused, selective phase in which frequent initial codes were compared, condensed, and iteratively refined with ongoing analyses of the larger data corpus (Charmaz, 2014). Axial coding yielded more robust codes that provide analytical, not summative, perspectives of the data. Coding took a deductive turn near the end, as focused codes were revised and grouped into categories based on the assimilation or accommodation of PedChemSense. Saturation was achieved once our categories could comprehensively account for all salient properties within our data. In some instances, PedDis-HSE dyads had suggested PCC but were too vague for the researchers to classify as assimilation or accommodation. We accounted for these cases by including an ambiguous category. Found in Appendix 4, we provide a codebook detailing our analytical criteria of mechanisms with corresponding examples.

Ensuring Trustworthiness

We follow Lincoln and Guba's (1986) evaluative criteria to increase the trustworthiness of our qualitative analysis. On credibility, the first and second authors conferred weekly to refine and reflect on the theories and codes. The first author also collaborated with two undergraduate researchers, one of whom was involved in the first coding phase while the other in the second coding phase. Weekly research meetings consisted of gradual calibrations wherein the first author and the undergraduate researchers discussed and reflected on emergent discrepancies, planned future courses of action, and created a mutually agreed upon codebook. To test the codebook's robustness, the first author and the undergraduate researchers independently coded 10% of the data, a comparison that resulted in an interrater agreement of 85% and 91% for the first and second phases, respectively. On transferability, our analysis is informed by the findings and suggestions of situating literature and is presented as a thick description (Geertz, 2008). On dependability, the final categories (e.g., assimilation, accommodation, and ambiguous) were deemed theoretically saturated as they accounted for the similarities and differences within and among themselves.

Finally, on confirmability, we engage in reflexivity by unpacking the influences between the researcher and the phenomenon being studied (Probst and Berenson, 2014). Because reflexivity entails mindfully considering one's role to the context and vice versa (Longhofer and Floersch, 2012), we consider our positionalities as both professional developers and researchers of secondary teachers. The first and second author helped design and implement the VCI. Coupled with our experiences as both pre- and in-service teacher educators—in addition to the second author having been a former in-service secondary chemistry teacher herself—we purpose our subjectivities as a strength to perceive subtle differences within VCI reflections. However, we may possess innate lenses that preferentially seeks conditions for PCC. We as researchers chose to proceed cautiously and strategically. One example includes VCI teachers' imprecision in language. Intended meaning may at times be difficult to ascertain. The research team dialectically considered various lines of analyses and meticulously configured ideas into what eventually became finalized codebooks. Furthermore, we present our results not as evidence showcasing the extent of the VCI's effectiveness but as a collection of insights with the potential of broadening current understanding of secondary chemistry teacher learning.

Results and Discussion

Precursors for Pedagogical Conceptual Change

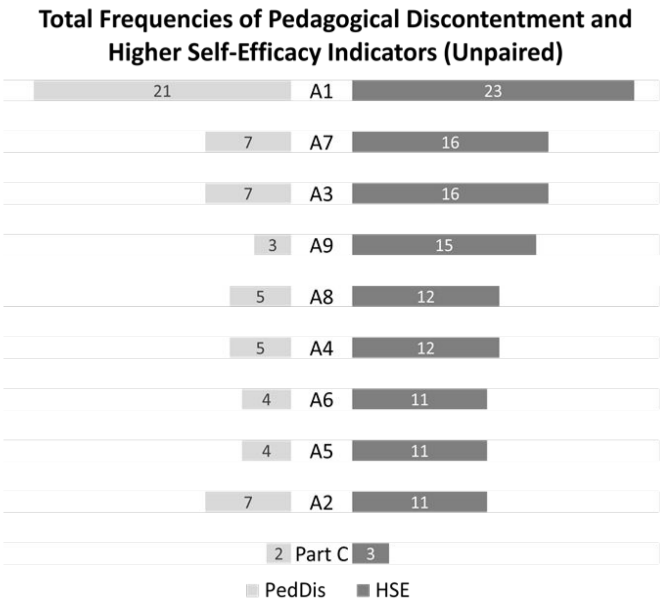


Fig 4. Total counts of Pedagogical Discontentment and Higher Self-Efficacy indicators throughout the VCI final reflections, organised in descending order from greatest Higher Self-Efficacy frequency to least.

PedDis and HSE indicators among the final reflections were totaled prior to dyad assembly (Fig. 4). Frequencies of HSE-coded excerpts are fairly uniform, with Part A1 having slightly more and Part C having the fewest. Part A1 also instigated the most instances of PedDis. The remaining learning outcomes and Part C are largely similar in terms of total PedDis count. We notice that throughout Parts A1-A9 and Part C, there are more statements coded for HSE relative to those for PedDis. Our results reiterate a key position asserted by Southerland *et al.* (2011a): understanding teacher learning requires more than a focus on self-efficacy. Analyzing both PedDis and HSE provides a more in-depth understanding of the precursors for PCC. The lower PedDis frequencies could stem from VCI teachers not being accustomed to reflecting on past/current CTIs. More explicit instructions and additional facilitation may be required to focus teachers' reflections on the alignment (or lack thereof) between their own CTIs and those of reform-based instruction.

Fig. 5 shows the prevalence of PedDis-HSE dyads among both cohorts of VCI teachers. Because one VCI teacher may have more dyads relative to another, we report the number of unique VCI teachers with at least one dyad for each reflection prompt. Percentages on the *y*-axis are based on the original sample of 35 VCI teachers.

Parts A1 and A7 have the highest percentages of unique teachers, but they only account for 37% and 20% of the sample, respectively. The remaining reflection prompts all have lower percentages. Only 14% of VCI teachers have both PedDis and HSE for Parts A2-A8, 11% for Parts A4-A6, 9% for Part A9, and 6% for Part C. In summary, VCI teachers with HSE are, to some extent, expressing PedDis in response to all VCI learning outcomes. Relatively similar percentages make discerning noteworthy differences in PedDis challenging.

Nevertheless, CTIs related to Parts A1 and A7 may be useful for surfacing precursors for PCC. We first present Part A1, which is related to Johnstone's triangle, by using an excerpt from Teacher 201's reflection on instructional practice.

Teacher 201: "*I often only address two of the three domains of the triangle, focusing only on the macroscopic and submicroscopic or on the macroscopic and symbolic domains. I can think of several topics where intentionally incorporating all three domains will support student understanding of the chemistry concepts (types of chemical reactions, stoichiometry, concentration are just a few).*"

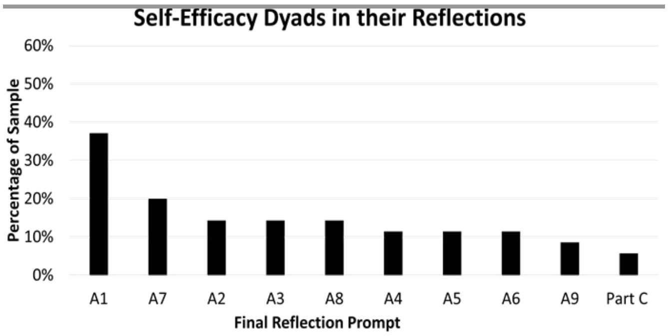


Fig. 5 Percentages of VisChem Institute teachers who expressed both Pedagogical Discontentment and Higher Self-Efficacy for each reflection prompt, organised in descending order of highest sample prevalence to lowest.

The first portion underscores Teacher 201's awareness of previous CTIs. Having *only* addressed two of the three representational levels at a time, what seemed formerly acceptable is now recognized by Teacher 201 as an area for improvement. In other words, Teacher 201 experiences PedDis for not addressing all three vertices of Johnstone's triangle simultaneously. The end of the reflection more likely signifies HSE given 201's comment to "intentionally incorporate[e] all three domains." The feasibility for future CTI implementation is reinforced by 201's additional identification of appropriate chemistry topics. Teacher 201's HSE is more strongly evidenced because of the initial declarative statement ("I can think") and that considerations of various curricular entry points to inject VCI CTIs have begun.

Part A1 generating the most PedDis and HSE is surprising because the three representational levels are so ubiquitous in chemistry education research (Talanquer, 2011). Then again, we as a field may be overestimating the extent that Johnstone's triangle is embedded in chemistry teaching. Popova and Jones (2021) interviewed chemistry instructors from different US universities and found that none had mentioned the interconnections of the macroscopic, symbolic, and submicroscopic. Wu and Yezierski (2022a) documented instances of secondary teachers over-emphasizing symbolic heuristics in lieu of particulate interactions. These observations may again reflect what Woodbury and Gess-Newsome's (2002) "change without difference." Despite decades of research with Johnstone's triangle, uptake in US chemistry instruction can still be improved.

Part A7 addresses evidence, explanations, and models (i.e., storyboards) within the overarching narrative of molecular processes. Part A7 as a VCI learning outcome references *Practice Six: Constructing Explanations* of the NGSS. The National Research Council (2013, p. 52) states that students must create "logical coherent explanations of phenomena that incorporate their current understand of science, or a model that

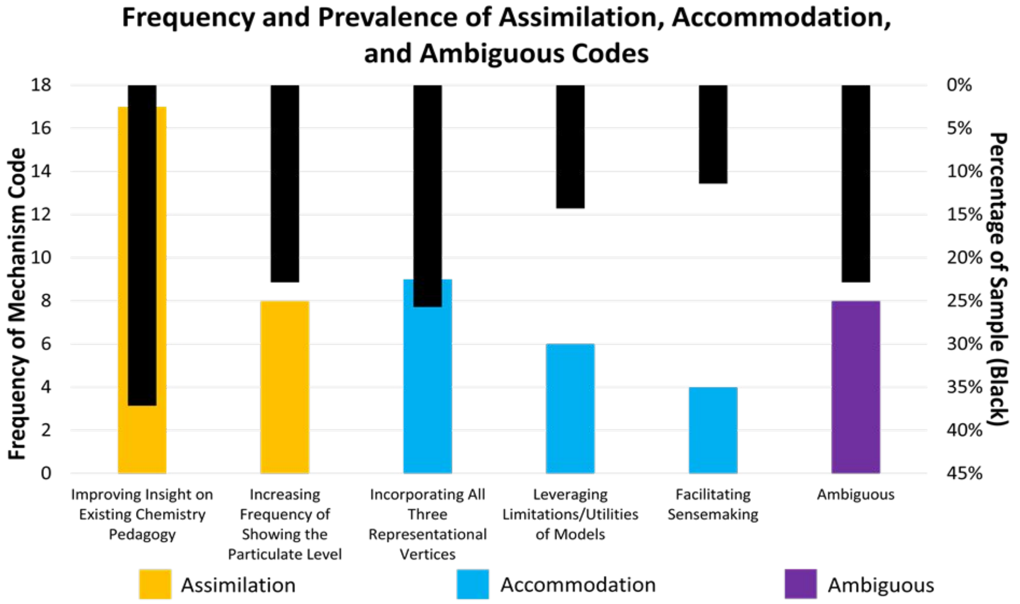


Fig. 6 Frequency and prevalence of mechanism codes. Assimilation, accommodation, and ambiguous categories are color-coded respectively. Percentages of sample is reported on the right-hand axis in reverse order (ascending from top to bottom).

represents it, and are consistent with available evidence." The key difference is Part A7's focus on molecular processes as the groundwork for students' chemistry understanding, a feature that secondary chemistry instructors may have neglected as shown with Teacher 102's reflection.

Teacher 102: "*I do facilitate class discussions when lecturing and have done many narratives (historical chemistry) but I never thought of using narrative for molecular processes. I will from now on because when I use narrative to teach concepts the students (and I) are more engaged.*"

Teacher 102 states previous CTIs, particularly those that "facilitate discussions" regarding "historical chemistry." The phrases, "never thought of using narrative for molecular processes" and "more engaged" are compelling. Admitting that molecular processes as a narrative had not crossed 102's mind, followed by the intention to remediate ("will from now on"), suggests the emergence of PedDis. This may be due to increases in 102's own chemistry teaching expectations as well-designed narratives using the particulate level can be effective for students' active learning (de Souza and Kasseboehmer, 2022). Despite studies stressing the teaching of molecular-level entities and their roles in causal mechanisms (Cooper *et al.*, 2017; Crandell *et al.*, 2020), chemistry instruction (in the case of Teacher 102) has not yet realized this ideal. One reason could be secondary teachers having alternative ontologies of evidence, explanation, and models that detract students away from molecular-level processes (Wu and Yezierski, 2022a). Foregrounding atomic/molecular behavior as the threads that weave evidence, explanations, and models of chemistry appear propitious for rousing PCC.

Mechanisms of PCC

We shift our account of our analyses to the mechanisms of PCC. In Fig. 6, we report the frequency of PedDis-HSE dyads for assimilation, accommodation, and ambiguous categories. The prevalence is shown by the number of unique VCI teachers per category, conveyed as percentages of our original sample of 35 VCI teachers. We note that VCI teachers have instances of assimilation, accommodation, ambiguous, or a combination of all three. Although some teachers have more PedDis-HSE dyads than others, the number of dyads across unique teachers per category is fairly similar. For additional delineation, Fig. 7 shows all VCI teachers organized into different categories to gauge the ways they may (or may not) be signifying PCC. More teachers exhibited assimilation (n = 11) than accommodation (n = 6) in their reflections. There are also six VCI teachers who were coded for both instances of assimilation and accommodation. Only three VCI teachers had PedDis-HSE dyads that were coded strictly as ambiguous while nine teachers were not coded at all. Because assimilation is identified among more VCI teachers, our findings corroborate with the notions that assimilation is the first stage of conceptual change (Posner *et al.*, 1982) and that teachers assimilate before they accommodate reform-based instruction (Dolfing *et al.*, 2020).

We present our results by delving into categories of assimilation, followed by categories of accommodation. Analysis of PedDis-HSE dyads coded as ambiguous, in addition to the reflections that were not ascribed with any codes, are not presented as both do not pertain to PCC (Fig. 6). However, ambiguous excerpts are included in Appendix 4 for additional reference.

We identified two assimilation categories (Fig. 6). The first, *Improving Insight on Existing Chemistry Pedagogy* (17 dyads, 37% of sample) is shown in Teacher 119's response.

Teacher 119: "*I had seen the triplet before but after this institute, I have a better understanding of how to use and teach it on a daily basis. Using the VisChem Approach will help me accomplish this.*"

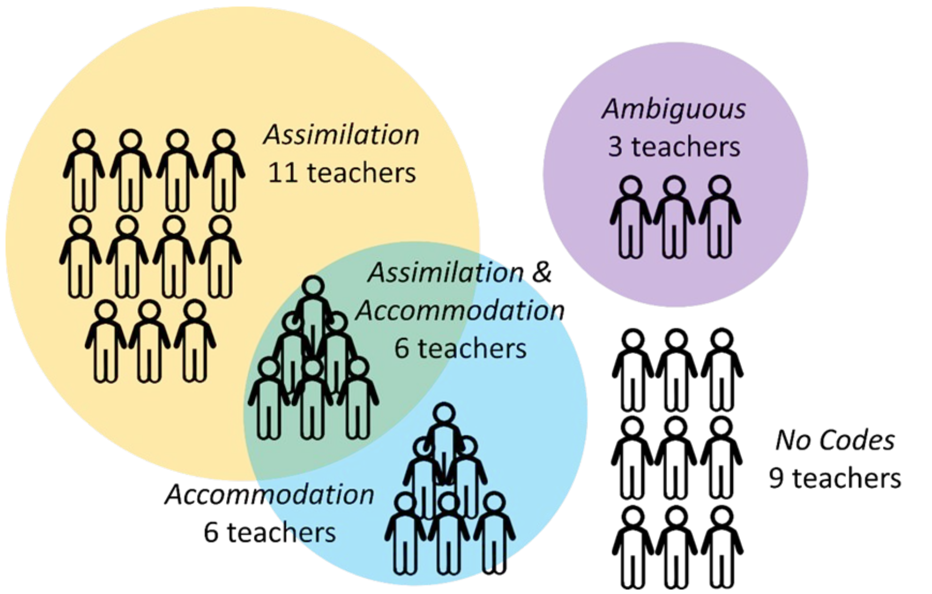


Fig. 7 VisChem Institute teachers sorted by their reflections having codes in assimilation and/or accommodation, just ambiguous, and no codes categories.

Teacher 119, like other VCI teachers, had previously "seen the triplet before" which indicates that what was learned during the VCI was something familiar. Although "a better understanding" of Johnstone's triangle may indicate accommodation, the phrase, "teach it on a daily basis" indicates otherwise. Teacher 119 has learned more ways of teaching with the three representational levels, thereby enhancing 119's current repertoire of chemistry instruction. Because Teacher 119 does not find it salient to describe new ways of using Johnstone's triangle (e.g., informed by PedChemSense), original CTIs are likely maintained via assimilation. What Teacher 119 likely acquired was a better understanding of *when* to implement the VisChem Approach as opposed to ways of configuring CTIs to best fit the VisChem Approach.

Instances in which VCI teachers identify avenues to improve CTIs that are already being enacted are more pinpointed in the second category *Increasing Frequency of Showing the Particulate Level* (8 dyads, 23% of sample). For example, Teacher 111 writes about the prior and future use of particle-level diagrams.

Teacher 111: "*Even reflecting on the first learning outcome, one in which I said I absolutely do and feel comfortable with in the classroom, my understanding now of how to appropriately use a particulate level diagram with my students has drastically changed. The sheer number of my particulate model sharing has to increase in my future teaching.*"

Juxtaposing "I said I absolutely do and feel comfortable" and "drastically changed" might imply accommodation of PedChemSense at a glance. However, the determination to increase "the sheer number of [111's] particulate model sharing" enables an alternative interpretation. First, the goal of supplementing more opportunities of student engagement with the particulate level parallels *Improving Insights on Existing Chemistry Pedagogy*. Existing CTIs appear stable as there are no indications of 111 dramatically changing anything other than the frequency of teaching with particulate models. Second, there may not have been enough PedDis to initiate accommodation of PedChemSense. It is likely that Teacher 111 already possesses some reform-based CTIs (e.g., attention to the particulate level) similar to how Teacher 119 had previously seen Johnstone's triangle. Given PD programs that may commonly assume participants entering with unreformed practice and leaving with reformed practice (e.g., Abell and Sevian, 2021; Blonder *et al*., 2013), innovative ways to elicit PedDis for chemistry teachers who fit somewhere in the middle of this dichotomy need to be devised.

We now switch to accommodation by analysing responses with respect to PedChemSense's three constructs: (1) Johnstone's triangle, (2) the models *for* perspective, and (3) sensemaking with molecular-level animations (Fig. 6). Shown with Teacher 202, *Incorporating All Three Representational Vertices* (9 dyads, 26% of sample) consisted of VCI teachers realizing a missing component in their chemistry teaching.

Teacher 202: "*In the past, I have tried to tie together macroscopic phenomena (labs and demos) with symbolic representations, while sprinkling in the math. I have almost completely ignored the particulate level or quickly showed an illustration before moving on. The VCI has completely changed my teaching game and I can now confidently include the missing puzzle piece—particulate level drawings.*"

Teacher 202's accommodation is evidenced by the mentioning of the "missing puzzle piece." Continuing this analogy, it appears that CTIs have been re-arranged. Instances in which 202 realizes avenues for improvement include the mentioning of how the particulate level may have been "completely ignored" or how a representation was "quickly show[n]" to students. Coupled with confidence in enacting reform-based CTIs for the future, we surmise that 202 is poised for PCC. The excerpt, "VCI has completely changed my teaching game," further reinforces the extensive shift in current CTIs to accommodate reform-based CTIs. Introducing the particulate level into a chemistry classroom that has only experienced "macroscopic phenomena" and "symbolic representations" can yield a pronounced difference in terms of both short-term (Ling *et al*., 2021) and long-term student learning outcomes (Stieff, 2019). Accommodating PedChemSense in this manner can therefore be conducive for supporting students' chemistry understanding.

Leveraging Limitations/Utilities of Models (6 dyads, 14% of sample) coincides with the models *for* perspective of PedChemSense. Teacher 206 best exemplifies this accommodation mechanism in the discussion of various models for chemistry instruction.

Teacher 206: "*I haven't used the space filling model in drawing before and now see the value in representing the interaction between electron clouds. Although ball and stick models still have their place in instruction, they can add to student misconceptions and I will incorporate the space filling models more in my class and only strategically use ball and stick representations in the future.*"

"Value," "have their place," and "strategically" signify accommodation. Unlike the aforementioned assimilation examples, 206's response suggests a fundamental change in the ideas about the nature of models. CTIs now resemble the models *for* perspective wherein contextual utility informs chemistry teaching and learning. Teacher 206's mentioning of "the interaction between electron clouds" likely indicates a realization that space-filling models can enhance students' ideas about molecular processes. Noting how certain chemistry models can "add to student misconceptions," as other studies have shown (e.g., Luxford and Bretz, 2014), points to an awareness that models can be counterproductive. Finally, Teacher 206's resolve to use multiple chemistry models demonstrates the understanding that models are only partial renderings of phenomena (Morrison and Morgan, 1999). Using different models that are related to the same chemical phenomenon can sustain a learning environment where students, as epistemic agents, can evaluate a model's function for refining their thinking (Passmore *et al*., 2014).

Facilitating Sensemaking (4 dyads, 4% of sample) is the most under-emphasized among accommodation processes. We noticed that when VCI teachers described what we interpreted as sensemaking, their thoughts would be associated with practices related to the cognitive learning model that informs the VisChem Approach (Tasker and Dalton, 2006). For example, this quotation shows the change in Teacher 116's CTIs when teaching with VisChem animations.

Teacher 116: "*Also now that I have learned about priming the filter, I think it will be something that I can easily incorporate into my teaching practice in order to point students towards key features without just telling them what the answer is but encouraging that exploration and discovery.*"

"Priming the [perception] filter" is a phrase that was repeatedly used throughout the VCI by both PD facilitators and VisChem teachers. Because dynamic visualizations, especially ones related to chemical processes, risk overwhelming the viewer's memory (Mayer *et al*., 2005; Lin and Wu, 2021), chemistry teachers must activate students' attention networks for effective learning. Teacher 116 interprets priming the filter as "point[ing] students towards key features." We find 116's response intriguing. While this practice may naturally result in a teacher dictating what students should do, 116 finds it salient to underscore "exploration and discovery" with the additional stipulation that one should not just give students the answer. We interpret 116's careful conciliation as an instance of accommodation. Although Teacher 116's excerpt may not explicate all tenets associated with sensemaking, it does exude the balancing act required to effectively direct students' perceptions (teacher-centered CTI) and promote investigation (student-centered CTI). Such cognizance is nevertheless progress towards reform-based instruction.

Summary

For RQ1, we identified that when prompted to describe CTIs and reflect on instructional change, VCI teachers with HSE express PedDis for all VCI learning outcomes. However, the frequency and variability of these responses are relatively low. Despite the filtered signal, A1 (Johnstone's triangle) and A7 (evidence, explanation, and models) appear to potentially be useful as a baseline to better understand the manifestation of PedDis for secondary chemistry teachers. For RQ2, we characterized and compared mechanisms of PCC, namely assimilation and accommodation of PedChemSense. On one hand, PCC could just involve VCI teachers' maintaining their original CTIs via improving insight on existing pedagogy and/or increasing frequency of the particulate level. On the other, PCC could consist of more considerable realizations such as effective chemistry teaching necessitating all three representational levels, the utility/limitations inherent in models, and the epistemology of sensemaking with dynamic visualizations of molecular processes. Our analyses assert that mechanisms of chemistry teacher change and the precursors that catalyze them are both nuanced and multifaceted.

Implications and Future Research

Our study expands current endeavours for both teacher educators and chemistry education researcher communities. From a practitioner perspective, our current conceptions of US secondary chemistry teaching may still be incipient. The voluminous research undertaken with respect to Johnstone's triangle (Edwards and Head, 2016; Seethaler *et al*., 2018; Towns *et al*., 2012) and evidence, explanations, and models (Dori *et al*., 2014; Ling *et al*., 2021; Stieff, 2019) is incongruent with the uptake of these reform-based CTIs. Perhaps this source of incoherence itself can be a starting point for envisioning future PD design. Heredia (2020) claims that opportunities for teachers to conceptually make sense of how their beliefs align with reform-based practices is beneficial for growth. We build upon this work by advising fellow professional developers to foreground the incongruity between chemistry education research and secondary teaching. Johnstone's triangle and evidence, explanations, and models may especially function as accessible PCC entry points for teachers to confront their current CTIs and identify concepts that can be modified.

The assimilation categories furthermore helped us realize that secondary chemistry teachers entering PD may reside along a spectrum of reform. In other words, the binary perspective of unreformed practice pre-PD and reformed practice post-PD, which some studies may implicitly assume (e.g., Abell and Sevian, 2021; Blonder *et al*., 2013), can be unproductive for supporting chemistry learning and teaching. How then does one stimulate PedDis for teachers who possess varying degrees of reform-based CTIs? One suggestion could be leveraging teachers' prior knowledge and experiences to adaptively tailor PD. Palmer (2003) reminds us that teachers need environments to attempt new strategies and to be risk-takers. PD facilitators in this manner can adjust to their teacher participants, identifying ways to effectively enable the precursors for and guide the mechanisms of PCC. We also suggest professional developers to account for secondary chemistry teachers' beliefs and own capacities for change (Balgopal, 2020). This type of PD improvisation can be conducive for strengthening teachers' resilience and agency throughout PCC (Wright *et al*., 2019).

From the researcher perspective, we problematize the circumstantial efficacy of the Science Teacher Pedagogical Discontentment (STPD) scale. While previous studies have effectively used the scale to evidence their claims (Adigozel *et al*., 2012; Enderle *et al*., 2014; Nadelson *et al*., 2012), we question its functionality when adapted to chemistry contexts. Because greater specificity confers enhanced predictive power (Naibert *et al*., 2021), the broadness of the STPD scale may be detrimental to its intended function. We call for the development of a new instrument that more directly corresponds with CTIs. In addition, using PedChemSense as inspiration for a chemistry-specific PedDis measure could be worthwhile. Because PedChemSense was originally theorized to assist teachers in planning their model-based instruction (Wu and Yezierski, 2022b), it tightly adheres to the teaching and learning of chemistry concepts. Having a valid and reliable instrument to measure PedDis among secondary chemistry teachers can help our community understand more meaningful ways of effecting PCC.

Finally, we consider how our work is theoretically generative. We prioritized PedDis and PCC which parallel conceptual dissatisfaction as one of the four prerequisites for conceptual change (Posner *et al*., 1999; Strike and Posner, 1992). Our findings also show that melding the conceptual change model with the *Search for Meaning of Reforms* framework (Luttenberg *et al*., 2013) when operationalizing PCC is informative for PD contexts. What remains underexplored is the other conditions for conceptual change. Namely, the ways that CTIs are intelligible, plausible, and fruitful can be re-theorized for a more comprehensive understanding of precursors for and mechanisms of PCC. We conjecture that expounding these additional components may be useful not just for secondary but also tertiary chemistry teaching and learning. There may be additional processes of warranting and sustaining uptake of reform-based CTIs for university-level chemistry instructors and graduate teaching staff that have yet to be fully conceptualized. Theorizing PCC in new directions can lead to additional guidelines informing how we as a research community can better support both the teaching and learning of chemistry.

Limitations

While some limitations have already been identified in Methods (e.g., the omission of toleration and distantiation as well as the potential imprecision in teachers' reflections), we acknowledge additional constraints and how they impact our study. The nature of teachers' reflections inherently restrict what claims we can make and how we evidence them. For example, because teacher reflections evidence their CTIs at a specific moment during the VCI, we cannot report how PCC actually occurs outside of the VCI. How teachers describe their CTIs in the reflection may be misaligned with what was done in the past and will be done in the future. This uncertainty can be better clarified through triangulation using additional evidence such as video recordings of teacher-student interactions, narratives of teachers' lesson plans, and student artefacts. Our research team is currently investigating such data sources with findings regarding VCI impact in various classrooms underway.

Our analyses also require careful interpretation due to our small sample size of VCI teachers and specificity to the VCI context. Nevertheless, our qualitative study overcomes the potential lack of transferability due to several reasons. Our conceptual framework is an extension of the conceptual change model: the root of various cognitive learning theories that are employed throughout chemistry education research. Our use of PedChemSense as an analytical framework enables further resonance with readers because of its ties with NGSS-aligned chemistry teaching and recommendations from the teacher education and chemistry education literature. Finally, the new questions that our study raises can provoke new and fruitful investigations and applications to advance teaching and learning of chemistry at both secondary and tertiary levels. While our study design may be limited in scope, the focus of our lens affords greater depth in re-conceptualizing chemistry teacher learning.

Conclusion

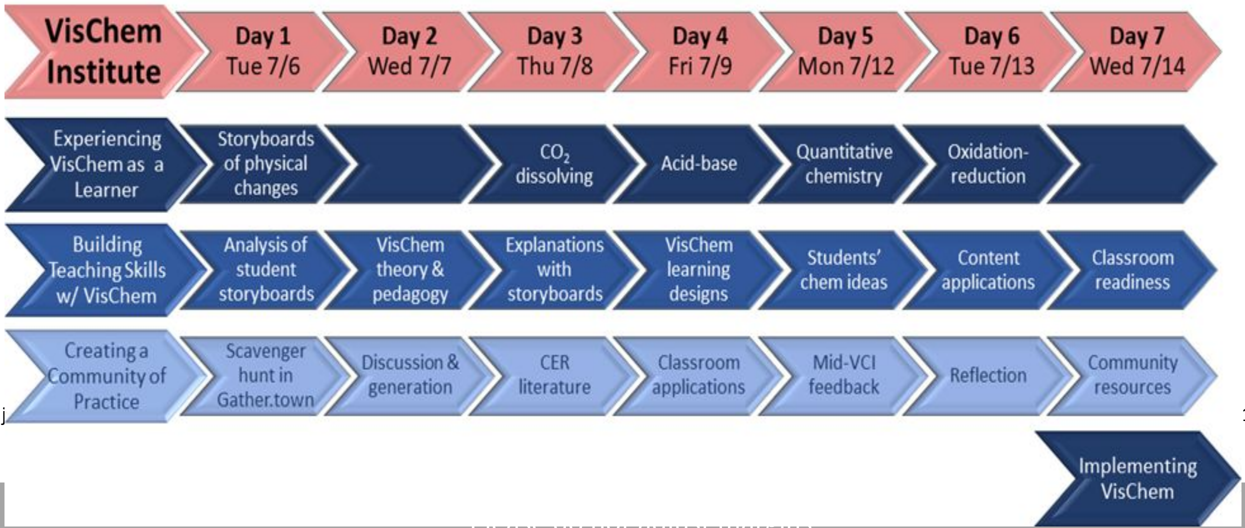
Pedagogical conceptual change is complex, requiring scrupulous attendance to both its precursors and mechanisms. Our first research question highlights how self-efficacy alone may not necessarily be most conducive for predicting teacher change. Pedagogical discontentment as an additional prerequisite provides a new dimension for understanding what prompts chemistry teachers to adjust their instructional practice. However, ways to trigger pedagogical discontentment for chemistry-specific instruction and for secondary chemistry teachers along the spectrum of reform-based instruction require additional investigation. We also portray the nuanced mechanisms of pedagogical conceptual change. Adoption of reform-based chemistry teaching ideas is a professional development goal that should not be established superficially. How new chemistry teaching concepts are assimilated and/or accommodated must also be considered when designing, implementing, and analyzing teacher education programs. Just as how orchestrating student learning of chemistry concepts involves intensive work, theorizing and enacting ways to support teachers' learning and teaching of chemistry simultaneously is just as demanding. Thus, we hope that our study serves as a platform for launching creative research that facilitates change *with* a difference.

Conflicts of interest

There are no conflicts to declare.

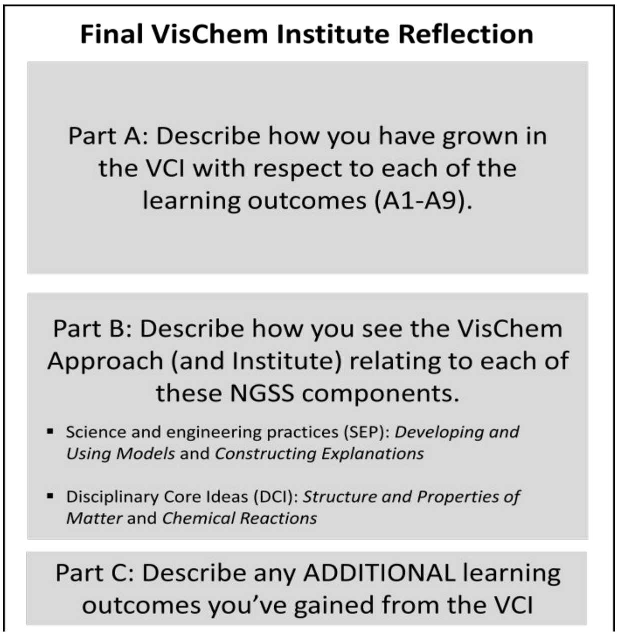
Appendix 1

Timeline of activities to support VisChem Institute 2021 teachers' learning of chemistry and of pedagogy.



ARTICLE

Appendix 2


Final VisChem Institute Reflection

Part A: Describe how you have grown in the VCI with respect to each of the learning outcomes (A1-A9).

Part B: Describe how you see the VisChem Approach (and Institute) relating to each of these NGSS components.

- Science and engineering practices (SEP): *Developing and Using Models* and *Constructing Explanations*
- Disciplinary Core Ideas (DCI): *Structure and Properties of Matter* and *Chemical Reactions*

Part C: Describe any ADDITIONAL learning outcomes you've gained from the VCI

Representation of the VisChem Institute assignment with corresponding instructions.

Appendix 3

Codebook of Phase One analysis with examples.

Phase One: Coding for *Precursors*			
Code	**Definition**	**Coded Examples**	**Un-coded Examples**
Higher Self-Efficacy (HSE)	Phrases/sentences that must include: (1) Future tense or present tense words suggesting future activities (e.g., I can, I am able, I will, I feel confident); (2) Explicit connection to their CTIs; (3) Clear indication about participant's ability to enact	I've always felt that if you can draw it, you know it - well, now I know it because I can draw it. - **Teacher 210** I have become significantly more proficient in visualizing and utilizing the particulate level to explain core chemistry concepts	I am not 100% confident using VisChem but I think it is important to use in the classroom. I will continue to work toward better understanding. - **Teacher 117** I think having routines and procedures in the classroom are super important for students to feel comfortable in class and take educational risks - **Teacher 214**

		and relating them to macroscopic phenomena. - **Teacher 203** I intend to model VCI slides in some way reflect the symbolic, macroscopic, and microscopic perspectives of these activities - **Teacher 101**	The work that the PD facilitator led us through over the course of this institute was very helpful in allowing us to see how to translate particle thinking into symbolic representations or mathematical relationships. - **Teacher 118**
Pedagogical Discontentment (PedDis)	Phrases/sentences that must include: (1) Past or present tense words referencing previous/current activities; (2) Clear indication of extent to dissatisfaction (e.g., negative-tone words and/or something the participant has learned or realized that could be better); (3) Explicit connection to their CTIs	I can honestly say that my teaching of particle-level diagrams in chemistry was basic and often incomplete. - **Teacher 210** I previously struggled with chemistry visualizations both as a chemistry student as well as a teacher, and instead focused on oversimplifications and mathematical models. - **Teacher 203** I have been thinking about the conversations and demos I already incorporate into the classroom and determining how I can make the conversation purposeful to bring in all corners of the triangle - **Teacher 101**	I now realize that much of my curriculum (not by me but dictated by non-chemists) needs reorganization and revision - **Teacher 109** This is a bit of a tough one because I think, at first at least, students will find it difficult to ignore spectator ions or water molecules in the background. - **Teacher 206** I have experience facilitating class discussions that help students to revise their understanding at a particle level. - **Teacher 213**

Appendix 4

Codebook of Phase Two analysis with examples.

Phase Two: Coding for *Mechanisms*			
Category	**Code**	**Definition**	**Coded Examples**
Assimilation	*Improving Insight on Existing Chemistry Pedagogy*	When a VCI teacher realizes aspects of new ideas that can boost (or contribute) to chemistry teaching practices (broadly) that they currently use/have used	Whereas I came into the Institute feeling relatively confident about my ability to draw, interpret, and teach particle diagramming, VisChem provided deeper insight into valuable topics such as particle spacing, interaction, and connections. As outlined in the learning outcomes, I feel more confident in my ability to connect particulate level diagrams to macroscopic and symbolic representation, including evaluating the limitations of the models in VisChem - **Teacher 106**

Category	Code	Definition	Coded Examples
			I think I will be better at generating questions to guide students while they are observing a phenomenon. I usually ask students to write down what they observed, but guided questions during the process will go a long way to understanding the content. - **Teacher 209**
	Increasing Frequency of Showing the Particulate Level	When a VCI teacher explicitly acknowledges use of the particulate level in past/current teaching practices but further notes a need for additional emphasis (e.g., repeated use in various chemistry topics)	I believe I will be okay with this aspect. I always have to create or modify my worksheets, labs, and etc. so I will be thinking about how I can integrate the molecular into the triangle. I believe I am proficient with the macroscopic and the symbolic. My lessons just need the submicroscopic to enhance and pull together the information that I will impart. - **Teacher 204** What I found helpful was finding ways to use particulate diagrams in several different topics in chemistry. I was initially a bit unsure how particulate level diagrams could be used throughout the chemistry curriculum, but I feel more confident doing so with the tools described in VisChem. - **Teacher 114**

Appendix 4 (cont.)

Phase Two: Coding for *Mechanisms*

Category	Code	Definition	Coded Examples
Accommodation	*Incorporating All Three Representational Vertices*	When a VCI teacher realizes aspects of new ideas that can boost (or contribute) to chemistry teaching practices (broadly) that they currently use/have used	Whereas I came into the Institute feeling relatively confident about my ability to draw, interpret, and teach particle diagramming, VisChem provided deeper insight into valuable topics such as particle spacing, interaction, and connections. As outlined in the learning outcomes, I feel more confident in my ability to connect particulate level diagrams to macroscopic and symbolic representation, including evaluating the limitations of the models in VisChem - **Teacher 106**

			I think I will be better at generating questions to guide students while they are observing a phenomenon. I usually ask students to write down what they observed, but guided questions during the process will go a long way to understanding the content. - **Teacher 209**
	Leveraging Limitations/Utilities of Models	When a VCI teacher explicitly acknowledges use of the particulate level in past/current teaching practices but further notes a need for additional emphasis (e.g., repeated use in various chemistry topics)	I believe I will be okay with this aspect. I always have to create or modify my worksheets, labs, and etc. so I will be thinking about how I can integrate the molecular into the triangle. I believe I am proficient with the macroscopic and the symbolic. My lessons just need the submicroscopic to enhance and pull together the information that I will impart. - **Teacher 204** What I found helpful was finding ways to use particulate diagrams in several different topics in chemistry. I was initially a bit unsure how particulate level diagrams could be used throughout the chemistry curriculum, but I feel more confident doing so with the tools described in VisChem. - **Teacher 114**
	Facilitating Sensemaking	When a VCI teacher realizes a new idea regarding the cognitive learning model about chemistry teaching that better facilitates students' sensemaking of chemistry phenomena (e.g., discovery, exploration, etc.)	I feel capable of doing this but recognize the value of thinking through these questions in advance so that I can support student sense-making instead of giving answers. - **Teacher 201** The paper and presentation on cognitive learning was a EUREKA moment for me. I was so taken by the information, I immediately forwarded my notes to my department chair and told him we needed to discuss these concepts in PLC for the science department. Being able to compartmentalize student ability, holding and processing with their ability for long term success is essential for being a successful teacher. I know that this information has me considering how much to put into a question, activity, or lab, where the task is challenging and purposeful but not too much as I don't want to lose my students. - **Teacher 101**

Appendix 4 (cont.)

Phase Two: Coding for *Mechanisms*			
Category	**Code**	**Definition**	**Coded Examples**
Ambiguous	*Ambiguous*	When a VCI teacher does not provide enough information regarding current and/or past teaching practices and/or when there is no explicit indication which suggests development of current teaching practices and/or change towards	I learned what key features to look at during this institute, which helped me tremendously, so I now feel comfortable being able to do that with my students. - **Teacher 102** The VCI facilitated discussions to encourage students to think deeply and critically about the animations and thoughtfully revise the original storyboards. Teaching the VisChem method will greatly shape how I would facilitate discussions in my own classroom - **Teacher 211**

	PedChemSense	I have learned a lot about competing attractions and how that "tug of war" shown in the animations can help students understand the WHY behind the activity series, solubility rules, and polar / non polar solvents. I will be able to help students to transfer their understanding to new chemical systems. - **Teacher 212** I know how to facilitate the use of VCI tools with my students and see the value of asking students to complete a pre storyboard to uncover their initial thinking of a chemical phenomenon. While I know the theory behind the approach, I need practice implementing this approach with my students. I appreciated the modelling done by the facilitators during this institute as I have been able to watch experts in the approach teach a lesson with the approach. - **Teacher 201**

Acknowledgements

The authors are forever grateful to Roy Tasker for serving as a consultant on the VisChem project as well as developing VisChem-related resources and pedagogy. We thank our participants for their time and commitment. Finally, we acknowledge Emilia Kamis and McKenna Miller for their contributions to the coding of the reflections. This material is based upon work supported by the US National Science Foundation under Grant No. DRL-1908121.

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