Investigating the mangle of teaching oxidation-reduction with the VisChem Approach: problematising symbolic traditions that undermine chemistry concept development

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ARTICLE

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Specific to the topic of oxidation-reduction (redox), teachers are obligated by the discipline to prioritise symbolic traditions such as writing equations, documenting oxidation states, and describing changes (*e.g.*, what undergoes oxidation/reduction). Although the chemistry education research community endorses connecting the vertices of Johnstone's triangle, how symbolic traditions undermine chemistry concept development, especially during lesson planning and teaching, is underexplored. To clarify this gap, we use the Mangle of Practice framework to unpack the clash between symbolic *vs*. particulate-focused instruction. We investigate teachers' (n = 3) co-planning and micro-teaching of a redox learning design at the VisChem Institute-2 using a narrative approach and video research methods. Our results show that the traditions of redox instruction are problematically entrenched in chemistry symbols. Mnemonics, the single replacement reaction scheme, and the written net ionic equation all constrain instruction focused on chemical mechanism and causality in various ways. We assert that the nature of redox knowledge in terms of what is worth teaching and learning must first be re-evaluated for reform-based efforts to succeed. Implications and suggestions for chemistry teaching and research at both secondary and tertiary levels are discussed.

Introduction

Johnstone's triangle and its representational models (macroscopic, symbolic, and submicroscopic or particulate) have persistently influenced chemistry education research throughout the years (Johnstone, 1982; Talanquer, 2011). One of its tenets assumes that comprehensive chemistry understanding demands seamless transitions from one level to another (Taber, 2013). As a result, incorporating representations that bridge the macroscopic world with chemical models is recommended for understanding chemical properties and behaviours (Talanquer, 2022). However, particulate-level ideas do not readily appeal to learners' senses (Johnstone, 1993). Johnstone (p. 704) adds that attempting to "sell the sub micro concepts" through "symbols, formulas, and equations" overloads learners' working memory, and re-examining the nature of the subject and its instruction is necessary for progress. Otherwise, learners may attend more superficially to the symbols instead of the particulate-level ideas they represent. While many chemistry topics may have unique symbolic and particulate tensions, this study specifically explores oxidation-reduction (hereafter redox) due to its reputation as one of the most challenging chemistry concepts to learn and teach (Österlund *et al.*, 2010).

A wealth of literature documents the various alternative conceptions associated with redox. Some include confusion between charge and oxidation states (Brandriet and Bretz, 2014a), attribution of macroscopic properties to particulate species (Jaber and BouJaoude, 2012: Kelly *et al.*, 2017; Rosenthal and Sanger, 2012), and electron transfer (Brandriet and Bretz, 2014b; Garnett and Treagust, 1992). Many of these ideas can be traced to an unproductive decoding of molecular information from chemistry symbols, an incongruity exacerbated by teachers' obligations to prioritise symbolic-level engagement. Early US reform efforts have recommended assisting students to define oxidation, assign oxidation states, apply rules for rapid identification, and write equations (Davis, 1990; Hall, 1929; Yalman, 1959; Goodstein, 1970). The *Teacher's Guide for Chemistry: An Experimental Science* (1963, p. 98), the instructor's manual used for *Chem Study*, states in the redox chapter that "the point to stress here is the meaning of the equation" that later "takes on a molecular meaning." Yuen and Lau (2022) recently offered a new method of balancing oxidation numbers that nevertheless appropriates symbolic algorithms as a benchmark for redox competency. Even the 2022 edition of *AP Chemistry: Course and Exam Description* defines essential redox knowledge as balancing equations from half reactions (Mui and Tully, 2022).

The longstanding prominence of the symbolic level, originally meant as shorthand, is problematic when superseding particulate-level explanations during redox instruction. Such a phenomenon is not unique to the US. For example, pre- and in-service German teachers delineated electron transfer as a key learning outcome but recalled more student difficulties with writing and balancing redox equations (Goes *et al.* 2020). Norwegian pre-service teachers' use of the particulate level was

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primarily descriptive, limited to the loss and gain of electrons akin to what the written equation would indicate (Jegstad *et al.*, 2022). Aydin *et al.* (2014) showed that Turkish, Indian, and American textbooks most frequently use written equations when presenting different types of chemical reactions—many of which are fundamentally redox. Although there is an overwhelming number of features to which one could attend (Hansen *et al.*, 2019), teachers treat redox symbolically by default, an echo of how it has historically been treated in the discipline.

While simultaneously addressing Johnstone's three vertices is endorsed by the chemistry education research community, *how* the symbolic detracts attention away from the particulate when explaining redox, especially during lesson planning and teaching, remains unclear. Further clarification is motivated by current US reform efforts such as *The Framework for K-12 Science Education* and the *Next Generation Science Standards* (NGSS). *Practice 2: Development and Using Models* asserts that learners must recognise limitations as models "bring certain features into focus while minimising or obscuring others" (National Research Council, 2012, p. 56). In addition, *Practice 6: Constructing Explanations* urges students to link "their knowledge of accepted scientific theory" to "models and evidence" (National Research Council, 2012, p. 69). These science practices and the topic of redox are especially relevant when contextualised in *Physical Sciences 1.B Chemical Reactions*. By grades 9-12, students should develop a particulate conceptualisation that consists of "collisions of molecules, rearrangement of atoms, and changes in energy" (NGSS, 2013, p. 41).

Complacency with instructional traditions that frontload symbols can enable the persistence of certain alternative conceptions and ultimately thwart development of redox concepts. We remind readers of Gabel *et al.*'s (1987, p. 695) statement: "the ability to represent matter at the particulate level […] is fundamental to the nature of chemistry itself." Unless we first identify how content-specific lesson planning and teaching prioritises symbols in place of concepts, suggestions to advance understanding of chemical mechanism (*i.e.*, sequence of events) and causality (*i.e.*, enthalpy and entropy) will be ineffectual (Loh and Subramaniam, 2017; Sevian and Talanquer, 2014). Our study thus unpacks the underexplored clash between symbolic *vs.* particulate-focused redox instruction. Spotlighting key events in video footage of our professional development (PD) program known as the VisChem Institute-2 (VCI-2), we provide a narrative of in-service secondary chemistry teachers' use of a pedagogy known as the VisChem Approach. We elaborate on how resistances, accommodations, and goals unique to redox arise in the teachers' co-planning and micro-teaching. Uncovering how pedagogical and curricular redox conventions are negotiated with current goals of reform-based teaching thus requires a cutting-edge framework. The framework needs to take into consideration practice and historical connections associated with the nature of science, teaching, and the chemistry discipline.

Theoretical Framework

We employ Pickering's (1994) Mangle of Practice (MoP) for exploring how ingrained customs direct present-day teaching and broaden deliberations for future practice. MoP allows us to interrogate the nature of redox instruction norms and explain why some teaching moves are preferred over others. We introduce key theoretical assumptions and thread an example for better comprehension. MoP first emphasises *situated practice*. Pickering (p. 111) claims that science does "not take place in isolation." For example, Otto Stern, a German-American physicist, probed space quantisation via a beam of silver atoms and a specific arrangement of magnets (Barad, 2007). Stern assumed that because orbiting electrons have discrete orientations, two separate traces should be displayed on a detector (pp. 162-163). The rationale of Stern's work becomes clearer when considering the tumultuous climate of the physics community in the 1920s. Stern's ambitions crystallised as a need to verify quantum physics as the new worldview, a notion that physicists could not readily accept given their ties to classical physics. This vignette exemplifies knowledge-as-practice being truly historical. Knowledge is "chained to particular communities" and does not "float free of its conditions of production (Pickering, 1994, p. 110).

Second, Pickering expands upon the connection of knowledge and community by underscoring *historicity*. Historicity is defined as the relationality with past knowledge, dismantling the separation of individuals from objects and people from sociocultural contexts (Stewart, 2016). Instead, historicity posits that people, objects, and culture are interpreted *via* their relationships (Hirsh and Stewart, 2005), similarly to how teachers and chemistry symbols (*e.g.*, oxidation states and balanced equations) are seemingly intertwined during redox instruction. Revisiting Stern, his experiment required not only the expertise of Walther Gerlach but also a flash of serendipity. After consecutive failures to visualise silver atoms, it was only until a combination of Gerlach's relative impoverishment, his habit of smoking cheap cigars, and the resultant sulphur lingering on his breath did he discern hints of the beam as silver sulphide (Barad, 2007). Researchers using historicity thus contemplate mutually constitutive connections (*e.g.*, economics, a cigar with high sulphur content, the atomic beam apparatus, and the scientist) as past, present, and future practices intersect (Ohnuki-Tierney, 1990; Wagner, 1986).

Finally, Pickering showcases *resistances*, *accommodations*, and *goals* as interrelated constructs. Stern and Gerlach were unable to visualise a split beam (Barad, 2007). They—like teachers taken aback by their students' lower-than-expected test scores—had encountered a resistance wherein the paradigm shift that Stern had wanted had not been ushered. Accordingly, Pickering (p. 112) refers to resistances as "obstacles on the path to some goal" such that the creation of new associations fails, and local knowledge and practices are disrupted. Overcoming resistances necessitates the search for accommodations, defined as "the revision of open-ended modelling sequences, the exploration of new directions" (p. 112).

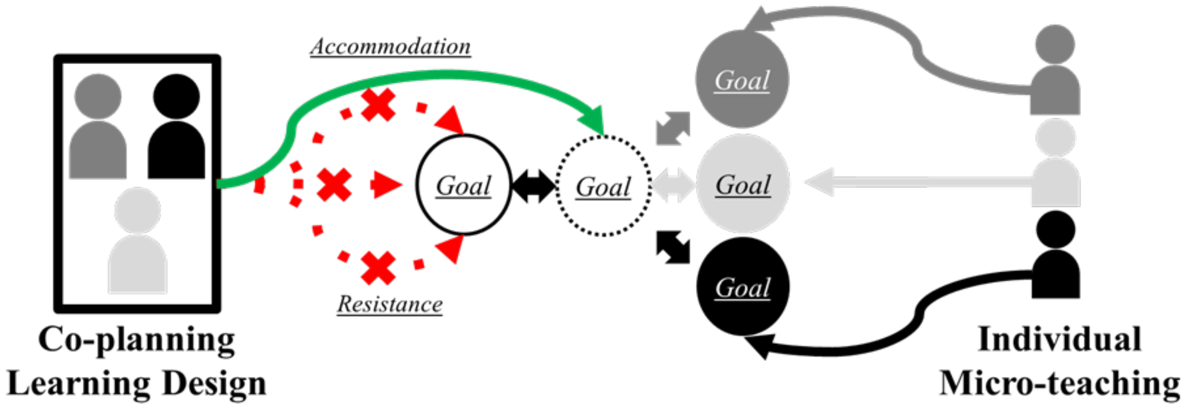

Fig. 1 Contextualising Mangle of Practice where we focus on VCI-2 teachers' resistance (red dashed arrow), accommodation (green solid arrow), and goal modification (solid to dashed circle) during co-planning as well as individual accommodation and goal modification during the micro-teaching.

It is essential to note that *accommodation* is operationalised for this study in MoP and in a manner dissimilar to the role of accommodation found within the conceptual change model (Strike and Posner, 1992) or in pedagogical conceptual change (Wu and Yezierski, 2022c).

For Stern and Gerlach, years of accommodation led to the round beam slit being replaced with a rectangular one (Barad, 2007). This back-and-forth competition between resistances and accommodations is what Pickering signifies as the mangle. It is the "genuinely emergent process that gives structure to the extension of scientific culture in the actual process of scientific research" (p. 112), precipitating new goals, understandings, and practices (Manz, 2015). Although Stern and Gerlach did not achieve their initial objective of spatial quantisation, they had succeeded in another: the demonstration of the electron's angular momentum.

MoP allows characterisation of teachers' planning and implementation of redox instruction in various ways. Similar to Manz's (2015) study, we observed the competition between resistances and accommodations to explain how teachers' redox-specific practices are tuned and stabilised. Using MoP also revealed obscured relationships among educational goals, school and disciplinary traditions, and the purpose of teaching, thereby elucidating how reforms (un)successfully merge with established traditions (Leden *et al.*, 2019). Finally, our study highlights not only resistances, accommodations, and goals but also performative agency via teacher authoring (Leden *et al.* 2019; Manz, 2015). Our intent is neither to criticise VCI-2 teachers nor speak to their detriment (Harshman and Yezierski, 2015; Schafer and Yezierski, 2021; Schafer *et al.*, 2022). We instead present how humans and materials engage in reciprocal relationships and co-create rich redox teaching narratives *via* historicity (Saari, 2019; Waltz, 2004).

For organisational and analytical purposes, we used MoP to leverage past redox teaching traditions for making sense of chemistry teachers' planning and teaching practice. We first describe VCI-2 teachers' resistances and accommodations with the goal of identifying a redox learning outcome during the co-planning component of our PD (see Fig. 1). We later elaborate on teachers' symbolic accommodations and modifications of their unique goals, evidenced by their individual micro-teaching with a particulate-level VisChem animation (see Fig. 1). Our interpretation of goals manifesting in the video data generates future pedagogical and curricular suggestions to maximise conceptual understanding for secondary and tertiary redox learning. We ask the following research questions.

1. During the co-planning of a learning design, what are VCI-2 teachers' resistances and accommodations with the goal of identifying a redox learning outcome?
2. In what ways do VCI-2 teachers symbolically accommodate and modify their goals during their individual micro-teaching with a particulate-level VisChem animation?

Methods

Research setting

We designated our practice of investigation as the VisChem Approach (see Fig. 2). This modelling-based pedagogy draws upon a cognitive learning model (Tasker and Dalton, 2006).

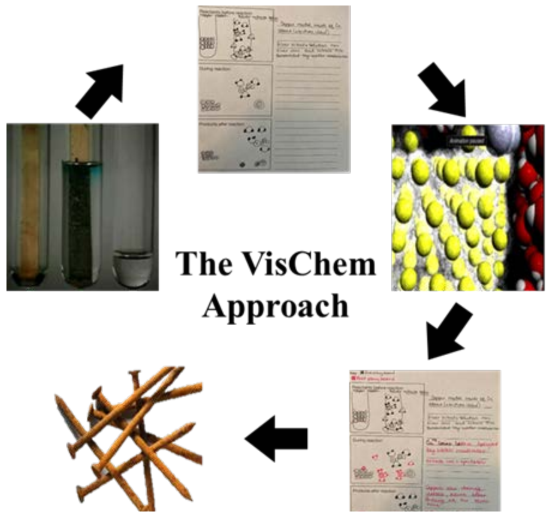

Fig. 2 The VisChem Approach, a reform-based pedagogy that uses macroscopic phenomena, student-generated storyboards, and molecular animations to facilitate transfer of understanding to new contexts.

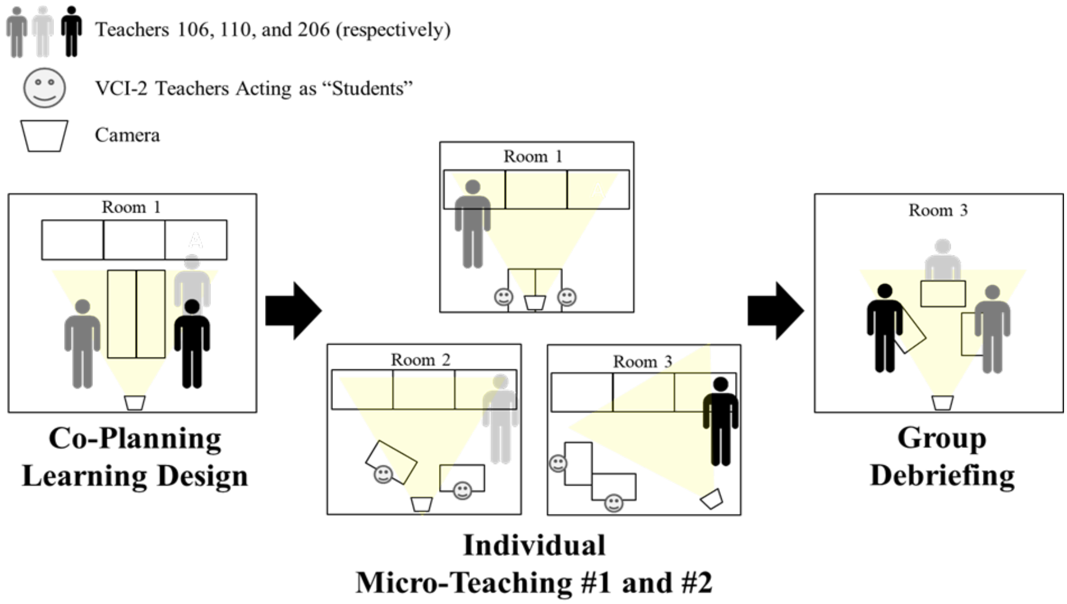

Fig. 3 Diagrams of co-planning, micro-teaching sessions, and group debriefing in which we indicate a legend of actors, camera placement, and relative positioning of actors and objects (whiteboards, projector screens, and tables).

Using dynamic, molecular-level animations and storyboards (drawings with written captions), the VisChem Approach comprises (1) introducing a macroscopic-level phenomenon to prime learners' perception filter, (2) prompting initial ideas *via* a pre-animation viewing storyboard, (3) facilitating engagement with a VisChem animation that reduces cognitive load, (4) creating a post-animation viewing storyboard after evaluation, discussion, and revision, and (5) fostering linkages between prior knowledge and new understanding. The VisChem Approach promotes student engagement with both Johnstone's triangle as well as *Practice 2: Development and Using Models* and *Practice 6: Constructing Explanations* (NGSS, 2013; National Research Council, 2012). Adhering to these reform efforts, the VisChem Approach aims to push learners beyond description and towards explanation of chemistry phenomena.

The VisChem Approach is a pedagogy that we modeled for participants at the VisChem Institute (VCI), a PD program for US in-service secondary chemistry teachers. Taking place in July, the VCI had been delivered in both remote (2020 and 2021) and in-person (2022) settings. The VCI maximises teachers' experiences as both learners of chemistry and of pedagogy (Wu *et al.*, 2021). Initially, VCI teachers as students storyboarded and viewed VisChem animations. VCI teachers afterwards learned about the cognitive learning model, read and discussed literature on students' alternative conceptions, and created their own learning designs (student-centred lesson plans that use the VisChem Approach). Near the VCI's conclusion, we focused on classroom readiness so that VCI teachers would be prepared to launch the VisChem Approach in their classrooms.

To optimise VisChem Approach implementation and strengthen teacher community, we hosted another in-person PD program known as the VisChem Institute-2 (VCI-2) in July 2022. Building upon participants' experiences, VCI-2 consisted of 28 PD hours (with additional time for completing pre-work/asynchronous work) interspersed throughout activities like lesson planning, instruction, reflection, and peer feedback. Unlike the sampling procedure used for the initial VCI (detailed in a forthcoming paper), purposive selection for the VCI-2 depended on two criteria. In March 2022, we inquired about whether student data had been collected and teacher interest for more PD. We asked the first question given our aims to broaden the student impact of VCI teachers who were already enacting the VisChem Approach. The second was motivated by the prospect of building rapport face-to-face, a feature that 2020 and 2021 cohorts were unable to experience given the pandemic. Of the 22 emails that were sent *via* Qualtrics, we received nine responses from VCI teachers who had submitted student data and were enthusiastic for more PD. All nine teachers were invited and eight (five from the 2020 cohort and three from the 2021 cohort) participated in the VCI-2.

Before arriving, VCI-2 teachers were assigned one of three chemistry topics (phase change of water, dissolution of sodium chloride, and redox). This study focuses on the redox group (n = 3). As part of their pre-work, Teachers 106 and 110 (2020 cohort) as well as Teacher 206 (2021 cohort) were instructed to create a learning design on the redox of solid copper with aqueous silver nitrate as it might fit into a types of reactions unit. Teachers 106, 110, and 206 have 10, 7, and 10 years of teaching experience, respectively. To simulate naturalistic classroom settings, they were notified that the scope of their learning design (pre-work) should encompass two 45-minute class periods with time in between to review student work and give feedback. During the VCI-2, Teachers 106, 110, and 206 synthesised a learning design using aspects from all three of their pre-work. Afterwards, all three teachers individually taught the co-planned learning design in a mock-classroom setting for fellow VCI-2 teachers acting as "students" (hereafter, referred to as "micro-teaching) and debriefed as a group.

Table 1 Total minutes of VCI-2 footage on Teachers 106, 110, and 206

VCI-2 Activities	VCI-2 Teachers by Code Number		
	106	110	206
Co-Planning	180 min.		
Micro-Teaching #1	45 min.	45 min.	45 min.
Micro-Teaching #2	45 min.	45 min.	45 min.
Group Debriefing	25 min.		
TOTAL	**475 min. (7 hours and 55 min.)**		

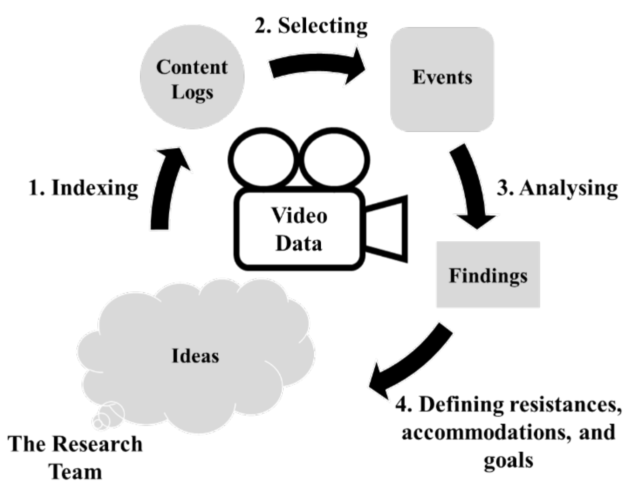

Fig. 4 Procedures of video research in which definitions of resistances, accommodations, and goals became more refined after rounds of indexing, selecting, and analysing.

Data Collection

We used video footage of the VCI-2 as our primary data source. Our choice to analyse recordings coincides with Pickering's (1994) assumptions that the mangle of resistances and accommodations manifest in real time as enacted practices. With a camera lens directed at Teachers 106, 110, and 206, we captured their co-planning of the redox learning design in Room 1, the micro-teaching in Rooms 1-3, and their group debriefing in Room 3 (see Fig. 3). During the second day of the VCI-2, Teachers 106, 110, and 206's joint-assembly of a redox learning design resulted in 180 minutes of lesson planning. On the third, day, Teachers 106, 110, and 206 taught the co-planning learning design for their peers in two 45-minute sessions, accumulating 270 minutes of recorded instruction (90 minutes per teacher). Finally, the group debriefing, which occurred shortly after Micro-Teaching #2, was approximately 25 minutes. In total, the data corpus for the redox group consists of 475 minutes (7 hours and 55 minutes) of video footage (see Table 1).

Given this study's scope and boundaries established by MoP, we narrowed our attention to the co-planning and micro-teaching portions as they provided better resolution for viewing how resistances, accommodations, and goals emerge in real-time. All protocols of data collection, analyses, and subsequent reporting had been reviewed and approved by the PD-hosting university's institutional review board.

Data Analyses

We followed specific video research principles, underused in chemistry education research, to guide our back-and-forth procedures (Derry *et al.* 2010). We report our findings using a novel narrative account of Teachers' 106, 110, and 206 resistances, accommodations, and goals during their co-planning and micro-teaching of a redox learning design.

Indexing the Data and Selecting Events. Using an inductive approach, we initially organised stories from minimally edited recordings into interconnected, digestible chunks using *Inqscribe*. Videos in their entirety were exhaustively scrutinised (Erickson, 2006). Matching the methods of other studies (*e.g.*, González *et al.*, 2016; Kahn, 2020; Wilmes and Siry, 2019), we viewed the videos in several ways. Indexing the data entailed watching the video frame-by-frame (Wilmes and Siry, 2018), muting the audio during playback (Erickson, 1982), attending to gestures and spatial positioning (Harrigan, 2005), and focusing on discourse (*i.e.*, distinctive ways of being in the world given the particular identities in specific groups) (Gee, 2008). Shown in Fig. 4, we generated content logs (descriptive notes, timings of specific moments, and initial thematic categorisations) for developing a quick sense of the data (Glaser, 1965; McNaughton, 2009).

These steps led to the selection of an *event* (see Fig. 4), defined as "a bounded series of actions and reactions that people make in response to each other at the level of face-to-face interaction" (Bloom *et al.*, 2005, p. 6). Having defined the practice as the VisChem Approach, we observed how Teachers 106, 110, and 206 determined a redox learning outcome during their co-planning and incorporated the VisChem animation as part of their enacted pedagogy during their micro-teaching. We also considered interactions between teacher and objects (*e.g.*, the whiteboard and the projector screen), given their mutually constitutive relationships per MoP. Selection then became deductive as the research team used the historicity of redox instruction to parse events from the video data and from each other. We relied on resistances and accommodations to inform our event selection during the co-planning session. However, we could only detect accommodations during the micro-teaching events because Teachers 106, 110, and 206 were not vocal and/or expressive about their pedagogical struggles during instruction. Events ranged from a minute to several minutes in length, depending on the starting-up and winding-down of resistances and/or accommodations.

Analysing Events and Defining Goals, Resistances, and Accommodations. Although the pre-work instructions stated, "create a learning design on the redox of solid copper with aqueous silver nitrate as it might fit into a types of reactions un", we specified the goal to be "identifying a redox learning outcome" for this study. The reason was two-fold. During the co-planning, the topic of a redox learning outcome produced fascinating conversations. We classified 106, 110, and 206's tensions, disagreements, and ambivalences as resistances. The decisions, resolutions, and modifications to the redox group's goal were then classified as accommodations. These events afforded scrutiny of symbolic features clashing with particulate redox concepts. Also, by setting the learning outcome as the baseline goal, we detected the ways 106, 110, and 206 author (*i.e.*, accommodate) their co-planned learning design in their micro-teaching. The resultant variation in teacher-specific goals allowed us to holistically determine how present findings of teaching redox (and their ties to the symbolic and particulate levels) are influenced by the past and can be configured for future implications.

Events were transcribed verbatim, with respect to Teachers 106, 110, and 206's discourse (*i.e.*, what they say and what they do) (Gee, 2008). Ethnographically attending to both verbal and non-verbal behaviours capitalised on the rich details within video data (Jordan and Henderson, 1995). Following video research principles by Derry *et al.* (2010), our analyses were cyclical (see Fig. 4). Definitions of resistances, accommodations, and goals became more precise as our ideas regarding the historicity of redox instruction were refined. Furthermore, we adopted what Erickson (2006) calls a tree-wise and forest-wise interpretation. Solely providing rich examples was not enough. Our play-by-play findings also showed typicality or atypicality with respect to the broader phenomena. By pinpointing redox-specific instances where the symbolic was juxtaposed with the particulate, we investigated how the VisChem Approach was renegotiated during teachers' co-planning and micro-teaching. Finalised events are provided (see Appendices 1-4).

Establishing Trustworthiness. We used Lincoln and Guba's (1986) evaluative criteria to ensure the trustworthiness of our work. On credibility, the research team met weekly to discuss and resolve competing interpretations as recommended by video research principles (Jordan and Henderson, 1995). This resulted in events that are robustly well-evidenced and theoretically salient to our framework. On transferability, our events were selected, analysed, and chronologically layered to convey a narratively thick description (Geertz, 1973). Mentioned previously in our tree-wise and forest-wise narrative approach (Erickson, 2006), we provided patterns consistent not only across Teachers 106, 110, and 206's redox instruction but also those that resonate with secondary and tertiary levels of redox instruction. On dependability, we applied video research methods whose rigor have consistently been demonstrated (González *et al*., 2016; Kahn, 2020; Wilmes and Siry, 2019).

On confirmability, we triangulated our findings with events from both the co-planning of the learning design and the micro-teaching. We also acknowledge our positionality. Our roles as teacher educators and researchers equip us with an insider perspective on VCI-situated meanings and practices. In addition, the first author attended the VCI-2 but the second author did not. We, however, took advantage of the second author's absence. Events were consequently chosen to both exemplify instances of resistance and accommodation and immerse readers as if they too were present at the VCI-2. The second author brings additional insights given her experiences supporting in-service secondary chemistry teachers, using the VisChem Approach, conducting observational research, and noticing symbolic trends in chemistry instruction. The first author is knowledgeable in video research methods, ensuring that undertaken procedures were congruous with the literature from the onset. Combining our mutual expertise in chemistry pedagogy, past and current reform efforts, and Johnstone's triangle, we purposed our subjectivities for generating insights that are novel and relevant to chemistry education research.

Results and discussion

The findings are presented through excerpts of the finalised events (additional context found in Appendices 1-4). Starting with the co-planning of a learning design, we showcase and discuss the mangle of resistance and accommodation per the historicity of redox instruction and its embedded learning outcomes. We focus on teachers' difficulties with the "five types of reactions" scheme and the potential conflation of the word, "charges." Afterwards, our analyses further trace the trajectories of teachers' symbolic accommodations observed in their individual micro-teaching with a particulate-level VisChem animation. We highlight three different instances in which chemistry symbols obstruct redox conceptual development.

Co-Planning a Learning Design

Fig. 5 shows Teachers 106, 110, and 206 sitting at a table with their personal computers, raptly sharing their teaching experiences, curriculum, and their classroom features during the co-planning of their learning design. Resistances emerged within the first five minutes, attesting to the difficulties of teaching redox. Teacher 110 mentioned having inadequate time to address net ionic equations and redox (see Appendix 1). Teacher 106 also confessed that teaching redox without the five types of reactions scheme is difficult (see Appendix 1). As teachers deliberated on the redox learning outcome for their learning designs approximately an hour into the co-planning

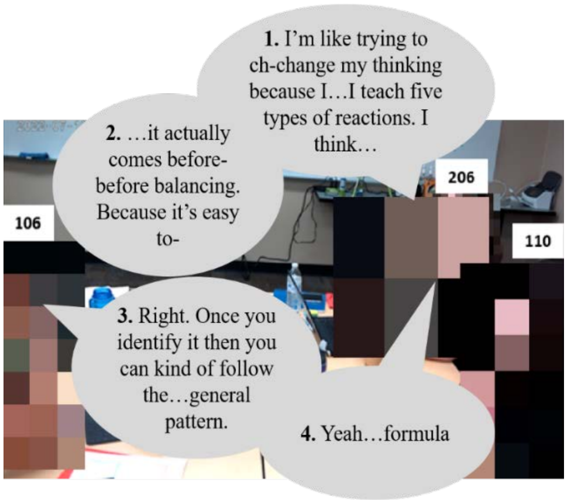

Fig. 5 The five types of reaction taxonomy as a resistance during the co-planning session. Text bubbles are sequentially numbered to indicate order of reading.

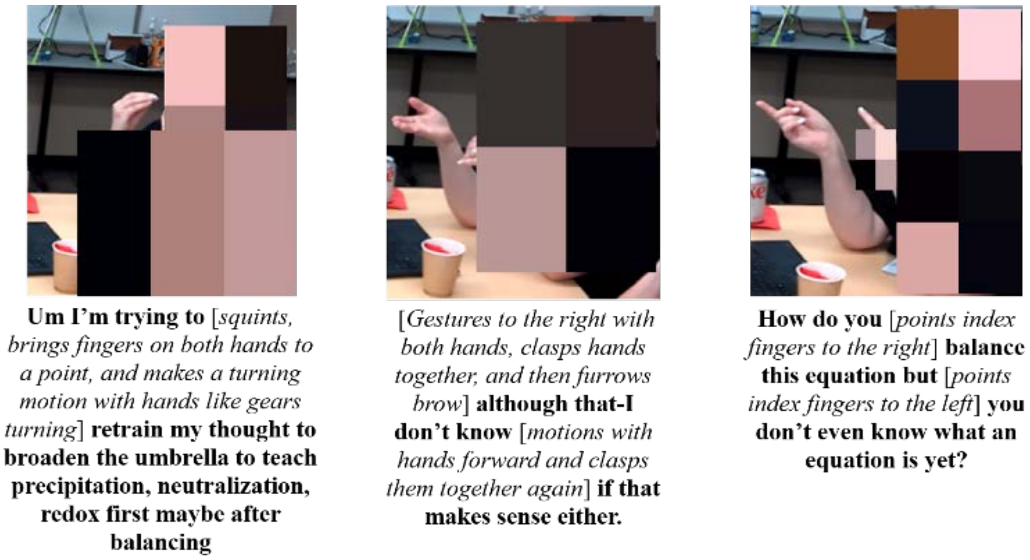

Fig. 6 Teacher 206 expressing uncertainty between teaching the five types of reactions before balancing and redox before balancing, even though neither proposition address chemical mechanism or causality.

session, Teacher 206 built upon 106 and 110's resistances and alluded to the symbolic level's ubiquity during redox instruction (see Fig. 5).

Teacher 206 stated using the five types of reactions, a taxonomy frequently used in chemistry education research (Jaber and BouJaoude, 2012; Shehab, 2021; Yan and Talanquer, 2015), and noted that it precedes balancing ("it actually comes balancing"). On the next turn, Teacher 106 affirmed what 206 had said, implying the benefits of teaching fives types of reactions first. The phrase, "you can kind of follow the general pattern" led to a synonym stated by 206: the "formula." While formula has multiple meanings, we understood formula to be the symbolic algorithms needed to decipher the five types of reactions for predicting products. Given the prevalence of this taxonomy, the assumption that patterns of symbols swapping locations in equations would help learners interpret chemical reactions is unsurprising.

Shortly afterwards, Teacher 206 elaborated on another resistance that resonated with Teachers 106 and 110. Teacher 206 considered teaching balancing chemical equations before addressing redox (Fig. 6). We interpretated the phrase, "retrain my thought" to indicate that this sequence is not business-as-usual. The gesture that looks like gears turning provided additional evidence of 206 actively attempting to accommodate this resistance. The inner conflict became more apparent with the furrowing of 206's eyebrows and the phrase, "I don't know if that makes sense either." We identified the question, "How do you balance this equation but you don't even know what an equation is yet?" as the key resistance. Teachers may presume that balancing requires initial familiarity with the concept of "equation." The debate on introducing the five types of reactions before balancing *vs.* teaching balancing before redox can be perplexing for many chemistry educators. However, *both* 206's pedagogical reasoning processes were symbolically oriented. There was no explicit mentioning of particulate-level concepts. This inclination for the symbolic may stem from learners' identifying the written formula *first* and mapping onto the redox reaction *afterwards* (Lu *et al.*, 2020). Had the particulate level been more apparent when identifying the learning outcome, this turmoil would not have been germane because chemical mechanism and/or causality are beyond what the written equation can feasibly convey.

After thirty minutes, the redox teachers accommodated by agreeing on a learning outcome (see Excerpt 1). Teacher 206

Excerpt 1. Teachers' accommodation of the redox learning outcome as the transfer of charges (bolded = utterances, italicised in brackets = gestures)

Line number	Speaker	Discourse
1	110	[*Crosses hand over chest*] **So they can identify the species and it's happening when they're** [*holds up hand with index and*
2		*thumb indicating a small space in between*] **bonded to something you know how** [*moves both hands in front in an alternating*
3		*circular motion, like arrows indicating movement in a single-replacement reaction*] **like how that changes *vs.* they're solid *vs.***
4		**when they're bonded** [*holds up both hands clasped together in a ball but then resumes previous alternating circular motion*]
5		**what's going on?**
6	206	**Maybe that's an SLO. Student will be able to…recognise the fact that** [*motions with left hand downward on the beat of every*
7		*following word*] **charges are transferred like** [*uses both hands—fingers extended and pointed down making a V-shape—to*
8		*make downward motion on the beat of every following word*] **like that's what makes redox.**
9	106	**Mmm…yup**
10	110	**OO! THERE! THERE! YOU GOT IT!**
11		[*claps*] **I think we got it.**
12	206	**That there's a** [*uses similar gesture with both hands to punctuate every following word*] **transfer of charges that occurs.**

Excerpt 2. Teacher 106's interactions with Student A (SA) and Student B (SB) regarding the tug of war (bolded = utterances, italicised in brackets = gestures)

Line number	Speaker	Discourse
13	106	**What** [*moves closer and gestures at projector screen with both hands*] **do you suppose these yellow spheres are?**
14	SA	**I think copper?**
15	106	**Copper, yep they're all kind of stationary** [*gestures hands towards project screen strongly*]. **What do you suppose** [*forms a*
16		*slightly incomplete circle by motioning with both hands*] **the fuzziness was? We talked about that yesterday**.
17	SB	**We said that's where there's electrons.**
18	106	**Electrons good. Remember: metals, when they're metallically bonded, they're** [*moves hands haphazardly across projector*
19		*screen, around the copper lattice in the VisChem animation*] **just sharing electrons in kind of this big sea of electrons. And**
20		**then the** [*points to silver ion in VisChem animation*] **grey spheres, what must those be then?**
21	SA	**They're the silver.**
22	106	**Silver! Good! So is silver** [*points to the silver ion in the VisChem animation*] **with the nitrate, like we said in our overall**
23		**molecular equation?**
24	SB	[*Shakes head*] **Mm mm.**
25	106	**No!** [*points to left portion of whiteboard*] **Remember: from our uh total ionic equation, it was separate. It was aqueous.**

suggested the transfer of charges (lines 6-8), as the movement of electrons is quintessentially redox ("like that's what makes redox"). This student learning outcome (SLO) was positively received by both 106 and 110 (lines 9-11). We were delighted that Teachers 106, 110, and 206 have surmounted their initial resistances and arrived at a particulate-level concept. This decision was likely spurred by the VisChem animation's depicting transfer of charges as the loss/gain of fuzzy electron clouds (Tasker and Dalton, 2006). However, there may be conflicting connotations of the word, "charges." On one hand, "charges" could correspond with electron clouds. On the other, "charges" could reference the plus and minus superscript symbols. The transfer of charges, situated in the latter context, would nevertheless be symbolic manipulation that simplify particulate-level interactions included in the VisChem animation (*e.g.*, the simultaneous loss/gain of electrons at *different* parts of the copper lattice or the *ratio* of two silver cations being reduced while one copper atom is oxidised). To clarify this ambiguity, we investigated the ways in which 106, 110, and 206 symbolically accommodated the goals during their micro-teaching with the particulate-level VisChem animation.

Teacher 106's Micro-Teaching: Description and Mnemonics

Teacher 106's micro-teaching in Room 1 was engaging, enthusiastic, and humorous. Teacher 106's fluid interactions with the other VCI-2 teachers in the student role demonstrated experience with not only the topic of redox but also its valuable connections to everyday examples such as batteries (Jegstad *et al.*, 2022). Despite the positive reception, we noticed chemistry symbols had affected 106's accommodation of the learning outcome. At the beginning of Micro-Teaching #2 (see Appendix 2), 106 responded to a student's thoughts about the tug of war, a VCI phrase that encapsulates the competing intermolecular forces among solvating water molecules, the silver cation, and the delocalised electrons on the copper lattice, all of which is shown in the VisChem animation.

Teacher 106 reacted to the tug of war comment by describing present chemical species (see Excerpt 2). Teacher 106 cued the student's attention to copper atoms (lines 15-16) and silver cations (line 20) by gesturing to the VisChem animation displayed on the projector screen. Teacher 106 surprisingly did not connect back to the tug of war comment that incited this conversation. Instead, 106 re-appropriated the VisChem Approach as a segue into definitions ("metallically bonded," line 18) and vocabulary ("sea of electrons," line 19), familiar terms that usually surface during redox instruction. Shown with 106's emphasis on definitions and vocabulary, chemistry teachers may be compelled to opt for description as opposed to explanation (Wu and Yezierski, 2022a). While there may be innumerable reasons, one possible source could be redox' longstanding ties to the symbolic level, evidenced in 106's next event.

Near the end of Micro-Teaching #2, Teacher 106 explained the VisChem animation in greater depth. While 106 did attend to the sequence of particulate-level interactions that led to the loss/gain of electrons, shown as movement of fuzzy clouds (see Appendix 2), 106 accommodated by abruptly transitioning into

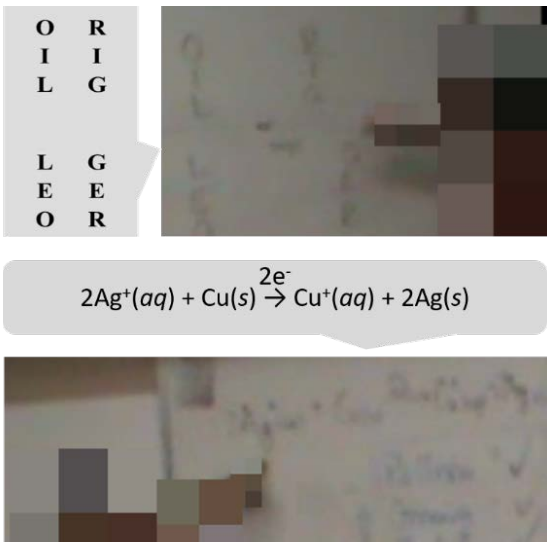

Fig. 7 Teacher 106 pointing to mnemonics and the net ionic equation. Text boxes are provided for greater clarity. Note that although Cu(*s*) and Cu^{+}(*s*) are written, 106 verbally instructs students to imagine as if 2Cu(*s*) and $2Cu^{2+}$(*aq*) were written instead.

what appears to be the goal of the redox learning design: mnemonics and the net ionic equation (shown in Fig. 7).

Mnemonics like OIL RIG and LEO GER are convenient for memorising oxidation is electron loss and reduction is electron gain. This delineation then transitions into the enduring practice of organising oxidation states (Levin, 1974), as demonstrated by 106's gestures to the net ionic equation written on the whiteboard. Oxidation state bookkeeping can be pedagogically disingenuous, implying the existence of chemical species with charge values that are not possible in nature (VanderWerf *et al.*, 1945; Sisler and VanderWerf, 1980). Yet the utility consistently outweighs the risk, rationalising 106's accommodation. Having gestured to the previously written mnemonics and equation on the whiteboard, Teacher 106 signalled the redox takeaway to be symbolic in nature. Charges as symbols swap left to right because of the transfer of electrons. We acknowledge that tracking electrons is indubitably important for redox, hence 106's inclusion of *two* mnemonics. We instead problematise how the goal of counting appeared more crucial than addressing how or why electron transfer occurs. Reform-based pedagogy that advances particulate-level understanding (*e.g.*, the VisChem Approach) may be re-appropriated as a descriptive transposition of the net ionic equation if symbolic customs of redox instruction are not examined and challenged.

Teacher 110's Micro-Teaching: Separation of Ions and "Kicking Out"

Despite having the same co-planned learning design, Teacher 110 added a subtle flair when implementing the VisChem Approach in Room 3. Teacher 110 actively encouraged sensemaking and discussion. Some teaching moves included recording what students had wondered about and looping back to these open-ended questions when appropriate. At 27 minutes into Micro-Teaching #2, 110 narrated the VisChem animation. Identification of chemical species, the sequence of events leading up to the transfer of electrons as fuzzy cloud movement, and the formation of a silver lattice atop a copper lattice were addressed in great depth (see Appendix 3). During this thorough orientation to the particulate level, we noticed a

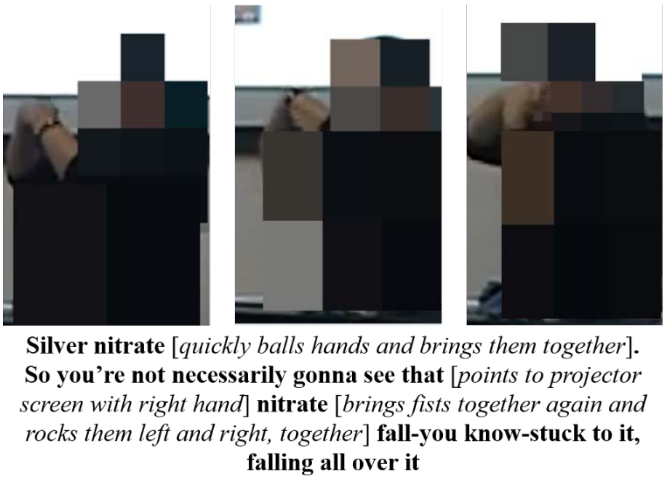

Fig. 8 Teacher 110 emphasizing to students that silver and nitrate ions do not stick together in aqueous solution through words and gesture.

moment of accommodation when 110 elaborated on the silver nitrate solution (see Fig. 8).

Teacher 110 emphasised that silver nitrate exists as dissociated ions in aqueous solution ("you're not necessarily gonna see that nitrate fall-you know-stuck to it"). Teacher 110's balling up the two fists and rocking them left and right represented what students should not be conceptualising. Teacher 110's gesture contrasted with the silver and nitrate ions depicted as discrete entities (each hydrated by bulk water molecules) in the VisChem animation. At the same time, 110 referenced molecular motion ("falling all over it"), appealing to the dynamic molecular level shown in the VisChem animation. With one performance, Teacher 110 conveyed information to facilitate student visualisation of both what *is* and *is not* scientifically accurate. Separation of ions in solution, especially in the context of redox, was widely reported to be an idea with which students struggle (Hansen *et al.*, 2019; Rosenthal and Sanger, 2012). Teacher 110 appropriately used the particulate level and the VisChem animation to help students confront a common alternative conception about ionic compounds dissolved in water.

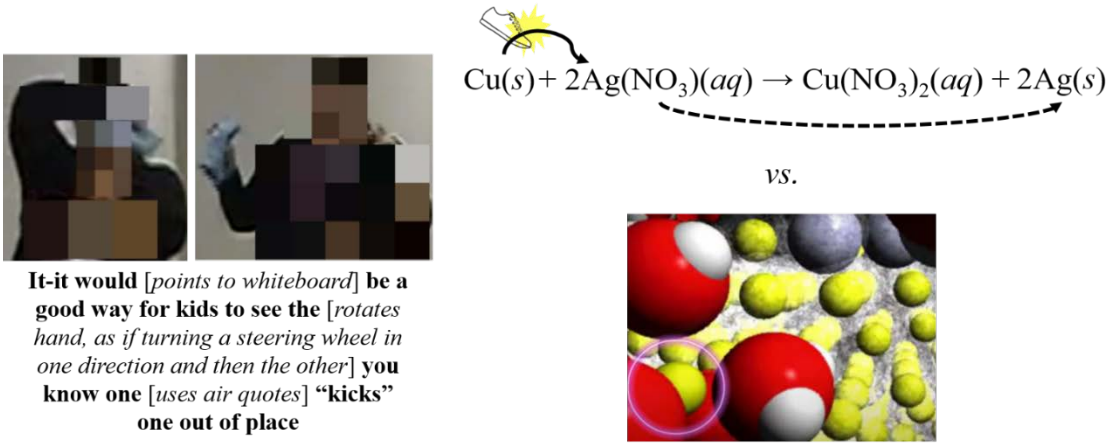

Fig. 9 Teacher 110 using the "kicking out" analogy with its corresponding visualisation as a written equation, contrasted with a screenshot of the VisChem animation showing copper(II) cation being solvated by water molecules and leaving the copper lattice (indicated by the pink circle).

Near Micro-Teaching #2's conclusion, Teacher 110 addressed the students now as teachers, mentioning some of the pedagogical rationales behind the redox instruction (see Fig. 9). Teacher 110 stated that presenting redox using the VisChem Approach would "be a good way for kids to see" how "one 'kicks' one out of place." This seemingly innocuous statement is deleterious for conceptual understanding. "Kicking" references the symbol Cu(*s*) replacing the Ag in $Ag(NO_3)$(*aq*) *via* a single replacement reaction (see Fig. 9). Teacher 110's waving of arms also mimicked the movement of Cu and Ag symbols within a chemical equation as opposed to metal atoms in a lattice or hydrated cations in solution in the VisChem animation. There are two reasons that this heuristic is alarming. First, "kicking" assumes that silver is "ejected" from the formula while copper takes its place. But the VisChem animation shows the opposite. Silver cations, after gaining electrons, are deposited on the copper lattice while copper atoms, after losing electrons, become copper (II) cations and enter solution. Second, this heuristic is more applicable if $Ag(NO_3)$(*aq*) is written together. The effort that Teacher 110 had expended to scaffold student understanding of ion separation may be for naught in light of this inconsistent information.

Considering that "kicking" was mentioned at the end of the learning design and when Teacher 110 spoke to the students as teachers, we fear that the single replacement reaction scheme may be more integral to the core of not only 110's but also other chemistry educators' pedagogy as well. While 110 addressed particulate-level phenomena, the bedrock atop which these ideas were constructed is symbolic. The single replacement reaction may nevertheless serve as an instructional backdrop, thereby sowing incongruities (*e.g.*, the lack of ion separation) that impede chemistry conceptual development. The goal of charge transfer is also vague. The "kicking" theme of the written equation occludes the plus and minus superscript symbols. As a result, any symbolic representation of a redox reaction, especially what is characterised by the single replacement reaction (rather than synthesis, decomposition, or combustion of hydrocarbons), is limited in its capability to explain the mechanism and causality of electron transfer. The goal of redox instruction consequently becomes mastering the stepwise procedure of symbolic manipulation on either side of the "yields" arrow in a chemical equation.

Teacher 206's Micro-Teaching: Exclusion of Species Not Explicitly Depicted in the Net Ionic Equation

In Room 2, Teacher 206 authored the co-planned learning design in certain ways, leaning more into the written molecular and net ionic equations. Concerns with time seemed more pronounced in 206's VisChem Approach implementation. This was demonstrated in 206's guidelines on how to storyboard the VisChem animation near the end of Micro-Teaching #1 (see Excerpt 3). Teacher 206 advised ignoring the nitrate ions (line 28) and bulk water molecules (lines 32-33). The pedagogical decision to disregard these chemical species was due to copper atoms in the lattice and silver cations in aqueous solution being perceived as the primary actors of redox (*i.e.*, "what we really care about"). Already, 206's attention to the net ionic equation has situated the presentation of redox concepts. These choices seemed justified by the symbolic treatment of the reaction; bulk water molecules are routinely replaced by the (*aq*) symbol and nitrates are "cancelled" out.

Teacher 206's instructions were pragmatically mindful of the time constraints that may hinder students from producing a quality storyboard ("we're not gonna draw four million waters"). At the same time, 206's symbolic accommodation also prepared students to understand the overwhelming scale of water molecules in an aqueous environment. Teacher 206 also pointed out that nitrates are present in the animation (line 30), and that omitting this species was strictly for simplification purposes (line 27). Cole *et al*. (2019) and Lin and Wu (2021) similarly used simplified redox animations that filter out the water molecules to help students convert particulate-level phenomena into balanced equations. Like 206, other chemistry teachers may have goals of streamlining redox instruction by using components of the net ionic equation as scaffolds for understanding.

Despite its tenure as a compass for informing redox instruction, we critique the net ionic equation because of its troublesome effects on redox conceptual understanding. Teacher 206 accommodated the VisChem animation by aligning its constituents with chemistry symbols at the beginning of Micro-Teaching #2. When the VisChem animation was shown, Teacher 206 mostly remained at the whiteboard (contrasted with 106 and 110 who moved closer to the projector screen). Rather than physically motioning at the VisChem animation, Teacher 206 verbally called out solid copper atoms/aqueous copper(II) cations and pointed to the equations on the whiteboard, anchoring the depicted particulate-level species to their symbolic counterparts. Teacher 206's accommodation of saving time re-emerged, stating that spectator ions were to be left out because they are "not actually participating in the production of formation of anything new" (Fig. 10).

The "formation of anything new" qualifying what should or should not be included is appropriate for a net ionic equation but inefficacious if the goal were to understand chemistry mechanism and causality. For example, students had expressed

Excerpt 3. Teacher's 206's instructions on storyboarding the VisChem animation with Student E (SE) (bolded = utterances, italicised in brackets = gestures)

Line Number	Speaker	Discourse
26	206	**Was there anything that maybe we could have like** [*moves hands slowly and haphazardly*]**...ignored not because it's not**
27		**there but maybe because it can simplify the illustrations a little bit?**
28	SE	**The nitrates.**
29	206	**Very good. We could've ignored the presence of the nitrates. Um we know that the nitrate is there. We're gonna see it**
30		**there when we kind of take a look at the animation. But when we go back to the idea of this net ionic equation, what we**
31		**really care about is what's happening between the copper-the solid copper** [*points at left side of the net ionic equation on*
32		*the whiteboard*] **and the silver ion. Um, so a lot of times when we sketch, we know there's a lot of water but we're not**
33		**gonna draw four million waters in our storyboard. So that would potentially be an option to minimise the muddiness.**

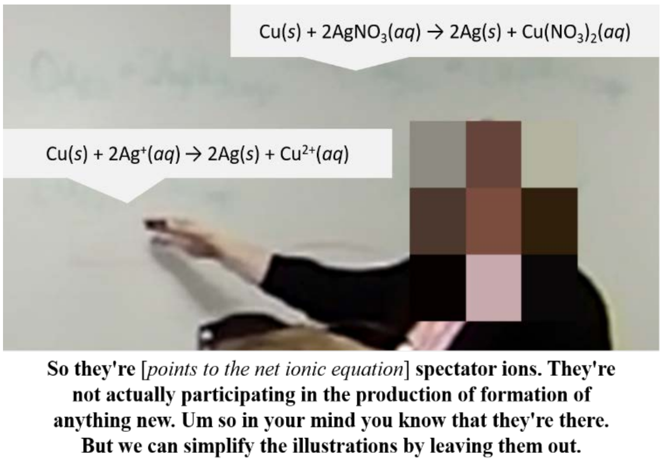

Fig. 10 Teacher 206 staying near the whiteboard when narrating the VisChem animation, pointing to the net ionic equation and advising students to ignore what is not explicitly written to simplify their storyboards. Text boxes are provided for greater clarity.

difficulty conceptualising the role of spectator ions as a driving force of redox (Brandriet and Bretz, 2014b). Part of the reason could be the rhetoric of effacing the spectator ions. The exclusion of bulk water is also troublesome for concept development. Kelly *et al*. (2017) found students cannot accept solvent water as part of the chemical process because of its absence in the overall balanced equation. Furthermore, by not addressing bulk water, a chemistry teacher prevents discussions of water's enthalpic and/or entropic contributions that make redox thermodynamically favourable (Yan and Talanquer, 2015). Teacher 206's symbolic accommodation inadvertently established blinders to particulate-level chemical species. Whatever explanatory details the VisChem animation offers regarding the transfer of electrons were curtailed by the tradition of emphasising the written equation itself, likely conceiving redox as merely a transfer of symbolic charges. Our pedagogical instinct to make learning more efficient has led to the tenacious and unquestioned preference of chemistry symbols over the actual information they represent.

Summary of Results

For research question #1, we characterised VCI-2 teachers' resistances and accommodations with the goal of identifying a redox learning outcome. Resistances included the five types of reactions scheme and uncertainty with sequencing topics. Specifically, teachers' difficulty with deciding when to teach balancing alludes to both the complexity of teaching redox and the pervasiveness of its symbolic associations. Later in the co-planning, the teachers accommodated by settling on the transfer of charges as the redox learning outcome. However, the meaning of "charges" was ambiguous as it possessed both particulate and symbolic interpretations, thereby warranting research question #2. Further investigation of VCI-2 teachers' symbolic accommodation and modification of their goals during the micro-teaching led to three unique narratives. Teacher 106's transitioning into descriptions and mnemonics, 110's framing of redox as Cu kicking out Ag, and 206's exclusion of species not explicitly depicted in the net ionic equation collectively evinced the symbolic roots in the discipline itself. Despite using a particulate-level VisChem animation, all three teachers accommodated the redox learning outcome by centring the goal around chemistry symbols, detracting attention away from chemical mechanism and causality. Until we carefully inspect the historicity of redox instruction, advancing chemistry concept development will not be a tenable outcome of this mangle.

Implications for practice and research

For Practitioners

Using Pedagogical Chemistry Sensemaking (Wu and Yezierski, 2022b), we provide lesson-planning guidelines and teaching moves that theoretically assume accentuating the limitations/utilities of one representational level relative to another will catalyse productive sensemaking. According to *Physical Sciences 1.B Chemical Reactions*, grades 9-12 students should develop a particulate conceptualisation that consists of "collisions of molecules, rearrangement of atoms, and changes in energy" (NGSS, 2013, p. 41). We thus urge chemistry educators to plan beyond the five types of reactions scheme. Its underlying principles are based on a rearrangement of *symbols*, not atoms. Neither collision of molecules, atoms, or ions nor energetic changes can be conveyed. The five types of reactions scheme should be communicated as a useful visual shorthand, with limited representation of particulate phenomena. Furthermore, both secondary and tertiary chemistry educators must not become complacent if using any reaction description that is solely symbolic. The predilection to rely on symbolic heuristics has alarmingly gone uncontested insofar that particulate-level mechanism and causality are no longer salient redox learning outcomes (Mui and Tully, 2022; Yuen and Lau, 2022). Particulate-level phenomena cannot be substituted with chemistry symbols if the goal were to promote chemistry concept development.

What are possible teaching moves that engage in chemical mechanism and causality? For Teacher 106, redox mechanisms (*e.g.*, the sequence of events that include molecules colliding and atoms rearranging) can be more strongly emphasised. One could ascribe more detail to the tug of war (*i.e.*, competing intermolecular forces) among solvating water molecules, the silver cation, and the delocalised electrons on the copper lattice. One could also use the VisChem animation to indicate how redox occurs at different parts of the copper lattice and dispel the presumptions of a direct and localised electron transfer, as mnemonics like LEO GER and OIL RIG may imply. Acknowledging that the bookkeeping of oxidation states is a set of largely arbitrary rules would also be prudent (Sisler and VanderWerf, 1980).

In the case of Teacher 110, the "kicking" out analogy can be reshaped into a student-centred discussion of the symbolic level's limitations. Chemistry teachers can bring certain features of the VisChem animation into focus (*e.g.*, copper atoms leaving the lattice as solvated cations) when comparing with the single replacement reaction and enable students to decipher the conflicting information (National Research Council, 2012). The practice of identifying, working through, and figuring out these incongruities between different models can result in more cohesive knowledge structures (Phillips *et al*., 2017; Schwarz *et al*., 2016). With greater opportunities to discern the context of a model's explanatory function, learners can be empowered to recognise that the VisChem animation is not just a depiction of some phenomenon but rather a tool for making sense of redox (Wu and Yezierski, 2022b).

Finally, frequently omitted chemical species, as observed in Teacher 206's use of the net ionic equation, should be reappropriated to examine the cause of a redox reaction. For example, water's enthalpic and entropic contributions can be a platform for understanding chemical causality. Calculating ionisation energies, solvation enthalpies, and electron affinities *via* a Born-Haber cycle conveys that solid copper's oxidation is more exothermic than its reduction. The VisChem animation also depicts silver and copper(II) cations each hydrated by six water molecules. Given that the stoichiometric ratio between silver and copper cations is 2:1—and assuming negligible contributions of solid silver and copper—one can reason how more microstates available to water molecules is entropically favourable. Expectedly, the Gibbs free energy of the reaction shown in the animation is negative, corroborating with macroscopic observations. While calculating enthalpy and entropy changes are outside the expectations of first-year secondary chemistry learners, we note how we gauge redox "mastery." Mastery has too long been informed by the writing of net ionic equations, documenting oxidation states, and describing changes (*e.g*., what species is oxidised) without connection to the observable phenomenon or particle-level change. Improving redox conceptual understanding cannot be realised if explanations and models situated in scientific theory, energy, and particulate-level species remain unaddressed (National Research Council, 2012; NGSS, 2013).

For Researchers

The question of what constitutes scientific knowledge (symbols *vs.* particulate) for conceptual development raises additional research implications. The nature of scientific knowledge is broadly taxonomic, measurable, causal, and relational (Schwab, 1949). Relational science, according to Schwab, is devising associations that do not literally have a one-to-one correspondence but provide helpful mechanisms that approximate behaviours. Understanding the relationships between reality and its depictions thus requires multiple models and understanding of their contextual relevance. This dynamic process, if unsuccessful, could result in surface-level conceptions of science (Schwab, 1949). Based on our study's findings, we assert that chemistry education practices are limited by the community's prioritisation of the symbols that mask redox concepts.

Demonstrated by Teachers 106, 110, and 206, there is a pedagogical tendency to apply chemistry symbols in situations that necessitate particulate-level reasoning for redox conceptual understanding. This "square peg in a round hole" scenario parallels how students routinely used a covalent model for determining ionic compounds (Bowe *et al.*, 2022). In addition, Schafer *et al.* (2022) provided evidence that curricular materials embody certain epistemological messages that inform processes of teaching and learning. We thus advocate future researchers to re-evaluate redox-specific pedagogy and curriculum by reflecting on the nature of redox knowledge itself. More research can be conducted to design formative and summative assessments that strengthen learners' particulate-level concepts instead of their writing of chemistry symbols. Specific, accessible, and practical redox teaching moves that uses the limitations of the symbolic level for warranting sensemaking with the particulate also require further investigation (Wu and Yezierski, 2022c). By problematizing current epistemologies associated with redox, we can begin generating the necessary precursors for pedagogical conceptual change towards reform-based instructional practices (Wu and Yezierski, 2022b).

The insidious effects of the symbolic level may also be pertinent to other areas of the chemistry education discipline. In general, representations like chemistry symbols fail to tell readers what is intended to be represented *via* their use (Ainsworth, 2007). We suggest researchers incorporate MoP for surveying the agentive dance among teachers, students, chemistry symbols, and particulate-level concepts manifesting in real-time, similar to how other studies have done (Manz, 2015; Leden *et al*., 2019). There may exist additional instances in which the undisputed history of teaching with chemistry symbols confine and disrupt conceptual understanding for other chemistry topics. Given teachers' reliance on chemistry textbooks (Gkitzia *et al.*, 2011; Vojíř and Rusek, 2022), researchers should explore not just whether the symbolic and particulate levels are included but the extent to which the former facilitates and/or disrupts understanding of chemical mechanism and causality. By identifying teachers and students' resistances, accommodations, and goals using MoP, we as a research field can more deeply evaluate the extent ongoing historicities of chemistry education actually align, in practice, with the principles of the NGSS and other reform efforts.

Limitations

We discuss three limitations of our work. First, video recordings only represent a certain frame of a given setting (Smets *et al*., 2014). In addition, the camera's presence may have influenced participant behaviour (Jordan and Henderson, 1995). We mitigated this limitation by deliberating on an unobtrusive and informative location for camera placement. Nevertheless, we acknowledge that, no matter the data collection method, recording every possible detail of a phenomenon is unfeasible (Erickson, 1992). Second, our decision to forego the footage of the group debriefing limited our analyses. There may have been signals alluding to teacher resistances in their micro-teaching. Although events from the group debrief were not selected, the video recordings were still subjected to our research methods.

We found that because the group debriefing was relatively less structured than the co-planning and micro-teaching, there was no additional information that could have either meaningfully expanded upon the narratives presented thus far or provided evidence for alternative interpretations of the previous videos analysed. The last limitation is the lack of member checking. Although video-stimulated recall interviews could have been used (Muir, 2010), the intent of this study is neither to understand VCI-2 teachers' experiences nor evaluate the PD. We instead used our disciplined subjectivities to understand situated practices of planning and teaching redox using the VisChem Approach (Derry *et al.*, 2010). Our analyses considered the historicity of redox instruction typical in secondary and tertiary settings, a slice of which is captured in the VCI-2.

Conclusions

Cooper and Klymkowsky (2013, p. 1120) have argued that "while more active pedagogical strategies are clearly valuable, it is time to think about the curriculum itself, what is important for students to master, and how best to present these ideas and skills." While we agree that nurturing both pedagogical and curricular change is vital, the nature of the knowledge—rooted in the chemistry education community itself—must also be considered. Our analyses of situated practice; historicity; and the resistances, accommodations, and goals of redox instruction indicate that various symbolic traditions within the discipline not only undermine learner engagement with particulate-level concepts but also alter the VisChem Approach, diminishing its fidelity and efficacy. If the nature of chemistry knowledge itself remains immutable, the prospect of improving chemistry concept development *via* reform-based practices is inevitably futile. We as members of the chemistry education research community have a responsibility to re-examine the traditions of the discipline and what is worth teaching and learning.

Conflicts of interest

There are no conflicts to declare.

Appendix 1

Finalised events of Teachers 106, 110, and 206's co-planning of a learning design.

Co-Planning a Learning Design Event 1: Resistance as Not Having Enough Time to Cover Redox (bolded = utterances, italicised in brackets = gestures)

Timestamp	Speaker	Discourse
[00:01:37.18]	106	**I'm curious as to what-what time of year, what pre-knowledge**
[00:01:43.04]	206	[*Nods*]
[00:01:43.07]	106	**do the students have? One of the things that I-the trouble that I've run into,** [*lifts chin away from left hand and repeats circular motions with left hand*] **especially with the past year because of all the issues we've already talked about**
[00:01:49.29]	110	[*Nods*]
[00:01:50.04]	106	[*makes a quick sweeping motion with left hand in front of face*] **just coming back to being in-person and stuff, is BARELY** [*scrunches forehead and quickly creating a small space between left thumb and left index finger*] **got to** [*motions left hand on each subsequent topic*] **net ionic equations and aqueous stuff**
[00:01:54.27]	110 & 206	[*Nods*]
[00:01:57.14]	106	**at the end of the school year. Like one of the last things** [*makes a small space gesture between left thumb and left index finger again*] **we even got to and** [*rests chin on left hand*]**...and that was a struggle**.
[00:02:02.24]	206	**So…in my-I have not historically in my first year chem course taught net ionic equations.**
[00:02:09.05]	106	[*Nods*] **mmhmm**
[00:02:10.01]	206	**Um I had** [*makes circular motion with left hand*] **the bright idea…uh…during** [*gestures left hand down once*] **COVID year that…**
[00:02:15.29]	106	[*Nods*]
[00:02:17.10]	206	**when we start** [*gestures left hand down again*] **solutions unit**
[00:02:18.20]	106	[*Nods*]
[00:02:18.29]	206	**that might be a great place to then use it**
[00:02:20.11]	110	[*Nods*]
[00:02:20.24]	206	**because then…helping** [*gestures left hand down again*] **them understand like** [*gestures with outstretched left hand*] **what does aqueous truly mean?**
[00:02:22.27]	106 & 110	[*Nods*]
[00:02:25.11]	206	[*Positions left hand on chin*] **um…and of course solution** [*claps hands together and moves left hand further away from right*] **comes much later in the year than**
[00:02:28.09]	106	[*Nods*]
[00:02:30.15]	206	**uh…than** [*curls fingers back in towards herself*]**…**[*quickly makes circular motion with index fingers from both hands*] **like redox** [*gestures right hand forward and clasps hands together again*] **types of equations would.**
[00:02:34.05]	106 & 110	[*Nods*] {inaudible}
[00:02:35.25]	206	**But the more I go-I dunno over the last few years it feels like net ionic equations** [*claps back of right hand into palm of left hand*] **might be something that we should introduce MUCH earlier** [*extends space between left and right hand, with left hand making a downwards motion at the end*]**.**
[00:02:46.14]	110	[*Nods*]
[00:02:46.15]	106	Mmhmm
[00:02:46.17]	206	**Because it really** [*waves left hand to the left side*] i**t really seems like it supports** [*places back of right hand into palm of left hand again*] **the VisChem Approach and um…**
[00:02:49.17]	106	[*Nods*] **Sure**
[00:02:52.25]	110	**Helps you understand what a reaction is.**
[00:02:52.26]	106	[*Nods*] **Right.**

Co-Planning a Learning Design Event 2: Resistance as Struggling to Get Away from Five Types of Reactions Scheme (bolded = utterances, italicised in brackets = gestures)

Timestamp	Speaker	Discourse
[00:04:22.04]	106	**I've-I've tried** [*swipes computer screen with right hand*] **the last couple of years to get away from like the** [*sits up (outside of frame) and motions with both hands to his left*] **classic five types and try to** [*motions both hands downwards, palms down and fingers outstretched*] **teach it with respect to redox** [*leans forward (back into frame) and rests chin on left hand*] **because I think then** [*traces a left to right direction with outstretched left index finger*] **when you get to like** [*motions outstretched left hand, palm down on each subsequent topic with hand moving slightly right to left*] **single replacement and precipitation and precipitation it makes more sense.** [*Rests cheek back into left hand again*] **But it's hard** [*laughs*]. **It's hard for me** [*points to self with both hands*] **as the teacher as well as** [*points forward with both hands*] **the students.**

Co-Planning a Learning Design Event 3: Resistance as Not Actually Addressing Electron Transfer (bolded = utterances, italicised in brackets = gestures)

Timestamp	Speaker	Discourse
[01:18:10.17]	206	**Do they already know what redox means?**
[01:18:14.20]	110	**I did not and I** [*scrunches both hands together in a ball shape*] **just put like a super tiny amount…in the** [*motions both hands, outstretched, to the right*] **very end. I spent a lot more time** [*points to computer screen*] **on the…reaction itself** {inaudible}
[01:18:27.09]	206	**Yeah the reaction itself. Not so much like**
[01:18:30.10]	110	**Yeah.**
[01:18:31.06]	206	**this falls under** [*makes a circular motion with both hands, with hands forward and palms up at the end*] **a classification of reactions** [*clasps hands together with fingers interlocking*]**.**
[01:18:38.01]	110	**I have** [*makes a small circle shape with both hands*]**-I did like a couple slides at the very end on that-but just again** [*shakes head*]**-just enough context-to even oxidation numbers and seeing how** [*alternates waving hands back and forth in front and shrugs*] **those charge numbers mean.**
[01:18:46.14]	106	**Sure**
[01:18:47.01]	110	**but I don't think I would ever do-you guys** [*stretches hands forward quickly*] **would do more** {inaudible}**.**
[01:18:51.09]	106	**I'd argue that proper…I feel** [*buries face in palm of right hand*]**-vast majority** [*lifts and shakes head*] **of first year chem classes don't do redox.**
[01:18:57.08]	110	**I-I wouldn't** {inaudible}
[01:18:58.16]	106	**They-they-they do single replacement** [*motions left hand to the right, palm up, and nods*]**.**
[01:19:00.03]	206	**Mmhmm.**
[01:19:00.03]	110	**Yeah.**
[01:19:00.25]	106	**But they don't call it** [*uses big air quotes with both hands*] **redox or talk about actual electron transfer.**

Co-Planning a Learning Design Event 4: Resistance as Sequencing Balancing and Redox (bolded = utterances, italicised in brackets = gestures)

Timestamp	Speaker	Discourse
[01:22:42.24]	206	**I'm-**[*gestures both hands forward, pointing at 106 and briefly sighs*] **I'm with you 106 I'm like trying to cha-change my [*places hands on both temples*] thinking [*puts hands together*] because I…I teach [*claps hands once*] five types of reactions [*clasps hands together with fingers interlocking*]. I think……it actually comes before [*claps hands on each subsequent word*] balancing. Because it's easy to-**
[01:22:59.00]	106	**Right** [*nods*]. **Once you identify** [*points left index finger in front*] **it then you can kind of follow the…**[*swirls left hand in a clockwise motion*] **general pattern.**
[01:23:02.29]	206	**Yeah** [*nods*] **formula**. **Um I'm trying to** [*squints, brings fingers on both hands to a point, and makes a turning motion with hands like gears turning*] **retrain my thought to broaden the** [*stretches fingers out, palms down in front*] **umbrella to teach** [*counts things off left hand fingers and extends them forward again*] **precipitation, neutralisation, redox first maybe after balancing.**
[01:23:16.05]	106	[*Nods*] **mmhmm.**
[01:23:16.08]	206	[*Gestures to the right with both hands, clasps hands together, and then furrows brow*] **although that-I don't know** [*motions with hands forward and clasps them together again*] **if that makes sense either. How do you [*points index fingers to the right*] balance this equation but [*points index fingers to the left*] you don't even know what an equation is yet?**
[01:23:27.23]	106	**Mmhmm** [*nods*]**.**
[01:23:29.08]	206	**But then** [*stretches both hands out, palms down*] **take-where do five types** [*shakes both hands left and right and starts motioning upwards as if sorting*] **fit under those umbrellas**
[01:23:32.26]	106	[*Nods*] **Right…**
[01:23:35.07]	206	[*Clasps hands together*] **and are there some** [*motions both hands to the left*] **that can like…be in** [*motions hands sideways quickly several times before clasping them together*] **multiple categories um** [*makes the gears turning motion again*] **so it's like difficult to go against** [*places hands near chin, rubs chin with thumb, and smiles*] **my natural instinct at-for student ability.**
[01:23:49.13]	106	[*Nods*] **mmhmm sure.**

Co-Planning a Learning Design Event 5: Accommodation as Setting Transfer of Charges as Redox Learning Outcome (bolded = utterances, italicised in brackets = gestures)

Timestamp	Speaker	Discourse
[01:28:43.24]	110	**So we're supposed to** [*extends hands out, two feet apart and palms facing each other*] **do an oxidation-reduction of copper with silver nitrate and make them into…um types of reaction unit. So I think we have to-we have to-**
[01:28:52.16]	206	**But** [*puts left hand out—palm down—and rests it on the table and then rests hand back into prior position*]
[01:28:53.24]	110	**…**
[01:28:54.05]	206	[*Nods and quickly shakes head*] **go ahead.**
[01:28:55.27]	110	**Well I was gonna say…we have to include an oxidation-reduction-even if it's** [*holds up right hand with fingers scrunched together*] **not a lot. It doesn't mean like when you talk about something it doesn't mean** [*moves left hand in a circular motion*] **you're talking about everything related to it out of context.**
[01:29:05.02]	106	**Right.**
[01:29:06.17]	110	**Everything that eventually you might talk about.**
[01:29:09.04]	206	**But I don't think you have to use oxidation reduction verbage** [*puts forward left hand, fingers curled and pointed down*]**…and all the** [*two taps and pushes hand forward*] **components of it…as it would fit in a first year types of reaction.**
[01:29:09.04]	110	**I think** [*stammers and laughs*]
[01:29:24.11]	206	[*Whispers, "Am I making sense?"*] **and I'm not sure how you scaffold** [*moves both hands—outstretched and parallel to each other—in a circular motion like dominoes being sequentially placed*] **all the way to RE-DOX** [*taps left hand twice on table*] **and ionic bonds**
[01:29:32.23]	110	**If you're just talking…if you're talking-well that's one of the challenges I've had** [*stammers*] **just that-that reaction, if you're just looking at redox as that transfer of electrons you can pick up** [*leans in and stretches out both hands and places them on the table in front]* **those species and I think most kids** [*nods*] **are pretty capable of doing that. Um…that are involved and** [*sits back*] **they know about charges** [*drops pen and opens hands and turns palm facing upwards*] **that's-that's not a complex.**
[01:30:10.12]	106	{Inaudible} [*nods*]
[01:30:11.12]	206	{Inaudible} [*nods*]
[01:30:11.12]	110	[*Crosses hand over chest*] **So they can identify the species and it's happening when they're** [*holds up hand with index and thumb indicating a small space in between*] **bonded to something you know how** [*moves both hands in front in an alternating circular motion, like arrows indicating movement in a single-replacement reaction*] **like how that changes *vs.* they're solid *vs.* when they're bonded** [*holds up both hands clasped together in a ball but then resumes previous alternating circular motion*] **what's going on?**
[01:30:12.16]	206	**Maybe that's an SLO. Student will be able to…recognise the fact that** [*motions with left hand downward on the beat of every following word*] **charges are transferred like** [*uses both hands—fingers extended and pointed down making a V-shape—to make downward motion on the beat of every following word*] **like that's what makes redox.**
[01:30:35.03]	106	**Mmm…yup**
[01:30:36.04]	110	**OO! THERE! THERE! YOU GOT IT!** [*claps*] **I think we got it.**
[01:30:37.16]	206	**That there's a** [*uses similar gesture with both hands to punctuate every following word*] **transfer of charges that occurs.**
[01:30:40.18]	110	[*Leans forward and then back*] **Because that's truly** [*extends arms out to the left and right with palms facing up*] **and again** [*brings hands together and gestures a gathering motion in front*] **there's a whole bunch of other things but for 10th grade general kids that are all gonna take is...that maybe in AP bio next year that…that's enough for them to have some base…**
[01:30:56.08]	106	**Yep**
[01:30:56.12]	110	**…if they are going to go on but...not as much as you guys** [*points with both hands at 206 and 106, respectively*] **need.**

Appendix 2

Finalised events of Teacher 106's accommodation during Individual Micro-Teaching #2.

106's Individual Micro-Teaching Event 1: Accommodation as Responding to Tug of War (bolded = utterances, italicised in brackets = gestures, SA = Student A, SB = Student B)

Timestamp	Speaker	Discourse
[00:14:23.07]	106	**Alright, what were some things that you noticed…from the video? SA, what was something that you saw?**
[00:14:31.10]	SA	**There was a tug of war.**
[00:14:33.26]	106	**Oh, I like that. Tell me where you saw that?**
[00:14:36.13]	SA	**Ah as the grey spheres are moving towards the yellow ones**
[00:14:40.28]	106	**Mmhmm.**
[00:14:41.19]	SA	**there was a sort of,** [*puts both hands in front and alternates short and medium distance between them*] **like resistance, that was happening**
[00:14:44.23]	106	**Mmhmm.**
[00:14:45.00]	SA	**until the sphere got fuzzy** [*right fingers curl in*] **and water** [*retracts hands quickly and rests hands on table*] **decided to let go.**
[00:14:48.14]	106	**Interesting! So, from** [*points to left portion of whiteboard*] **our key that we talked about yesterday and the one you all drew......obviously** [*moves closer and gestures at projector screen with both hands*] **this key matches those** [*gestures at left portion of whiteboard again*] **video keys... yours may or may not have been exactly the same but pretty close! You all did a great job of differentiating the different particles. What** [*moves closer to projector screen and points at copper lattice in VisChem animation*] **do you suppose these yellow spheres are?**
[00:15:06.27]	SB	**I think copper?**
[00:15:06.27]	106	**Copper, yep they're all kind of stationary** [*gestures hands towards projector screen strongly*]. **What do you suppose** [*forms a slightly incomplete circle by motioning with both hands*] **the fuzziness was? We talked about that yesterday.**
[00:15:14.06]	SA	**We said that's where there's electrons.**
[00:15:16.28]	106	**Electrons good. Remember: metals, when they're metallically bonded, they're** [*moves hands haphazardly across projector screen, around the copper lattice in the VisChem animation*] **just sharing electrons in kind of this big sea of electrons. And then the** [*points to silver ion in VisChem animation*] **grey spheres, what must those be then?**
[00:15:27.17]	SB	**They're the silver.**
[00:15:28.04]	106	**Silver! Good! So is silver** [*points to the silver ion in the VisChem animation*] **with the nitrate, like we said in our overall molecular equation?**
[00:15:33.06]	SA	[*Shakes head*] **Mm mm.**
[00:15:34.02]	106	**No!** [*points to left portion of whiteboard*] **Remember: from our uh total ionic equation, it was separate. It was aqueous.**
[00:15:44.29]	SA & SB	**Mmhmm yes.**
[00:15:45.16]	106	**Yeah!** [*waves left hand in front of projector screen*] **It kind of just floats by.**

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106's Individual Micro-Teaching Event 2: Accommodation as Using Mnemonics (bolded = utterances, italicised in brackets = gestures, SA = Student A, SB = Student B)

Timestamp	Speaker	Discourse
[00:32:54.19]	106	**So...we talked about the fuzziness** [*points to the left portion of the whiteboard*]. **What does the fuzziness represent?**
[00:32:58.10]	SB	**Those are ions, right?**
[00:33:00.06]	106	**Not ions but what makes them ions?**
[00:33:01.10]	SB	**Oh electrons!**
[00:33:02.27]	106	**Yeah! Electrons. It's all about the electrons. So the copper's** [*moves hands haphazardly but in a general circular motion*] **had all those fuzzy electrons buzzing around all of them to begin with…you noticed that the silver wasn't fuzzy** [*brings hands together, approaches the projector screen]* **when it was being transported by the water. Once it got** [*motions both hands downwards*] **deposited, it was fuzzy now. And when the copper got** [*makes retracting motions with both hands, fingers curling in*] **pulled away it wasn't fuzzy anymore. So we're gonna introduce a couple of terms.** [*Moves towards right portion of white board and points to the written content*] **So I've got two different mnemonic devices. This is the way I learned it when I was in school: OIL RIG.**
[00:33:29.04]	SB	**Mmhmm**.
[00:33:29.17]	106	**What it stands for is** [*writes on the whiteboard*] **OXIDATION and that IS the LOSS of electrons. And then REDUCTION IS the GAIN of electrons. Those words are kind of confusing because [*puts hand atop the words, "Reduction is Gain"*] when you think of something being reduced what do you think of?**
[00:33:56.23]	SB	**They get** [*scrunches hands together*] **smaller.**
[00:33:57.18]	106	**Yeah it gets smaller BUT what happened to** [*moves towards the left side of the white board and points to net ionic* equation] **silver's charge when it got reduced? When it gained electrons?**
[00:34:07.06]	SB	**Negative got smaller.**
[00:34:09.10]	106	**Yeah the** [*points to the left side of the net ionic equation*] **charge got smaller. It went from positive to zero** [*points to the right side of the net ionic equation*] **over here. So it's the charge that's getting reduced. It's not the number of electrons.**

Appendix 3

Finalised events of Teacher 110's accommodation during the Individual Micro-Teaching #2.

110's Individual Micro-Teaching Event 1: Accommodation as Showing Ion Separation (bolded = utterances, italicised in brackets = gestures, SC = Student C, SD = Student D)

Timestamp	Speaker	Discourse
[00:27:05.03]	110	**So let's just play that. What are we-what are we seeing there, do you think? Kind of went off-screen there.**
[00:27:11.00]	SC	**That's the penny.**
[00:27:12.01]	110	**That's the penny** [*puts forward right hand, palm up*] **which is made of what element?**
[00:27:15.09]	SC	**Copper.**
[00:27:16.00]	110	**The copper. We see that** [*quickly makes a circle shape with both hands*] **lattice structure-it's kinda off** [*moves towards the projector screen and points at copper atom and lattice structure*]. **But do you see the clouds here?**
[00:27:20.26]	SC	**Mmhmm.**
[00:27:21.19]	110	**Because those are the solid ones, right? Just elemental** [*moves back to the computer podium*] **copper** [*plays and pauses VisChem animation*]. **And then what's that one?**
[00:27:35.22]	SC	**That's the silver.**
[00:27:38.08]	110	**And let me go back just a titch** [*rewinds VisChem animation*]. [*Moves towards projector screen and points at the copper lattice structure*] **What do you notice about it right here?**
[00:27:45.23]	SD	**The cloud exchange?**
[00:27:47.26]	110	**Yep and what are these** [*points to solvating water molecule around the silver ion*] **like-Addie said she saw a ton of?**
[00:27:52.07]	SD	**Water.**
[00:27:53.02]	110	**Water. So we see that silver coming in** [*moves back to the computer podium*]. **Where did that silver come from?**
[00:28:01.07]	SD	**From the solution.**
[00:28:03.28]	110	**Cuz** [*points to students*] **what is our solution?**
[00:28:05.25]	SC & SD	**Silver nitrate**
[00:28:06.22]	110	**Silver nitrate** [*quickly balls hands and brings them together*]. **So you're not necessarily gonna see that** [*points to projector screen with right hand*] **nitrate** [*brings fists together again and rocks them left and right, together*] **fall-you know-stuck to it, falling all over it. So we know that it came from the solution** [*plays VisChem animation*]. **Did you guys see that where one of them had the cloud and then kind** [***waves hand slowly***] **of...disappeared?** [*Pauses and scrubs through the VisChem animation, trying to find a specific moment*] **There's that one** [***points to computer screen in front of her***] **that was-**
[00:28:45.16]	SC	**Ohh yeahh**
[00:28:47.03]	110	**oop there-there its cloud came off**
[00:28:48.15]	SD	**Yeah.**
[00:28:53.25]	110	**That's what I wanted to catch and I missed it again. Did you guys see that** [*makes a ball with right hand and gestures a downward motion*] **one coming with the blue?**
[00:28:57.27]	SD	**Nitrate.**
[00:28:58.20]	110	[*Points to students*] **There's the nitrate. So when we had our** [*raises both fists and presses them together*] **silver nitrate in our** [*points to whiteboard and presses fists together again*] **key, that's where that is.** [*Plays through the VisChem animation from the beginning, trying to find a specific moment*] **There's that nitrate again. There's the silver. What I want to do is pause it there but it's not letting me but** [*moves towards projector screen and points to the silver lattice*] **what do you notice is happening with the silver here?**
[00:29:48.24]	SD	**They're bouncing on top.**
[00:29:50.14]	110	[*Moves towards students and loosely flaps hand*] **It's bouncing on top. Do you see them um** [*waves both hands*] **floating around still?**
[00:29:55.12]	SC	**No.**
[00:29:56.03]	110	**What's happening with them?**
[00:29:56.29]	SC	**They're st-stuck to the copper.**
[00:29:59.14]	110	**Yeah they're** [*takes right hand and tucks it into left hand several times*] **like-look like they're being stuck on top of that copper, right? Do** [*moves towards projector screen and points at silver lattice*] **you remember the name of that structure when we have um-they're closely aligned** [*curls both fingers and brings hands close together*] **with each other when we** [*moves towards students*] **did that with your sodium chloride in their solids?**
[00:30:11.28]	SC & SD	**Lattice?**
[00:30:12.24]	110	**It looks like they're making a lattice, right? They weren't. It looks like they're making a lattice**

110's Individual Micro-Teaching Event 2: Accommodation as "Kicking" Symbols Out (bolded = utterances, italicised in brackets = gestures, SC = Student C, SD = Student D)

Timestamp	Speaker	Discourse
[00:37:32.02]	110	**Um** [*moves towards students*] **in-in the context of the types of reactions and in the single replacement, I think it's kind of it-it would** [*points to whiteboard*] **be a good way to for kids to see the** [*rotates hands, as if turning a steering wheel in one direction and then the other*] **you know one** [*uses air quotes*] **kicks one out of place like they can actually visually be able to see that so…**
[00:37:49.05]	SC	**Yeah.**

Appendix 4

Finalised events of Teacher 206's accommodation during Individual Micro-Teaching #1 and #2.

206's Individual Micro-Teaching Event 1: Accommodation as Ignoring Nitrates and Water (bolded = utterances, italicised in brackets = gestures, SE = Student E)

Timestamp	Speaker	Discourse
[00:40:54.27]	206	**I know sometimes when I practice my drawing...when there is** [*rolls hands forward in a circular fashion*] **so much going on it can get kind of muddy. Was there anything that maybe we could have like** [*moves hands slowly and haphazardly*]**...ignored not because it's not there but maybe because it can simplify the illustrations a little bit?**
[00:41:12.24]	SE	**The nitrates.**
[00:41:13.14]	206	**Very good. We could've ignored the presence of the nitrates. Um we know that the nitrate is there. We're gonna see it there when we kind of take a look at the animation. But when we go back to the idea of this net ionic equation, what we really care about is what's happening between the copper-the solid copper** [*points at left side of the net ionic equation on the whiteboard*] **and the silver ion. Um, so a lot of times when we sketch, we know there's a lot of water but we're not gonna draw four million waters in our storyboard. So that would potentially be an option to minimise the muddiness.**

206's Individual Micro-Teaching Event 2: Accommodation as Using Net Ionic Equation (bolded = utterances, italicised in brackets = gestures, SE = Student E, SF = Student F)

Timestamp	Speaker	Discourse
[00:11:11.15]	206	**So the silver, as it's coming** [*moves towards the projector screen and points to a hydrated silver ion in the VisChem animation*] **in as a hydrated substance um carries a +1 charge, yeah? So it's a +1 ion. What** [*moves hand closer to the copper lattice in VisChem animation*] **comes in is very attracted to these negative electrons and so...the attraction** [*moves hand back and forth between silver ion and copper lattice*] **to this negative electron cloud um is much greater and that's why we see this** [*makes circular motion with index finger*] **silver ion kind of deposit itself.** [*Moves back to the computer podium*] **And then we see that fuzzy cloud. It's almost like** [*makes a hugging motion with both arms in an upwards direction*] **it swallows it like a...big blob or whatever. It swallows that um silver atom. It deposits itself on the surface there. And...we can kind of watch another one** [*begins rewinding VisChem animation in the search for a particular frame*] **Oop, back up just a bit. What do we see right here? What do you notice?** [*Pauses video at hydrated copper(II) ion*] **Boom**.
[00:12:04.03]	SE	**All of a sudden, the copper** {inaudible}**.**
[00:12:05.28]	206	**All of a sudden, the copper that is...what's the word that we've been using to describe when it's got water around it?**
[00:12:11.14]	SE	**Hydrated**.
[00:12:12.00]	206	**Yeah we can have copper, hydrated copper. Um or we would-another term to describe that would be** [*points to net ionic equation on the right portion of the whiteboard*] **aqueous, right? So now** [*points to the right side of the net ionic equation*] **we have the production of, when there wasn't before** [*taps whiteboard*] **some aqueous copper ions**. **What else can we notice** [*plays through the VisChem animation*]**? Oh. Did we miss it** [*pauses VisChem animation, rewinds, and plays it again*]**?**
[00:12:41.03]	SE	**Blue!**
[00:12:41.27]	206	**There's blue! But was it just blue? Let me go back a little bit** [*rewinds VisChem animation*]**. Boop** [*pauses VisChem animation, showing the hydrated nitrate ion*]. **Okay so we got blue. But what else is there? Wha-what is the blue?**
[00:13:13.11]	SF	**Must be a nitrate because it has three oxygens attached to it.**
[00:13:18.24]	206	**Very good! I'm so glad you made that observation** [*moves towards the projector screen*]. **This must be the nitrate because you notice there's the blue but it also has** [*points to all of oxygens in the nitrate ion one at a time*] **three red balls attached to it and so it makes sense that this** [*points to the centre of the nitrate ion*] **must be nitrogen. Then we have we our three oxygens. What else do you notice about** [*backs away from the projector screen*] **the orientation about the water that can kind of help provide evidence that this is probably a negatively charged ion?**
[00:13:41.15]	SE	**Hydrogen is pointing to oxygen.**
[00:13:43.08]	206	[*Points at the water molecule that is solvating the nitrate ion*] **Maybe a little hard to see but kind of looks like the** [*points specifically at hydrogen*] **hydrogen ends are** [*gesturing towards the centre of nitrate*] **pointing in the direction of this nitrate maybe we can see it pointing...let this kind of...play on by. But remember you have** [*moves in front of the computer podium*] **my full permission um in storyboards to omit or exclude the nitrates and why did we say that's okay?**
[00:14:06.26]	SE	**Spectators.**
[00:14:07.24]	206	**They're spectators. I love that you're using that vocabulary. So they're** [*points to the net ionic equation*] **spectator ions. They're not actually participating in the production of formation of anything new. Um so in your mind you know that they're there. But we can simplify the illustrations by leaving them out.**

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