Title
(Re)Figuring the World of General Chemistry: Possibilities for Participation, Learning, and Identity

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Publication Date
2018

Peer reviewed|Thesis/dissertation

(Re)Figuring the World of General Chemistry: Possibilities for Participation, Learning, and Identity

By

Erin Palmer

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Science and Math Education

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Angelica M. Stacy, Chair
Professor Marcia C. Linn
Professor Michelle H. Wilkerson

Summer 2018

Abstract

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Scholars have called for the design of alternative educational spaces that counter dominant narratives about who is capable of learning science (Nasir et al., 2013) and what it means to be "good" at science (Carlone et al., 2011). This design-based research study examines possibilities for learning and identity in *CHEM 101B,* an undergraduate general chemistry course re-designed to dismantle racialized, gendered, and classed hierarchies of competence in chemistry and provide broad access to rich chemistry learning and identities of competence for students. Specifically, this study sought to understand: 1) shifts in students' conceptions of chemistry, chemical competence, and themselves; 2) shifts in students' participation in chemistry learning; and 3) how course design was organized to support these shifts. Classroom video, fieldnotes, student artifacts, and written course reflections were collected and interviews were conducted with students. Analysis was carried out through close examination of students' participation in groups, and through analyzing students' meaning making about competent participation in chemistry learning and their chemical identities.

Findings indicate that developing more authentic conceptions of chemistry as a social practice supported students to reject the notion that being good at chemistry requires innate intelligence. Giving students opportunities to participate in ways aligned with notions of authentic chemical practice supported students to both develop identities as competent participants in chemical thinking and learning, and engage in rich and rigorous chemistry learning.

This study found that supporting rich and authentic participation in and conceptions of chemistry learning required a significant restructuring of the classroom systems around: (1) coherent content connected to core ideas, (2) engagement in collective investigation of big scientific ideas and relationships, (3) opportunities for students to be scientists as themselves and connect science to their lives, and (4) reflection that creates awareness of tensions between common sense notions and new conceptions of science. This dissertation has implications for institutions of higher education, course designers and instructors committed to constructing learning settings that deconstruct and disrupt hegemonic narratives in science and build more productive counter narratives in their place.

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Acknowledgements

There is no way that I can adequately express my deep gratitude for my family, mentors, colleagues and friends who have supported me in this journey. This dissertation is a collective accomplishment that benefited from your intellectual support, love and care.

To my family whom I adore you. Thank you. Your unconditional love, expressed through countless emails, phone calls, visits to the Bay Area, and letters has sustained me. Mom, your ability to care for and connect with others is unparalleled. Dad, I admire your adventurous spirit, your energy for people, and your commitment to your family and work. I feel blessed to have been shaped by you both. Ryan and Dane, you both delight my heart more than I can express. I'm so thankful for the closeness we share and for the ways we have and will continue to support one another as we move through this life together.

Angy Stacy, you are a force of nature. I so admire your brilliance, the ways you wield your power for good on this campus, and your tireless efforts to improve the educational experiences of our students. I have learned so much from you about chemistry, teaching, navigating systems, and celebrating progress. It is impossible for me to name all the ways in which I am thankful for you. For the late nights you stayed up with me creating demo lessons, for your countless hours helping me refine my ideas and my writing, for your endless cheerleading and reminders that I know enough chemistry, for your nurturing when fears of qualifying exams or job talks became overwhelming, for being so open to take risks and try out new design ideas. What an enormous treat to have gotten to imagine and then transform CHEM 101B with you over the past five years. I look forward to our continued work together in the years to come.

Marcia Linn, from the moment I stepped foot on Berkeley's campus you have been a strong supporter of my work. Thank for opening doors for me, for inviting me to coauthor an article for Science magazine (that was so special!), for believing in my potential, holding me to high standards and helping me move my work forward. I am forever grateful for your investment in me and for your continued support.

Michelle Wilkerson, what a treat it has been to engage with you over the past several years. I have so enjoyed the time that we've had to think together, be it in person or via email. I only wish you had joined us at Berkeley earlier. The graduate students at the GSE are so lucky to have you. Please know that your care for and investment in our professional development does not go unnoticed.

Kris Gutiérrez, I am so thankful for that hiring committee that began our relationship several years ago. I have learned so much from you! Thank you for your patience as I slowly wrapped my mind around CHAT and activity triangles, for your deep engagement with my ideas and my writing, for being such a warm and relational mentor. Thank you for teaching me how to do qualitative work that is systematic and rigorous and to see myself as both a writer and a scholar in addition to being a teacher. My work and my personhood has benefited greatly from our relationship.

To Sabriya, my work wife and friend. Having you as a partner in this work has been such a gift. CHEM 101B would not have been what it was without you. I will always look fondly upon those times we spent on the couch at Common Ground planning curriculum and loosing our minds during intense weeks of interviewing students. I am inspired by your commitments to justice and human flourishing, and admire the way you balance caring for others with taking care of yourself. Here's to many more years of supporting one another in the work of institutional change!

Evie and Mallika, this dissertation would not be what it is without our writing group. I am deeply grateful that we collectively created a space where we could be humans together, sharing the range of feelings one experiences in graduate school and supporting one another through them. I cannot put into words how much I have learned from you both about equity, teaching and learning.

To my Bay Area family. Although not a comprehensive list, I want to say thank you to Colette, Ryan, Sharon, Jason, Andrea, Carrie, Matt, Irene, Garrett, Zach, Christie, Eve, and Tony. You have seen and shared my tears, frustrations, and my joys. You have feed me, offered me dog therapy, and gotten me out of town to adventure and reconnect with myself. Often, I find myself reflecting on how incredibly lucky I am to share life with you all! Your friendships sustain and inspire me, and I could not ask for better people in my life.

Lastly, to the students of CHEM 101B. You are the reason I do this work. I am indebted to you for the countless hours you volunteered sharing your experiences in interviews. Getting to learn from and with you has brought me so much joy. Thank you.

Chapter 1: Introduction

Lee is a confident, high-achieving, young African American woman who loves science and aspires to be a pediatrician. During her first year at university, she enrolled in a large general chemistry lecture course. As a Black student, Lee does not look like most of her peers in general chemistry, nor does she fit into stereotypes about who typically belongs in science (nerdy, white or Asian, male). During an interview about her experiences learning chemistry in a large lecture course, Lee recalled a series of racialized interactions that led her to drop the class:

> And I shortly found out that it was gonna be more than just intellect that I needed to get through the course, because I know it's not something that I like to point out, but it's there, the fact that I am a Black student. And when I was in chemistry - the big lecture with [professor] Graham - I would sit in the front. And I'm always so confident about my answers. But just raising your hand and noticing everyone look at you in unison, like "What the hell, *she* knows the answer?" … and [Professor] Graham was kinda dismissing me, like she knew I was one of those kids that was going to get "weeded out." It's like they have a set expectation of who they know is going to remain in the sciences, so they try to nurture that one. It's kinda like the bird effect. You feed the strongest bird before you feed the weaker bird, and so that's how it felt.

Lee recounts having to contend with presumptions others held about her as someone who lacked the ability to be good at chemistry, which made it unsafe for Lee to participate in the course fully as herself. She moved her seat to the back of the lecture hall, stopped asking questions or offering explanations, and, two weeks later, dropped the course. Reflecting on her decision, she described, "I was so upset, because I love science and I feel so interested in it, but I couldn't put that foot forward being in a lecture like that."

Scholarship over the past several decades has established that while students of color report equal levels of interest in majoring in Science, Technology, Engineering, and Mathematics (STEM) fields as their white peers, they switch out of STEM majors at disproportionate rates (Harackiewicz, et al., 2015; Hurtado, Egan, & Chang, 2010; Ong, Wright, Espinosa, & Orfield, 2011). Research has further established that the highest rates of attrition occur during students' first two years of undergraduate study when they are taking introductory courses, like the general chemistry course in which Lee was enrolled (Chang, Cerna, Han, & Saenz, 2008). Such courses have earned reputations as *weed-out* courses for their role in causing many students (in particular women and students of color) to consider alternative career paths (Barr, Gonzalez, & Wanat, 2008; Barr, Matsui, Wanat, & Gonzalez, 2010; Carlone & Johnson, 2007; Seymour, 2000).

Lee experienced *weeding out* as a racialized process. Her dark brown skin was read as a sign of her lack of chemical competence, cueing her professor's dismissal and her peers' surprise when she answered a question correctly. Lee's experience of racial micro-aggressions in her undergraduate science course is in no way unique (Mcgee & Martin, 2011). Recent scholarship has established that cultural narratives linking race to ability in math and science perpetuate hierarchical understandings of "smartness" that locate Asians at the top, Black and Brown students at the bottom, and White students as the invisible norm (Nasir & Shah, 2011; Nasir, Snyder, Shah, & Ross, 2013). These narratives have implications for students' access to participation, learning, and identity as educators and students act in accordance with racial storylines (McGee & Martin, 2011; Nasir & Shah, 2011; Palmer, 2016; Steele & Aronson, 1995). This dissertation investigates the ways in which the re-design of a general chemistry course might prevent the deployment of these racialized narratives, thus allowing more students of color to persist in STEM.

As racial storylines are invoked in undergraduate science courses, certain identities are made available, imposed, or shut down (Nasir et al., 2013). In Lee's case, and more broadly across institutions of higher education, the design of lecture-oriented introductory science courses creates the conditions in which Black and Brown students are positioned as the kind of people who are not that good at science. Moreover, such course design also offers them few ways of re-positioning themselves. I suggest that course design limits opportunities for students to re-position themselves as competent scientific learners in three distinct but interacting ways.

First, what counts as "good at science" (and, more generally, who counts as "good at science") is narrowly constructed through the instructional practices of large lecture courses. Lectures frame science as a large, static body of discrete facts to be memorized and of mathematical procedures to be executed, and only "'right' answers, phrased in the 'right' way" tend to be recognized as "smart" (Carlone, Huan-Frank, & Webb, 2011, p. 475). It is through these practices that "good at science" gets defined as thinking quickly, being correct, using big words, recalling large amounts of information, and getting good grades (Carlone et al., 2011). These characteristics are associated with innate intelligence in US society, thus reifying the notion that being good at science requires innate intellectual talent.

Second, large introductory science courses are organized such that students have few opportunities to participate in ways that support them to recognize themselves or be recognized by others as "good at science." In most introductory science courses (even in ones that incorporate active learning pedagogies), students' demonstration of their understanding only officially count on exams, through which their performance gets socially transformed into an evaluation of what students can do by nature of their ability (McDermott & Raley, 2011). Exams, and the grades attached to them, are among the most powerful ways that instructors and students determine competence in these courses. Yet, scholarship has established that exams invoke evaluative pressure and activate stereotype threat in ways that mask students' competence (Cohen, Purdie-Vaughns, & Garcia, 2012; Steele & Aronson, 1995; Beilock & Carr, 2005; Beilock, 2008; Nguyen & Ryan, 2008). Further, multiple choice and short answer exams ignore all the ways in which students question, critique, connect, and revise ideas – iterative processes which are part of competent chemical practice – as they learn to make sense of the world as scientists do. In summary, "good at science" is narrowly defined, and, apart from exams (which are problematic measures of competence), students have few opportunities to participate in ways that "count."

Third, students who lack access to rich opportunities to learn science in K-12 education are less likely to enter undergraduate introductory courses with the kinds of prior knowledge that support them to perform in ways that are considered "good at science" (i.e. know lots of correct information, employ academic jargon, etc.). Given the inequitable distribution of opportunities to learn science in American society along classed and racial lines (Kozol, 2005; Lee & Orfield, 2007), white, middle-class students end up having greater access to opportunities that matter for building identities of competence in introductory science courses.

Scholars have called for the design of alternative educational spaces that counter dominant narratives about who is capable of learning science (Nasir et al., 2013) and what it means to be "good" at science (Carlone et al., 2011). This dissertation is a design-based research (DBR) study, which investigates an undergraduate general chemistry course re-designed to dismantle racialized, gendered, and classed hierarchies of competence in chemistry and to provide broad access to consequential chemistry learning and identities of competence for students. What results is a theoretically robust understanding of how course design interacts with cultural narratives to mediate students' participation in chemical learning and meaning-making about themselves in relationship to chemistry.

Chapter 2 of this dissertation begins by laying out a framework that draws from social theories of learning (Wenger, 1998), *figured worlds* (Holland, Skinner, Lachiocotte, & Cain, 1998), and social approaches to design-based research (Engeström, 2011; Gutiérrez & Jurow, 2016; Gutiérrez & Vossoughi, 2010) to articulate how learning and identity are afforded and constrained as students participate in day-to-day activity and make sense of their own participation within classrooms. A *figured world* is a "socially and culturally constructed realm of interpretation in which particular characters and actors are recognized, significance is assigned to certain acts, and particular outcomes are valued over others" (Holland et al., 1998, p. 52). People develop different senses of themselves in figured worlds, because senses of self are grounded in experiences of power, and because people have different access to the social positions that afford these experiences. Narratives, for example, serve as resources for positioning in figured worlds that afford or constrain opportunities for individuals to be recognized as particular kinds of people. Within worlds, *frames* (Goffman, 1974) organize the meaning of particular situations, acting as interactional roadmaps that guide moment-to-moment activity (Hand, Penuel, & Gutiérrez, 2012). In establishing the scene and organizing roles for people within it, frames shape who gets to do what in interaction. Chapter 2 suggests that worlds are built and frames are cued in and through interacting elements of classroom systems.

Chapter 3 situates the DBR study in the context of California University (pseudonym), details iterative cycles of course development, and discusses research methodology. It begins by describing several pilot studies, which informed the redesign of the general chemistry course activity system (pseudonym CHEM 101B) that is the subject of this dissertation. These studies examined the experiences of students of color in the traditional lecture-oriented course and students' sense-making about two salient narratives that serve as resources for positioning: "Asians are good at science" and "chemistry is a weed-out class." The chapter then details the cycles of course re-design, data collection, and analytic methods that inform findings presented in Chapter 4-6. The analytic methods detailed heavily rely on frames as a tool for examining how figured worlds play out in moment-to-moment interaction (Hand et al., 2012).

This theoretical and methodological work sets the stage for empirical investigation. Chapter 4 investigates how frames mediate students' interactions within teams in CHEM 101B, and the implications of these frames for chemistry learning. It further considers how course design makes new and more productive learning frames available. Analyses of students' written reflections about chemistry learning and of classroom video across the semester reveal that despite the predominance of the *doing school* frame (Hand et al., 2012) in US systems of schooling, students largely participated in what I term a *collective investigation* frame within CHEM 101B. Framing analysis of two focal episodes indicates that the positional frame of *collective investigation* entails active roles for students as authors of chemical ideas. Further, this analysis suggests that an epistemological frame was established in which chemistry is about collectively making sense of molecular level attractions and motions to explain the properties and behavior of matter. This chapter argues that the classroom system of CHEM 101B shifted intellectual authority away from instructors and held students accountable to one another and to the discipline in ways that provided the positional and epistemological framings of *collective investigation* and supported rich engagement in chemical thinking and learning.

Chapter 5 complements the empirical investigations in Chapter 4 by examining how students, who were largely participating within a *collective investigation* frame*,* came to make sense of what it means to be "good at chemistry" in the new figured world of CHEM 101B. Interviews and course reflections reveal that most students in the course constructed new, broad, and more inclusive meanings about competent participation in chemistry that disrupted the narrative of links between "good at chemistry" and innate intelligence. The second half of Chapter 5 investigates who students get to be and what kinds of power they are afforded by the *collective investigation* frame. Analyses of interviews, video data, and classroom assessments suggest that the world of CHEM 101B is complicated, populated with meanings that both afford and constrain students' perceptions of themselves with respect to chemistry.

Finally, Chapter 6 examines how the predominant *doing school* frame was disrupted and the ways in which course design supported the cultural accomplishment of *collective investigation* within particular teams in CHEM 101B. I analyze moments in which one team of students is organized around *doing school* and an extended moment in which a separate team successfully accomplishes *collective investigation* in order to investigate connections between these two frames and course design. Findings indicate that course design supports the accomplishment of *collective investigation,* and that particular elements in design create contradictions, which students have to navigate.

What emerges from this dissertation is a rich understanding of course design that creates powerful opportunities for chemistry learning and identities of competence, and of the ways that the broader context of the universities within which general chemistry courses are situated present challenges for designing towards equity in undergraduate science education that warrant further investigation.

Chapter 2: Theoretical Perspectives

Learning and identity as socially negotiated processes

In order to think further about how educational contexts (such as a general chemistry course) mediate learning and identity, we need to understand learning and identity not as merely cognitive or psychological processes, but as social processes. Within the learning sciences, Wenger (1998) foregrounds learning and identity as characteristics of practice that take shape as people engage in social activity, make meaning of their participation and community membership, and connect that meaning to themselves. Wenger (1998) demonstrates that learning and identity are negotiated outcomes of participation in social activity that are intricately linked; learning is a process of becoming by which our experiences and their social interpretation inform one another. Wenger's theory of learning and identity, however, does not account well for the ways that social activity is embedded in larger systems of power and privilege, which constrain the meanings available for negotiation. Holland et al.'s theory (1998) of *figured worlds* lends us a sociopolitical lens for understanding how processes of learning and identity take shape within activity organized by hierarchies and status.

Figured worlds and frames

Figured worlds rests upon people's abilities to shape and be shaped within "collectively realized 'as if' realms" (Holland et al., 1998, p. 49). In his study of child development, Vygotsky (1978) was fascinated by children's abilities to construct and enter into imaginary worlds where the everyday meanings of objects were set aside and replaced by imagined ones. For example, in children's play the meaning of a sheet as material to cover a mattress is suspended, and instead becomes a cape that empowers a superhero to fly. Drawing on Vygotsky (1978), Holland et al. (1998) suggest that it is people's ability to collectively imagine and enter conceptual worlds that makes figured worlds possible.

A figured world is a "socially and culturally constructed realm of interpretation in which particular characters and actors are recognized, significance is assigned to certain acts, and particular outcomes are valued over others" (Holland et al., 1998, p. 52). Activities (in the world of general chemistry: exam taking), narratives ("chemistry is a weed out class"), and artifacts (grades) take shape within and give shape to figured worlds. Figured worlds are populated by sets of particular kinds of people (professors, graduate student instructors, undergraduate students), engaged in meaningful actions (sitting in the front of the lecture hall, answering questions, getting As on exams), and propelled by forces particular to the world (looking smart, understanding material, passing the course). Holland et al. (1998) describe figured worlds as organized around positions of status and power (intellectual ability, race, gender) and the narratives that suggest particular kinds of people and how they should interact (the dismissive professor and the Black woman who is not good at science). Altogether, the social organization of figured worlds mediates people's agency and identity via its artifacts, narratives, and positions as people participate in day-to-day activity within it.

As events and people get categorized in particular ways within worlds, we develop expectations for how activity should unfold and for the roles different people should take on within it (Hand et al., 2012; see also Lakoff, 1987). I find Goffman's (1974) concept of a *frame* to be productive for understanding how figured worlds cue and organize these situated expectations in ways that mediate moment-to-moment activity. A *frame* answers the question: "What's going on here?" (Goffman, 1974). It guides the meaning of a particular situation, implying certain kinds of actors with particular roles and making certain kinds of actions sensible (Goffman, 1974). Frames are not stable, nor are they necessarily aligned across participants (Hammer, Elby, Scherr, & Redish, 2005). Instead, they are collectively constituted in moment-to-moment interaction as participants draw on contextual cues within figured worlds to make sense of and organize their activity (Goodwin & Duranti, 1992). Frames are only said to be 'at play' when people act as if they are functioning (Goffman, 1981; Greeno, 2009; Hand et al., 2012). A particular action misaligned within a frame 'at play' can signal a shift to a new frame. For example, a punch that lands too hard might shift an activity from play to fighting. Given the ways that individuals mobilize around frames as they engage in activity, framing analysis serves as a useful analytic tool for examining how figured worlds play out in moment-to-moment interaction.

Identities of competence mediated within figured worlds

Consider how the figured world of general chemistry (which I see as consistent with the larger cultural world of school science) constructs particular self-understandings in relationship to chemistry. Before the semester starts, students tell one another stories about how difficult the course is and how few students pass the course; it's a weed-out course designed to show students whether they can "hack the sciences," and racial narratives posit the skin colors of students with the intellectual talent to do so. Undergraduate students who are just beginning their college experience, new graduate student instructors, and professors populate the world of general chemistry. Within the course, students occupy seats in a tiered lecture hall facing forward. They are expected to acquire understanding from an expert professor positioned in the front of the room. They answer questions and try to avoid asking questions in class. Outside of class, students practice problems, memorize important terms, and form study groups as they prepare for exams. They worry: "Will I pass the exam?" "Will my peers or professor think I'm smart?" "Do I have what it takes to be a science or engineering major?" They take exams and compare their scores against the average. Altogether, these acts take on significance as students come to understand themselves as more or less able, more or less competent, and more or less fit for the sciences. In line with Horn's (2008) description of the figured world of the mathematics curriculum, the figured world of general chemistry socially organizes participants. In doing so, it (re)produces historical notions of scientific ability and divides students accordingly.

The instructor-centered activities and tools, such as lectures, individual practice worksheets, textbooks and exams, that construct the world of general chemistry cue what scholars have termed a *doing school* frame (Hand et al., 2012). *Doing school* organizes particular roles and positions for instructors and students. Within this frame, instructors are presumed to be expert knowledge-holders, responsible for deciding what students need to know and imparting that information to them. Students are presumed to be novices and are invited into rather passive and powerless roles as knowledge-receivers.

By implying particular roles and positions for different kinds of people, frames have implications for relations of power between actors.

Altogether, people develop different senses of themselves in figured worlds, because senses of self are grounded in experiences of power, and because frames constrain access to the social positions that afford experiences of power for certain kinds of people. Research that has analyzed the structure and function of racial narratives in STEM learning environments gives us insight into the ways that narratives unequally distribute students' freedom to identify with particular subject positions (Nasir & Shah, 2011). Narratives encompass beliefs about the actors and/or the activity taking place in the world. They reflexively take on meaning and constrain meaning as they get appropriated by and deployed within social interaction. Narratives, such as *Asians are good at math* or C*hemistry is a weed-out course,* create subject positions that recruit, for example, African American students into the subject position of someone who lacks the innate talent to be good at math (Nasir & Shah, 2011), or a struggling chemistry student into the position of someone who is a weed that does not belong in the up and coming crop of scientists (Palmer, 2016). Individuals coordinate around cultural narratives via the frames they engage in moment-to-moment interaction (Hand et al., 2012). While narratives serve as resources for positioning, it is important to understand narratives as co-constructions whose meanings get modified and repurposed in use by the people who use them. McGee and Martin (2011) highlight how academically successful Black engineering undergraduate students manage racial narratives about ability, using them as a means of motivation towards high achievement. The engineering students in this study never fully defied racial narratives, but they repurposed them to fuel their desire to excel in ways that challenged societal expectations.

Developing an identity as a competent and capable chemistry learner requires that students have experiences in which they recognize themselves and are recognized by others as competent in moment-to-moment interactions governed by frames. In Chapter 1, I argued that competence is constructed in the figured world of general chemistry in ways that constitute a narrow set of students as "smart" while constituting many others as not-so-smart. In order to understand how some students are taught their intellectual supremacy while others their intellectual inferiority, we must first acknowledge the socially constructed nature of competence. Competence is not a merely a collection of skills or abilities, nor is it solely individual or communal - competence is negotiated in practice and what counts as competent reflects what the community values (Wenger, 1998). Often, competence in science courses is constructed in a narrow sense - what students need to know and do to be "correct" (Gresalfi, Martin, Hand, & Greeno, 2009) - and competence is almost solely assessed via students' answers to multiple choice or short answer questions on high stakes exams. This version of competence reifies understandings of science as a finished body of objective answers. Gresalfi et al. (2009) illuminates more expansive versions of competence. For example, a student who shares a mistaken idea, asks a clarifying question, or who justifies their answer with evidence all could be seen as competent in a classroom where these practices are considered useful for science learning.

Drawing on the work of critical race theory, Leonardo and Broderick (2011) contend that conceptualizing competence as a social construction does not help us to fully account for the oppressive ways that power and privilege operate in educational environments. They invite us, instead, to consider constructs like competence or smartness as "systems of ideology that operate to constitute and sustain unequal relations of power" (p. 2219). Similar to Whiteness, competence and smartness are relational systems that cannot exist apart from their denigrated other, the incompetent or the not-so-smart (Leonardo & Broderick, 2011). Such constructs exist solely to stratify people along a spectrum of ability, offering material advantage to those who develop identities as "smart" or "competent" in the form of particular kinds of honor, investment, and access to opportunities (Leonardo & Broderick, 2011). Moreover, ability is not the only ideological system at work in the constitution of people as competent - competence is bound up with racist, classist, and sexist ideologies as well. Following the assumption that the concept of smartness is false and oppressive, Leonardo and Broderick (2011) argue for the need to disrupt smartness as it operates as an ideological system. However, their theoretical analysis falls short of offering possible avenues for doing so in practice.

Viewing the space of general chemistry as a figured world is productive for understanding how activities, narratives, and artifacts serve as resources for organizing and interpreting moment-to-moment interaction through frames. Altogether, figured worlds offers a promising theoretical lens for examining how broader cultural narratives and the design of traditional general chemistry lecture courses interact to mediate the experiences of low income students of color, such that many are supported to walk away from the course feeling incapable (i.e., "I don't have what it takes to be successful") and/or alienated (i.e., "this isn't for me"). Such experiences in general chemistry along racial and gendered lines points to a pressing need to re-figure and re-frame the world.

Imagining alternative worlds and social design experiments

Holland et al. (1998) demonstrate that new worlds can be imagined. For example, the authors describe how women envisioned counter-worlds that rearranged gendered relations through political songs at the yearly Tji festival in Naudada, Nepal. These songs contested the roles and positions afforded to women in Nepal and instead sung of a world in which women had equal value and rights. While these songs imagined new storylines, new values, and new roles for women, the Tji festival happens only once a year. Consequently, the newly envisioned world did not yet have the space or the power to up-end the dominant world of gender relations in Naudada.

Given that figured worlds are formed and re-formed in relation to the everyday activity, positions, meanings, and artifacts which figure them (Holland et al., 1998), re-figuring worlds requires significant social transformation. Within the learning sciences, social design experiments have been proposed (Gutiérrez & Jurow, 2016; Gutiérrez & Vossoughi, 2010) as a methodological approach for envisioning, constructing, and researching new equity-oriented cultural systems. Grounded in cultural historical approaches to learning and development (Engeström, 2011), such design experiments are built from the assumption that changing the individual circumstances for youth from non-dominant communities requires a significant restructuring of educational systems that oppress. By focusing on educational systems rather than individuals, social design experiment approaches attend to the ways that different aspects of activity systems – tools and artifacts, roles and positions, norm and values – work together to mediate students' participation, learning, and identity.

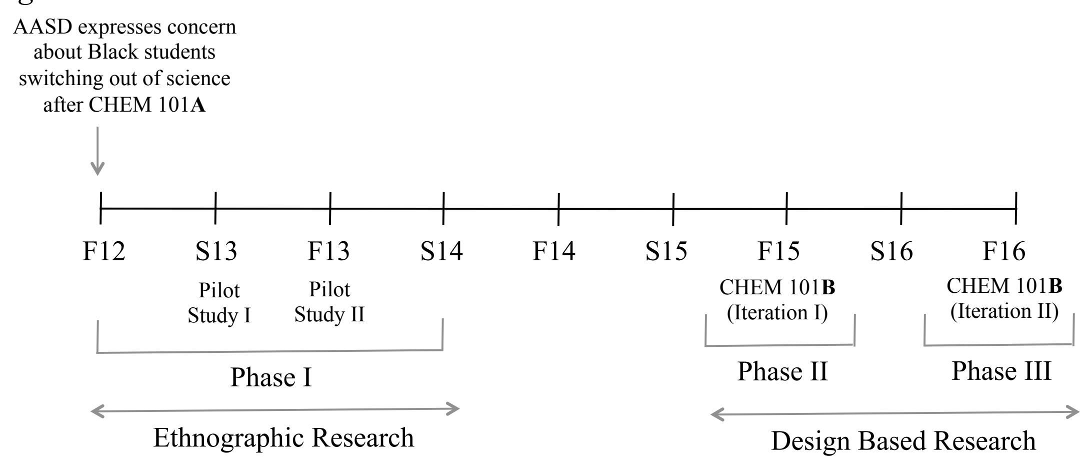
My dissertation draws from theories of figured worlds, framing, and social design experiments to re-figure a general chemistry course towards transformative and more equitable ends. In line with Gutiérrez & Jurow (2016), analyses of the newly designed world of general chemistry in CHEM 101B focuses on the interaction between individual students and their social world, including the course activity system, the social interpretations of its practices, and the present and historical narratives that students must negotiate as they participate in order to understand how learning and identity are mediated within it. As I will discuss further in Chapter 3, the redesigned course was situated within the context of broader university systems and policies (i.e., assessment and grading policies) that added complexity to our research team's world-building efforts, raising questions about how designers, instructors and students navigate the contradictions inherent in any world-building work.

Chapter 3: Methods

This dissertation evolved from empirical and professional questions that emerged during my time as a graduate student instructor for the introductory chemistry lecture course – CHEM 101A. CHEM 101A is a one-semester general chemistry course for non-chemistry majors. It is typically the first science course students in STEM majors take during their first year at the university, and is a prerequisite to both advanced chemistry courses for non-majors and required biology and engineering courses. Students in the course represent majors across the fields of biology, engineering, natural sciences, and pre-medicine.

In Fall 2012, I was invited to a series of conversations organized by the director of the office of African American Student Development (AASD) and a professor emeritus in the Department of Chemistry to discuss concerns about the numbers of African American students who start out as STEM majors, yet change their major due to stress and the belief that they cannot do the coursework required by STEM courses. In their experience working with students, they found that introductory chemistry was the turning point for those who changed majors. Though my research questions have shifted over time, my personal experiences supporting students in CHEM 101A and the conversations launched by AASD were the foundation for my initial research questions: (1) What are the experiences of students of color in CHEM 101A? (2) How can instructors best support the science identities of students of color in general chemistry?

Figure 1. Evolution of dissertation research



This research began as a project to better understand why CHEM 101A had so much power to influence students' conceptions of themselves and their sense of belonging in the sciences, and subsequently grew into a design-based research study that draws on principles foregrounded in social design experiments (Gutiérrez & Vossoughi, 2010). In this chapter, I talk about the evolution of the project in three phases (see Figure 1). Phase I includes two exploratory pilot studies carried out in Spring 2013 and Fall 2013 with students enrolled in CHEM 101A. The first pilot study investigated the experiences of students of color in CHEM 101A. The second explored students' sense-making about two narratives that populate the world of general chemistry: "Asians are good at science" and "chemistry is a weed-out course." Emergent findings in Phase I informed Phase II of the study, which includes our research team's first attempt at designing and studying a new stand-alone general chemistry course in Fall 2015. I refer to the new stand-alone course throughout this dissertation as CHEM 101B. Phase III represents our research teams' second attempt at iterating upon the design of CHEM 101B in Fall 2016. My findings chapters focus their analyses on data collected in Phase III. In the sections that follow, I discuss the first and second iterations of CHEM 101B course design in Phases II and III, but detail research questions, data collection, and analytic methods for Phase III only.

Research Setting

This study took place at a top tier, public university in California (pseudonym California University). The university student population is predominately Asian and White. The general chemistry course in this study, CHEM 101, is a one-semester, introductory general chemistry course covering topics in structure-property relationships, thermodynamics, equilibrium, acid-base chemistry, and quantum chemistry. The course meets for three 50-minute sessions per week and is facilitated by a professor of record and graduate student instructors (GSIs).

> CHEM 101**A** refers to the traditionally-designed lecture-oriented course, which is taught in a large lecture hall of 500 students.
>
> CHEM 101**B** refers to the student-centered collaborative discussion-based course our research team newly designed and that I report on in my findings chapters. CHEM 101B is taught in a large active learning classroom.

Phase I – Pilot Studies

The design-based research study reported on in this dissertation was informed by two pilot studies I carried out in Spring 2013 and Fall 2013. In the first study, I conducted focus groups with Chicano/Latino and African American students to better understand how students of color navigate and make sense of their experiences in CHEM 101A. In the second study, I collected interview data to explore students' sense-making about the "chemistry is a weed-out class" narrative that emerged from students in the first study and how this narrative about chemistry interacts with racial narratives linking race to ability in science.

Pilot Study I

This exploratory study draws on data collected from two focus groups with students enrolled in CHEM 101A in Spring 2013. Participants in the first focus group included four Latino and six Latina students who were in the second semester of their freshman year at the time. The students were part of the Corazón (pseudonym) Chicano/Latino theme program, a live-in familia housed within the residence halls of the university that allows students to explore Mexicano/Chicano and Latino culture and foster a sense of community among the Corazónitas. The second focus group included four African American young women who were in their second semester of freshmen year. Students were invited to the focus group by the director of AASD.

The focus group conversations were framed as an opportunity for students to share their experiences in CHEM 101A in order to inform the design of social and structural supports for improving the class. Focus group questions centered on the students' experiences in the course, including questions about their expectations for beginning chemistry, their approach to being successful in the course, the climate of lectures and discussions, how language affected learning in the course, their interest in science, and whether beginning chemistry had affected their trajectories in science.

During the focus group conversations, I was particularly interested in the rhetoric students used to describe the course. Students talked about the class as a "jump" or a "road block" standing in the way of their larger professional goals, rather than helping them accomplish those goals. And students' talk seemed to treat the course as designed to test their ability to handle the rigors of medical school or future science courses. As one student explained: "It was a road block, because I know a lot of people say it's like the class that you don't think you can handle it, then they don't think you can handle sciences, so you go a different way" (Mera, African American Student, Focus Group 2).

Other students explicitly named this process of testing as a "weeding out" and named the course as a "weeder" or "weed-out" class. In the excerpt below, Isha, a molecular biology major and aspiring pediatrician, is responding to a question about her interest in science. She begins her response by explaining why she chose molecular and cellular biology (MCB) as her major, but her answer quickly moves into her uncertainty about whether or not she will be able to continue on this pathway given her experiences in general chemistry:

> I have to take three semesters as well, of chem, before I can get into biology. Chemistry- I was just dreading that. It's making me question what I want to do, if I still want to go down the MCB route. Because everybody's like "You could try integrative biology" and that sounds interesting, but I still have to do all this stuff. So should I change to public health and still be on a pre-med track? Should I do that 'cause that seems like something I can handle? Because, I really, it's like, If I can't get through this general chemistry that's the weeder class, they've weeded me out. Because I'm just like struggling so much in the class. (Isha, African American Student, Focus Group 2)

At the time that I was conducting these focus groups, I was beginning to explore Nailah Nasir's work around racial narratives about ability, such as "Asians are good at math," and the ways these narratives socialize people to think about race in particular ways. I was new to and compelled by the idea that sociocultural discourses have the power to shape meaning-making about activity and the practice-based identities students construct. This body of work left me wondering how the narrative of "chemistry is a weed-out class" was shaping students' understanding of their competence and belonging in relationship to science. I wanted to explore more deeply the content and function of the weed-out narrative. Moreover, given the racialized nature of intelligence in America, I was curious about whether the weed-out narrative interacted with the racial narrative of

"Asians are good at science" as students build a sense of their scientific competence and belonging. I explored these questions further in my second pilot study.

Altogether, the focus groups illuminated the extent to which students experienced the course as a kind of trauma. For many students in the focus group, introductory chemistry made them deeply question whether they belonged in the sciences at all and/or left students feeling frustrated that the course was so difficult for seemingly no reason and so disconnected from their identities as future biologists and health professionals.

In response, I partnered with a chemistry professor, Angelica Stacy (who chairs this dissertation), and a graduate student, Sara Tischhauser, to design a supplementary discussion section to CHEM 101A that we rolled out in Fall 2013, which we referred to as Small Section. This section aimed to provide opportunities for students to interact in a smaller learning environment organized around collaborative problem-solving. Problems were designed to support students in seeing the real world applications of chemistry. Following the first CHEM 101A midterm, students who earned less than a 47% on the exam received an email invitation from their chemistry professor to participate in the supplementary section.

Pilot Study II

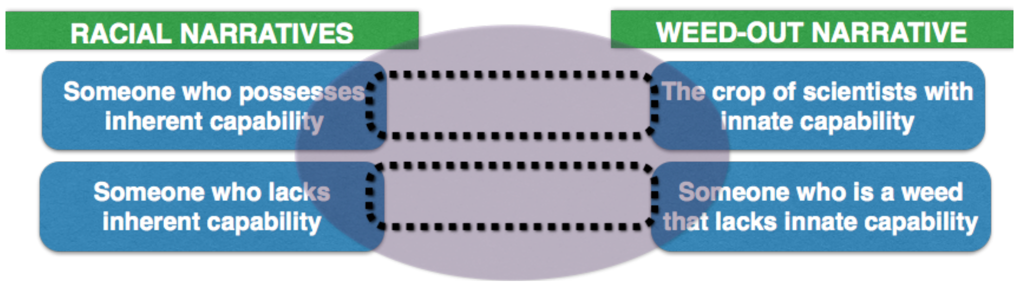
My second pilot study was an extension of the first pilot. Participants were students enrolled in CHEM 101A who were invited to join the newly designed supplementary discussion section (Small Section) after scoring less than a 50% on the first midterm. Small Section was intended to deepen students' understanding of the content covered in CHEM 101A by engaging them in collaborative problem-solving in small groups and in large group discussions of the lecture material.

Given the weed-out narrative's potential connection to issues of persistence and retention of students of color in the sciences, I sought to characterize the range of ways students made sense of the weed-out narrative and how the narrative affected students' experiences in the course. Small Section students were in a unique position to shed light on the role of the weed-out narrative given that they had the experience of failing the first exam and of engaging in an alternative context designed to provide students with extra support.

I collected semi-structured interviews to probe students' sense-making about both the weed-out narrative and the "Asians are good at science" racial narrative. Interviews were audiotaped and transcribed in full. On my first pass through the interview transcripts, I focused my attention on how students made sense of the weed-out narrative. Fourteen of the fifteen students interviewed were aware of the narrative and readily articulated an explanation about the mechanism for how weeding-out works and about who is to blame when students are weeded out. Through a process of open coding (Corbin & Strauss, 1990), emergent themes were developed in relation to students' explanation of the narrative. The interviewees' weed-out stories made sense of the roles and responsibilities of characters involved (e.g., students are responsible for weeding themselves out) and the processes at work (e.g., the course weeds students out based on their ability in science). In my analysis, I traced students' sense making process about how the weed-out narrative functioned for them in the course. Most students understood the course as separating the smart students who can "hack the sciences" from the not-so-smart students who should reconsider their path. While students understood the weed-out narrative in different ways, each version of the weed-out storyline led students to understand their struggles in the course as a problem with themselves, rather than with the pedagogy or the way the discipline is constructed. By placing the onus on the student who is in most cases failing, the weed-out narrative perpetuates deficit perspectives about students and does not support systemic change.

I then analyzed the ways students draw on the weed-out narrative and racial narratives as they build identities of scientific competence. It was evident in the data that both the weed-out narrative and the racial narrative suggest subject positions for struggling students as people who lack the innate capability to succeed in science (Figure 2). Both narratives sow doubt about students' senses of competence and their belonging in the sciences.

Figure 2. Overlapping subject positions produced by racial and weed-out narratives



Altogether, this study adds to evidence that narratives are salient aspects of science learning environments that come to bear on how students think about themselves in relation to the discipline through processes of positioning (Nasir & Shah, 2011). An important take-away for me was that messages about race or about weed-out courses are not created in this chemistry class, but that the course instead serves as a context where messages about race and competence are made available, taken up, or resisted. In other words, the practices of the large lecture course (CHEM 101A) and their social interpretation make racial narratives about scientific ability available for students to access.

Altogether, we saw some evidence that Small Section expanded some students' notions of what counts as "good at chemistry." However, these meanings were largely constrained by the dominant world of general chemistry in the CHEM 101A lecture course. It was becoming clear that constructing a new "web of meanings" about chemistry and competent chemical participation would require re-designing the course activity system organized around new tools, new participant structures, and new norms. In the sections below, I describe our design-based research that draws on principles foregrounded in social design experiments (Gutiérrez & Jurow, 2016) to redesign the general chemistry course. Recall that the re-designed course will be referred to throughout the chapter as CHEM 101B.

Moving into Phases II & III: Design-Based Research as a Methodological Approach

Design-based research (DBR) is a problem-based, collaborative, and iterative approach to research that focuses attention on how learning takes place within the complexity of a learning environment in its attempt to contribute to learning theory and educational practice. My work builds on design experiment approaches that aim to effect broad social change through small scale transformation in systems of educational activity. Gutiérrez and Jurow (2016) have proposed social design experiments as a model for small scale transformations by organizing design around the three key principles of equity, re-mediation, and historicity, and by focusing analysis on the interaction between the individual and the social world (Gutiérrez & Jurow, 2016).

Creating access to consequential chemical learning and positive chemical identities requires more than the introduction of new pedagogical practice. Instead it requires reorganizing all aspects of the course activity system in ways that work towards shifting students' social interpretation of the activity within it. In other words, it requires constructing an alternative figured world where students are engaged in authentic chemical activity and are supported to see that competent chemical thinking and learning include a diverse set of practices, skills, perspectives, and understandings.

I employed DBR in Phases II and III as a way to intervene in the current practices and discourses of undergraduate chemical education, and as a way to create and study new processes of learning and identity in interaction. My dissertation investigated the extent to which the new design of CHEM 101B supported students to take up invitations into new chemical activity and new, more inclusive meanings about chemical participation.

The design questions that guided Phases II and III include:

1. How do we design a classroom system that supports rigorous chemistry learning – according to the tools, practices, and norms of the discipline?
2. How can we support students to understand chemical thinking and learning in ways that are more authentic to the discipline, and how do we disrupt narratives linking success in science to innate ability?

Before turning to specific data collection and analysis methods, I describe the context and design principles informing iterations of redesign of CHEM 101B, making visible how these principles are instantiated in the design.

Design and Research Team for Phases II & III

The design and research team for Phases II and III consisted of a chemistry professor, Angelica Stacy, a postdoctoral fellow, Sabriya Rosemond, and myself. All three members of the design team were actively involved in designing and implementing the CHEM 101B course. Angelica Stacy is a highly experienced instructor who has been involved with teaching CHEM 101A at the university for over 20 years. She was the professor of record in CHEM 101B. In keeping with her role as the head instructor for the course, she launched and closed each lesson. Both Sabriya and I were active facilitators during class.

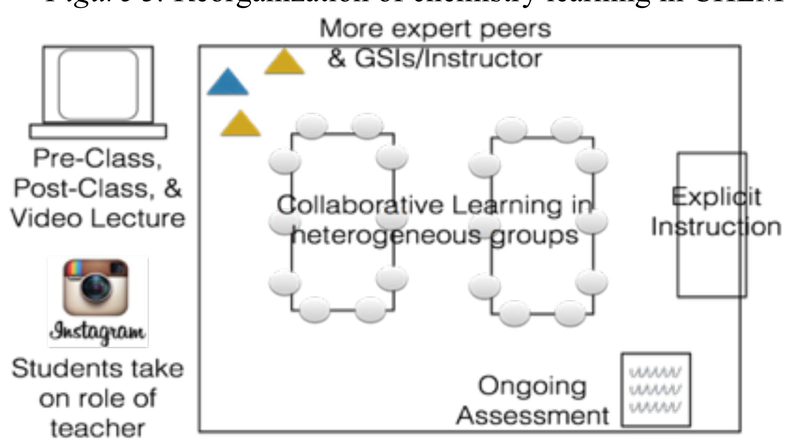
Phase II: Design of the First Iteration of CHEM 101B

In this section, I describe our research team's efforts to redesign the entire classroom system of CHEM 101A. During this stage of the project, we drew from equity-oriented education research to articulate a set of opportunities that matter for learning and identity that we hoped to provide students via course design. In the sections below, I discuss how we instantiated these opportunities in the activity system of CHEM 101B, and I share what we learned from this first iteration of design.

Based on insights gleaned from Phase I of the study, we aimed to redesign CHEM 101A with three explicit goals in mind: (1) to support students to see chemistry as a social practice rather than a body of knowledge to be acquired, (2) to expand opportunities for students to experience themselves as competent thinkers and doers of chemistry, and (3) to help students experience chemistry learning as consequential by connecting chemistry to other scientific disciplines (e.g., biology, engineering, etc.) and to the everyday.

Our efforts to redesign CHEM 101A included reorganizing how learning was supported both within and outside of class. Across the design, in and out of class activity, we aimed to make a set of opportunities that mattered for learning and identity development available to students. These included opportunities for students to: (1) make their own sense and engage in the sense-making of others, (2) see science as connected to self and to larger social issues, (3) engage in valuable social relationships, (4) feel safe and take intellectual risks, and (5) be recognized as competent and capable chemistry learners.

Figure 3. Reorganization of chemistry learning in CHEM 101B



Building these opportunities into the course meant reorganizing the physical classroom space and participant structures. Rather than sitting in rising rows facing the front of a lecture hall, students were seated around tables of eight to support collaborative work. Because nearly all the science-oriented spaces at the university were lecture halls, finding space for our class of 66 students was a difficult task. We settled on dividing the students between three smaller classrooms within the chemistry library. Figure 3 illustrates the social organization of learning within the classroom of Section 4. Within their table groups, students organically formed smaller groups of 2-4. Joint activity was valued over individual problem-solving. Students had access to multiple forms of assistance during collaborative work. The instructor of record and GSIs rotated across the three classrooms. Each instructor independently introduced and closed the day's work in their respective classroom. Undergraduate student instructors (USIs), undergraduate mentors who have taken introductory chemistry and earned an A or a B in the course, were assigned to a specific classroom as instructional assistants.

We aimed to shift intellectual agency and authority to students (Barton & Basu, 2007; Engle & Conant, 2002; Gresalfi et al., 2009; Horn, 2008; Lemke, 1990). Grounded in the science and mathematics literature on learning and identity, we conjectured that students learn deeply and are most likely to develop identities as scientific thinkers when they are positioned to author scientific knowledge by engaging in the practices of scientists. Rather than mostly listening and taking notes as students would typically do in a lecture-based chemistry course, in CHEM 101B, students were provided the opportunity to make sense together via the scientific practices of analyzing data, interpreting and using models, and constructing explanations from evidence.

The professor and GSIs did, however, take up the role of expert chemist through direct instruction during the first and last ten minutes of class, introducing and closing the day's activities. Additionally, after class, students watched an online lecture created by the professor. The lectures served as a tool for modeling how an expert chemist might think through the problems students encountered in class. Explicit instruction about chemistry concepts also happened during lecture.

Redesigning the course also meant changing the core activities we engaged students in. Students in CHEM 101B regularly engaged in the following core activities, each of which is elaborated upon in more detail below:

- Pre-class and post-class assignments
- In-class assignments organized around joint activity
- Chemistry of Stress project
- Science Skill reflections

Pre-Class, In-Class and Post-Class Assignments

Three types of assignments were used to scaffold students' chemical understanding. A pre-class assignment typically asked students to a) observe and explain an everyday phenomenon, b) explore a collection of data, or c) investigate a computer-simulated model. Students were often directed to notice specific variables and construct an explanation about the relationships between them based on observable patterns. These assignments were designed to give students an opportunity to engage in chemical thinking on their own before coming to class to work with others.

The in-class activities used the pre-class activity as a launching point to further challenge and grow students' understanding of the concepts. Three main tools scaffolded joint activity. First, each subgroup at a table was provided a data sheet that students were directed to keep in the middle space. Data sheets contained data sets, representations of substances at the molecular and macroscopic level, or representations of models. In essence, the data sheets were a collection of artifacts to engage students in collective thinking. Second, a worksheet, referred to as the in-class assignment, provided students with a set of questions, tasks, or problems to guide their interaction with the data sheet. Third, dynamic visualizations technologies, such as PhET (https://phet.colorado.edu/) or The Concord Consortium (http://concord.org/), were used as tools for modeling interactions at the molecular level. Additionally, Jmol (http://jmol.sourceforge.net/), a tool often employed by professional chemists, was used to visualize representations of chemical structures as large as proteins. The students primarily used Jmol to visualize structures related to their Chemistry of Stress project described below.

Following the online lecture, students completed the post-class assignment. This assignment involved a mix of conceptual and computational questions that asked students to think with the chemical models they had developed in class.

Chemistry of Stress Project

In addition to providing opportunities for students to make their own sense and engage the sense-making of others, we conjectured that students' learning and identity are supported when students are able to make meaningful connections between their lives and the chemistry they are learning (Barton & Basu, 2007). Because our class serves students who are non-chemistry majors, many of whom are on the pre-medical track, we focused on connecting chemistry to biology and human health. Our course partnered with the university student health center to create an Instagram account that would be used by the health center to educate other university students about the chemistry and biology of the body's stress response. The questions students explored in this project included: (a) What causes university students to feel stress? (b) How does stress manifest itself in our bodies? (c) How do the structure and properties of cortisol allow it to travel in the blood and signal a stress response in the body? (d) Which researchers study stress? and (e) How can people alleviate stress?

Students were expected to take the chemistry they had learned in class and translate their knowledge into language that any university student would understand. They were then asked to find an image that would be uploaded on the Instagram account to support their audiences' understanding of their post. Students worked in groups of 3-4 on each post. They completed eight posts over the course of the semester. This project was meant to position students as expert knowers and gave students practice translating back and forth between the scientific and the everyday. The Instagram account constructed by the class was shared on the university health center's website.

Science Skill Reflections

Enduring socio-historic meanings of what it means to be a scientist shape students' understanding of who can do science, what science is and what it means to be good at science. The science skill reflections were designed to serve as a "mirror" (Engeström, 2011; Gutiérrez & Vossoughi, 2010) to foster reflection about students' mindsets towards their own learning and interaction in class. We sought to turn students' unexamined assumptions about being successful at science and turn them into examined ones. Students completed six science skill reflection assignments over the course of the semester. They identified the skill they wanted to examine each week and wrote about their progress in those skills in the Science Skills Development Form. The skills students could choose to reflect on were the following: (a) bouncing back from setbacks, (b) diligent skepticism, (c) intellectual courage, (d) collaboration, (e) connections, and (f) resourcefulness.

Table 1. Instantiation of opportunities for learning and identity in course activity

Opportunities that matter for learning and identity	**Chemistry of Stress Project**	**Pre-, In- and Post-class assignments**	**Science Skill Reflection**
Opportunities to make their own sense and engage in sense making of others (shift authority/ agency) (Barton & Basu, 2007, Engle & Conant, 2002; Gresalfi, et al., 2009; Lemke, 1990)	Students talk about science and collectively decide how to translate their own understanding to the public.	Students can make sense of chemical ideas individually and together, and engage in the practices of "talking science." (requires collaborative culture and equitable participation)	
Opportunities to see science as connected to self and to larger social issues. (relevant science) (Barton & Basu, 2007)	Project facilitates students to think both about how stress affects all humans, themselves in particular and then asks them to make sense of stress in terms of underlying chemical processes in the body.	Problems are often contextualized in everyday scenarios, particularly related to biology and stress.	Students are given opportunities to reflect on the connections they are making between chemistry and themselves.
Opportunities to engage in valuable social relationships (Barton & Basu, 2007)	Students can forge relationships with one another outside of class	Students can form supportive, collaborative relationships with one another and form supportive relationships with GSIs and teaching scholars.	Students are given opportunities to reflect on the ways in which they engage in group work.
Opportunities to feel safe and take intellectual risks (Nasir, Rosebery, Warren, & Lee 2006)		Asking questions and expressing both what students do know and where whey are confused is a norm of the class.	Students are given opportunities to reflect on their intellectual courage
Opportunities to experience self as competent and capable science learner (Horn, 2007; Wenger, 1998; Holland, 1998)	Project positions students as having expertise in the chemistry of stress - it is their job to share their knowledge with Cal community via Instagram.	Students have opportunities to explain within their groups, to the class via group presentations, make connections between ideas - all of which might be recognized by peers, teaching scholars or instructors	Reflection is designed to broaden what students think of as competent or central for success in science. The reflection gives them an opportunity to reflect on how they interpret what it means to struggle.

Summary of learning in Phase II

In the sections below, I share how data collected in field notes, classroom video, and interviews illuminated what was and what was not yet working about CHEM 101B in the first iteration of course design.

For some students in CHEM 101B, participation in new chemical activity did some work to expand their conceptions about what it meant to do chemistry and to be good at chemistry. In general, students came to understand that chemistry learning was about understanding and applying chemistry to the real world, and not about memorization. That said, students were not yet talking about chemistry as a verb – as a set of practices people engage in to iteratively construct the new understanding they referenced. In other words, while students' notions of chemistry and chemical learning did shift, their articulations of chemistry still tended to prioritize the knowledge chemical investigations produce, rather than the process through which chemists participate in investigations.

In addition, many students reported not understanding the big idea for the day or what they were supposed to have learned. This finding was not altogether surprising – during class we had noticed that students often approached each question on their worksheets as a separate endeavor, and thus were not provided with enough support to make holistic connections. Altogether, it became clear to us that the worksheets we intended to support joint activity were not yet sufficiently organized around big ideas.

Further, in class, we observed uneven patterns of participation that shut down opportunities for all students to learn chemistry and to experience themselves as competent. It was clear to us that the in-class worksheets we designed privileged students who entered our class with more formal chemistry knowledge. This privileging had the effect of shutting down inquiry and separating students into those who "know" and those who "do not know." Worksheets also allowed students to work at uneven paces. Further, patterns of participation across teams varied significantly, depending on the relationships and norms students built within their teams. In interviews, students also talked about the ways in which fears about being wrong or asking "dumb" questions held them back from participating to their full capacity.

Altogether, data collected in Phase II suggested that we needed to more explicitly work to (1) remove barriers to equitable participation in teams, (2) develop norms and practices that foster interdependence, (3) develop more explicit language to name the practices and mindsets that matter for competent chemical participation, and (4) design chemical tasks that invite students to collectively investigate big chemical ideas.

Phase III: Design of the Second Iteration of CHEM 101B

Moving forward into Phase III, our research team articulated a framework for equitable course design grounded in a series of assumptions about chemistry, learning, teaching, and students, as well as a set of design principles that guided the second iteration of CHEM 101B course design. These assumptions and principles draw heavily from literature on Complex Instruction, an equity-oriented set of pedagogies and techniques to equalize status and support rich and equitable mathematics learning in K-12 classrooms

(Cohen & Lotan, 1995; Boaler & Staples, 2008). In the sections that follow, I describe our framework for equitable course design, articulate our design principles, and then describe changes we made to course design through the lens of these assumptions and principles.

Framework for Equitable Course Design

The primary question we were asking as we moved into Phase III was: How do we develop a chemistry learning environment where all students' "scientific smartness" is allowed to surface, be recognized, and be developed? The following assumptions about chemistry, students, teaching, learning and intelligence undergirded our work towards rich and equitable chemistry instruction. First, that chemistry is a social practice involving the investigation of chemical substances and phenomena in search of explanations for their properties and behaviors. Secondly, that chemistry is not primarily body of knowledge, but instead a creative and powerful way of thinking and building new understanding to explain everyday phenomena in chemical terms (Sevian & Talanquer, 2014; Cohen & Lotan, 1995). Third, we see competent engagement in chemistry as including a diverse set of practices (i.e., asking chemical questions, identifying and interpreting patterns in data, making connections across chemical representations, supporting and revising claims using evidence, developing and revising models).

We also assumed that intelligence is multi-faceted, distributed among all human beings, and developed in and through human activity (Dweck, 2006). Thus, all students are capable sense-makers with various perspectives, skills, and understandings that contribute to the work of doing chemistry (Aguirre, Gutierrez, Martin, & Wager, 2016; Corrales, 2015; Leonard & Martin, 2013; Perkins-Gough, 2015). Learning chemistry is complex, ongoing, takes place through human interactions, and takes time (Wenger, 1998). Finally, teaching chemistry requires facilitating rich and equitable chemical thinking.

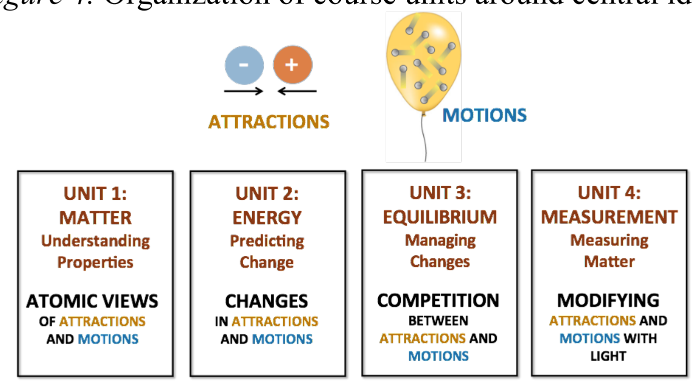
Design principles guiding the redesign of CHEM 101B included:

- Organize curriculum around big and connected ideas (Cooper, Posey & Underwood, 2017; Talanquer, 2015)
- Design chemical tasks that collectively engage students in chemical investigation (Kang; Windschitl, Stroupe & Thompson, 2016; National Research Council, 2012; Talanquer, 2015; Tekkumru-Kisa, Stein, & Schunn, 2015)
- Develop explicit language to name the practices that matter for competent chemical participation
- Foster interdependence and intellectual risk-taking (Cohen & Lotan, 1995; Nasir, Roseberry, Warren & Lee, 2006)
- Provide opportunities for students to connect chemistry to themselves and to larger social issues (Barton & Basu, 2007)

Reorganizing curriculum around big and connected chemical ideas

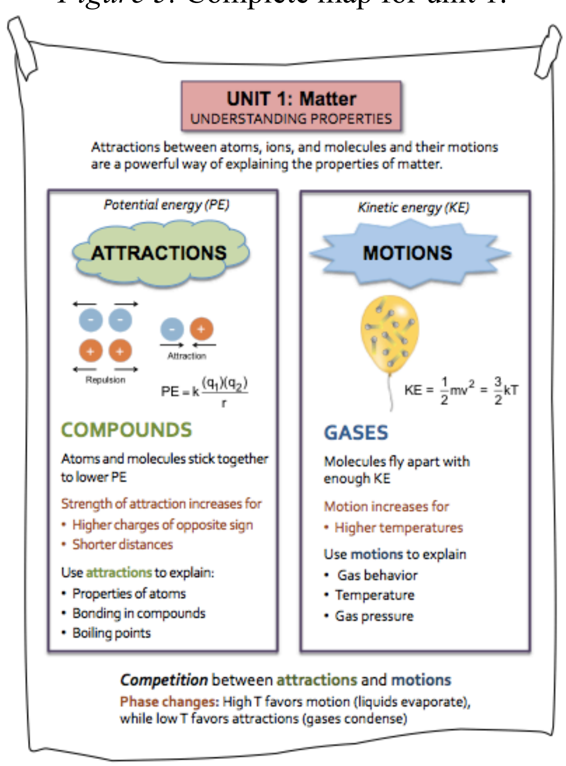
The curriculum was organized around this central idea: potential and kinetic energy considerations provide a powerful basis for explaining the macroscopic properties of matter and the ways in which matter interacts, combines, and changes on the atomic scale. Each of the four units spanning the semester was then organized around the relationship between potential energy considerations (i.e., molecular-level attractions) and kinetic energy considerations (i.e. molecular-level motions) and the observable world (see Figure 4).

Figure 4. Organization of course units around central ideas



Given that research has shown students often miss connections between chemical ideas that may be obvious to experts (Cooper, Posey & Underwood, 2017), we created maps that made visible to students how the big ideas of each task connected to the core ideas for the course. At the end of each class period, the map was populated with new ideas from the day's task (Figure 5).

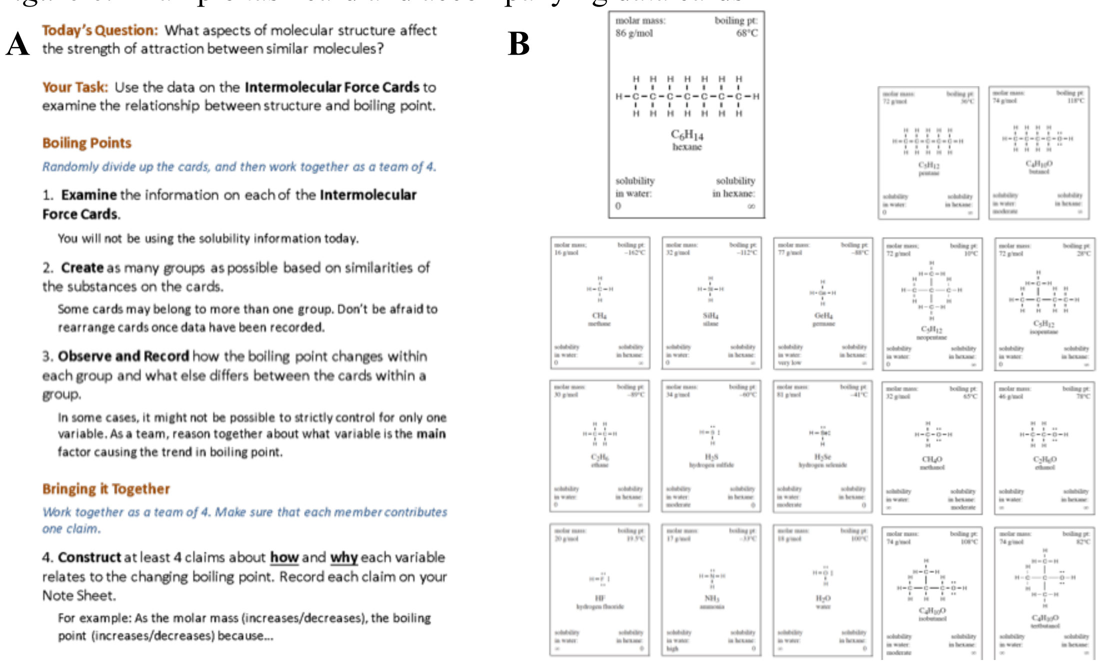
Figure 5. Complete map for unit 1.



Transforming worksheets into tasks that support collective chemical investigation

Our team returned to the in-class worksheets with the aim of transforming them into tasks that would support teams of students to engage in rich, collaborative chemical investigations. This work required our team to: (1) identify the big chemical ideas for each lesson that we wanted students to make sense of, (2) identify or generate data and chemical models to support investigation, and (3) design a clear and specific team product that would call on a diverse set of skills, practices, and understandings to complete, such that the resources of the entire team were necessary for successful completion.

Figure 6. Example task card and accompanying data cards



Altogether, we designed chemical tasks that included a task card, chemical resources, and a note sheet. The task card laid out the key question teams would need to make sense of, a short description of the task with accompanying points for discussion, and a description of the team product. Given our goal of supporting chemical investigation, each team was provided with chemical resources to investigate. These resources took the form of: (1) online simulations that required students to carry out experiments to collect their own data, (2) already collected data presented in the form of data cards to sort or data tables and graphs to analyze, and (3) chemical models in the form of diagrams, computer animations, or physical models. Resources needed to be rich enough to allow for multiple valid solutions and/or multiple pathways for successful completion. The team product was intended to make team discussion essential. Team products ranged from asking students to argue/explain from evidence, generate a set of generalizable rules from evidence, construct a model, use a model to make predictions, or design an experiment. Kang et al. (2016) suggest that tasks with these kinds of products are *high intellectual demand tasks* because they ask students to link observable phenomena or data to unobservable ideas. They tend to be open enough to support interdependence, but specific enough to support students to know when they were "done." Finally, students were provided a note sheet that often included graphic organizers to support them to organize the ideas their team produced. Each of these tools worked together to mediate students' engagement in collective chemical investigation.

Given that the worksheets in the Phase II iteration tapped into particular kinds of prior knowledge that separated students into "knowers" and "not-knowers" and created barriers to equitable participation, we removed most scientific jargon from the task cards and note sheets. We wanted to give students opportunities to discuss and make sense together without having to navigate doing so using unfamiliar scientific vocabulary, and to do so as themselves - to feel comfortable using everyday language to articulate their ideas rather than only privileging "academic" or White, middle class ways of talking.

Framing and facilitating interactions during class

We knew that the kinds of participation that would support rich chemical investigations – asking questions, offering ideas that might not turn out to be right, articulating uncertainty – are risky for students given the narrow conceptions of what counts as "good at chemistry." To foster intellectual risk-taking and to communicate more expansive views about what it means to competently participate in chemical thinking and learning, we planed to open the first five minutes of class with a task launch led by the professor. The goals of the launch were to frame the nature of the scientific thinking and learning that students would engage in, situating students' work in the larger context of the course, orienting them to the chemical artifacts that would guide their work, and to name the "smart things" they could do to think together like chemists.

The list of "smart things" was created as a tool that would do several kinds of pedagogical work. First, it was intended to communicate to students that competent chemical participation includes a wide variety of practices, skills, and understandings. Second, it was meant to invite students into these practices and to provide common language for publicly recognizing students' participation in them as important chemical work.

While students investigated, we planned that the instructors' primary role would be to step back and let students work, listening closely for opportunities to name students' questions, connections, and predictions as important intellectual contributions. We planned to use whiteboards around the room as tools for recognizing and publicizing students' chemical participation (see Figure 7). Finally, we planned to close the task by highlighting specific moments of student thinking during class and connecting it back to the competent practices named in the "smart things" list.

We also planned to institute a norm for holding teams accountable for thinking together, called "team questions." This practice meant that when students' hands were raised, instructional staff would ask anyone of their choosing in the team to articulate the team question. If that student did not know, the instructor would then encourage the team to talk together about the question to make sense of it together.

Figure 7. White boards lined the perimeter of the CHEM 101B classroom

Online video lectures

Video lectures were designed to bolster and expand upon the learning and connections students made during the task. The lectures reviewed the major points from the day's task, situated those points within the context of the unit, introduced students to formal chemical language, and provided direct instruction for skills or procedures that were algorithmic in nature (i.e. if students derived Coulomb's law in class, the lecture might focus on solving particular problems using Coulomb's law). Check-in questions were interspersed throughout the lecture to provide opportunities for students to practice using concepts from class. Students were also provided with examples of how these concepts are relevant to everyday life.

Communicating Chemistry Project

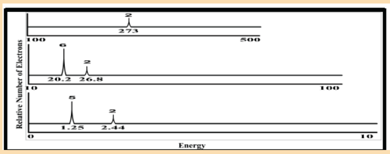
We transformed the Chemistry of Stress project into the Communicating Chemistry Project. Like Chemistry of Stress, this project was designed to help students connect chemistry to themselves and larger social issues. Unlike Chemistry of Stress, this project offered students more choice in deciding chemical topics of interest, included two audiences that mimicked the different registers at which actual chemists must communicate, and had a peer review component. At the beginning of the semester, students selected either a toxic metal salt or a hormone from a list of 20 substances. At the end of each unit, students were assigned a prompt that asked them to link the central ideas introduced in the unit to teach two different audiences—the CHEM 101B classroom community and their friends and family – about the chemistry of their substances. Each assignment included an image and accompanying text. For the family and friends audience, students were encouraged to use the language with which they were most comfortable, connect to pop-culture, and employ analogies to which their audience could relate. For the CHEM 101B audience, students were required to use chemical language, to write in a tone appropriate to giving an academic presentation, and to relate back to what they learned in class (e.g., "If you recall, in L7 we discussed polarity…"). Figure 8 includes an example prompt and excerpts from a student post. By requiring students to translate their chemistry for two different audiences, we sought to develop fluency and flexibility in students' ability to "talk science" (Lemke, 1990), and to give them opportunities to talk science as themselves. For each post, students were assigned a peer's post to read and were required to offer feedback.

Figure 8. Communicating Chemistry prompt for unit 4 and excerpts of example student work

Unit 4: Spectroscopy

Design a post to teach your audiences about how you can use **spectroscopy** to gain information about your compound (example: mercurous chloride, Hg_2Cl_2)

Classroom Community



This energy must be large enough to break Coulomb's attractions between the negatively charged electrons and the positively charged nucleus. This suggests that those electrons furthest from the nucleus would require less energy to break because it has a lower attraction, whereas those in the innermost shell would be the most difficult to eject.

Friends and Family

Think of the picture above (Figure 1), where the man has a bunch of layers on. Which layers would be easiest to take off? Well, they would be the ones that are outermost or on top. To take off one of the base layers, you would need more energy because you'd have to dig through all the ones on top

Reflections

In an effort to create more opportunities for students to reflect on their experience in the class, we added a "Team Pulse" (inspired by Teaming by Design) component to the Science Skill Reflections. Students were asked to consider how they and their teammates contributed to their collective work during class. This activity was meant to develop students' attention for noticing their peers' strengths and the ways in which a diversity of strengths contributes to the team's learning. We then planned to provide the class with feedback about trends in what students named as strengths and areas of growth, intending to support students to see that they were not alone in the challenges and triumphs they experienced in class.

Further, we designed a course reflection assignment as a culminating sense-making activity for students. Reflections were organized around three prompts: (1) In what ways has the course changed, challenged, or confirmed your ideas about learning chemistry?; (2) How have your conceptions of what it takes to think like a chemist changed, been challenged, or confirmed this semester?; and (3) Drawing on your own experiences in this class, how would you redesign the class so that everyone in the course could have the opportunity to experience themselves as smart and competent chemistry learners?

Students were also encouraged to discuss other ways the class influenced them as students.

Exams and quizzes

Quizzes and exams consisted of sets of data-centered, interrelated questions that required students to draw on conceptual and practical understandings they developed. In grading all assessments, we assigned full credit for normative chemical thinking and partial credit for reasonable thinking. Furthermore, to curtail high levels of competition between students, we utilized a fixed grading scale, did not make exam averages public, and throughout the semester encouraged students to focus on how they could improve their scores as opposed to comparing their score to those of their peers.

Table 2. Instantiations of design principles across curricular organization, task design, instructional practices, assessments and reflections

Design Principles	**Details/Instantiations**
(1) Organize curriculum around big and connected ideas	• Curriculum organized around core ideas of "attractions" and "motions" rather than by topics (e.g., atomic structure, periodic trends, etc.) • Tasks consistently return to and build upon core ideas • Communicating Chemistry project asks students to draw upon core ideas to teach their audiences about their substance • Exam items designed to draw on core ideas to analyze and interpret data
(2) Design chemical tasks that collectively engage students in chemical investigation	• Question of the day designed so that students can answer by drawing on the chemical resources provided and core ideas • Tasks require students to work with data and models the ways chemists do: using data to develop, refine and use models; construct evidenced explanations and arguments • Tasks support conundrums • Chemical resources and team products are rich enough as to allow for multiple different pathways towards a precise solution (e.g., many different ways to organize data cards and identify patterns that can support students to develop a precise explanation about why some substances dissolve in both water and hexane)
(3) Develop explicit language to name the practices that matter for competent	• "Smart things" lists in task launch name practices that matter for successfully doing chemistry • Task cards repeatedly name scientific practices (e.g., identify patterns) • Science Skill Reflections name five skills that are essential to doing science (e.g., diligent skepticism) • Communicating Chemistry project emphasized communication as a scientific skill
(4) Foster interdependence and intellectual risk taking	• Designed tasks complex enough to push students to have to say "I don't know" • Designed task resources rich enough to allow for multiple pathways for successful completion • Positioned "asking questions" as valued in "smart things" list, publicly assigned competence to questions on white boards, left room for students to record lingering questions on note sheets • Communicated the importance of multiple perspectives for doing good science, and that science is about developing useful models, not finding right answers • Instructors made their own mistakes visible • Instructors held teams accountable to "team-question" norm • Science Skill Reflections emphasized "intellectual courage," "collaboration" & "bouncing back from setbacks"

Design Principles	Details/Instantiations
(5) Provide opportunities for students to connect chemistry to themselves and to larger social issues	• Contextualized investigations in contexts familiar to students (e.g., smell, energy to power a car, air pollution, color) • Contextualized exam questions in contexts familiar to students (e.g., food preservatives, lead in drinking water, caffeine extraction, airbags, hot packs) • Selected substances for Communicating Chemistry project that would be relevant to human health (e.g., hormones such as cortisol, or toxic metal salts such as lead phosphate)

Research Questions and Data Collection for Phase III

In the following sections I elaborate on my research questions and data sources as they relate to my research questions.

Research questions

Through pilot studies and the first iteration of CHEM 101B, I began to learn about the ways students were making sense of what chemistry is and who they are in relationship to it. In Phase III, I focused my study on how the second-generation activity system of CHEM 101B mediated students developing conceptions of chemistry, learning, and what it means to be "good at chemistry." I was further interested in how the course mediated students' perceptions of themselves as chemical thinkers and learners.

Table 3. Research matrix with research questions and associated data sources.

Research Question	Data Sources
1) What meanings about chemistry, learning, and "good at chemistry" do students articulate after one semester of participating in CHEM 101B?	- Interview (audio, end of semester) - Course Reflection Paper - Science skill reflections
2) What learning frames organize students' participation within CHEM 101B?	- Classroom video recording
4) What forms of mediation are available in CHEM 101B for meaning making, framing, and identity construction?	- Interview (audio, end of semester) - Classroom video recording - Audio recording and field notes of the task launch and close - Classroom artifacts (task cards, note sheets, practices recorded on whiteboards, "smart things" lists)

Data collection included end of semester interviews, four science skill reflections, and a culminating course reflection. These data gave me access to students' meaning making about chemistry, learning, and competent participation. Further, classroom video and observational data gave me access to the forms of mediation that shape students' conceptions of chemistry and their participation within it in CHEM 101B. I have summarized my research questions and data sources in Table 3 above.

Data sources

Participant Observation.

During a four-month period between September 2016 and December 2016, I conducted approximately 39 hours of participant observation in CHEM 101B. During the task launch and close, I typically sat in the back of the classroom and recorded field notes. During the middle portion of class, I primarily walked around the room, listening to students' conversations, assigning competence to students' questions and interesting connections, recording students' contributions on white boards, checking in with teams when I saw hands raised, and consulting with instructional staff when questions arose. During class, I wrote and time stamped notes to myself. Then, immediately following class, I developed these notes into longer field notes while interactions and observations were fresh in my memory.

The decision to take an active role in the classroom beyond observation was based on several factors. First, supporting a class of 116 students to participate equitably together in chemical thinking was a large challenge, especially given that most of the course instructional staff was comprised of first year graduate students and undergraduate students who were not formally trained in facilitating equitable collaborative discussion-based courses. Given my background as a high school chemistry teacher and my developing expertise in facilitating equitable interactions within teams of students, I felt obligated to support both students and instructional staff as we leaned together how to do this work. Second, from a research perspective, participant observation afforded me the opportunity to get to know students. While I could not develop relationships with all 116, the mutual trust and care built over time with a handful of students gave me access to understanding the classroom life - how students were feeling in the course, what was and was not yet supporting their learning, etc. Further, the large class size and heightened noise level in the course made it such that when even when I did sit in the back and attempt to observe, I could not meaningfully hear students' conversations. Hence, actively moving through the classroom and interacting with teams gave me a richer picture of how students were participating and learning together within the course.

Video and audio recordings.

Beginning in lesson six, I collected video recordings of teams as they engaged collectively in the day's task. I began the semester with two video cameras, one stationary camera and one wide-angle camera that sat on students' desks. Two-thirds of the way through the semester, the stationary camera stopped working. This meant that beginning in lesson 27, I recorded interactions of one team per day only. In total, I collected over 46 hours of classroom video representing the interactions of 14 different teams.

Science Skill Reflections
Science Skill Reflections were distributed to students using a Google form, and students were expected to complete them at the end of each unit. Science Skill Reflections had three sections: (1) a series of Likert skill questions that asked students to rate their development in their chosen skills, (2) a narrative of a time in class when students employed a particular skill accompanied by a reflection about how it felt, (3) a "team pulse," which asked students to describe the ways their peers contribute to the team's success in addition to their own contributions.

Course reflection papers
I collected students' (n = 86) course-reflection papers at the end of the semester. This activity was designed to help them reflect on how their participation in CHEM 101B changed, challenged, or confirmed their ideas about chemistry and learning.

Culminating assignments.
For students who gave consent (n = 86), I collected students' Communicating Chemistry assignments and midterm exams.

Semi-structured interviews.
My colleague, Sabriya Rosemond, and I carried out end-of-semester interviews. It was not within our capacity to interview all 118 students enrolled in the class. As such, we narrowed the pool of potential interviewee to students from teams that had been recorded in classroom video. The participant pool was assembled using maximum variation sampling with the goal of attaining diversity across gender, race, and socioeconomic status. We also sought representation from students who were repeating general chemistry, and from students who had postponed taking the course until after their freshman year at the university. In total, 21 of the 28 students invited took up our invitation to interviews. Students were offered one extra credit point for participating. Students who did not participate in interviews were offered an alternative assignment to earn an extra credit point.

Table 4 Racial Demographics for Interview Pool based on students' self-reports.

	Asian (includes Filipina/o)	White	Middle Eastern	Black or African American	Latino/a	Did not report
Interview Pool (*N*=21)	3 (14%)	3 (14%)	2 (9.5%)	7 (33%)	6 (29%)	1 (0.5%)

Interviews followed a semi-structured protocol (see Appendix A). Each interview was audiotaped and lasted between 30 minutes to one hour. The stated purpose of the interview was to learn as much as we could about students' experiences in the course so as to improve upon future iterations of CHEM 101B. Interviews were conversational in tone, and students were offered tea and donuts to create a safe, informal mood. The interview probed students' interest in science, their previous histories in chemistry, and their experiences in CHEM 101B. Further, questions were designed to elicit students' sense-making about chemistry, what it means to be good at chemistry, and students' perceptions of themselves as chemical thinkers and learners.

Data Reduction and Analysis for Phases III

In this section, I briefly outline the data reduction and analytic methods used in each chapter.

I began by selecting a manageable amount of video to activity log based on the following criteria: (a) selected video should be distributed across time, (b) selected video should represent the diversity of designed tasks, (c) selected video should represent cycles of connected activity. Altogether, I selected 10 lessons from which to activity log video. For most lessons, two different teams were video recorded, though in the later half of the semester my second camera broke. Table 5 indicates the kinds of chemical resources provided for students to examine in the day's task, the unit each lesson came from, and the number of teams recorded for each particular lesson.

Table 5. Summary of selected classroom video

	Unit 1			Unit 2		Unit 3				Unit 4
	L7	**L10**	**L11**	**L12**	**L14**	**L24**	**L29**	**L30**	**L31**	**L36**
Data Tables/Graphs	X				X			X	X	X
Data Cards	X	X	X			X	X	X	X	X
Online Animations	X			X						
Online Simulations				X			X		X	
Total # of teams recorded	**2**	**2**	**2**	**2**	**3**	**2**	**1**	**1**	**1**	**1**

From October 2016 to January 2017, I created activity logs with one of my undergraduate research assistants for each video recording (n=17) with summaries of participation, partial transcription, and observer comments for every 2-3 minutes of activity over the course of the lesson. As we activity logged, we kept memos of interesting moments or patterns we saw.

During these same months, a second undergraduate research assistant and I worked on transcribing all 21 interviews. We time stamped and paraphrased sections of interviews pertaining to students goals and histories with chemistry, and transcribed in full sections of the interview relating to how students perceive chemistry, what it means to be good at chemistry, and themselves in relationship to it. We also recorded observer comments as we transcribed to keep track of our initial reactions to interviews, and recorded memos to capture larger patterns we observed across interviews. Finally, I took an initial pass at reading through students' course reflections and science skill reflections, and kept memos of patterns and talk I was particularly struck by.

From these initial passes, I was particularly interested in the nuanced, practice-centered language students were using to describe their own participation and learning in CHEM 101B in interviews. Alongside three other researchers (Angelica Stacy, Sabriya Rosemond, and Kelly Wong), we began developing a set of inductive codes to characterize the ways students described their participation in and conceptions of chemistry learning. Two big bucket codes emerged as we analyzed students' talk about their learning: (1) rooted in practice and (2) rooted in content. The rooted-in-practice code captured students' talk about their learning that was rooted in perceptions of chemistry as a verb, as a set of practices people engage in. The rooted-in-content code captured students' talk about their learning that was rooted in perceptions of chemistry as a noun, as a body of knowledge to be taken in. Table 6 summarizes each code respectively.

Table 6. Summary of talk coded as either "rooted in practice" or "rooted in content"

Rooted in Practice	**Rooted in Content**
This code applied to talk that included any of the following: (1) Chemical thinking and learning involves iteratively engaging in sets of chemical practices (e.g., asking questions, analyzing data) to build new knowledge and ways of understanding the world. (2) There are multiple approaches for building chemical understanding and thinking with chemical knowledge. (3) Chemical thinking and learning is a collaborative process. (4) Chemical knowledge enables further practice (predict, explain, etc.). It can be leveraged to think about everyday life; its applications extend to the real world.	This code applied to talk that included any of the following: (1) Chemistry is primarily body of knowledge (to understand), and learning chemistry is primarily about memorizing this established knowledge. (2) There is one approach to learning chemistry or solving a chemical problem. If you don't get the correct answer, you didn't follow the correct approach. (3) Learning chemistry requires being taught by an expert or learning from outside sources who have figured it out; student's' job is to listen, memorize, and try to understand. (4) Chemical knowledge is truth; it's stable; data can always be explained with existing knowledge.

In course reflections, students described their practice-centric conceptions of chemistry learning as a significant shift from the content-centric conceptions of chemistry learning they developed in high school. To capture these shifts across the larger data corpus, I made a table that separated out how students described their prior ideas or assumptions about chemistry learning alongside their new ideas about chemistry learning after participating in the class, as articulated in course reflections. I then applied the rooted-in-practice and rooted-in-content codes.

It was clear that students were talking about their participation in chemical thinking and learning very differently than how they talked about it prior to the class. However, I wanted to return to video data to investigate how students actually participated compared to their self-reports. I returned to activity logs and, with my research assistant, Vishu Murthy, began developing a set of codes that were both inductive and deductive. Codes emerged from what we saw students actually doing in the data, and we used the Next Generation Science Standards science and engineering practices rubric to inform our code development. We initially were interested in developing codes that would make visible the ways that students were developing and connecting their understanding over time as they engaged in the practices of science. These codes foregrounded the different kinds of knowledge and understandings students were drawing upon to engage in chemical practices (e.g., "using and applying everyday knowledge to (a) explain, (b) interpret data, (c) make predictions"). We then shifted directions when we found we could not reliably apply these codes.

Our next set of codes foregrounded the chemical practices students engaged in – asking questions, identifying patterns, making evidenced claims, making evidenced challenges, and constructing causal explanations. For each activity log, two undergraduate research assistants and I used these codes to independently code each activity log. We then compared codes and came to consensus on codes for which we disagreed. Finally, I created an activity log index that marked the location of each code within each activity log (see Table 7 for an example, see Appendix B for full index).

Table 7. Excerpt from activity log index.

Code #	**Code Title**	**Location (Lesson #, team name, minute interval)**
SP1	Asking chemical questions	**L7** Na-B (7-9);(27-29) **L10**-NaA (14:30-16:30);(28:30-30:30) **L11**-BkB (8-10);(12-14); (14-16);(16-18); (18-20);(20-22);(22-24);(27-29);(33-37);(37-40:30); (40:30-42) **L12**-KA (10-12); (34-36); (38-40); (40-42) **L14**-GeB (8-10); (12-14); (16-18); (20-22); (22-24); (24-26); (26-28); (28-30); (30-32); (32-34); (38-40); (40-42); (42-44); (44-47) **L24**-BkA(2) (4-6); (12-14:30); (14:30-17:00); (14:30-17:00); (19-22); (19-22); (22-25); (35-37) **L29**-BkA (18-20); (22-24); (30-32); (42-44)

While coding chemical practices captured students' high-level participation across the data corpus, a close analysis of students' moment-to-moment interaction in teams was necessary to characterize the new frame students were participating in, including the frame's content, positional, and epistemological aspects.

The focal episodes I selected for framing analysis in Chapter 4 come from two teams, Germainum-B in L14 and from Berkeleium-A in L24. These focal episodes were representative of the broader data corpus in terms of students' participation in chemical practices. I selected these particular episodes for framing analysis because they were characterized by a high frequency of coded practices from multiple different students, and they got the students somewhere new – either to new conclusions or new questions – in a relatively short time span (1-3 min). These features of participation suggested that the answer to the question 'what's going on here?' was very different than *doing school.* Hence, these moments allowed me to characterize the new learning frame students were coordinating around, and to investigate how this new frame was supporting powerful chemistry learning.

Focal episodes identified in activity logs were transcribed in full, annotating verbal (e.g., intonation) and non-verbal features of talk (e.g., overlapping speech) and gesture (e.g., gaze, facial expression). I then examined features of students' participation together and considered what students' responses to one another suggested about their positional and epistemological framings (Greeno, 2009). Comparing and contrasting students' participation to participation with a *doing school* frame helped me to name differences. Altogether, I identified three features that marked students' participation together and that were made available via the design of CHEM 101B: (1) authority to author chemical ideas, (2) accountability to each other, and (3) accountability to the discipline.

My third line of analysis in Chapter 4 focuses on CHEM101-B as a system, seeking to understand how different aspects of the CHEM101-B design worked together to achieve such reframing. I began by analyzing examining excerpts of the task launches documented in field notes across the ten activity logged lessons, returning to video when my field notes were missing consequential sections of the launch. On my first pass through field notes, I noticed that during the task launch Professor S regularly framed three aspects of participation – the nature of chemical learning, students' roles as learners, and the nature of competent participation. Field notes were uploaded into Dedoose. Building from the framing analyses presented in Engle (2006) and Engle, Lam, Meyer, and Nix (2012), I began coding the moves the instructor engaged in to frame activity in CHEM 101B. I then analyzed the specific practices highlighted in the "smart things" lists presented in the task launches. I did so by grouping similar practices until larger categories emerged. Practices fell into one of three categories: (1) scientific practices, (2) practices that support learning together, (3) practices that develop socio-chemical norms. Altogether, these analyses yielded the findings in Chapter 4.

In addition to coding students' talk about chemistry learning, in Chapter 5 I present findings from a related inquiry aimed at understanding how students are newly perceiving what it means to be good at chemistry, and how students perceive themselves in relationship to their new definitions. My analysis focused a question posed in interviews regarding chemical competence (i.e. "people often use the phrase 'I'm good at chemistry' or 'I'm not good at chemistry.' What do you think it means to be 'good at chemistry' in this class?"). Similar to the approach used in Chapter 4, students' responses were coded in an iterative fashion until patterns emerged. These themes serve as a basis for the findings presented in the first section of Chapter 5.

I then turned to investigate identity construction in relationship to new meanings about chemical competence and students' own participation in the course. I was particularly interested in Kehlani as a case study. More detail on selecting Kehlani as a case is provided in Chapter 5. Through a back and forth process of analyzing Kehlani's case (via data from her interview, science skill reflections, communicating science assessments, exams, and classroom video data) in light of the broader interview data set, I identified a set of claims about who students get to be in CHEM 101B.

In the third and final empirical strand presented in Chapter 6, I return to classroom video data to analyze the frames individual students within teams coordinate around during the early weeks of the semester. In my initial activity logging, I remembered that in early group work, students participated in ways akin to *doing school* rather than *collective investigation.* I was interested in understanding if and how particular aspects of course design were cuing the *doing school* frame. Further, I was interested in understanding how students successfully contested the *doing school* frame and accomplished *collective investigation*.

The earliest classroom video I collected comes from L6 for two separate teams (Sodium A and Sodium B). I began my analysis by watching video for Sodium A and B as these teams participated in both the L6 and L7 tasks and then characterized students' participation. In L6, I examined students' framings by characterizing individual students' focus, the roles they participate in, and the forms of participation that are sensible. Altogether, individual students within both teams participated in ways that were consistent with a *doing school* frame. Given that the intention of the task was to collectively engage students in chemical investigation, I was curious to understand how aspects of the classroom system were falling short of disrupting the *doing school* frame. I selected episodes from team Sodium B for further analysis because this team's dynamic illuminated the ways in which the task design cued the *doing school* frame and tapped into particular kinds of chemical prior knowledge that made for less productive collaborative work.

I then analyzed framing dynamics within both teams as they engaged in the following day's (L7) task. Students in team Sodium B largely engaged in *collective investigation* as intended by the task; however, in Sodium A, an extended framing battle ensued between *doing school* and *collective investigation*. I selected this battle as a focal episode for deeper analysis in order to understand how individual students make bids for particular frames, whose frames get taken up, and under what conditions. This analysis revealed how particular resources made available through course design supported students to interactionally accomplish *collective investigation*.

Chapter 4: Reframing and Supporting Chemistry Learning in CHEM101B.

> This course has definitely changed and challenged the way I used to approach learning chemistry. The way the material is presented in this class has taught [me] to more learn concepts and whatnot instead of just memorizing a bunch of facts and equations. [...] I'm not just trying to **find the answer to something**, I am thinking about it critically, coming at it from different angles, and trying to **figure out how and why** something behaves the way it does [emphasis added]. (James, Course Reflection)

James stated that before engaging in CHEM 101B, his understanding of and approach to learning centered around memorizing information: "I was mainly just trying to get through the coursework, not necessarily absorbing everything." To him, science learning was a destination arrived at by memorization, rather than a process of making sense of data and models. James' understanding of science learning is an example of how ideas about learning and students' roles as learners get organized through dominant, and often taken-for-granted, schooling *frames* made available to students in and through participation in typical school science settings. His experience of science learning reflected that of many of his peers entering CHEM 101B.

A *frame* answers the question: "What's going on here?" (Goffman, 1974). It guides the meaning of a particular situation, implying certain kinds of actors with particular roles and making certain kinds of actions sensible (Goffman, 1974). Frames are not stable, nor are they necessarily aligned across participants (Hammer et al., 2005). Instead, they are collectively constituted in moment-to-moment interaction as participants draw on contextual cues within figured worlds to make sense of and organize their activity (Goodwin & Duranti, 1992). Frames are only said to be 'at play' when people act as if they are functioning (Goffman, 1981; Greeno, 2009; Hand et al., 2012). A particular action misaligned with a frame 'at play' can signal a shift to a new frame. For example, a punch that lands too hard might shift an activity from play to fighting.

Within the learning sciences, important work has been done to demonstrate the effects of different types of frames on disciplinary thinking and learning. In particular, researchers have considered how the positional and epistemological aspects of frames work to open up or limit opportunities for learning (Greeno, 2009; Hammer et al., 2005; Hand et al., 2012). Positional frames organize learners' understandings of what they are expected to do and what they are responsible for. Epistemological frames organize learners' sense of the discipline in relationship to their participation in formal class activity. To illustrate the affordances and constraints of frames on learning, Hand et al. (2012) describe the logic of participation within two contrasting learning frames: the *doing school* frame and the *productive disciplinary engagement* (or *PDE*) frame.

The content of the *doing school* frame is less about subject matter learning than it is about acting in line with the rules and values of schooling. Within this frame, instructors are presumed to be experts responsible for deciding what knowledge students need and imparting it to them. Students are invited into rather passive roles as knowledge receivers. They are held responsible for recalling facts and correctly executing procedures to figure out answers on worksheets, homework and exams. *Doing school* carries an epistemological framing of science as a static and straightforward body of facts and equations owned by instructors and available to be memorized and recalled (Hand et al., 2012; Redish & Hammer, 2009). Within this frame, individual practice is the most sensible form of participation – students have no need to make sense of chemistry together when they are held accountable to memorizing and recalling information.

Alternatively, Hand et al. (2012) show us the work the *PDE* frame does to invite learners into collective practice, which supports rich engagement in scientific thinking and learning. The *PDE* frame is about constructing disciplinary ideas by engaging the content and practices of the discipline. Within a *PDE* frame, students are positioned as active sense-makers who have the intellectual authority to problematize and author new scientific ideas (Engle & Conant, 2002). It is their job to question, justify, dispute, and revise ideas as they negotiate new scientific understanding together. With respect to epistemological framing, science is perceived as a connected body of ideas to be addressed creatively (Hand et al., 2012; Redish & Hammer, 2009). And it is precisely the fluidity and multisidedness of scientific knowledge within a *PDE* frame that necessitates collective practice – students need to rely on each others' diverse contributions as they construct new knowledge together.

While the affordances of a *PDE* frame for learning are clearly established, the *doing school* frame is deeply entrenched in school science. Teacher-centered activities and tools such as lectures, individual practice worksheets, textbooks, and exams cue *doing school* as the dominant school frame, preserving its hegemony over time. In order for students to take invitations into the new roles and epistemic positions offered in frames like *PDE* seriously, explicit cultural work is needed to signal that the *doing school* frame is no longer at play (Hand et al., 2012). This work requires attention to how classrooms function as activity *systems* (Engeström, 2011; Gutiérrez & Jurow, 2016), in which different aspects of design – tools and artifacts, norms, and participation structures – work together to mediate students' shared sense of what they are doing together.

In this chapter, I contend that the newly designed activity system of CHEM 101B successfully invited students into a new and more productive learning frame. I support this conjecture through three strands of analysis. First, I demonstrate that students develop new understandings about what it means to participate in chemistry learning. To capture students' sense-making about their prior chemistry learning experiences and their participation in CHEM 101B, I draw on students' course-reflection papers and end-of-semester interviews, both of which were culminating sense-making activities. I find that students move away from viewing chemistry learning as memorizing facts and executing procedures (consistent with a *doing school* frame) towards chemistry learning as the collaborative process of investigating data to construct new understanding about chemical phenomena in the ways chemists do. I take students' new articulations of learning as evidence that new learning frames took hold in ways that were sustainable. I characterize this new frame as *collective investigation.*

Second, I pivot from students' sense-making about learning to examining students' participation in chemistry learning within CHEM 101B, investigating how students' collective participation in chemical practices are rendered sensible by the *collective investigation* frame. Classroom video serves as my primary data source for this framing analysis, as it provides robust data about how students participate in chemistry learning. For 10 different lessons throughout the semester, I created activity logs with summaries of participation, partial transcription, and observer comments for every 2-3 minutes of activity over the course of the lesson. I began analysis by systematically coding for the kinds of chemical practices students participated in over the course of each lesson to get a sense of how chemistry learning was unfolding across teams and tasks. I find that students consistently engage in chemical practices throughout the semester, not individually but collectively in joint activity.

I then selected several moments of powerful chemistry learning – one in which joint activity is clearly supporting chemistry learning – and conducted a close analysis of students' speech, physical positioning, gestures, and tool use to characterize features of students' participation that work together to achieve *collective investigation*. Similar to the *PDE* frame, I find that the following features support students' collective chemical participation: (1) students have authority to author chemical ideas, (2) students are accountable to one another – the team's work is not done until everyone is satisfied that the reasoning makes sense – and (3) students are accountable to the content, practices, and disciplinary norms of chemistry. I then consider what these features suggest about the content, epistemological, and positional framing of *collective investigation*.

Finally, I contend collective chemical practice did not occur simply because we arranged students in groups with tasks centered around data. The *doing school* frame is taken for granted in school science, and attempts to introduce new frames in learning contexts are often reinterpreted via the *doing school* frame (Hand et al., 2012). Therefore, my third line of analysis focuses on CHEM 101B as a system, seeking to understand how different aspects of the CHEM 101B design are working together to achieve such powerful and sustainable reframing. In particular, I consider the tools and robust practices that comprise chemical tasks, task launches, and classroom interactions.

Shifts in students' understandings of chemistry learning

In the following sections, I describe students' reports of their perceptions of chemistry learning prior to and after participating in CHEM101 B. The overwhelming number of students who shift from seeing chemistry learning as an outcome arrived at through memorization towards seeing chemistry as the collaborative work of building chemical understanding suggests that CHEM 101B offered students new ways of making sense of 'what's going on here?' (Goffman, 1974).

Traditional school science framed as doing school

To understand shifts in students' articulations of learning, I made a table that separated out students' prior ideas or assumptions about chemistry learning alongside their new ideas about chemistry learning after participating in the class, as articulated in their course reflections. Though the prompt asked students to reflect on whether their own thinking about chemistry learning shifted, expanded, or remained the same, many students did not clearly articulate how they understood or approached chemistry learning prior to participation in CHEM 101B. Rather, they reflected on past experiences in chemistry learning settings and/or their incoming expectations for their college chemistry course. Of the 86 course reflections, 29 were coded as not having explicitly articulated their initial approach to or understanding of what it means to learn chemistry. Strikingly, of the 57 students who described chemistry learning, 46 reflections included explicit talk about learning chemistry as memorizing facts and executing mathematical procedures. The excerpt from Sofia below typified these descriptions:

> In high school, honors chemistry focused mostly on just **memorizing chemical formulas and periodic tables**, and **tests were based on just regurgitating information from a textbook**. This made chemistry extremely unenjoyable for me because I was **forced to memorize so much**, but I never felt like I was really understanding any of the information…Whereas in high school, classes were mostly spent **listening to long lectures** and working **on our own** [emphasis added]. (Sofia, Course Reflection)

Sofia described that her time spent in high school chemistry was primarily a matter of listening to long lectures, reading a textbook, and memorizing facts and equations. Across descriptions, students cited listening to lectures, taking notes, reading textbooks, and practicing problems as the dominant learning practices in their past chemistry experiences. Further, students descriptions indicated rather passive roles for themselves as learners, often using words like “handed,” “fed,” or “given” to describe the ways expert instructors transferred information to students who were positioned as knowledge receivers, and – like Sofia – students used words like “regurgitate,” or “spit-up” to indicate their sole responsibility to recall information on exams. In the excerpt above, Sofia clearly indicates not having the obligation to actively make sense of the chemical ideas and procedures she was expected to know and execute on exams. Hence, it is sensible for her to work “on her own.”

Students’ interpretations of their activity in past chemistry learning settings are consistent with the positional (i.e., receivers of knowledge) and epistemological (i.e., chemistry as set of facts owned by experts and available to be individually acquired) aspects of *doing school*.

CHEM101B framed as collective investigation

In course reflections, students were more likely to articulate their new understandings of learning after participating in CHEM 101B. Of the 86 course reflections, only 11 were coded as not having explicitly articulated their approach to or understanding of what it means to learn chemistry. The remaining 75 students painted a remarkably different picture of learning in CHEM 101B. They described the focus of activity as about collectively building new chemical understanding, which for them was about “understanding how properties of atoms affect the way we experience the world,” “understanding interactions and relationships,” and “understanding why events occur.” Within this new activity, students referenced more active positions for themselves as chemistry learners. For example, Kehlani described:

> I feel like the reason we do the **tasks first is that this class is really focused on us being scientists.** I'm **asking questions** and **trying to understand first** rather than trying to memorize and get a grade. Because you can get a grade, memorize and forget next semester, or in this class, you're trying to install [sic] in us **for chemistry to be part of us.** (Kehlani, Interview)

In the excerpt above, Kehlani makes sense of her participation in the redesigned chemistry course in terms of what scientists do when they learn about the everyday world. In the same way that chemists make predictions and ask questions to construct new understanding, in CHEM 101B she engaged in these same chemical practices with her team to draw new conclusions from data. Across course reflections, students most often cited asking questions, recognizing patterns in data, considering multiple perspectives and approaches, making connections, and drawing conclusions as practices required for chemistry learning. While practices like asking questions and considering multiple perspectives are by nature collective, 26 students explicitly cited "collaboration" and working out ideas with peers as essential to their chemistry learning.

It is noteworthy that in Kehlani's description of chemistry learning above, students, rather than instructors or textbooks, have the authority to construct meaning and to have ownership of it. Replacing the passive verbs that described students receiving knowledge from instructors, students now placed themselves at the center of chemical practice and understanding. For example, Noel articulates:

> In this class, **we studied** trends **ourselves**, learned ways in which **we could apply** logic to **explain** trends, and overall **question** the reasoning behind the chemistry of what **we are learning**. For example, rather than just learning about the ionization energy trends, **we observed** them, **tried to understand** them, and even **tried to create a shell model** to explain them [emphasis added]. (Noel, Course Reflection)

Here, students are the ones observing, analyzing, applying, explaining, and questioning as they develop understanding that they are the owners of knowledge. It's important to notice that Noel, like many students in their descriptions, uses plural personal pronouns to describe activity in the class, indicating that she experienced chemistry learning as a collective practice.

Students' new understandings of activity in CHEM 101B suggest that they successfully took up invitations into a new frame, the content of which is no longer about acquiring and performing knowledge, but about collectively investigating and constructing understanding from data in the ways chemists do.

Characterizing Participation within a collective investigation frame

In the sections that follow, I examine participation within a *collective investigation* frame and demonstrate what it entails for chemistry learning. Recall from Chapter 2 that I understand chemistry learning to be the process of socially negotiating meaning about the structure and behavior of matter in and through participation in chemical practices

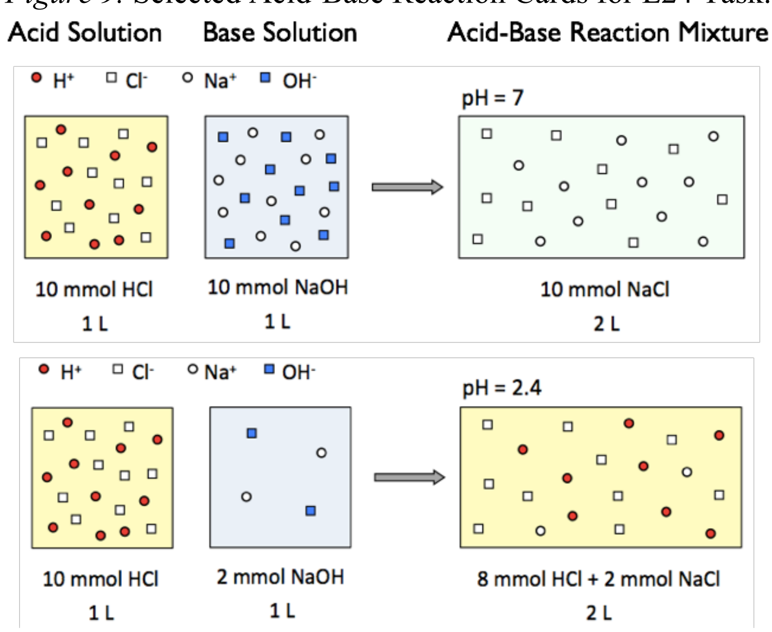
(Wenger, 1998). I take as evidence of chemistry learning both students' collective engagement in the practices of chemistry and in chemical meaning making. For the sake of clarity, I will talk about meaning and practice separately; however, I do not mean to imply that one can be separated from the other. Alongside Wenger (1998), I contend that practice is a process by which we make meaning.

I ground the discussion in two cases of teams coordinating around a *collective investigation* frame. I first demonstrate that within this frame, students are engaging in chemistry learning, as evidenced through their participation in chemical practices, and that this participation is fundamentally collective in nature. While *collective investigation* starts and unfolds in different ways within and across teams, students' mutual attunement to this frame is signaled by common expectations about what practices count as sensible to do together. Next, I consider how *collective investigation* is achieved and what students' participation suggests about the positional and epistemological aspects of this frame.

Case 1: "But what happened to the H+ ions?"

I begin with an example of classroom activity within the *collective investigation* frame below to illustrate how the frame supports rich engagement in chemistry learning. The excerpts from this first case, which make up the scene below, come from classroom video collected midway through the semester (task L24) at the opening of a new unit on acid-base reactions. Three students, Keyshia, Cadence, and Olivia are working on a task that asks them to draw on a series of acid-base reaction cards (see Figure 9) to construct a model that accounts for the composition of a reaction mixture when particular amounts of acids and bases react. The task card prompts students to examine the representations of acid-base reactions, to identify similarities and differences across the reactions, and to consider why they don't always see H^+ ions after the acidic and basic solutions are mixed.

Figure 9. Selected Acid-Base Reaction Cards for L24 Task.



Leading up to the scene below, Keyshia, Olivia, and Cadence have already engaged in important chemistry learning. They have correctly identified the extent of acid dissociation, the volume of base, and the moles of base as relevant variables to examine, controlled for these variables as they have sorted cards into groups, and have begun to construct an explanation about why H^+ only shows up in some reaction mixtures. Cadence has correctly proposed that the remaining H^+ in solution depends on the moles of base reacting with the acid, citing as evidence two cards (Figure 9). Her observation has supported her to conclude that when more acid than base is reacting, H^+ is present in the final reaction mixture. Keyshia, Olivia, and Cadence are clearly engaged in chemical learning – asking chemical questions, organizing data to reveal patterns, and identifying relationships between variables as they make sense of how acid-base reactions happen.

Recall that the task prompt asked the team to discuss why they don't always see H^+ after acid and base solutions are mixed. If the students were focused on finding answers or merely completing the task, deciding that the "amount of base determines whether you see H^+ in the mixture" might be a sensible place for the team to consider themselves done. Instead, the team persists in making sense together, drawing on chemical ideas to propose reasons for why the amount of base seems to matter in these reactions. After some discussion, Keyshia offers up a possible explanation to the team – the base might be dissolving the H^+ and making it "disappear" from the final reaction mixture. After some negotiation about what Keyshia means, the team seems to settle on this reasoning. Keyshia announces, "So, I, uh, think we've come to a conclusion, guys," and Cadence and Keyshia turn to writing the conclusion on their note sheet. Olivia, however, remains leaning over the cards and thinking aloud, indicating that this conclusion is not yet satisfying:

Olivia*:* Acids have the H plus ion and bases do not. (*8 second pause. For a moment Olivia turns her body towards her note sheet and picks up her pen as if to write, but almost immediately turns back and uses her pen to point to one of the cards*) But I don't know where they go.

Keyshia: (*looks up at Olivia and stops writing. She speaks tentatively*) Um… it's probably because there's enough of these (*points to the base*) to dissolve these (*points to the acid, then looks up tentatively at Olivia*). But since there are more of these (H+) not all of them (H+) can be dissolved by the base?

Olivia: Wait, can you say that again?

Keyshia: (*speaking with more confidence*) Like, because there's more of this (*base*), it can dissolve all of this (*acid*) so we don't see it anymore. But since there are more of these (H+), not all of this (*base*) can dissolve it (H+). So there's gonna be some of these (H+) left over. (*Olivia nodding along as Keyshia describes*) Does that make sense?

Olivia: Yeah… but I'm just like – I'm still wondering where they are.

Several aspects of this interaction are noteworthy. The fact that Olivia does not join Keyshia and Cadence in writing the team's conclusion is clear evidence that she is participating within a *collective investigation* frame. If she were *doing school*, it would be sensible for her to accept answers, even ones that do not make sense, for the sake of completing the task. Instead, she invites her team back into chemistry learning by posing an important chemical question – where do the H^+ ions go? Keyshia is immediately responsive to this invitation. She interrupts her writing to share her reasoning about where the H^+ ions go, doing so in a register that communicates uncertainty, both making room for disagreement and inviting Olivia's questioning. Olivia expresses agreement that the amount of base matters, but is not yet satisfied that "dissolving" and "disappearing" accounts for what happens to the H^+ in the reaction. Her statement "I'm still wondering where they are" is a bid for further investigation.

As the exchange continues, the team organizes around a *collective investigation* frame as they build on, author, and justify ideas to further the team's sense-making about how H^+ interacts with the base in the reaction. We see the affordance of the frame for these students' chemistry learning as they work to revise their explanation. Olivia continues by thinking aloud about what ions in the acid and base are available to react. While Cadence is initially still writing, halfway through the excerpt we see Olivia looking to Cadence, indicating that the team needs her ideas in the conversation.

Olivia: Like if you have H plus, Cl minus (*pointing to the acid)* then Na plus and OH minus (*pointing to the* base) You have 2 milimoles of NaOH (*pointing to the base*)
So you have this together. And then you have 10 of NaCl.
So you have this and this (*Olivia points to Na and the Cl on the card*)
But what happened to the hydrogen ions?
Like where are they? (*briefly glances up to Keyshia then back down)*.
(*Keyshia is leaning in, has her hand on her neck and is looking at the card Olivia is pointing to. She brings one of the data cards nearer to her and examines it*)

Olivia: Or like where did they combine? Did this (*points to* H^+) combine with the OH? Is that the water?
(*Olivia turns her head and looks at Cadence. Cadence leans in to examine the cards*. *Keyshia has her hand on her head and continues looking down, examining the data cards.*)

Olivia: It might be the water. Like H plus and OH minus
(*Cadence leans in even further. There is a long pause; students are examining the cards together*.)

Keyshia: Yeah that might be (*Keyshia picks up her pencil and points to the card*) the H_2O (*She looks up at Olivia*). And that would still make sense to like- (s*he points to another data card that the team referenced earlier in the conversation*)
[that this is water

Olivia: [so that's this stuff in here (*Olivia points to a card*)

Keyshia: [Yeah the background (*Keyshia looks to where Olivia is pointing*)

Olivia: Ah okay (*nodding*)

Keyshia: And there is some hydrogen left over that can't bond (*Keyshia nods her head, sits up, pushes the card back to the middle and picks up her pencil* *to write*)

Olivia*:* That can't bond with OHs (*Oliva is nodding*. S*he snaps her fingers and points at Keyshia while smiling*)
Genius! Got it. Alright.
(*The three students all turn to write their conclusion*)

This exchange begins with Olivia naming what ions exist in the acid ("H plus, Cl minus") and base ("Na plus and OH minus") solutions to begin with, and the amount of base ("2 milimoles of NaOH"). She then sees that the Na^+ from the base and Cl^- from the acid get "together" in the reaction mixture, which leaves her to wonder if the H^+ in the acid, then, also combined with something in the base – the OH minus. Keyshia builds on this idea by adding that when the H and the OH combine they would make water, a proposal that is consistent with the H^+ "disappearing" from the representation. Water's concentration is too high to be represented on the cards so it is assumed to be, as Keyshia describes, in "the background." Finally, the team links their new reasoning about water formation to their initial claim about the amount of base mattering to construct an accurate chemical explanation. Namely, the amount of base matters *because* if there is less base than acid around, there will be "some hydrogen left over that can't bond with OH." The scene closes with expressions of satisfaction that their new explanation about bonding makes sense, and that the thinking they did to get there was "genius."

Throughout the excerpt, there is clear evidence that Keyshia, Cadence and Olivia are engaging in chemistry learning. They actively negotiate and produce new meaning about how ions in an acid base reaction interact, and do so via the sense-making practices of chemistry: asking disciplinary questions about how and why substances interact, making claims about how acids and bases react, drawing on scientific reasoning to link evidence to their claims, disputing and finally revising their explanations. The rich chemical thinking and learning illustrated in the above vignette is consistent with participation across teams over the course of the semester. Our research team (two undergraduate researchers and I), analyzed activity logs across 10 hours of classroom video, representing seven different teams participating in 10 different tasks. We found that participation in the following scientific practices typified students' participation together:

(1) *Asking chemical questions*: Students ask questions (1) about how and why things work, (2) to determine relationships between variables, (3) about unexpected data, (4) to clarify or refine a claim, explanation or model, or (5) to urge team members to provide evidence or reasoning. (e.g., "How can this H bind with the O if it's already fulfilled its octet - it can only make 1 bond?" [L11 Activity Log, 12-14])
(2) *Identifying patterns, trends, or relationships in data:* Students are identifying patterns or trends, but are not yet providing reasoning or *using* the relationships to make further claims or draw bigger conclusions (e.g., "You guys notice that the molecules that don't have a smell have zero lone pairs?" [L7 Activity Log, 13:00-15:00])
(3) *Justifying ideas with evidence or reasoning*: Students propose ideas or make claims that they justify in some way, either citing evidence or some reasoning, but without yet reaching a full explanation. (e.g., "The fact that the electrons have to

get closer to each other to touch each other might explain why the H-H bond is shorter." [L14 Activity Log 28:00-30:00])

(4) *Challenging claims using evidence or scientific reasoning*: Students are justifying why they do not think something is right using data or scientific ideas/reasoning. (e.g., Jack: "All the ones that have a smell are tetrahedral." Ali: "Wait, but these ones have tetrahedral too, and they don't have a smell." [L7 Activity Log, 19:00-21:00])

(5) *Constructing causal explanations:* Students articulate how or why a phenomena occurs, and support their claim(s) with reasoning that links evidence to the claim. Evidence or reasoning may be implicit if it has already been established as a given within the team. (e.g., "With double and triple bonds, more electrons are being shared, so you need more energy [*citing bond dissociation energy data*] to break the bond." [L14 Activity Log, 42:00-44:00])

It is important to note that because activity logs are summaries of activity that include only portions of transcript, this analysis cannot capture every instance of engagement in chemical practices. Nor do the practices that we decided on capture the entirety of the chemical work students participated in. For example, on days where data are represented on a set of cards, like in the L24 vignette above, students invest a lot of time interpreting the representations on the cards and organizing the cards to reveal patterns. Though we consider "organizing data to reveal patterns" a scientific practice related to analyzing and interpreting data, our team found it challenging to reliably decide what moments counted or did not count as such practice and therefore did not include it in our set of codes. Finally, I note (and will discuss further in the next section) that because students are engaged in collective practice, some instances of chemical practice account for contributions across multiple students. For example, Student A might make a claim about a particular relationship. Student B might then immediately build on this claim by linking it to evidence and reasoning. Our team would then code both contributions as one instance of constructing explanations. Hence, the practices and accompanying frequencies in Table 8 characterize students' chemical participation in broad brush strokes. I take students' participation in chemical practice as evidence that chemistry learning happened across the semester.

Table 8. Instances of Chemical Practices Coded in Activity Logs

	Task 7 (25 min)	Task 10 (20 min)	Task 11 (40 min)	Task 12 (32 min)	Task 14 (42 min)	Task 24 (35 min)	Task 29 (39 min)	Task 30 (39 min)	Task 31 (42 min)	Task 36 (38 min)
Asking Chemical Questions	2	2	11	5	20	8	4	15	6	7
Identifying Relationships	5	6	1	5	9	4	0	7	7	7
Justifying claims usinig evidence OR reasoning	2	1	4	2	7	8	3	3	6	5
Challenging	1	0	6	0	1	1	0	0	0	0

	Task 7 (25 min)	Task 10 (20 min)	Task 11 (40 min)	Task 12 (32 min)	Task 14 (42 min)	Task 24 (35 min)	Task 29 (39 min)	Task 30 (39 min)	Task 31 (42 min)	Task 36 (38 min)
claims using evidence OR reasoning										
Constructing explanations	2	0	2	2	2	4	0	2	1	5
Total # instances	**12**	**9**	**24**	**14**	**39**	**25**	**7**	**27**	**20**	**24**

*See Appendix B for complete index of science practice codes in activity logs

Students participation is fundamentally collective

In my analysis above, I presented evidence that across teams students are engaged in chemical practices and negotiating meaning about chemical substances and phenemona. Such evidence demonstrates that students are deeply engaged in chemistry learning. While we could imagine a learning environment in which these particular chemical practices show up as collections of what individual students are doing (perhaps elicited by a well-designed worksheet), it is evident in video data that participation in these practices is distributed among students as they work together to further collective sense-making. This collectivity – when achieved – moves the teams' thinking to new places. In the section that follows, I return to the above vignette to demonstrate how students' participation in chemical practices is fundamentally collective.

Collectivity across teams is evidenced by participation that is distributed across team members, responsive to team members' contibutions, and towards a shared goal. Students' responsiveness to one another across video data is seen in the ways team members take up one another's questions, build on one another's ideas, even complete one another's sentences. Students actively invite one another into conversation by speaking in a tentative register, pausing or glancing up after speaking, and at times explicitly asking for team members to weigh in. In the vignette above, we see Keyshia's responsiveness to Olvia as she interrupts her own writing and tentatively offers an explanation to make sense of Olivia's question. When it becomes clear that Olivia is not satisfied by Keyshia's reasoning, both Olivia and Keyshia take up the question of why H^+ "disappears" as a joint project. Later, Olivia invites Cadence to join the discussion by glancing directly at her, to which Cadence responds by leaning in and orienting to the same data cards as Olivia. Altogether, Keyshia and Olivia offer up and build upon one another's chemical questions, identifed patterns, and evidenced claims, which ultimately lead them to authoring a new and astute explanation about how H^+ is transformed into water via bond formation with OH^-. Hence, their collective investigation leads them somewhere new that might not have been possible if they were orienting to activity as individuals rather than as collective actors.

The collective nature of this team's participation is typical of participation in chemical practices observed across activity logs. These practices – asking questions, naming patterns, justifying, challenging, and offering explanations –unfold within teams as part of the work of negotiating meaning together. Hence, I take the frequency of chemical practices in Table 8 both as evidence that students were participating in chemical learning in CHEM 101B *and* that this participation was fundamentally collective.

Collective investigation vs. doing school

It is important to notice that participation within a *collective investigation* frame is fundamentally different than participation within a *doing school* frame in ways that are consequential for the chemistry learning that students do together. When students are *doing school*, even in classrooms where they are committed to helping one another be successful, the focus on finding answers and successfully finishing the task is likely to shut down inquiry and students' ownership over the meanings they construct. What is remarkable about the *collective investigation* frame is the shift from finding answers and sharing knowledge to pursuing disciplinary questions (that may or may not be prompted by the task) and keeping inquiry open until students decide they are satisfied with the depth of understanding they have reached. These differences are summarized in Table 9. As I highlighted in the former vignette and will demonstrate in following section, orienting to investigation, and taking up investigation as a collective practice is a fundamentally different way of engaging in a science learning setting that opens up powerful opportunities for chemistry learning.

Table 9. Sensible forms of participation within *doing school* and *collective investigation*

Doing School	Collective Investigation
Sharing knowledge	Proposing ideas for collective evaluation
Working for everyone to finish the task successfully	Pursuing important disciplinary questions that are not necessarily prompted by the task Continuing to ask and process together
Deciding that work is finished when questions given by the task are answered	Deciding that work is finished when all members of the team are satisfied that conclusions make sense
Focusing on getting a lot done	Strongly resist being done until the teams gets underneath the surface to deeper chemical understanding

Case 2: "H-Cl doesn't really fit the trend…right?"

While I have established that the *collective investigation* frame happens broadly and is marked by sensible forms of participation, I do not wish to claim that participation within the frame unfolds in the same way within or across teams. What does appear to hold true across teams is that *collective investigation* is initiated when a team takes up a question together of how or why matter behaves. The example of *collective investigation* with Keyshia, Olivia, and Cadence is an example of a case of a student wanting to investigate why the H^+ ion seemily disappears from the representation of the final reaction solution. In the section that follows, I present a second moment of *collective investigation* initiated as a student engages in the normal work of responding to a task prompt by offering his own reasoning about why H-Cl is an exception to trends the team has identified in data.

What is important to notice in the episode below is the remarkable amount of effort the team invests into following the reasoning of one team member, and the important chemical ideas and questions that come out of this extended moment of collective sense-making. While the reader may notice that *collective investigation* unfolds differently in this case than from the previous vignette, in both cases the team's *collective investigation* gets them somewhere new.

The series of excerpts that makes up the scene below comes from a task earlier in the semester (L14) during a unit on thermodynamics. A team of four students, Kevin, Sue, Atrey, and Ann, are working together on a task that asks students to analyze bond energy data (Figure 10) to generate an argument that supports or refutes the statement energy is stored in a bond.

Figure 10. Bond energy and bond length data for L14

Bond	Bond energy (kJ/mol)	Bond length (pm)
C−C	346	154
C=C	602	134
C≡C	835	120
O=O	494	121

Bond	Bond energy (kJ/mol)	Bond length (pm)
C=O	799	123
C≡O	1072	113
N≡N	942	110
H−H	436	74

Bond	Bond energy (kJ/mol)	Bond length (pm)
H−C	411	109
H−O	459	96
H−F	565	92
H−Cl	428	127

The task card prompts students to start by identifying three variables that account for bond strength (synonymous with bond energy). At the opening of the scene, Kevin, Sue, Atrey, and Ann have correctly identified shorter bond lengths, greater differences in electronegativity, and larger number of bonds between atoms as correlating with stronger bonds. The task card then prompts students to identify at least one pair of atoms that does not fit the trends they have identified.

Kevin offers up H-Cl as a bond that does not fit the trend in electronegativity they identified and offers reasoning as to why: "H-Cl doesn't really fit the trend, because the bond length is larger than on H-H, but H-Cl is a more electronegative bond." Ann responds to Kevin's proposal, though she misses his point, moving Kevin to rearticulate his initial reasoning. While his register is neither tentative nor definitive, his calm tone and lingering gaze towards his teammates suggests he is expecting their feedback. Ann holds his gaze for a second then looks to her teammates who pass glances around the table. They are seemingly uncertain about what Kevin has proposed. Within a *doing school* frame, any number of responses – ignoring, rejecting, or merely accepting and moving on from Kevin's idea – might be sensible to avoid making their lack of understanding visible. It might also be sensible for Kevin to decide that it is not worth the effort to help his team understand his idea. Instead, in the activity that unfolds in the excerpt below, Kevin works hard to explain his idea to his team, and his team persists in their efforts to follow his line of argumentation.

Kevin: Right? I mean with high electronegativity it means shorter bond length, right? And a stronger bond?

Sue: (*referencing an earlier agreed upon trend*) We said higher electronegativity difference leads to stronger bond.

Kevin: Right, and we also said shorter bond, stronger bond.

Ann: Oh yeah yeah yeah.

Kevin: Therefore, greater difference in electronegativity is shorter bond length. (*10s pause. Ann looks at Atrey who shrugs and shakes his head. Sue finally breaks the silence by naming the exception out loud ("HCl") followed by more silence.*)

Ann: (*attempting to write conclusion on note sheet*) Because longer bond length, but

Sue: (*finishing Ann's thought*) – Has longer bond length but more energy? Wait. What? A longer bond length? (*5s pause*)

Atrey: Is it because Cl is a bigger atom? Because it's one row down? (*referring to it's location on the periodic table*)

Ann: That way it would, what, have a larger bond length?

Atrey: Yeah, because they are farther apart, (*demonstrating with his hands*) they can't get close.

Ann: I thought that the larger it is, the closer they get.

Here we see the team taking up and struggling to make sense of Kevin's proposal together. Sue puts Kevin's proposal in conversation with an earlier relationship the team identified. Kevin builds on Sue's contribution and adds reasoning to it that matters for making sense of his proposal. At this point, Ann and Sue take a stab at rearticulating Kevin's reasoning as to why H-Cl is an outlier, but they both get stuck. Atrey then proposes a chemical question related to atom size. He is wondering about a new idea that the team has not yet considered – perhaps the size of the Cl atom could account for H-Cl's unusually large bond length. Ann now takes a turn at making sense of Atrey's new proposal, but her understanding of a chemical bond contradicts Atrey's suggestion. At this, Sue again asks, "so wait, why is HCl an outlier?" and Ann and Atrey ask Kevin to say his idea again. The excerpt continues with Kevin rearticulating his idea.

Kevin: So I was saying that it doesn't make sense that H-H is longer than the H-Cl because-

Ann: (*correcting Kevin*) But it's shorter.

Atrey: (reminding the team of his new idea) They are smaller.

Ann: (*to Kevin*) H-H is shorter.

Kevin: No, I know. I'm saying this (H-H) length shouldn't be shorter.

Ann: [shouldn't be shorter?

Atrey: [Why?

Kevin: I, I, I don't know.

Ann: (*with a coy smile*) Do you have any evidence to back up that statement?

Kevin: Well, I did, but I mean my evidence might be wrong.

Atrey: What's your evidence?

Kevin: I told you earlier, that Cl is more electronegative. So like it pulls it close together. So it should be shorter.

Ann: [Oh, it should be.
Atrey: [Ah, but at the same time -
Kevin: [But H is really small too.
Ann: [It should be. (*looking towards* Atrey) Electronegativity dominates.
Atrey: H is like so small though, so can't they be like really close? (places his fists together to mimic two H atoms getting close together)
Ann: But it shouldn't be closer than with a more electronegative atom, right?
Atrey: Wait, wait, wait. Okay, so if, so then if the Cl is here (draws an imaginary circle with the index finger on his right hand), and we're talking about valence electron bonding, right?
Sue: Yeah
Atrey: So then its electrons are all the way out here (*draws an imaginary circle with a wide diameter in the air*), but then hydrogen's electrons are way closer to it because their valence shell is only core electrons (*Sue and Ann both nod heads and say yes*)
Atrey: So then the fact that the two hydrogens have to get closer together to touch each other at all, maybe that's why the bond length is so short. Because with HCl, they are all the way out here (*draws a wide circle with hands*)
Kevin: Right. Yeah. Because we're not talking about the actual length of the two molecules; we're talking about the bond length in particular.

That the team invests so much energy in trying to understand Kevin's proposal suggests they clearly see value in continuing the conversation. And their insistence on understanding one another and making sense of the underlying chemistry leads to rich chemical sense-making about which variable – size or electronegativity of participating atoms – offers more explanatory power for describing trends in bond strength. Further, in the moments following the excerpts above, the continued conversation prompts Atrey to pose several important and challenging questions about how bond length gets measured that the team attempts to take up (e.g., "What is the bonded self? How do you measure the distance of the bonded self? What is the bond length?"). It is important to note that questions of such abstract and complex nature are not often posed to or engaged by first year chemistry students. As such, we as designers and instructors did not expect nor prepare resources to support such sense-making. Hence, when the team asked an undergraduate instructor to explain what bond length means and how to measure it, the undergraduate instructor was also stumped. Altogether, it is evident in this episode that the *collective investigation* frame supports powerful chemistry learning for this team, in that the students' collective insistence on understanding leads the team to rich contemplation about bond length and its relationship to bond strength.

Positional and epistemological framings of collective investigation

In the sections above, I used two cases to illustrate students' participation within a *collective investigation* frame. I now return to the first case (Keyshia, Cadence, and Olivia) to examine three features of their activity that support their collective engagement in chemical thinking and learning: (1) intellectual authority, (2) accountability to the discipline, and (3) accountability to each other. I then consider what these features suggest about the positional and epistemological aspects of the *collective investigation* frame.

Authority vis-à-vis positional framing

In the excerpt above, we see Olivia, Cadence, and Keyshia operating as though they have the intellectual authority to author new chemical ideas and explanations together. They take up an active role in making decisions about how they will organize data, in asking questions and generating explanations from data, and in deciding when they are satisfied with those explanations. Moreover, they take up the authority to question and challenge the raw data generated by the instructors when it does not seem to make sense. For example, following their discussion about where the H+ goes, the team turns to consider the relationship between the concentrations of ions in the final reaction solution and the pH of the mixture. Keyshia notices that most of the pH values reported range between 4-9, but one reaction mixture reports a pH of 87. She challenges this data ("it's not supposed to say that, right?"), and the team laughs about it together, deciding it's a mistake ("it must be 8.7") and moving forward.

Their authorship role suggest a positional frame is established in which students are positioned as responsible for actively making new sense of data and as capable of doing so. In other words, the students are being invited to take up positions as chemists. The chemistry learning students engage in necessitates this positional frame - students would not have made evidenced claims, asked questions about them, or constructed explanations about how and why unless they were clearly positioned with the intellectual authority to do so. Additionally, authority is required for students to engage collectively – student contributions are the raw material of collective practice.

Accountability to the discipline vis-à-vis epistemological framing

While students are positioned with authority to make sense and produce knowledge, they do not have unrestricted freedom to construct any kind of explanation they want. Instead, we see Olivia, Keyshia, and Cadence taking disciplinary norms into account as they make sense of why H+ is present in some reaction mixtures and not in others. Olivia is accountable to the norms of chemical practice when she does not join Keyshia and Cadence in writing the "dissolve and disappear" conclusion, and instead opens up inquiry by saying "but I don't know where they go." In chemistry, atomic level explanations must account for how particles, like H+, move and interact with other particles, like the base. Suggesting that H+ "disappears" does not yet count as an acceptable chemical explanation because it does not account for *how* H+ interacts and how it is transformed in the final reaction mixture. Olivia's role as disputer and questioner here suggests an epistemological frame was established in which chemistry is about making or finding a certain kind of sense of atomic arrangements.

Keyshia is also accountable to the disciplinary norm of having evidence and reasoning to support chemical explanations. As she responds to Olivia's question, she is linking her reasoning about the base dissolving the H+ to evidence in the data, doing so in a register that makes room for disagreement and further questioning. The tentativeness with which Keyshia shares her reasoning might suggest an epistemological framing in which chemistry is perceived as sense-making process that necessitates, or benefits from, alternative explanations. Altogether, authority to author chemical ideas and the disciplinary accountability to do so in way that is responsive to the norms and practices of chemistry support students participation in the chemical practices coded for in Table X, and therefore is consequential for students' chemistry learning.

Accountability to the each other vis-à-vis epistemological framing

While authority and accountability to the discipline help us to see how participation in chemical practice was supported, these features do not yet account for the collective nature of participation that became the norm in the course. It is students' accountability to one another alongside authority and disciplinary accountability that accomplish the collectivity that governs students' participation together. The accountability that we see exhibited in the vignette is what Engle and Conant (2002) refer to as an internal accountability in which students, and not an outsider, decide *together* when they are *all* satisfied that their reasoning makes sense. Accountability to one another does not require acceptance of others' views, but it does require responsiveness to them. We see this responsiveness evidenced in the turn following Olivia's question. Keyshia takes Olivia's question as an indication that the team is not yet done making sense together. And, in the second excerpt, Olivia turns to Cadence and invites her into the conversation, indicating that it is important that the entire team think together about the issue at hand. Once again, this accountability suggests an epistemological frame in which chemistry, though sensible, is complex and multidimensional, requiring the work of the entire team for success.

Designing the classrooms system to support collective investigation

Thus far, I have established that students' participation within CHEM 101B was organized around a *collective investigation* frame, the content of and positional and epistemological aspects of which supported students to participate in the chemical practices as they negotiated meaning about data together. Recall from the introduction that dislodging the *doing school* frame and inviting students into frames - like *collective investigation* - that are more productive for learning is challenging and requires attention to re-mediating the entire classroom activity system. In this section, activity theory prompts me to look relationally at how tools, practices, and participation structures are organized to create the conditions in which the *collective investigation* frame was created and successfully taken up.

CHEM 101B as an activity system – supporting collective practices

> We create, I want to say - I don't know how to get my words together - **but we're a community** of not just - we're not just a normal class. We are like a, **a community**, like group activities. It's not like the typical class. Um, there's a lot of interaction and we work together as a team for one - we have **one problem** that we work on together. And I believe there is **no sense of hierarchy** as much, and it's more collective where **everybody brings something to the table**. There's a lack of hierarchy and there's a lack of elitism. There's no elite, there's none. And the **instructors try to pull what people -** instead of pushing people**, pulling the best out of them. They highlight what everyone is capable of doing.** What's

> special about each individual instead of assuming that everybody can learn that way - **just providing different opportunities for them to learn and highlight it.** Highlight the positivity and not highlighting the negativity as much. There is so much if you break it down that CHEM 101B can do to students that it's definitely different from the typical [university] lecture class on this campus [emphasis added]. (Malik, Interview)

The new activity system of CHEM 101B that Malik describes – one that values collective chemical practice over individual practice, that presumes competence and supports students to recognize it in themselves and in one another –runs deeply counter to what is typical in schools, and particularly in STEM 'gateway' or 'weed-out' courses at the undergraduate level. I chose to begin this section about designing for collective practice with these words from Malik because they remind us that accomplishing collectivity requires systemic transformation that disrupts the dominant cultural frame of school science. McDermott and Raley (2011) tell us "the social world is always well organized. Participants in the social world constantly struggle to figure out what to do next, and they use their ongoing contact with others to guide them to usually regular outcomes" (p. 372). Our chemistry students have spent most of their lives in school science learning that science is a body of knowledge that only some people are smart enough to understand and use, and also learning the rules of looking smart and avoiding looking not-so-smart. Students have learned to be careful not to ask questions or to articulate out loud in class what they do not understand. They have been socialized into practices that do not support the rich engagement in disciplinary learning we hope to support.

Our work to re-mediate this general chemistry course, then, was rooted in an awareness of the cultural barriers to collective engagement in chemical practice. As such, two questions were central to our design choices as we worked to re-mediate the system: (1) How do we set students up to participate collectively in sense-making the ways that chemists do – according to the tools, practices and norms of chemistry as it is practiced? And (2) How do we create the conditions where all our students' "scientific smartness" is surfaced, recognized, and developed? Movement towards this vision requires significantly changing the social organization of learning – curricular tools, participation structures, norms and values, and language practices – to invite students into *collective* engagement in chemical practice such that both students and instructors have opportunities to see and build on the many ways in which they are already brilliant. We designed CHEM 101B as a tool rich system, which included material, conceptual, and human tools that were part of robust practices that organized participation in the course. As I observed and interacted with students in the class, activity logged video and read their reflections throughout the semester, I gained insight into the tools and practices that mediated students' collective activity and their sense-making about it. In the section that follows, I describe three aspects of course design that did important work to organize the activity system of CHEM 101B: (1) chemical tasks, (2) task launch, and (3) supporting interactions during class.

How task design fosters collective investigation

Our team designed group-worthy chemical tasks that invited teams to take on a more active role in making sense of data together to construct understanding in ways that parallel the work of chemists. In developing each task, we identified the big chemical ideas that we wanted students to make sense of, and then generated driving questions and accompanying data and or chemical models that would motivate the investigation of the big idea. Finally, we developed a team product that would (a) hold students accountable to collectively engaging in the kinds of chemical practices and meaning-making that would support students' sense-making about the big idea, and (b) be open-ended enough to allow for different avenues of arriving at a possible solution. Tasks with only one successful solution pathway would get in the way of supporting students to see that there are many valid ways of competently participating in chemistry. Team products often required students to argue/explain from evidence, generate a set of generalizable rules from evidence, construct or revise a model from data, use a model to make predictions, or design an experiment. Finally, as we constructed chemical tasks, we kept in mind that variations in prior knowledge can quickly separate students who "know" from students who "don't know," creating problems for equitable participation. To mitigate this possibility, we removed most scientific jargon from the task cards, allowing students to discuss and make sense together without being encumbered with the use of new scientific lingo.

Tasks were explicitly designed to cue a *collective investigation* frame. The focus of activity was signaled by the driving questions, which were overwhelmingly articulated as how or why questions (e.g., "How do the properties of the elements relate to shell models of the atoms?" [L2 Task Card] or "Why are some bonds harder to break than others?" [L14 Task Card]). In total, 28 of the 39 total driving questions were articulated as how or why questions. In place of a lecture or a textbook, which students tend to view as authoritative sources of information, tasks instead oriented students to data as the primary tool for investigation, and positioned the team with the responsibility for and authority to produce knowledge from this data. Finally, teams of four to five were intentionally provided with two task cards and one shared set of data to orient hold them accountable to thinking together as a team.

Figure 11. Chemical tools provided for L7 task. (A) L7 task card, (B) periodic table of electronegativity values, (C) polar bear and penguin polarity cartoon

(A)

L7: THINKING (ELECTRO)NEGATIVELY – *Polarity*

Today's Question: How are the properties of molecules related to the 3D distribution of electrons and Coulomb's law?

Your Task: Use the **Bare Essentials of Polarity** comic strip, the periodic table with **electronegativity** values, and the molecular models to develop a model to predict if a small molecule has a smell.

Small Molecules and Smell

Work with your team of 4. Divide the work so that each member draws and builds two molecules.

The human nose contains smell receptors that detect molecules in the air that we breathe in. The smell receptors contain positive and negative charges.

1. **Examine** the data below. Draw Lewis dot structures.
   - Molecules that have a smell: H_2S, HOF, CH_2F_2, NH_3
   - Molecules that do not have a smell: O_2, CO_2, CF_4, C_2H_6
2. **Build** three-dimensional models of each of these molecules with the model kit.
3. **Identify** differences between the molecules that do and do not have a smell.

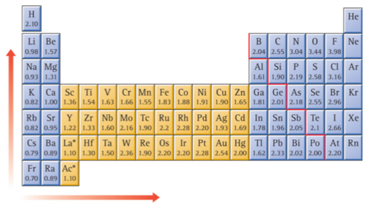
Bringing It Together

Work with your team of 4. Make sure everyone is included.

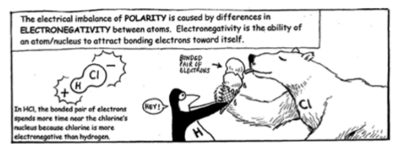
4. **Develop** a model that relates smell with molecular structure. Use the concepts of polarity, electronegativity, and Coulomb's law in your model.
5. **Illustrate** on your Note Sheet how each of the polar molecules are attracted to a smell receptor with a + charge.
6. **Use** your model to predict which of the molecules below have a smell:

CH_2O, $C_2H_6O_2$, C_2H_4, SO_2

(B)



(C)



How task launch fosters collective investigation

In this section, I contend that important cultural work happened in the task launch to support students to take up invitations into the *collective investigation* frame. I analyze how Professor S framed activity in CHEM 101B through the task launch. Recall from the discussion in the methods chapter that the task launch comprised the first 4-7 minutes of class and consisted of three routine practices: (1) orienting students to the driving question of the day, (2) orienting students to the chemical resources that would guide their sense-making about that question, and (3) naming the "smart things" students could do to think together like chemists as they participate in the task. To understand how aspects of activity were framed in ways that cued the *collective investigation* frame, I examined excerpts of the task launches documented in field notes across the ten activity logged lessons (L7, L10, L11, L12, L14, L24, L29, L30, L31, and L36), returning to video when my field notes were missing consequential sections of the launch. In particular, I noticed that during the task launch Professor S regularly framed three aspects of participation – the nature of chemical learning, students' roles as learners, and the nature of competent participation. The following five aspects were coded:

1. *Framing learning as making sense of data.* Establishing the focus of the day in relation to the driving question and establishing what students are trying to accomplish together. (e.g., "The key question is 'What is heat transfer?' What model, what picture, do you have in your head when heat is being transferred? When you say, 'Oh I'm being warmed by the sun, what does that mean?' And we want to know what factors affect how much heat gets transferred." [L12, fieldnote])

2. *Framing learning as ongoing and connected.* Referencing past tasks or chemical thinking and learning students had engaged in, and connecting that learning to the day's task. (e.g., "L10 is on interactions of molecules. We've already been developing these ideas" [L10, fieldnote])

3. *Framing students as active sense-makers.* Treating activity as involving the students and explicitly implicating students in doing the work of sense-making. (e.g., "You need to develop a convincing argument…" [L14 field note]; "so you're gonna be looking at trends in ionization energy." [L36 fieldnote])

4. *Framing competence as multidimensional.* Naming a wide variety of practices that matter for successful completion of the task, often that countered dominant understandings of scientific competence. (e.g., "One other thing is the smart things you're gonna be doing: apply Coulomb's law as you interpret the graph. Make predictions…" [L14 fieldnote])

5. *Framing competence as distributed.* Emphasizing the importance of valuing and learning from the contributions of all members of the team, often connecting needing the team to the need for multiple ways of seeing and thinking. (e.g., "And please ask others to explain their reasoning, because I think, as you're learning, there's often multiple valid ways of looking at things. There's not just one right answer. So it's very useful to hear what other people have to say." [L7 fieldnote])

Table 10. Professor S's Framing of Activity During the Task Launch

	Framing Activity				
	Focus	Time	Students	Competence	
Lesson #	making sense of data	ongoing and connected	active sense-makers	multi-dimensional	distributed
7	Y	Y	Y	Y	Y
10	Y	Y	Y	Y	Y
11	Y	Y	Y	Y	N
12	Y	N	Y	Y	Y
14	Y	Y	Y	Y	N
24	Y	Y	Y	Y	N
29	Y	Y	Y	N	N
30	Y	Y	Y	Y	N
31	Y	N	Y	Y	N
36	Y	N	Y	Y	N
Totals	**10/10**	**7/10**	**10/10**	**9/10**	**3/10**

Table 10 catalogues the frequencies of these particular framing moves across 10 task launches. I then considered how these framing moves interacted to establish the content and the positional and epistemological aspects of the *collective investigation* frame that supported collective engagement in chemical practice. Given that the L7 launch included each class of framing moves, I analyze it in the section below to illustrate how particular classes of framing moves work together to create the *collective investigation* frame. The series of excerpts below is organized according to the three routine practices that make up each launch.

Excerpt 1: Orienting students to the driving question for the day

> And the question is: How are the properties of molecules related to the 3D distribution of electrons? And as soon as you hear electrons you're thinking Coulomb's law, because electrons have charges on them. And we're building through the lectures. L5 we talked about how to just draw structural formulas, L6 we talked about shape, and now we're going to talk about where are the electrons now that we know these molecules have 3D shapes. So the question of the day actually has to do with small molecules that are often gases and that are in the air all around you. And some have a smell and some don't. I show there that H_2S - you would immediately detect that as the rotten egg smell. Ammonia you would detect as the window cleaner smell. But nitrogen, carbon dioxide, oxygen, they don't have a smell. **And so one of the goals today is to try to understand that, or to try to figure out <u>why</u> some do and some don't.** And smell is just one property that you can look at [emphasis added]. (L7 Fieldnote)

In the above excerpt, two classes of framing moves are present. First, the professor frames the focus of activity as making sense of data. She does so by explicitly naming what students are trying to accomplish together – "understand" or "figure out why" – in relationship to a driving question and data about smells. Hence, she is setting the scene as investigation, framing what is available to be investigated (i.e. why some molecules smell and some do not) and how (i.e. using smells data and their past knowledge). Second, she frames the learning students are doing as ongoing and connected. She does so by reminding students that they have already done some important thinking about the attractions and repulsions of charges, and about how charges influence the specific three-dimensional shapes that molecules form. She then makes clear that in L7's investigation, students will draw on these concepts as they consider how the distribution of those charges within a three-dimensional molecule affects the properties that students can experience on an everyday level – like smell. Additionally, she frames the learning as connected to students' actual lives by naming smells students would be familiar with and connecting those smells to particular molecules in the data students will examine. These framing moves work together to establish both the content of the frame – an ongoing investigation into how and why only some molecules smell – and to build an epistemological frame – chemistry is a connected set of ideas and models that makes sense of our experiences in the world.

As she continues in the launch, she begins to frame who students are in relationship to this activity and what they are expected to do with the chemical tools provided.

Excerpt 2: Orienting students to chemical resources

> **So what you're gonna do is** you're gonna have three – no two pieces of information and model kits. So one piece of information is called electronegativity. And in your packet there is a periodic table that has **some numbers on it that you're gonna examine**. And then we can have fun, there are 4 pages of a comic strip called the Polar Bear and the Penguin. (*Professor S*

> *describes the cartoon and makes a 'punny' chemistry joke. Then she introduces a slide that contains the data students will examine for the day.*) So these are **the molecules that you're going to be looking at** that have smell and don't have smell, but the main thing that **you're going to be doing** aside from using this information is also I distributed some model kits where **you can actually build 3D models**. (*She goes on to describe how to use the models and indicates there should be enough for groups of four*) [emphasis added]. (L7 Fieldnote)

Notice that in centering chemical data and models as tools for investigating, she continues to frame learning as making sense of data and begins to frame students' learning roles as active sense-makers. Her talk implicates students as the ones responsible for carrying out the work of investigating (e.g. "*you're* going to…") and uses active verbs (e.g., examine, look, build) to establish students' obligation and the authority to use the tools provided to build understanding about how and why certain molecules smell. These framing moves begin to establish a positional frame that students have the authority and the responsibility for using chemical tools to investigate and author understanding about the driving question.

Finally, she concludes by naming the practices that matter for successfully investigating together.

> *Excerpt 3: Naming the "smart things" to do*
>
> And the smart things you need to be doing today is you really need to be **thinking in three dimensions**. For molecules that aren't flat. How do they look in 3D? You want to **connect back to Coulomb's law** because we're going to be developing more and more – once we know where electrons are on these molecules we can start to think about how they interact with other charges on other molecules or the receptor sites in your nose. You're going to **synthesize information from varied sources** to **come up with some rules** that are pretty general that you're going to be using. And you want to **justify your thinking in ways that others can follow**. And please **ask others to explain their reasoning**, because I think, as you're learning, that there's often multiple ways, valid ways of looking at things. It's not just one right answer. So it's VERY useful to hear what other people have to say [emphasis added]. (L7 Field Note)

Nearly every framing move shows up in the "smart things" portion of the launch. The professor frames competence as multidimensional and distributed by naming five different practices as mattering for competent participation and then emphasizing that students need the diverse perspectives of students in their team to support them to build understanding together. Finally, as she names the practices that matter for competent participation, she continues to frame students as sense-makers ("*you're* gonna…") and learning as ongoing ("because we're gonna be developing *more and more…*")

These framing moves work together to construct the epistemological and positional frames that establish students' authority, accountability to the discipline and to each other.

Framing competent participation in relationship to practices builds an epistemological frame that chemistry itself *is* a social practice of constructing, refining, and using a connected set of ideas and models to make sense. Hence, by naming the scientific practices – connecting, synthesizing, justifying – that matter for competent participation, and by positioning students as responsible for engaging in them, the professor develops students' accountability to the discipline. While authority is embedded within these practices, students do not have unrestricted freedom to make any kind of sense they want of the data – they are being held accountable to making *chemical* sense. By signaling how to interpret chemical representations (i.e. imagining them in 3D) and what constitutes a good explanation (i.e. one that includes reasoning that links back to Coulomb's law), the professor is developing relevant socio-chemical norms. Finally, the professor emphasizes that students are accountable to their team and motivates this accountability via an epistemic framing of chemistry as including multiple valid ways of making sense of data or of explaining a phenomenon. Therefore, students are held accountable for justifying their ideas in ways that their team members can follow, and for asking for one another's reasoning to draw out a diverse set of perspectives to consider and evaluate.

Analysis of the comprehensive list of the smart things communicated in task launches shows that the particular practices named in the L7 launch typifies the categories of practices framed across the entire semester as competent. Practices fell into one of three categories: (1) scientific practices, (2) practices that support learning together, and (3) practices that develop socio-chemical norms. Table 11 shows the four most frequently mentioned practices in each of the three categories across the semester. An entire list of practices referenced in the "smart things" lists is located in Appendix C. I contend that students' authority to author ideas is embedded within all these practices, that scientific practices and practices that build socio-chemical norms hold students accountable to the discipline, and that learning-together practices do important work to build students' accountability to each other.

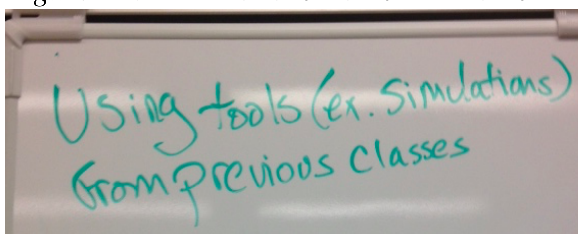
Table 11: Most frequent "smart things" mentioned across the semester

Categories and Frequencies of Practices					
Scientific	**Freq.**	**Learning Together**	**Freq.**	**Socio-chemical norms**	**Freq.**
Apply the ideas/models you've already developed	27	Justify your reasoning in ways others can follow	6	Imagine the atomic scale	9
Make connections across different representations	14	Ask for reasoning/evidence	6	Consider alternative possibilities	4
Recognize patterns	9	Rearticulate other people's thinking in your own words	3	Visualize molecular structure in 3D	2
Identify and control for variables as you consider relationships	6	Come to consensus about…	2	Check that your argument includes: a claim, evidence, and reasoning	1

How instructional practices fosters collective investigation

Finally, as students worked on the chemical task for the day, instructional staff planned to interact with students in ways that would reinforce their authority and accountability. During classroom activity, the instructors' primary role was to step back and let students work, and to listen closely for opportunities to name students' chemical questions and connections as important intellectual contributions. Whiteboards positioned around the room served as tools for recording students' interesting connections and questions. For example, during the L7 Task, an instructor noticed one team drawing on a tool from the L6 task that supported them to think about molecular shape. While this action was not explicitly positioned as a "smart thing," connecting to prior learning and drawing on a wide set of tools to support sense-making was an important learning practice. Hence, the instructor made this practice public by recording it on the whiteboard near this team (see Figure 12).

Figure 12. Practice recorded on white board



Given that the classroom was large and contained 28 teams in total, many teams were physically positioned too far away to see the content on the whiteboards clearly. However, Professor S ended each class by picking 2-3 interesting questions and connections on the whiteboards and publicly assigning competence to these practices, often making explicit connections between students' engagement and the practice of chemistry. During the L7 task, I walked past a team of students discussing the SO_2 molecules. Though I could not hear precisely what the discussion was about, one student in the team stopped me as I walked by to say of his teammate's thinking: "That's brilliant, put that up on the whiteboard." While these occasions were rare, they suggest that some students were aware that the purpose of these whiteboards was to highlight students' brilliant chemical thinking. These students may have reinforced other students' authority and accountability to one another by positioning their contributions as competent. As Malik put it in the excerpt opening this section: "We are like a, a community […] There's no elite, there's none. The instructors try to pull what people - instead of pushing people, pulling the best out of them. They highlight what everyone is capable of doing."

Summary

The findings in this chapter demonstrate that the newly designed CHEM 101B activity system supported powerful reframing of chemistry learning. As evidence of this reframing, I outlined shifts students articulated in their conceptions of learning, and I examined classroom video for 10 different teams engaged in tasks across the semester. These analyses suggest that CHEM 101B successfully cued a *collective investigation* frame and developed explicit language with which students could talk about their participation.

Through a close examination of activity within two different teams, I demonstrated that three important positional and epistemological aspects of the *collective investigation* are consequential for students' chemistry learning: (1) authority to author ideas, (2) accountability to the discipline of chemistry, and (3) accountability to one another. Finally, I considered the classroom as a system, asking how pedagogical practices and tools interact to invite students into collective chemical practice. I outlined several tools (i.e. tasks, "smart things" list, and whiteboards) and practices (i.e., the task launch, assigning competence to students' thinking) that interact to build the content, epistemological, and positional framing of *collective investigation.*

While the increasing integration of evidence-based pedagogies into undergraduate STEM courses marks an important stride forward towards supporting student learning, adding a practice or a new tool here and there is not enough to dislodge a *doing school* frame and overcome the barriers to collective participation (see Chapter 6 for further discussion). This chapter suggests that re-organizing entire classroom's systems, such that they shift intellectual authority to students and hold students accountable to the norms and practices of the chemical enterprise, is required to make the positional and epistemological framings of *collective investigation* available.

Chapter 5: Fostering Identities of Competence in the Figured World of CHEM 101B

> Notice, of course, the second midterm spreads out the class, which is not a bad thing to happen. These people over here (*circling the upper quartile)*, you're all headed for an A as far as I'm concerned. And in here (*circling the middle quartiles*), you're headed for a pretty good grade, I would say. And if you're down here (*circling the lowest quartile*), two things may be happening, and you are the best judge of what happened. One is you didn't believe me and you didn't work everyday, or nearly everyday, and you started cramming… and the result is you weren't prepared enough (…) The other possibility - and I've already talked to several of you steering you in the right direction - is that you're just not good at this (*students laugh nervously*). There is an innate capability issue. And you can't be good at everything. (…) You're here to find out what you're good at, and the complementary part of that is to find out what you're not so good at. It may lead to a situation where you start off something that sounds interesting like organic chemistry, or you have visions of what you want to do where organic chemistry is essential, and you find out, well, actually, this isn't for me. And that is a positive thing. You find out and you decide and then you just drop the subject. (…) That, I call enlightenment, not failure, you're learning something, so take it in that vein. (Organic Chemistry Professor)

Exams and the grades attached to them are among the most powerful ways that instructors and students determine competence in undergraduate STEM courses. This emphasis is not surprising since exam grades comprise nearly the entirety of a student's overall course grade. The organization of systems of schooling, and the actors within them, teach us how to *see* grades. Instructors, like in the excerpt above, interpret grade distributions for students. Students compare grades with one another and respond with praise or condolence. Course grades constrain or enable students' access to future classes, to research experiences and internships, and to future graduate or professional schooling.

Nearly all who have participated in the American system of schooling have experienced a talk like the one in the excerpt above – an instructor projecting a grade distribution on a board following an exam, teaching us to interpret the symbols attached to our work in particular ways. In this organic chemistry class, the story is clear. If you received a high score on this exam, rest at ease. The talent that earned you your score is innate. On the contrary, if you received a low exam score, you are facing a momentous hurdle. You lack the innate ability required for success in this course, and it is best that you accept this and switch to a discipline to which you are more suited. Students are well familiar with this story – the belief that innate talent is required for success in STEM is woven into the fabric of the American *common sense* (Leslie, Cimpian, Meyer, & Freeland, 2015) – and yet the nervous laughter that erupts and continues at the professor's words "an innate capability" suggests that such an explicit public retelling of this belief breaks the norm that these conversations are to be had in private.

This story is central to my research because CHEM 101B students went on to participate in this organic chemistry class and experienced this message the semester following CHEM 101B. Kehlani, whose case I will highlight in this chapter, was one of those students whose exam score sat in the lowest quartile, and who was consequently positioned as someone who lacked the innate talent to succeed in this chemistry class despite her many scientific strengths. This story highlights the lack of definition of "good" found in this type of narrative. Goodness is associated with high grades on exams, and with innate intelligence, but students do not actually know what it means to be "good at chemistry" apart from receiving high exam grades.

My research addresses the problem that students exiting chemistry courses at California University are unable to define what chemistry is or what it means to engage in chemistry, yet nonetheless emerge with a powerful sense of themselves as "good" or "not good" at whatever chemistry is. Even though the kind of "good" determined by chemistry exam grades has little relation to what students will eventually be doing in their careers as chemists, biologists, engineers, or doctors, positioning students as "good" or "not good" based on grades powerfully affects students' decision-making regarding these careers. Whether they pursue or veer away from STEM career paths is often determined by grades in introductory STEM courses.

To remedy this entrenched problem, our research team organized learning in CHEM 101B with the aim of re-mediating (Gutiérrez, Hunter & Arzubiaga, 2009) students' conceptions of chemistry and what it means to competently participate in it. By re-mediate, I mean we sought to redesign the entire activity system of the course – curriculum, participation structures, discourse practices, and assessments – in order to support more authentic, and therefore, more inclusive, meanings of chemistry as a social practice.

Recall that in Chapter 4, I described how the design of this new activity system cued what I termed the *collective investigation* frame in ways that were consequential for students' chemistry learning. Applying frames as a unit of analysis, Chapter 4 took a close look at how students oriented to chemistry learning in moment-to-moment activity. Chapter 4 focused on analysis of students' participation in chemical practices. In this chapter, I turn to more broadly examine students' new conceptions of chemistry after participating in CHEM 101B, and how new meanings of "good at chemistry" relate to the identities of competence students construct in the course.

Altogether, this chapter suggests that the organization of learning in CHEM 101B constructed a new *figured world* (Holland et al., 1998) that made *collective investigation* sensible. Throughout this chapter, I will refer to the old figured world as "the world of school science" and to this new figured world interchangeably as the "the world of doing chemistry" or as the "world of CHEM 101B." Recall from Chapter 2 that figured worlds are "socially and culturally constructed realms of interpretation, or webs of meaning, in which particular characters are recognized, significance is assigned to certain acts, and particular outcomes are valued over others" (p. 52). In figured worlds, people construct identities as they participate in practice and make meaning of their participation in relationship to the cultural meanings that shape the world.

I assert that the world of CHEM 101B offers new and more inclusive meanings about “good at chemistry” that are anchored in authentic chemical practice. Following Sevian & Talanquer (2014), I conceptualize authentic chemical practice as involving the investigation of chemical substances and phenomena in search of explanations for their properties and behaviors. Chemistry as it is practiced is not a static body of knowledge to be memorized, but instead a powerful way of thinking and building new understanding to explain everyday phenomena in chemical terms. It is a social practice with human beings at the center, engaged in asking questions, creatively making sense, and developing and revising models. This chapter argues that students' practice-based conceptions of chemistry up-end the narrow and exclusive meanings that figure the dominant world of school science (i.e., good grades, innate intelligence).

I further contend that the world of CHEM 101B makes new subject positions available to students, and that via its new meanings and new positions, the world opens up new possibilities for who students become in relationship to chemistry. Findings suggest that in the world of CHEM 101B students become: (1) people who do chemistry powerfully, (2) people who do chemistry as themselves, and (3) people who have power to co-construct the world as they want to see it. It is also evident in the data that students continue to be disempowered and positioned as not "good at chemistry" by exams and exam grades in the world of CHEM 101B.

In this chapter, I primarily illustrate these claims through the case of Kehlani, a sophomore who is taking CHEM 101B after failing introductory chemistry (CHEM 101A) during her freshman year at the university. Kehlani’s interview offers rare insight into how students navigate contradictions in the world of CHEM 101B. I close the chapter by considering the ways that the interview itself serves as a necessary tool of reflection that supports students to negotiate and momentarily resolve identity conflicts.

A New Realm of Interpretation: new meanings for "good at chemistry" emerge
In the sections below, I examine shifts in students’ conceptions of “good at chemistry” after participating in CHEM 101B for one semester. To capture students’ own understandings of their preconceived notions and of their new conceptions, I draw on student course reflections and interviews. In interviews (n=21), I asked students to describe what they thought it meant to be good at chemistry in CHEM 101B. In course reflections (n=86), students reflected on a similar question: "How has CHEM 101B changed, challenged or confirmed your ideas about what it takes to think like a chemist?" I began my coding process by coding responses to interviews and course reflections separately. Once codes were developed for both sets of data, it became clear that the questions asked in interviews and in course reflections yielded similar student responses. For this reason, I collapsed data from both interviews and course reflections into one table and applied the same set of codes across the entire data set. In total, 89 student responses are represented.

Since dominant cultural meanings about "good at chemistry" are ingrained into students' ways of making sense, they often cannot be articulated until students come in contact with new ways of thinking that create tensions with their common sense understandings. It takes a shift in understanding for common sense notions to emerge and become visible to students. As such, many of students' prior conceptions about "good at chemistry" were discussed in terms of shifts from old assumptions to new conceptions. I begin this section by documenting students' preconceived notions about "good at chemistry" and then move to examine the new conceptions students articulate.

Students' prior notions of "good at chemistry" are narrow and exclusive

As students make-sense of what it means to be "good at chemistry," they show a clear awareness of dominant, prototypical cultural understandings about "good at chemistry" that the world of school science (and dominant culture at large) offers them. Out of 89 total students represented across the data, 35 student responses were coded as not having explicitly articulated a prior conception of "good at chemistry." Of the remaining 54 who described their prior notions, 39 students (72%) named one or more characteristic associated with prototypical notions of "good" or "smart" at science – knowing lots of information (44%, n= 24), getting all correct answers (11%, n=6), getting good grades (11%, n=6), thinking quickly (2%, n=1), and having naturally ability (19%, n=10). Further, 12 (22%) students described chemistry as "difficult," "hard to comprehend," or a "lost cause." Carlone (2004; 2011), investigating the meanings fourth grade students and high school physics students associate with "smart science students," documented the same set of associations across both student populations. These meanings about smartness and "good at science" are part of the web of meanings that make up the dominant figured world of *school science*.

Table 12. Students' descriptions of their prior conceptions of "good at chemistry"

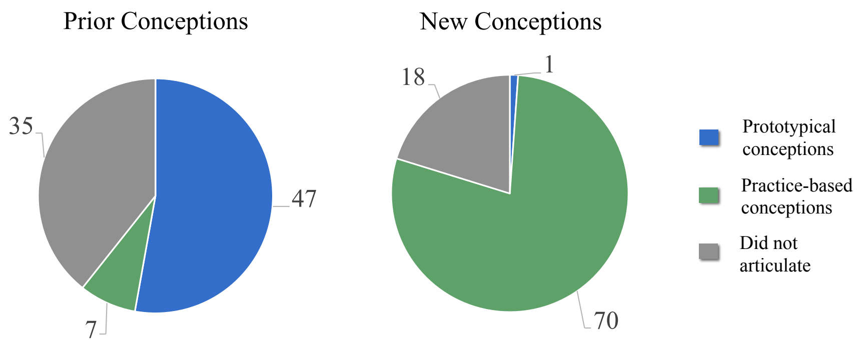
	Knowing lots of information	**Getting correct answers**	**Getting good grades**	**Thinking quickly**	**Having natural ability**	**Chemistry is difficult**
# of students*	24	6	6	1	10	12

*In total, 47 (87%) students were coded as expressing prior conceptions of chemistry or "good at chemistry" associated with prototypical views of science. Some students named more than one characteristic associated with prototypical views.

There is a clear narrowing in schools about what it means to do science and what then counts as "good at science." Scientific brilliance is made to seem scarce, rather than distributed across all students, as we know it to be (McDermott & Ralley, 2011). While these dominant constructions of "good at science" have no meaningful relation to science as it is practiced, they are made sensible via the practices of school science (e.g., lectures, multiple choice tests, classes that cover a wide breadth of information at a fast pace, privileging academic and scientific language, etc.). Given that the design of CHEM 101B aimed to disrupt these prototypical and narrow associations with "good at chemistry," building more meaningful and inclusive conceptions of chemical competence in their place, I now turn to analyze the new meaning students make about "good at chemistry" after a semester of participating in CHEM 101B.

Students' new conceptions about good at chemistry are broader and more inclusive
Students were more likely to articulate their new understandings of "good at chemistry" after participating in CHEM101B. Of the 89 total student responses analyzed, only 18 were coded as not having explicitly described what it means to be "good at chemistry" after one semester in CHEM 101B. Of the remaining 71 students who did articulate conceptions of "good" after the semester, nearly all students (99%, n=70) described new conceptions that were broader, more inclusive, and anchored in aspects of authentic chemical practice.

Figure 13. Students shift from prototypical to practice-based conceptions of "good"



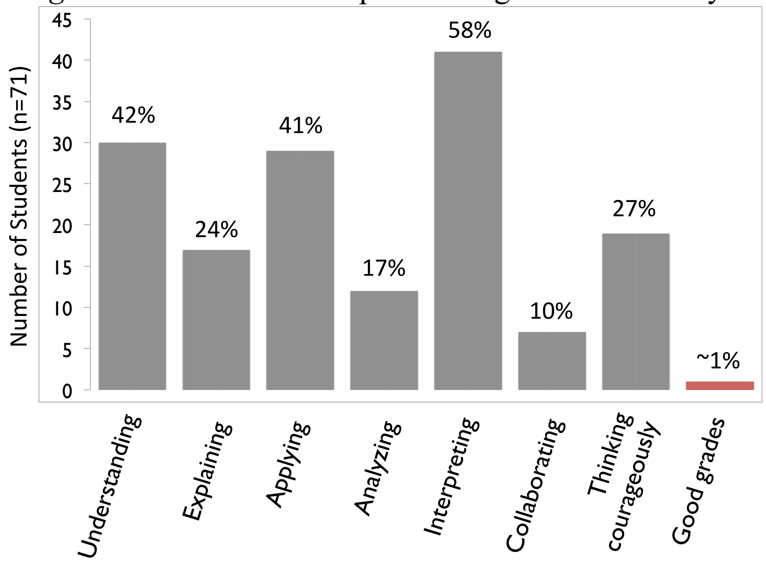
Two broad themes emerged in the ways students tended to define "good at chemistry." Some students foregrounded the overarching goals or outcomes of engaging in the chemical enterprise, namely generating new chemical understandings that can be applied to explain new phenomena. This theme I refer to as "actively understanding and applying chemical models." Other student responses foregrounded the process of building new chemical understanding, centering the practices and mindsets chemists employ as they investigate new phenomena. I refer to this theme as "investigating data to build new chemical explanations." In naming these two themes as separate, I do not mean to suggest that students' descriptions were only outcome- or process-focused. Many students discussed aspects of chemical practice that fell under both themes. I primarily use these themes as a tool for organizing the different ways students talk about what it means to be "good at chemistry" in the sections below.

To generate themes, I followed an analytic process that was grounded in the data. My research team and I began by open-coding students responses to develop a set of 18 different sub-codes to name aspects of chemical practice that students discussed. These codes were then categorized into the seven big-bucket codes shown in Table 13: (1) understanding chemical ideas, (2) explaining chemical ideas, (3) applying chemical models to the real world, (4) analyzing data, (5) interpreting data, (6) collaborating, (7) thinking creatively and courageously. I then considered what themes were embedded in these conceptual categories (Harry, Sturges & Klinger, 2005). Frequencies of each big-bucket code were tallied.

Table 13. Theme generation map

Themes	Big Bucket Codes	Definitions
Actively understanding and applying	Understanding chemistry	Students describe understanding chemical concepts, ideas, models and ultimately chemical phenomena as what it means to be good at chemistry
	Explaining chemical ideas	Students suggest that being able to explain chemistry to others well, and to communicate effectively to the public is part of what it means to be good at chemistry
	Applying chemical models to the real world	Students suggest that using chemical models and ideas to explain real-world situations, and seeing the world at the molecular level is part of what it means to be good at chemistry.
Investigating and explanation building	Analyzing data	Students describe practices such as asking questions, organizing data, finding patterns in data, and identifying evidence as part of what it means to be good at chemistry
	Interpreting data	Students describe practices that are about making sense of data that has been analyzed, including making connections, considering multiple possibilities, drawing conclusions and constructing & revising models as part of what it means to be good at chemistry
	Collaborating	Students describe collaborating with other people as part of what it means to be good at chemistry
	Thinking creatively and courageously	Students describe characteristics and mindsets that are about thinking outside the box and exercising persistence, including being creative, open-minded, appropriately skeptical, persistent, and intellectually courageous as part of what it means to be good at chemistry.

Figure 14. Students descriptions of “good at chemistry”



I represent students’ descriptions of "good at chemistry" in Figure 14. Notice that the prototypical descriptions of “good” have disappeared, and nearly all students incorporated descriptions of “good” that implied a broader meaning of chemistry. In the sections below, I use representative quotes from eight different students to provide rich descriptions of students’ new conceptions of chemistry as a social practice. Throughout the section, I argue that students’ culturally produced meanings of "good at chemistry" suggest that participation in CHEM 101B recruited students to a new cultural world, one in which students’ school-y and elitist notions of "good at chemistry" were no longer sensible.

Theme One: "good at chemistry" means understanding and applying chemical ideas

As students made sense of what it means to be "good at chemistry," they were very clear that being "good" is not about having lots of chemical information readily available to spit out. Instead, it is about deeply understanding information and about thinking with a connected set of chemical ideas and models. In total, 35 of the 71 students (49%) described "good at chemistry" in terms of actively understanding chemical concepts and applying chemical reasoning to make sense of the world. Of these 35 students, 17 students specifically called out explaining concepts and teaching others as part of what it means to have a deep understanding of chemistry. For example, in his interview, Garrett described this idea:

> I feel like what it means to be good at chemistry - actually, what I feel that it should mean to be good at anything in general - is your ability not just to reiterate information (which anyone can do) and regurgitate, **but to be able to take that and transform it and explain it in different ways**. And I think this class helps with that, because you could explain it to someone, and they’ll be like “What?” and someone else will be like “Duh.” You have to take that information, break it

> down into its core components, and make it into a completely different way. To be able to **restructure information in a way that everyone can understand** is to truly understand it yourself [emphasis added]. (Garrett, Interview)

Garrett emphasizes that being "good at chemistry" means having ownership of chemical ideas in ways that allow one to use those ideas flexibly, and to explain them in ways that make sense to others. It is noteworthy that his definition uproots two prototypical notions of "good at chemistry": knowing lots of information and deploying the seemingly complicated and technical chemical vocabulary associated with "good at science" in the dominant world of school science.

Eight students extended the idea of explaining in ways that make sense to others beyond the classroom as they emphasized the importance of sharing chemical understanding with the general public who might not have a rich background in chemistry. For example, Kehlani described:

> Because a person that gets good grades could be a book smart person who doesn't know how to carry themselves [sic] in the lab scene, or doesn't know how to communicate with people or connect chemistry to daily life. Now after this class, I feel like a good chemist is someone (…) **who can relate it to people** – because you can't just tell people there is global warming, but if you're **able to connect it to their understanding, that's a good chemist.** [emphasis added]. (Kehlani, Interview)

We see in Kehlani's articulation above a more expansive understanding of chemistry and what it means to be good at it. Here, chemistry extends beyond the classroom into the laboratory and then into the public sphere, where chemists are responsible for connecting with people and for making chemistry relatable and palpable to those who do not study it. Hence, competence is not a property of the "book smart," those who are adept at taking in and showing off knowledge, but is associated with people who can communicate chemistry in ways that relate to others and create human connection. In her course reflection, Kehlani reflected on the power of realizing that "good at chemistry" was not about positioning oneself above others through the use of esoteric, technical scientific language, but about being together with people in ways that makes space for shared understanding:

> Before this class, I thought a chemist was someone who was **smart**, **got good grades all the time**…[and] was someone who **knew chemistry** and if they explained it to a person with no scientific background **it should sound like gibberish**…. Personally, the biggest conception I had about how a chemist thinks that changed through this course was that a chemist shouldn't just make sense to another chemist, but that **a true chemist is someone who can** take something as complex as quantum numbers and explain it to someone with no knowledge of science using terms that **make sense** to them and not only to a scientist [emphasis added]. (Kehlani, Course Reflection)

The idea that chemistry should make sense, and that good chemists are those who can articulate chemical ideas in ways that make sense to anyone, shatters the illusion that chemists are naturally smart and understand ideas beyond the capacity of the not-so-smart. Not only is this idea powerful in how it moves away from linking chemical competence to innate smartness, but it also makes room for more of the strengths students bring to chemistry to be included in the definition of competent chemical participation. As I will show later in this chapter, Kehlani did not identify as being naturally smart or good at using complicated language; however, she had incredible strengths at making her thinking visible to others, explaining in different ways (using analogies, cultural references, pictorial representations, gestures, etc.), and finding ways to connect with people as she explained chemistry.

Finally, 29 students talked about being "good at chemistry" as leveraging the ideas and practices of the discipline to make sense of the everyday world. For example, Mariana articulated this definition of "good at chemistry":

> I feel that what it is, it's good - I would say just making connections. **Like seeing that chemistry is around you,** and knowing how to explain these reactions that take place even within us, you know, to someone. Being able to have that knowledge and explain it, versus being like "yeah, I can ace this test," or "I'm good at chemistry because I know how to solve this problem." I feel like being good at chemistry is being able to recognize that, and **see the world differently. You know, like seeing all these small reactions taking place and looking at things at a microscopic level** and appreciating that chemistry and appreciating your knowledge that you had in this and being able to share it with others. (Mariana, Interview)

Here, Mariana explicitly rejects the notion that "acing a test" or "solving a chemistry problem" have anything to do with being "good at chemistry." For her, being good means developing a different way of seeing the world – through the lens of molecular interactions and reactions – and reasoning about how it is that these interactions and reactions take place.

Across the excerpts, it is clear that students have gained new perspectives about chemistry as a discipline full of rich and connected ideas that make sense, and one that aims to understand phenomena in the real world. These excerpts begin to shed light on how anchoring conceptions of chemical competence in developing and applying a rich understanding of chemistry is both more meaningful and more inclusive than the narrow definitions available in the world of school science (knowing information, using big words, solving problems, or getting good grades).

Theme Two: "good at chemistry" means investigating and explanation building

While students who talked about understanding and applying chemical ideas tended to foreground the outcome of chemical investigation, a larger subset (n =43, 61%) of students defined "good at chemistry" in relation to the practices involved in the process of investigating data and constructing new explanations and/or models. Within these descriptions, students associate a broad set of practices and characteristics with competent chemical participation. In fact, most students name more than one aspect of investigating chemical phenomena as they describe what it means to be "good at chemistry." For example, in the excerpts below, Navid and Elizabeth anchor chemical competence in many different practices and characteristics that matter for investigating and building new explanations from data:

> I think everyone can be good at chemistry, but they just don't have an interest for it - people that aren't good. If you have interest for it, you actually **actively keep asking questions** off of each other…. But some people who like chemistry, they're like "Wait, but I thought I knew this… why?" They keep asking questions over and over again, which is good. It makes you learn more. To be good at chemistry, you need to be able to have a passion to learn chemistry, and be overly **skeptical** of what you learn. (Navid, Interview, emphasis added)

> I think it probably means being able to **find patterns** and **connections to concepts**…. A chemist **collaborates** with people and **has information/data** and **draws conclusions** from it, **formulating principles** and conclusions; it takes a lot of **analyzing**, **insight**, **relating** and **critical thinking** to be a chemist (Elizabeth, Course reflection, emphasis added)

Navid's and Elizabeth's descriptions are illustrative of the practices and characteristics students across the data most commonly associated with chemical investigation, including: asking questions (n=7), identifying patterns (n=2), connecting to chemical models to make sense of those patterns and coming to new conclusions (n=33). Being "good at chemistry" requires a deep sense of curiosity (n=7) about how and why matter behaves, a healthy sense of skepticism (n=4) that guards against premature certainty, critical thinking (n=4), and collaboration (n=7). Not only are these descriptions reflective of the working practices of chemists, they comprise a more open and expansive way of seeing what it means to be "good at chemistry" that includes many different practices, skills and perspectives.

The expansiveness of students' process-related articulations of chemical competence is connected to newly seeing chemistry as *human* activity – iterative, messy and imperfect. For example, in the two excerpts from Zion and Vera below, the school science notion that chemistry is about truth-finding and getting correct answers is getting dislodged, and in its place, students realize a different and more expansive set of practices are necessary for doing good chemistry:

> Beginning this semester, **I had an impression of scientists – including chemists – as people who sought some absolute truth.** This class taught me that the real work in science is in constructing models. Moreover, I learned that a model **does not have to be perfect**. In fact, we may never be able to create a perfect model of some processes. However, models are a tool to predict certain aspects of an object, system, or process, and, as long as the model works at explaining what concerns us, it is a valuable tool…. I've appreciated how **chemists are willing to revise**

> **their models and prior ways of thinking**…. This class showed me that **intellectual courage is one of the most valuable traits** a scientist can have when thinking like a chemist [emphasis added]. (Zion, Course Reflection)

> Thinking like a chemist, unlike what I had previously thought, **doesn't mean that you necessarily have all the answers**. Rather, thinking like a chemist means that you have the **intellectual courage** to hypothesize what might be happening in a situation and to consider how certain concepts might **apply to a real life situation**. Thinking like a chemist also necessitates **being okay with being wrong** at times…. I have realized that **learning from mistakes** is a big part of thinking like a chemist, as a chemist must revise thought processes and respond to anomalies in observations [emphasis added]. (Vera, Course Reflection)

Coming to understand chemical models as useful approximations rather than the absolute truth challenged students' prior assumptions that thinking like a chemist is about getting right answers. Instead, chemical thinking is redefined as the process of developing useful models that have explanatory power for particular kinds of observations, and revising models when those models fall short of explaining a new observation. What a powerful "ah-ha" moment for students, that being wrong, making mistakes, needing to revise ideas – things learners frequently encounter and that constitute students as not-so-good in the world of school science – are now included as central to doing good chemistry. Of further importance, if chemistry is about developing new models, then doing so requires a different and wide-ranging set of skills, practices, and characteristics for success. Both Zion and Vera highlight intellectual courage, or the willingness to share ideas that one is not yet sure about, as one of these characteristics. Other students named persistence (n=10), open-mindedness (n = 4), and the ability to examine problems from different perspectives (n=10) as important.

Seeing chemistry as a human activity makes room for students to understand chemists as human sense-makers like themselves rather than as a select group of intellectual elites who have been endowed with a special kind of talent. As one student reflected: "Chemists have not always known all that they do, they were once like us. Confused by real world properties that seemed to have no explanation" (Leonard, Course Reflection). When chemistry gets demystified and humanized, it becomes more possible to dislodge the idea that only some people can be "good at chemistry." For example, in course reflections, students wrote:

> Before **I had the preconceived notion that being a chemist took some form of innate ability and intelligence** but now I know that being a chemist is more than just that. **Thinking like a chemist is simply being inquisitive, hardworking, and open to new ideas.** Chemistry is more than just getting the right answers, learning the concepts actually means something to me now [emphasis added]. (Anna, Course Reflection)

> **I had always envisioned that chemists were just naturally smarter** than everyone else and that it did not take much hard work on their part but as I have

> been learning chemistry **I can now see that it takes more time and dedication to understand chemistry than just an advanced mind.** I have a lot of respect for the people who have mastered the concepts of chemistry [emphasis added]. (Keyshia, Course Reflection)

Across course reflections, 10 different students discussed how they used to think chemistry required innate brilliance; however, given their new conceptions of chemistry as a social practice, they now see that anyone can be "good at chemistry." This realization is particularly powerful given the ways that brilliance has developed as a racialized and gendered construct (Leslie et al., 2015; McDermott & Raley, 2011; Nasir et al., 2012). Disrupting the notion that brilliance is a requirement for successfully doing science is important progress towards making science more inclusive to historically-excluded populations.

Section Summary

Students across age levels, when asked what it means to be good at science, draw on the same narrow and exclusive narratives made sensible by the organization of learning in the dominant world of school science (see Carlone, 2004; Carlone et al., 2011, and Table 12). Strikingly, after only one semester of participating in the new world of CHEM 101B, students developed a richer and more nuanced understanding of chemistry as a social practice that upends prototypical notions of "good at science." Now, doing and being "good at chemistry" includes being wrong and making mistakes, not-knowing as the very site of investigation and knowledge construction, and iteration and refinement as normal and valued processes. Most important, perhaps, is that hard work, open-mindedness, courage, and persistence replace the notion that natural ability is required for success in chemistry. Thinking like a chemist is now possible for anyone.

I note here that while CHEM 101B does important work to re-mediate students' definitions of good at chemistry, this does not mean that grades and the powerful narratives surrounding them ceased to matter for students. Grades have existed as a central feature in students' entire lives in school and continue to exist in CHEM 101B. While most students no longer explicitly define "good at chemistry" in terms of grades (in fact many flat out reject grades as communicating anything meaningful), it is clear in interview data that students have to contend with what their exam grades mean as they make sense of themselves in relationship to chemistry, particularly if their exam grades were Bs and below. In later sections of this chapter, I will discuss both how exam-taking and grades constrain opportunities for developing identities of competence, and how particular kinds of reflective experiences support students to navigate the identity threats posed by exam grades.

Identity opportunities in the new world of CHEM 101B

In the sections above, I illustrated how students are making sense of what it means to be "good at chemistry" at the end of one semester of participating in CHEM 101B. I showed that students have developed a new vision of chemistry as a practice, carried out by humans engaging in a diverse set of activities aimed at investigating and explaining phenomena. Students' conceptions of competent participation in chemistry (i.e. what it means to be "good at chemistry") have developed in relation to this more authentic and expansive vision of doing chemistry. Social theories of identity contend that definitions of competence shape the identities people construct as they engage in activity together (Holland et al., 1998; Wenger, 1998). In the sections that follow, I turn to examine new identity possibilities available to students in the world of CHEM 101B as they construct a sense of themselves in relationship to chemistry.

I began my analysis by inductively coding the practices and characteristics students associated themselves with as they responded to the question, “do you see yourself as someone who is good at chemistry?” in interviews. Table 14 includes students’ paraphrased talk about what it means to be good at chemistry and how they perceive themselves in relationship to chemistry. Of the 21 students interviewed, nearly all students (n=19, 90%) associated themselves with the practices they newly associate with "good at chemistry." For example, Navid offered his ability to ask important questions about chemical phenomena as reasoning for why he saw himself as "good at chemistry":

> Yeah, relatively. I feel like **I’m good at asking questions - the questions that matter.** I’m just like, “why does this happen?” The way I ask questions is **not just like “why?”, but more like “how?”** They’re more thorough, I guess. I feel like even though sometimes I may not score the best on quizzes or midterms and stuff, but I feel like the ability to ask questions makes me pretty good [emphasis added]. (Navid, Interview)

In this new world, where asking *how* and *why* questions is now included in the definition of competence, Navid’s *how* and *why* questions position him as a competent chemical doer. Notice that not scoring as high as he might like on exams no longer excludes him from seeing himself as "good at chemistry" like it often does in the dominant world of doing school.

Table 14. Alignment between students' conceptions of "good at chemistry" and students' perceptions of self in relation to chemistry

Student	Talk About "good at chemistry"	Talk about self in relation to chemistry
Kehlani	Understanding chemistry, relating chemistry to everyday life; making chemistry relatable to others, and finding deep enjoyment in doing chemistry	I am analytical; ask good questions; communicate in ways others can follow; relate chemistry to everyday life; make chemistry relatable to others
Mariana	Understanding how and why things work at the molecular level; relating chemistry to everyday life; making chemistry relatable to others.	I explain chemistry in ways that help others learn; make sense of connections between chemistry concepts; apply chemistry to my everyday life.
Carmen	It's about fully understanding and applying concepts to new situations; asking questions; explaining chemistry to others.	I have a good understanding of chemistry concepts; make connections between prior knowledge and new chemistry concepts; explain my ideas to others.
Arash	Getting somewhere new in your understanding; explaining and teaching others; making connections to prior knowledge; asking questions.	I can figure stuff out; ask questions; understand how things work, recognize patterns in data; explain chemistry to my team.
Navid	Asking questions about why and how; connecting ideas to everyday life; being passionate; being skeptical	I ask questions that matter - like *why* and *how* questions.
Garrett	Transforming information into something you understand and can use; explaining in ways that make sense to others	I translate chemistry in ways others can understand and connect to
Lucas	Making connections between concepts; understanding chemistry; explaining chemistry to others.	In some units I make connections and explain things very well to others. I need to get better at asking questions.
Margaret	Thinking outside the box; challenging ideas using evidence; applying chemistry to new situations; communicating chemistry effectively	When people from scientific backgrounds assert claims, I tend to trust them if they sound confident. I want to push myself to challenge information based on my own understanding.

Student	Talk About "good at chemistry"	Talk about self in relation to chemistry
Carrrie	Thinking about ideas in ways scientists do; analyzing data in a scientific manner and drawing new conclusions.	I am good at understanding concepts and thinking in a scientific way; reason scientifically, but it doesn't always mean I gets to the right answer
Cadence	Asking questions that help you learn the material deeper so that you can connect things better; recognizing patterns; interpreting patterns using chemical principles; connecting everything together	I make connections sometimes, but have room to grow in terms of interpreting data.
Catalina	Applying chemistry	I am building towards a good understanding of chemistry; see myself as a beginner with a lot to learn.
Elizabeth	Identifying patterns; making connections between chemistry concepts; drawing conclusions; explaining	I find some patterns, but I do not always know what kinds of connections I should make to interpret data; I learned I was capable of more than I had imagined.
Sophie	Explaining concepts; connecting chemistry to the real world	For some chemistry concepts, like wavelength and absorbance, I can explain and teach others.
Julie	Connecting chemistry to world around you, understanding chemistry; explaining to others	I am good at understanding and explaining certain chemical concepts, and still struggling to better understand others.
Camilla	Understanding chemistry; explaining chemistry to others; connecting chemistry to new situations; messing up is part of the process.	When I do understand chemistry concepts, I am good at teaching and explaining to others.
Atrey	Teaching chemistry to other people; answering his peers' questions	I answer chemical questions asked in my group
Liel	Applying and connecting chemical ideas; knowing how to think like a chemist; approaching problems in different ways.	I make connections between chemistry concepts sometimes, and can think like a chemist even if I don't get to the right answer. I see myself improving, but also see room for growth.

Student	Talk About "good at chemistry"	Talk about self in relation to chemistry
Therese	Understanding chemistry concepts.	I understand some chemistry concepts and can explain, but see lots of room for growth.
Samuel	Knowing what happens in chemistry; using chemistry to explain world around you.	I connect chemistry to things I cares about, but I don't get good grades.
Sean*	Using chemistry to explain world around you; getting good grades on exams.	I do not see myself as good at chemistry, even if others do.
Malik*	Getting good grades.	I do not have the internal love and confidence to say that I'm good at chemistry because of grades.

*Sean and Malik define "good at chemistry" in terms of good grades. All other students articulate practice-based conceptions of "good at chemistry."

In fact, across the data it became evident that students' identities of competence no longer directly correlated with their exam grades (see Table 15). Students who associated themselves with aspects of "good at chemistry" ranged in their exam averages from As to Ds. Further, the two students who did not associate themselves with any aspect of "good at chemistry," received Bs (Sean) and Cs (Malik). Instead, students' identities of competence correlated with the expansiveness of their definitions of competence. In other words, students were more likely to associate themselves with aspects of "good at chemistry" when their notions of competence were anchored in an understanding of chemistry as a social practice. This data suggest that when "good" is defined expansively in terms of competent participation in scientific practices, and learning is organized such that students get to engage in these practices, more students are invited to see themselves as competent participants or as "good" at chemistry.

Table 15. Affiliation with culturally produced meanings of "good at chemistry"

	Identified self with practices associated with "good at chemistry"	Did not identify self with any aspect of "good at chemistry"
Defined "good at chemistry" in terms of practice, only.	Garrett, Navid (**A average**) Kehlani, Carrie, Carmen, Elizabeth, Margarete, Liel, Atrey (**B average**) Arash, Cadence, Lucas, Julie, Catalina, Sophie (**C average**) Camilla, Mariana, Therese, Samuel (**D average**)	
Defined "good at chemistry" in terms of good grades, only		Malik (**C average**)
Defined "good at chemistry" in terms of practice and good grades		Sean (**B average**)

As I continued to make sense of how students were constructing identities in relationship to chemistry, I was particularly interested in Kehlani's interview. Kehlani was a sophomore retaking chemistry for the second time when she was enrolled in CHEM 101B. As a freshman, Kehlani had enrolled in the traditional lecture-oriented course and received a failing grade. Her interview opens with an assertion from Kehlani that she is not "good at chemistry." She then proceeds to describe the many different ways in which she is a powerful chemical sense-maker and teacher, referencing her participation in class and on the Communicating Science project. It is only after redefining what "good" means that she is able to confidently reinterpret herself as "good at chemistry." Through a back and forth process of analyzing Kehlani's case (via data from her interview, science skill reflections, communicating science assessments, exams, and classroom video data) in light of the broader interview data set, I identified a set of claims about who students get to be in CHEM 101B.

In the sections below, I use Kehlani's story to situate these claims about identity possibilities made available in the world of CHEM 101B. I begin by presenting three claims about who students get to be: (1) people who do chemistry powerfully, (2) people who do chemistry as themselves, and (3) people who have the power to be world-builders. I then turn to make a fourth (less heartening) claim, that students continue to be disempowered and positioned as not "good at chemistry" by exams and exam grades.

While these opportunities show up across interviews, I have selected Kehlani as a focal case because her interview affords the rare opportunity of seeing a student negotiating competing voices about her competence (both as "not good" and "good") in relationship to chemistry, and momentarily resisting positioning as not-so-good. Her case suggests that opportunities to reconnect with what chemistry is and who students are in relationship to it matter for supporting students to navigate positioning by competing discourses.

Students get to be people who do chemistry and do it powerfully.

It is evident in the data that in CHEM 101B students get to be people who do chemistry, and who do it powerfully. Across interviews, nearly all students (n = 20, 95%) discussed particular moments in which they experienced themselves as powerful or "smart" chemical sense-makers. Students described these moments as moments when something "clicked" or "made sense"; when they found themselves "asking deeper questions"; when students supported their team to get somewhere new by noticing something unexpected in data; when students offered useful explanations to their team; or when students had "ah ha" moments and then articulated their thinking to others in ways that made sense and helped their team understand.

Kehlani often described experiencing herself doing chemistry powerfully. For example, when asked to talk about a moment in which she felt successful in the course, Kehlani described:

> **All the time we would go away, successful.** So, I felt like every time we would walk away successful, because in the end we struggled through and then the last question that you have to answer - like you know how to answer it because of the connections. In the beginning, you're like "This principle works," and then when you get to the second part, "This principle does not work!" And then you get to the third part: "Why doesn't it work?" And then the last part: "How do you revise it? How do you use it?" **So, it makes us feel successful because we were able to do that process. Chemistry is not just like, "the end."** There's different rules and exceptions [emphasis added]. (Kehlani, Interview)

Several aspects of Kehlani's dialogue are noteworthy. First, Kehlani clearly understands her participation with her team in CHEM 101B as doing chemistry. She describes her work in class as an iterative process of developing models from data, refining those models when they cannot account for exceptions, and using models to make sense of new observations. Then she states explicitly that chemistry is not an outcome or "the end." Instead, it is the iterative process she just described. Second, we get to see a new power relationship emerging between Kehlani and chemistry. Kehlani is no longer subject to chemistry and its rules; her team is not following a set of algorithms handed down to them by an instructor. Instead, Kehlani and her team are powerful chemical sense-makers, skillfully wielding chemistry – its practices, models, and ideas – to construct new chemical understanding about the material world. Wenger (1998) reminds us that "we experience and manifest ourselves by what we recognize and what we don't, what we grasp immediately and what we can't interpret, what we can appropriate and what alienates us" (p. 153). Kehlani names her team's work as successfully doing chemistry because she has many experiences in which she and her team are interpreting and appropriating like chemists.

Recall from my analysis in Chapter 4 that the ways in which students talk about themselves as doers of chemistry, and as smart and capable chemical-sense makers, are aligned with students' actual participation during class. In CHEM 101B, students participated in a range of chemical practices (e.g., asking chemical questions, identifying patterns, making connections, etc.) and experienced themselves getting to new places in their understanding.

Students get to be people who do chemistry as themselves.

In this new world, not only do students get to be people who do chemistry, and do it powerfully, but they also get to be people who do chemistry as themselves. Traditional notions of being a chemist then to privilege academic or technical language, and White, middle class ways of talking and being. Generally, students whose strengths fall outside of this narrow conception are not supported to see themselves as scientific. Yet in CHEM 101B, students get to "talk chemistry" (Lemke, 1990) authentically as themselves as they navigate the world of CHEM 101B. Below, I highlight how an aspect of course design – the Communicating Chemistry Project – explicitly invited Kehlani to do chemistry as herself, and illustrate how this project mediated Kehlani's identity construction in relationship to chemistry.

The Communicating Chemistry Project was a project-based assessment in which students were asked to teach two different audiences – an audience of friends and family and an audience of chemists – about the chemistry of a toxic metal, salt, or a hormone that they chose at the beginning of the semester. These substances were selected for their relevance to human physiology. At the end of each unit, students were provided a prompt that asked them draw on the central ideas and models developed throughout the unit to teach two audiences about an aspect of their chosen compound. For example, the central idea in Unit 1 is that properties of substances can be explained by the structure of that substance. Hence, the Unit 1 project prompt asked students to select one property of their substance and teach their audience about how this property relates to their substances' structural characteristics. Students were explicitly encouraged to bring themselves, their experiences, and their ways of talking to the work of communicating chemistry. They were invited to use informal language and slang where appropriate, to connect to pop culture, and to use analogies their friends and family could relate to.

I share Kehlani's post for Unit 1 below (Figure 15) to illustrate the ways in which Kehlani engaged in communicating chemistry brilliantly and authentically as herself in this project. She opens her friends and family post by activating the curiosity of her audience (e.g. "Have you ever looked at a piece of glass and wondered…"). Here, she poses a thought-provoking chemical question that draws on everyday phenomena familiar to her audience and motivates the need for a molecular level explanation. She then proceeds to make a series of complex chemical connections. First, she accurately establishes that the oppositely charged ions within her substance attract and hold the substance together. Then she continues on to discuss how applying pressure rearranges charges such that like charges align and repel. In both cases, Kehlani uses common cultural phrases familiar to her and to her audience as a way of making chemistry relatable (e.g., “we all know the phrase ‘opposites attract’ and they do!”). I also note that Kehlani does not follow the conventions of science writing in this post. Rather than using the passive voice, she includes herself in the learning her audience engages in through her use of the collective pronoun “we,” and she uses capitalization and exclamation points to infuse enthusiasm into the post (e.g., “of course we know too much of the same thing equals BORING!!!"). Kehlani animates her friends and family post with a sense of playfulness and humor as she teaches complex chemistry.

The significance of the Communicating Chemistry project for Kehlani’s identity construction is evidenced by the high frequency at which she talks about the project throughout her interview. Of particular importance, Kehlani describes the project as a humanizing experience in that it gave her the opportunity to be seen for who she is and for her strengths to be recognized as scientific:

> Through this project, I was able to see that **I truly do understand the concepts** because I’m able to connect it to my compound and I’m able to explain it to a sense that someone without a science background can understand, and then those with a science background can understand as well. And so, it **really helps me to be “all around” in a sense: not just a scientist, but a scientist that can connect to people** [emphasis added]. (Kehlani, Interview)
>
> You can put into words and express what you think. You're able to connect to people even if you don't know them. **You can show who you are as a person - not just a label,** but a person who actually understands chemistry and can make the connections [emphasis added]. (Kehlani, Interview)

In large chemistry courses, such as the one Kehlani enrolled in and failed her first semester at the university, students are one of hundreds taking a course. They are afforded few, if any, opportunities to authentically do chemistry, and typically students have to leave themselves (their ways of speaking and being) at the door when they enter the lecture hall. But through the Communicating Chemistry Project, Kehlani now has access to being seen for who she is – as a unique and gifted human being, as someone who deeply understands chemistry, who can apply chemical ideas to new contexts, and as someone who can make chemistry sensible to people who are not immersed in the discipline themselves. And in the cultural world of CHEM 101B, each of these strengths now counts as part of the intellectual work of doing science. Hence, in the cultural world of CHEM 101B, Kehlani gets to be an “all around scientist.” What a powerful position to occupy.

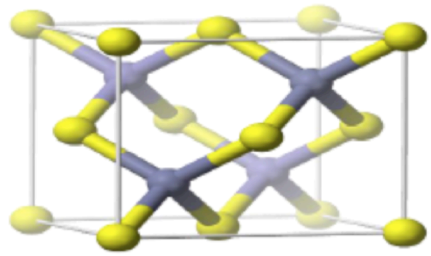
Figure 15. Kehlani's Post Communicating Chemistry Assignment for Unit 1

Audience A: Family and Friends

Have you ever looked at a piece of glass and wonder how could something so hard shatter so easily? Well, just like glass our highly dangerous Aluminum Phosphide (AlP) is a hard and brittle substance. As we know even though something like glass or in this case with our chemical compound (a substance formed when two or more elements combine) Aluminum Phosphide is a hard substance that if we apply pressure it will shatter/break. The bonds (connections) that form the compound Aluminum Phosphide is what causes AlP to be hard and brittle. For example, Aluminum has a positive charge and Phosphide has a negative charge and we all know that phrase "opposites attract" and they do! That's why when pressure is applied to AlP everything shifts and positives are with positives and negatives are with negatives. Of course, we know when there's too much of the same things it equals BORING!!! and we leave, but in chemical compounds like AlP it makes them brittle and they eventually shatter/break. So remember AlP like glass is a hard and brittle substance that when pressure is in the equation it can shatter and like broken glass AlP is a harmful substance so handle with care.

Image: http://wesharepics.info/imageggkl-glass-shattering-gif.asp

Audience B: Chemistry Community



Fellow chemist, today I will be addressing one of Aluminum Phosphide's chemical properties: hardness and brittleness. Both Aluminum (Al) and Phosphorus (P) have an incomplete valence shell; referring back to what we learned in lecture 2, Aluminum has three valence electrons and Phosphorus has five valence electrons. As we all have learned every element wants to be like the noble gases to have full valence shells and to be stable, therefore Aluminum gives up its three electrons to Phosphorus creating two ions: $[Al]^{3+}$ and $[P]^{3-}$. From lecture 4 we learned Coulomb's law that opposite charges attract and so the two ions $[Al]^{3+}$ and $[P]^{3-}$ bond to form the compound Aluminum Phosphide (AlP). However, when there are multiple Aluminum Phosphide molecules present (as shown in the image above) they bond creating a zincblende structure (cubic crystal structure) that consist of repeated tetrahedral structures that are formed from the intermolecular attractions of the AlP molecules (AlP only consist of two atoms) which we learned in lecture 7. In conclusion, the ionic bonds between AlP and its zincblende structure with the strong bonds between the negative and positive ions make it a hard solid, but when pressure is applied the same strong bonds shift and two of the same charges are aligned (same charges repel) causing the brittleness of AlP.

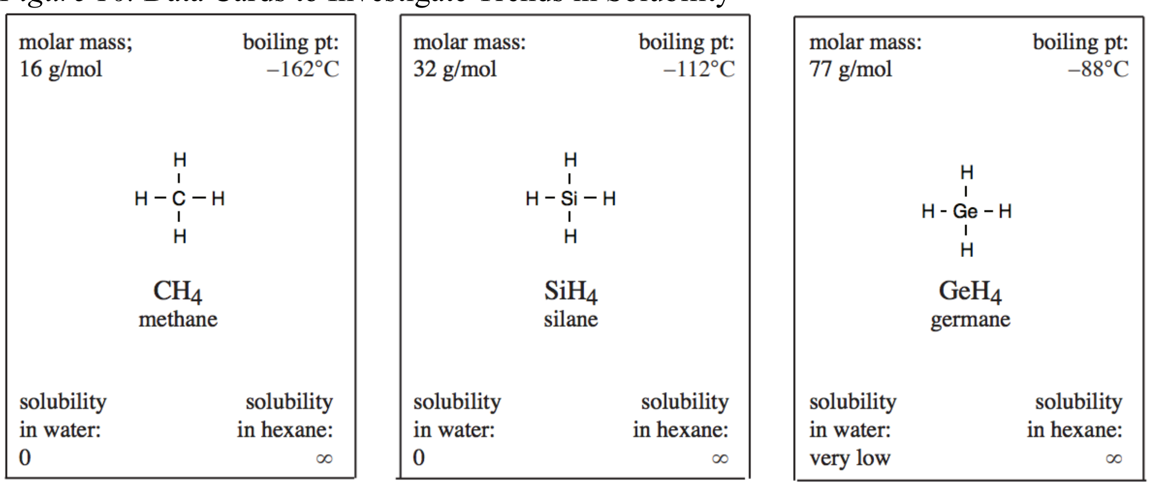
Image: https://en.wikipedia.org/wiki/Aluminium_phosphide

People who make the world as they want to see it

Thus far, I have established that in this new world students get to be people who do chemistry powerfully, and as themselves. Further, I presented evidence that elements of course design (e.g., design of the classroom activity system as established in Chapter 4, the Communicating Chemistry Project) afforded these new identity possibilities. I now consider a third aspect of who students get to be in this world – world builders. Holland et al. (1998) contend that figured worlds are always co-constructions. Worlds both take shape as people participate in day-to-day activity, and worlds also mediate ongoing activity. Thus far, I have foregrounded how the world of CHEM 101B mediates students' activity and identity construction within it. I now turn to examine students' power to co-construct the world of CHEM 101B – power to choose their ways of participating in the world and to make consequential choices about what matters to them.

I ground this discussion in a moment of classroom video in which Kehlani employs her power to claim the right to do chemistry, even when an instructor offers her team something different – doing school. The excerpts below come from classroom video collected at the beginning of the semester (Day 11 of class) at the end of the first unit on structure-property relationships. Four students, Kehlani, Cadence, Caroline, and Raquel, are working on a task which asks them to use solubility data to develop a model that accounts for why some substances mix together while others do not. Students are told that their model should help them predict the extent to which a particular substance would dissolve in hexane (a non-polar substance akin to oil or gasoline). Students have been provided with data cards that contain information about the structure, molar mass, and solubility of the substances in both water and hexane (Figure 16). The day prior, students investigated attractions between molecules, or intermolecular forces (IMFs). This task, then, prompts students to connect to their understanding across both days as they make sense of patterns in solubility and construct a model that explains them.

Figure 16. Data Cards to Investigate Trends in Solubility



Leading up to the moment below, the team has figured out that polar molecules tend to mix with other polar molecules, and similarly non-polar molecules tend to mix with other non-polar molecules. However, they are not quite sure how to explain why some substances dissolve in both polar and non-polar solvents. As the scene opens, Kehlani voices her confusion about this dilemma:

Kehlani: Substances that are soluble in both water and hexane. I don't know how to explain that part.

Cadence: *(Cadence turns towards Kehlani and reads the task card. Carolyn is now looking at it, too.)* In both water and hexane?

Kehlani: Yeah.
Cadence: So let's look at the bonds. *(Cadence leans in towards Kehlani)*
Kehlani: *(using her pen to point to particular molecules)* So hydrogen bonds, LDF's, dipole-dipole, except for this one [GeH_4], this one is -
Cadence: *(Cadence reaches under Kehlani's arm to point to the paper.)* Maybe the structure? or like-
Kehlani: Tetrahedral.
Cadence: Or like the more surface area, the more attractive? *(Cadence points to a molecule.)* Or it doesn't really apply to this one because this one is like the same thing as this. (*She reaches over even further to point at another paper.)*

In this interchange, Kehlani and Cadence are doing chemistry together. Kehlani has articulated a chemical question for investigation – why do some substances mix in both polar and non-polar substances? Cadence suggests an approach typically employed by chemists – considering the structure of the molecules to make sense of their properties (i.e., "let's look at the bonds"). Collectively, then, Cadence and Kehlani connect back to what they have learned about intermolecular forces the day prior as they name the strongest attractions that each structure can form (i.e. "so, hydrogen-bonds, dipole-dipole"). In making connections to prior chemical knowledge and looking for patterns, Kehlani recognizes that the intermolecular forces she just named are typical of polar molecules. And yet, strangely a non-polar molecule (GeH_4) also seems to dissolve in polar substance (i.e. "except for this one"). The excerpt closes with a new chemical question proposed by Cadence – does the surface area of the molecules matter, given that they have to interact in order to dissolve?

Before the team can make sense of the exception or the new question, an undergraduate instructor, Nina, approaches the team and asks the students what they are working on. Notice below that in response to the instructors' question, both Cadence and Kehlani position their work as doing chemistry – Cadence frames their work as investigating ("we're trying to see…") and Kehlani names a chemical practice they are engaged in ("[examining] the pattern"). The instructor; however, in trying to support their work invites them out of doing chemistry and into a participant structure that resides in the dominant world of doing school:

Nina: What are you guys trying to do?
Cadence: We're trying to see the substances that dissolve in both. *(Cadence points to the task card.)*
Kehlani: *(circling the task card with her hand.)* The patterns.
Nina: The patterns, yeah. This one? *(Nina shows her own copy of the task card to Kehlani. All four students are slightly turned towards Nina.)*
Kehlani: Mhm.
Nina: That are soluble in both water and hexane. So, do you guys remember what we talked about with polar and polar? Oh, did I talk about that with you guys?
Kehlani: No. *(Kehlani and Raquel shake their heads)*
Nina: No? Okay, so what happens if you have polar and polar? Do they mix or not?
Kehlani: Yeah, they mix.
Nina: They mix. Okay, so that's like water, right?
Kehlani: Mhm.

(Raquel nods slightly.)

Nina: What about nonpolar and nonpolar? Do they mix?

Kehlani: Yeah. *(Raquel, Caroline and Kehlani are all nodding.)*

Nina: Yes. How about polar and nonpolar?

Kehlani: No. *(Raquel, Caroline and Kehlani each shake their heads.)*

Nina: No. Okay, so in order for a substance to be mixing in both polar and nonpolar, what do you think has to be - what the substance has to be?

Kehlani: *(Kehlani is fidgeting with her pen.)* Polar and nonpolar?

Nina: Yeah! There you go!

Kehlani: *(Kehlani gives Nina an unconvinced glance and looks back at the task card.)* That's - that's just it?

Nina: Yeah. I mean, maybe finding one that's kind of like that.

Kehlani: Wait, what about this one? *(Kehlani points to GeH_4 with her pen and looks up at Nina. Cadence leans in and glances where Kehlani points.)*

Nina: That one is nonpolar, right?

Kehlani: Yeah. So why is it really low, but still soluble in water?

Holland et al. (1998) remind us that speech is not socially neutral, but that decisions about what one says and how one says it index claims to positions in the lived world. Kehlani and Cadence open their interaction with Nina by indexing claims to positions as doers of chemistry engaged in investigation. However, in her response to the team, Nina makes a different set of hierarchical positions available as she recruits them into the familiar terrain of *doing school* – knower and not-knower. In recruiting the team into an initiate-respond-evaluate sequence, Nina is focused on helping the team answer rather than helping them investigate their own question with knowledge she herself holds. The students politely participate with Nina, answering questions to which both Nina and the students know the answers, until they arrive at what Nina perceives as a satisfactory model to make sense of their original inquiry. It is immediately clear by Kehlani's furrowed brow and bewildered tone that she sees Nina's model as oversimplified. It does not yet account for the exception they have identified before the interaction with Nina – how can a molecule like GeH_4 dissolve in both nonpolar and polar substances, when it is not itself both polar and nonpolar?

Several aspects of Kehlani's brief response to Nina are noteworthy. In Chapter 4, I established that students are participating within the *collective investigation* frame most of the time. I offered different aspects of design – such as framing moves in the task launch and the organization of the task card – that cued this frame. In this excerpt of video, we get to see *collective investigation* not as a stable construct, but as one that students are negotiating as they participate together. In other words, *collective investigation* is not handed down to students through design, but rather co-constructed by students in interaction. In this world of CHEM 101B, as opposed to the world of school science, students are afforded more freedom of action, freedom to make consequential choices about what the world is all about. Hence, what is notable in this excerpt is that Kehlani has the power to reject *doing school* when it is offered and instead claim *collective investigation* as mattering to her. As the excerpt above closes, Kehlani asserts the power to push back (i.e., "that's – that's just it?"; "what about this one?"), and invites Nina to join her team in continuing to investigate.

As the excerpt continues, we see that Nina treats Kehlani's claim to *collective investigation* as normal and expected in this world, and joins the team in this pursuit:

> Nina: Solubility in water very low. Huh. Mmm.
> Cadence: *(Cadence leans over and points at the sheet in front of Kehlani. She looks up at Nina.)* So is it saying it's more nonpolar?
> Nina: *(Nina points to the molecule.)* It is more nonpolar, because it's infinitely soluble in hexane. *(5s pause.)* Why does it not say zero? Solubility in water - oh, I guess there just is no zero?
> Kehlani: There is. (*Kehlani points to a data card with zero solubility as an example.)*
> Nina: There is? No. All of them are soluble - oh, here. Ahh, okay. So I guess this element - this is very unique right? Germanium, you don't usually see that - when it's not strictly carbon - oh, no but silicon… *(Cadence picks up a periodic table and moves it closer to Kehlani and Nina.)* That's interesting, I don't know the answer to that. *(Cadence is now holding the periodic table at an angle for Kehlani and Nina to refer to.)*
> Kehlani: (*pointing to the column containing carbon, silicon and germanium*) Yeah, because they're in the same group.
> Nina: Yeah, right!
> Kehlani: Should I ask Professor S?
> Nina: Yeah, that's a good question!

Nina takes up Kehlani and Cadence's invitation to do chemistry and joins the team in investigating. Nina returns to the data (e.g., "Solubility in water very low. Huh"), poses questions, and attempts to make connections in an effort to construct a sensible explanation. Kehlani and Cadence take up positions as co-investigators with Nina by offering their own interpretations and challenges to Nina's proposals. It is notable that in having and asserting the power to claim *collective investigation*, the students disrupt the hierarchical positioning between instructors and students that is made available in the *doing school* frame by taking up positions of equal power as co-investigators. Hence, I argue that by possessing the power to be co-constructors of the world, students have more power to choose who they get to be, how they will participate, and with whom.

While this excerpt represents only one short moment of interaction, broadly speaking, students had power to make many different kinds of choices about how they would participate in the world of CHEM 101B. For example, during her interview, Kehlani explained that her team had the power to make choices about how they cared for one another during class:

> As a table, when you notice someone is discouraged, we're like okay, let's take a minute and go off-topic for a second. Because sometimes you just have to take a minute and step back or you just keep pushing yourself and pushing yourself towards the devastation.

Learning chemistry is a human activity that allows students to experience a range of human emotions – joy when the "ah ha" moment arrives and frustration or discouragement when one gets stuck or feels lost. This acknowledgement of feelings meant that sometimes supporting one another in class took the form of momentarily stepping away from doing chemistry to give one another space. Again, it is clear that when students have the power to make choices about what the activity is all about, they no longer have to step outside of themselves and what matters to them to do chemistry. In the above excerpt, Kehlani describes having the power to choose caring for themselves and for one another as part of what it means to do chemistry in the world of CHEM 101B. In her interview, Kehlani described the course in these terms: “CHEM 101B influences the students to be loving and caring to build each other up. So as a student, you learn to trust more people.” When students have the power to construct the world as they want to see it, they have freedom to bring their ways of talking, acting, and being to the work of doing chemistry in ways that matter for the identities they construct in relationship to chemistry.

People who are excluded from “good at chemistry” and disempowered

Thus far I have established that some aspects of the world of CHEM 101B make new meanings and positions available to students as chemistry doers and invites students to take up these positions as themselves. Further, I have argued that students have power in the world to make choices about who they want to be as they do chemistry. In the sections that follow, I complicate this story by examining aspects of the world that disempower and invite students to see themselves as not-so-good at chemistry. I focus my analysis on the role of exam-taking and grades in constructing Kehlani’s sense of herself as not-so-good at chemistry.

Despite many opportunities to experience herself as a powerful actor in the world of CHEM 101B, Kehlani opens her interview by constructing herself as someone who is not "good at chemistry":

> **Instance 1**
> My intended major is biochemistry and I think Southeast Asian studies. I got into biochemistry – well, because **I’m not really good at chemistry**, but I really love it, but I’m actually really better at biology. I really like chemistry but **I’m not good at it**, so I stuck with biochemistry - and that’s how I came up with biochemistry.
>
> **Instance 2**
> Interviewer: So, did you take chemistry in high school?
> Kehlani: Yes.
> Interviewer: How did that go for you?
> Kehlani: I love chemistry, **but it doesn’t love me**! (*laughs*) It’s a one-sided love.
>
> **Instance 3**
> But also because of the environment [of CHEM 101B], even though **I’m not really good at chemistry**, I was always excited to go to class because the way it’s set up [emphasis added].

In the first instance, Kehlani is responding to the opening question in the interview – can you tell me about your major and how you got interested in it. She names biochemistry as her chosen major and immediately follows with hedging – “I’m not good at it, but I love it.” Her response suggests she does not see herself as having the right to claim chemistry as her major given her presumed “not-so-goodness” at it. In instances two and three, a similar tension emerges – Kehlani loves chemistry and is excited to come to class, but the relationship is not mutual; chemistry does not love her back.

Given Kehlani's later construction of herself in the conversation as someone who successfully engaged chemical practice to develop and refine models, as someone who understands chemistry, who can use chemistry to connect to people, and as someone who is an all around scientist, a question emerges – what cultural tools are mediating Kehlani's construction of herself as not-so-good at chemistry? Kehlani's initial sense-making about what it means to be "good at chemistry" suggests that Kehlani is drawing on her exam grades and the dominant discourses about what grades mean to construct herself as "not really good" at chemistry:

> Interviewer: You opened up this conversation by saying that you're not good at chemistry, but you really like it. And we're just curious, what does it mean to be good at chemistry?
> Kehlani: I guess **good grades**
> Interviewer: And I should clarify, what does it mean in this class to be good at chemistry?
> Kehlani: Yeah, good grades. **Because we're in a society where you're based upon your grades**, and so being a good - for everyone, but for me specifically - being a good chemist is someone that gets a good grade [emphasis added].

Holland et al. (1998) remind us that "socially constructed selves…are subject to positioning by whatever powerful discourses they happen to encounter" (p. 27). While the world of CHEM 101B offers students new forms of participation in chemical practice, more expansive meanings about what chemistry is, and new positions as chemical doers, it also still includes taking timed exams and receiving grades. Consequently, the dominant narratives associated with exams and grades continue to exist in the world of CHEM 101B as powerful tools for positioning students as good or not good at chemistry.

While Kehlani's participation in chemistry with her team in class supports her to experience herself as a powerful chemical sense-maker, her exam scores position her as struggling or not-so-good. In her interview, she explained that while the majority of her course grades improved over the semester, her midterm grades dropped, which led her to feel like she was "digressing" in chemistry: "Just in my grade, the midterm grade. Everything else grade-wise it went up (…) So yeah, just with the midterms." Kehlani received a B- on the first midterm exam, and then received a C+ on the following two midterms. The dominant system US schooling supports students and teachers alike to interpret Bs and Cs as a sign of not-so-goodness. As another student, Malik, put it: "you get Cs, that's cute, you get B's, that's cute. But in this system, the grade matters," implying that an A is the only grade that counts as successful "in this system." Hence, Kehlani is left to contend with competing discourses that recruit her into contradictory positions (i.e. not good at chemistry v. competent chemical doer). Moreover, Kehlani has to negotiate what it means that this is not the first time she has received low grades in undergraduate general chemistry, given that she failed chemistry as a freshman.

I follow McDermott and Raley (2011) in suggesting that there is "great know-how in the world," but that "inattention to the intelligence of the people is so institutionalized that it now takes hard work to uncover it" (p. 375). McDermott proposes that finding intelligence requires a close and careful look at people's activity. Taking up his suggestion, I more closely examined Kehlani's exams to better understand how her exams could communicate her "not-so-goodness" when she was so clearly participating brilliantly in class and on the Communicating Science project. I found that on open response questions, which often asked Kehlani to develop an explanation to explain an observation or trends in data, Kehlani nearly always earned full credit. Yet, on multiple-choice questions, she often received no credit. See Table 16 for breakdown of Kehlani's midterm grades.

While this discussion might feel like a digression, I emphasize Kehlani's scores to suggest that her exam grades falsely recruit her to the position of struggling student or not-good at chemistry, when in fact Kehlani is a brilliant chemical thinker. The multiple-choice questions Kehlani missed were either those for which: (a) instructors had not given students multiple opportunities to practice and receive feedback, or (b) Kehlani was not attending to everything that mattered in the question. For example, one multiple-choice question asked Kehlani to make a prediction about the hardness of a new compound by examining trends in a data table that reported the hardness of different kinds of substances. Kehlani correctly identified trends in these data, but misinterpreted the bonding model of the new compound, and so she estimated incorrectly, receiving no points for the question. This is an example of a multiple choice question clearly missing the ways that students are making good sense, even if it is not yet complete sense.

Table 16. Breakdown of Kehlani's midterm grades by question type

	Midterm 1	**Midterm 2**	**Midterm 3**
Total Exam Score	**60/80 (B-)**	**71/105 (C+)**	**71/105 (C+)**
MC average	34/51 (67%)	31/52 (60%)	34/55 (62%)
Open ended explanation	17/20 (85%)	31/24 (88%)	23/36 (72%)
Open ended skill	9/9 (100%)	19/29 (66%)	11/14 (79%)

What we see, then, is that CHEM 101B is a complicated world. Some aspects of the world position Kehlani with power and as a competent chemical participant. Other aspects of the world assert upon Kehlani (however incorrectly) an identity of missing competence such that, at the beginning of the interview, Kehlani constructs herself as "not really good at chemistry." Though I have chosen to highlight Kehlani's story in this chapter, nearly all the students are negotiating competing senses of themselves in the class. In the final section of the chapter, I look at how opportunities for reflection made available by the interview conversation support Kehlani, causing her to reconnect with who she is and what chemistry is, such that she is able to resist positioning herself as not-so-good at chemistry.

Reflection as a resource for resisting positioning as not-so-good

Recall from the sections above that Kehlani constructs herself in contradictory ways – as someone who is "not good" at chemistry and who "digressed" in the class, and as someone who successfully engages in chemical practices to develop, refine, and apply her understanding of chemistry. It is clear that in the world of CHEM 101B Kehlani has to navigate positioning via differently powerful and competing discourses as she constructs her sense of self in relationship to chemistry. A pivotal moment in the interview comes when the interviewer asks Kehlani to articulate what she thinks it means to be "good at chemistry" in CHEM 101B. While I shared the beginning portion of this conversation in the prior section, it is excerpted fully below:

Interviewer: You opened up this conversation by saying that you're not good at chemistry, but you really like it. And we're just curious, what does it mean to be good at chemistry?

Kehlani: I guess good grades

Interviewer: And I should clarify, what does it mean in this class to be good at chemistry?

Kehlani: Yeah, good grades. Because we're in a society where you're based upon your grades, and so being a good - for everyone, but for me specifically - being a good chemist is someone that gets a good grade. But through this class I've learned that a good chemist isn't someone who necessarily gets a good grade, but someone that understands chemistry. Because a person that gets good grades could be a book smart person who doesn't know how to carry themselves in the lab scene or doesn't know how to communicate with people or connect chemistry to daily life. Now after this class, I feel like a good chemist is someone who can **make the connection**, is someone who is all around balanced, that **understands chemistry** and doesn't do it just for the satisfaction of acknowledgement, but does it for something deeper. And does it because **they enjoy it**, and **understands**, and who can **relate it to people**. Because you can't just tell people there is global warming. But if you're able to connect it to their understanding, that's a good chemist [emphasis added].

Kehlani first responds by associating "good at chemistry" with getting good grades and connecting this view to the dominant educational system that students inhabit, which places a high value on grades. It seems, though, that the very act of naming the association out loud reifies it and makes it available for critique. Kehlani in turn rejects grades as being able to say anything meaningful about actually doing chemistry as a chemist. Chemists work in research labs, they communicate chemistry to the public, they make lots of chemical connections, they understand chemistry such that they can use it and apply it, and they enjoy chemistry. They do not take exams. Exam grades may reveal someone as "book smart," but they are limited in their ability to say anything about the expansive set of practices and understandings that Kehlani now understands doing chemistry and being good at chemistry to mean.

Redefining chemistry in more expansive terms becomes a powerful identity resource for Kehlani. Now, she is able to confidently assert her inclusion in "good at chemistry":

Interviewer: Do you feel like, given that definition you've just given us, that you're a good chemist?

Kehlani: I do.

Interviewer: Could you tell us why or say a little bit more?

Kehlani: I feel like I'm a good chemist because of the Communicating Chemistry project. So I feel like a good chemist because of the task card in class and the communicating project. And that is the two things that really sets this class apart from any other class. Because through the task card **I learned to be analytical**, I learned to be – to **find out what I don't understand** and don't be afraid to **express it** and to be able to **communicate with people** I've never met before. And through the communicating project I learned how to

> be more specific on **how to do research as a chemist**. And most importantly how to be able **to relate the things that I've learned** and the research I've done to a chemist and then to a person. Because it's really important in the scientific field, because it's really important to communicate to your fellow chemists what you want to get done, the reaction and everything, and you have to communicate to people who are going to fund you and relate it to things they do in life. They will come to understand and appreciate the efforts more and understand why this needs to get done [emphasis added].

Recall that throughout the interview Kehlani has talked about all the ways she has successfully participated in the practices of chemistry to build, refine, apply, and share her developing chemical understanding. In essence, the interview has supported her to reconnect with who she has gotten to be in the world of CHEM 101B – a powerful doer of chemistry. Now, after explicitly redefining what it means to be "good at chemistry," all of her experiences of successfully engaging in chemical thinking and learning in class, and of successfully applying and teaching her friends and family about chemistry on the Communicating Chemistry Project, finally get to count as good.

It is important to note that the end of semester interview was not the only opportunity for reflection. At the end of each unit, students were asked to complete a reflection aimed at getting them to reflect on their unexamined assumptions about doing science successfully (see methods chapter for more details). While these reflections gave students the opportunity to make sense of their participation in the course in relation to new meanings about chemistry and to receive class-wide feedback about their reflections, it is clear that this opportunity was not sufficient to overcome powerful discourses surrounding exams and grades. Students need ongoing opportunities to negotiate meanings about the tools, practices, and discourse that have informed their understandings of chemistry (or science at large) and about who they are in light of their participation.

Summary

In CHEM 101B, students were recruited to a new cultural world – the world of doing chemistry. This chapter began by taking up the question – what is this world? Given that figured worlds can be thought of as "realms of interpretation" and "webs of meaning," I examined the meanings that students made about chemistry and being "good at chemistry." I find that in this world, students conceive of chemistry not as a body of knowledge, but rather as human activity, and of chemists as regular people (no different from the students in CHEM 101B) who engage in a broad array of chemical practices together to construct and refine understanding about chemical phenomena. Practice-based meanings are powerful in the ways they up-end school science notions of what it means to be "good at chemistry," which are both inauthentic to the chemical enterprise and exclusionary to most of our students.

I then argued that this new world also included new identity possibilities for who students get to be. Through a close look at Kehlani's experiences, I suggested that the world of CHEM 101B is a complicated world. Some aspects of the world afford students power to choose their own ways of participating and make room for students to be chemists as themselves. Both the classroom activity system and the Communicating Chemistry Project made these opportunities available, and invited students to construct identities as competent participants in chemistry. Other aspects of the world, such as exams and the grades attached to them, tend to disempower and invite students to construct identities as not-so-good at chemistry given the narrow range of outcomes (i.e. only earning As on exams) that count as good.

Cultural systems inevitably have internal contradictions (Engeström, 2011; Gutiérrez & Jurow, 2016; Gutiérrez & Vossoughi, 2010). It is important to give students support as they navigate these contradictions. Opportunities to reconnect with expansive notions of chemistry and opportunities to make sense of her own participation in CHEM 101B both supported Kehlani to navigate competing positioning as good and not good.

While the course design CHEM 101B did important work to mediate students' identities of competence, findings also suggest that one course may not be enough to fully cement students' new identities of competence. Though CHEM 101B offers a powerful counter discourse about competent participation in chemistry, students expressed awareness that much of science discourse and career discourse outside of CHEM 101B revolves around exams and GPA. Contextually new discourses in CHEM 101B exists within a discipline that is constantly pushing a competing discourse, one that is more powerful to students because they know they must inhabit it. This points to a need to expanding the work of re-mediation to the breadth of courses students encounter across their majors such that these hegemonic discourses can be disrupted.

Chapter 6: From Doing School to Collective Investigation – A Close Look at Framing Dynamics in CHEM 101B

As I established in Chapter 4, the activity system of CHEM 101B supported students to break out of the *doing school* frame and to take up instead a *collective investigation* frame. Literature has suggested that *doing school* is deeply entrenched in the U.S. educational system and difficult to dislodge (Hand et al., 2012). The accomplishment of more productive frames calls for investigation into how the classroom activity system signaled to students that *doing school* was no longer at play and successfully invited *collective investigation* instead.

From students' earliest days in classrooms, they are taught that 'performing well' is the principal aim of schooling, and that doing so requires acting in line with the rules and values of school (Hand et al., 2012). The college students, undergraduate student instructors, and graduate student instructors in this study are among the elite when it comes to *doing school.* Their well-honed skills in this arena have afforded them admission into such a highly selective university and continue to inform their success in the classes they take outside of CHEM 101B. Unfortunately, being great at *doing school* does not equate to rich disciplinary learning (Hand et al., 2012). A large body of research has established that the sensible forms of participation within a *doing school* frame (i.e. recalling and obtaining correct answers, showing what you know and hiding what you don't, getting a lot done, working individually, etc.) tend to support rote and shallow engagement in disciplinary learning (Hand et al., 2012; Pope, 2001). Hence, researchers have called for the need to dislodge *doing school* and to support more productive educational frames.

Dislodging *doing school* is incredibly challenging because students experience a myriad of subtle cues in moment-to-moment interaction that preserve the hegemony of the *doing school* frame (Hand et al., 2012), even within classrooms that seek to cue new learning frames by shifting participant structures. Hammer et al. (2005), for example, documented students participating within what they term a *completing the worksheet* frame (consistent with *doing school*) during an undergraduate physics discussion-based tutorial. Within this frame, students treated physics problems as opportunities to find answers via algebraic manipulations rather than as opportunities for intuitive sense-making. Further, students were more attentive to individual, rather than group, problem-solving. Hand et al. (2012) contend that for students to take invitations into new frames seriously, explicit signals must be given to convince students that dominant schooling frames are no longer at play. This line of research suggests that dislodging *doing school* requires a systems-level approach, one that attends to how different aspects of design – tools and artifacts, norms, participation structures, and discourse practices – work together to cue *doing school* in subtle and explicit ways. This chapter analyzes moments in which students were organized around *doing school* and an extended moment in which students successfully accomplished *collective investigation* in order to investigate connections between these two frames and course design. The findings that result add to the growing line of scholarship investigating how designers and instructors can create classroom systems in which *doing school* can be contested, dislodged, and replaced by more productive educational frames.

This chapter focuses on classroom video data of two teams of students – Sodium A and Sodium B – collected during L6 and L7, the earliest lessons for which classroom video was recorded.

Sodium A includes three students (Keyshia, Samuel, and Lucas) and Sodium B includes four students (Navid, Carrie, Garrett, and Arash). I began by analyzing the framing dynamics within Sodium A and Sodium B video in L6, finding that both teams largely coordinate around a *doing school* frame throughout the entire class. Given that the intention of the L6 task was to engage students in chemical investigation, I was curious to understand how aspects of the classroom system were falling short of disrupting the *doing school* frame. I selected episodes from team Sodium B for further analysis for two reasons: (1) this team's dynamic illuminated the ways in which the task design not only cued the *doing school* frame but also tapped into Garrett's and Navid's prior chemical knowledge in ways that made for less productive collaborative work, and (2) instructor interactions with this particular team reinforced the *doing school* frame.

I then analyzed framing dynamics within both teams as they engaged in the following day's task (L7). Team Sodium B largely engaged in *collective investigation* as intended by the task; however, in Sodium A, an extended framing battle ensued between *doing school* and *collective investigation*. I selected this battle as a focal episode for deeper analysis in order to understand how students make bids for particular frames, whose frames get taken up, and under what conditions. This analysis revealed how resources made available through course design supported students to interactionally accomplish *collective investigation*.

I begin the chapter by examining moment-to-moment interaction as Arash, Garrett, Carrie, and Navid orient to classroom activity as *doing school.* I present a series of narrative vignettes to demonstrate the persistence of the *doing school frame* early on in the course, and I illustrate what it looks like for students to be *doing school* in the particular context of CHEM 101B. Altogether, I highlight students' individual focus on figuring out answers and on getting a lot done, both of which result in a lack of collectivity in the team. I further illustrate that *doing school* organizes hierarchical roles and positions for students as "knower-tellers" and "not-knower-receivers," such that even within moments of joint activity, students' interactions are unproductive for learning together. I then turn to investigate the particular aspects of task design and instructor interactions with the team that supported students' framing of the task as *doing school*.

The second half of the chapter turns to analyze an extended moment of interaction in team Sodium B during L7, in which *doing school* is successfully contested and *collective investigation* is accomplished by two members of the team (Keyshia and Lucas). Analysis of the dynamics by which competing frames get negotiated within this team suggests that both *doing school* and *collective investigation* are sensible frames for students to participate within, with *doing school* as the dominant frame readily cued by the traditional chemistry classroom, but that particular design choices fostered the intellectual risk-taking and interdependence that mattered for Keyshia and Lucas to break out of *doing school* and instead accomplish *collective investigation* successfully in interaction.

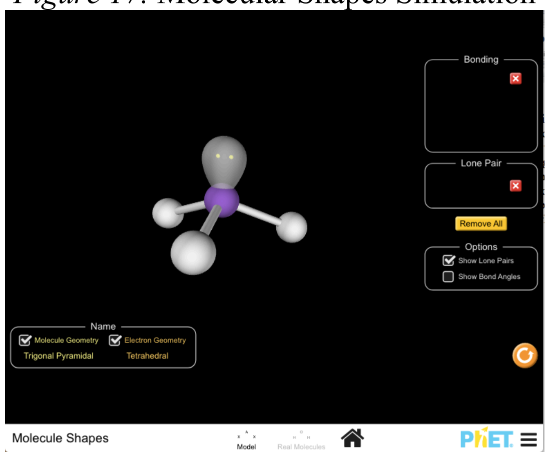
Students in Sodium B orient to the L6 task as *doing school*

While lesson six was intended to support *collective investigation*, it is evident across the 30 minutes of classroom video that Arash, Garrett, Carrie, and Navid primarily orient to the L6 task as *doing school*. In the sections that follow, I present several moments of classroom video data to illustrate that students treat their task in lesson six as figuring out answers to fill in the table on the note sheet, consistent with the content of the *doing school* frame. Students' participation within a *doing school* frame is further supported by the fact that students easily slip into the highly constrained and hierarchical roles organized by *doing school*: "knowers" and "not-knowers."

Lesson context

In L6, students investigate the three-dimensional (3D) shapes of molecules and develop a model they could use to predict the 3D shapes of molecules given their 2D Lewis structures. To support students' sense-making about why molecules take on particular geometries, the L6 task card (Figure 18) directs students to visualize the 3D shapes of different molecules using an online simulation tool called Molecular Shapes (www.phet.colorado.edu). Within the simulation, students can rotate molecules and explore what happens when they move bonded atoms closer together. Further, they can enable features in the simulation that report the electronic geometry, molecular geometry, and bond angles for the represented molecule (Figure 17).

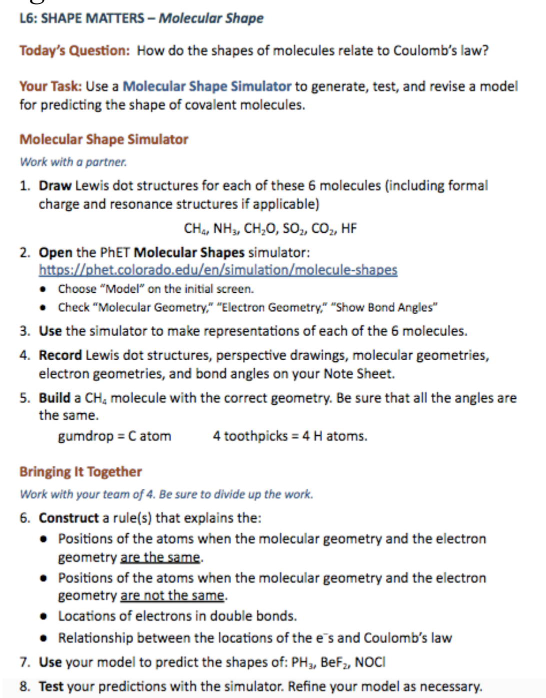
Figure 17. Molecular Shapes Simulation



In addition to the task card and Molecular Shapes simulation, students are each provided with a note sheet that includes graphic organizers to record their findings (Figure 18).

To frame activity as *collective investigation*, the professor opens the task launch by emphasizing the central question: "We've been looking at flat representations of molecules… But what we want to look at today is how do these take on 3D shapes? How do the shapes of molecules relate to Coulomb's law?" She then positions students as investigators who will need to use the simulation as a tool for building understanding towards this question (e.g., "You're going to use a molecular shapes simulator that's going to help you construct rules that explain the positions of the atoms"). Finally, she closes the launch by naming a list of "smart things" students could do to support their teams to successfully investigate the central question, including apply the bonding rules they generated last class, imagine molecular structure in 3D, make connections between different chemical representations, connect back to Coulomb's law, be open to revising their ideas, ask for other people's ideas, and reflect on the limitations of their model.

Figure 18. Lesson 6 Task Card and Note Sheet



L6: SHAPE MATTERS – *Molecular Shape*

Today's Question: How do the shapes of molecules relate to Coulomb's law?

Your Task: Use a **Molecular Shape Simulator** to generate, test, and revise a model for predicting the shape of covalent molecules.

Molecular Shape Simulator

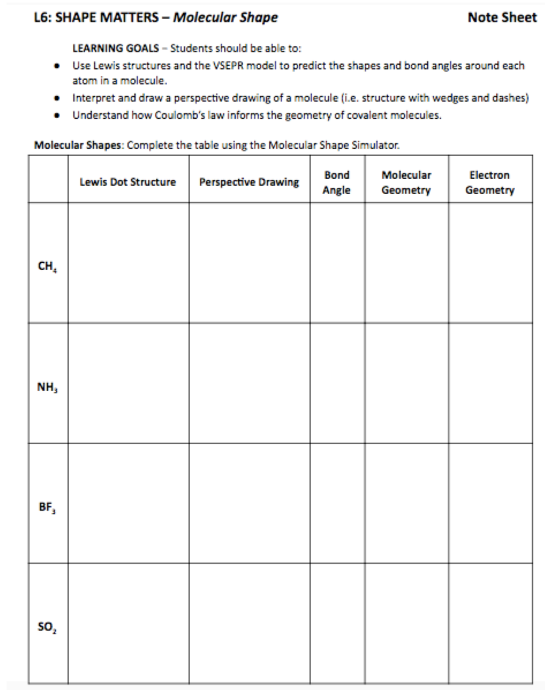
Work with a partner.

1. **Draw** Lewis dot structures for each of these 6 molecules (including formal charge and resonance structures if applicable)
   CH_4, NH_3, CH_2O, SO_2, CO_2, HF
2. **Open** the PhET **Molecular Shapes** simulator: https://phet.colorado.edu/en/simulation/molecule-shapes
   - Choose "Model" on the initial screen.
   - Check "Molecular Geometry," "Electron Geometry," "Show Bond Angles"
3. **Use** the simulator to make representations of each of the 6 molecules.
4. **Record** Lewis dot structures, perspective drawings, molecular geometries, electron geometries, and bond angles on your Note Sheet.
5. **Build** a CH_4 molecule with the correct geometry. Be sure that all the angles are the same.
   gumdrop = C atom   4 toothpicks = 4 H atoms.

Bringing It Together

Work with your team of 4. Be sure to divide up the work.

6. **Construct** a rule(s) that explains the:
   - Positions of the atoms when the molecular geometry and the electron geometry are the same.
   - Positions of the atoms when the molecular geometry and the electron geometry are not the same.
   - Locations of electrons in double bonds.
   - Relationship between the locations of the e^-s and Coulomb's law
7. **Use** your model to predict the shapes of: PH_3, BeF_2, NOCl
8. **Test** your predictions with the simulator. Refine your model as necessary.



L6: SHAPE MATTERS – *Molecular Shape* **Note Sheet**

LEARNING GOALS – Students should be able to:
- Use Lewis structures and the VSEPR model to predict the shapes and bond angles around each atom in a molecule.
- Interpret and draw a perspective drawing of a molecule (i.e. structure with wedges and dashes)
- Understand how Coulomb's law informs the geometry of covalent molecules.

Molecular Shapes: Complete the table using the Molecular Shape Simulator.

	Lewis Dot Structure	Perspective Drawing	Bond Angle	Molecular Geometry	Electron Geometry
CH_4					
NH_3					
BF_3					
SO_2					

Though we planned for the lesson launch and task design to signal that *collective investigation* (rather than *doing school*) was at play, it is evident in classroom video data that the *doing school* frame is not easily disrupted. As I will illustrate in the sections below, Arash's, Garrett's, Carrie's, and Navid's participation is marked by a focus on efficiently completing the note sheet, and by a lack of togetherness. I begin by presenting two narrative vignettes to illustrate the students' focus on individually completing the note sheet and getting a lot done.

Students focus on individually doing school rather than investigating together.

Directly following the task launch, Garrett and Carrie pull out their computers and open the Molecular Shapes simulation. Garrett then turns to the task card to figure out what the team needs to do. This particular task directs the team to think together in pairs initially, and to collectively generate and test their molecular shapes model as a team. Given their seating arrangement, Garrett and Arash naturally pair up, as do Carrie and Navid. I will first describe Garrett's and Arash's participation within the *doing school* frame and then turn to Carrie's and Navid's.

Garrett reads the first instruction on the task card to himself and then turns to Arash: “So okay, we have to draw the structures before we look at this,” gesturing to the Molecular Shapes simulation on his computer. Following this directive, Garret sets the task card off to the side, and he and Arash begin to draw the Lewis structure for the first molecule, CH_4, in the space provided on their respective note sheets. Garrett finishes ahead of Arash. Rather than draw the remaining structures and turn to the Molecular Shapes simulation as the task card directs, Garrett looks to the next column in the graphic organizer labeled “perspective drawings.” Here, Garrett encounters some confusion, and turns toward Arash: “I don’t know how to draw it in perspective though.” Notice in the conversation below that rather than investigating (as other teams do when they bump against questions they cannot explain later in the semester – see excerpts in Chapter 4), Garrett ultimately suggests that it would be easier to skip this section on the note sheet.

Excerpt 1 – Getting a lot done rather than getting underneath to deeper understanding

Garrett: They are as far away as they can be on a flat surface, but it’s a three dimensional structure.

Arash: Oh, I get it.

Garrett: There’s 90 degrees between them, but there can really be 120 degrees between them in real life. Because one will be straight upwards, one will go down this way. They separate by one third and they are angled downwards a little bit. But I don’t know how to draw that.

Arash: I get what you’re saying. That’s pretty hard to draw

Garrett: I would assume it would be like this. And then the wedge comes out of the page. (*drawing as he talks*). Like that. But all of these are a little bit into the page. So like, do you dot those? (3s pause) We can come back to it…

Garrett has a hunch that bonded atoms want to be “as far away as they can be” from one another. He has already represented this hunch in his Lewis structure for CH_4 by drawing the four bonded hydrogen atoms emerging from the carbon atom at 90 degree angles in relation to one another. Garrett offers what could potentially be an opening for investigation – he states out loud what he does not know – and continues to think out loud about what he imagines the molecule looking like in 3D. Arash confirms the challenge of representing a 3D structure in two-dimensions. Garrett then takes a stab at describing what it might look like (i.e., “the wedge comes out of the page,” “But all of these are a little bit into the page”), but quickly decides to skip this section. His eagerness to move on suggests he feels a certain pressure to get a lot done, which trumps any curiosity about the ways in which and reasons for why chemists represent particular molecules. In deciding to move on, the two students miss an opportunity for learning.

Navid is similarly intent on getting a lot done, a focus that does not lend itself to staying together with his partner, Carrie. Directly following the task launch, Carrie takes out her computer and begins loading the Molecular Shapes simulation. At first Navid sits and waits for her, but after 80 seconds he looks to his note sheet and starts to work his way down the first column on the note sheet, drawing the Lewis structures indicated in the spaces provided. Before long, Navid finishes and for a brief moment glances in the direction of Carrie’s note sheet to compare answers. When he sees she has only just begun, he returns his gaze to his own note sheet. In similar fashion to Garrett, he examines the remaining column headings on the graphic organizer. Not understanding the distinction between “molecular” and “electron” geometry, he looks up towards Garrett and asks his team for support: “Hey guys, when it says electron geometry does it mean without the repulsion?” Strikingly, Garrett shuts down Navid’s question and uses the opportunity of having Navid’s attention to get his own question about perspective drawings answered.

Excerpt 2 – Working individually rather than staying together or taking up one another’s questions

Navid:	Hey guys, when it says electron geometry does it mean without the repulsion?
Garrett:	(*looks up from his note sheet*) I don’t know what that means entirely-
Carrie:	Wait, where?
Garrett:	I feel like I did a few days ago when I did the pre-lab.
Navid:	Electron means like the one where you include the lone pair in the geometry-
Garrett:	(*interrupting Navid, he holds up his note sheet to Navid and points to the column title “perspective drawing”*) Is this how you do this?
Navid:	Oh no, I’m talking about this (*pointing to the last column*)
Garrett:	I know, but I’m just asking you also.

As activity unfolds, Navid is individually orienting to completing the note sheet and working at his own pace. He does not check in with Carrie, nor does he wait long for her before he begins drawing Lewis structures, and he then uses the note sheet (rather than the task card) to interpret what he needs to do next. When he realizes that Carrie is behind and presumably not ready to help him, he turns towards the rest of the team for help. Garrett is similarly oriented to the note sheet as an individual activity. Rather than treating Navid’s question as an opportunity to think together or to investigate one another’s questions, he jarringly changes the direction of the conversation by recruiting Navid to help him with his own question about perspective drawings. Within this team operating in the *doing school* frame, it is clearly sensible for each student to orient towards completing the note sheet, working at their own pace and moving on when answers are not readily available.

Roles and positions within doing school frame

Frames guide social action, serving as “interactional roadmaps” (Hand et al., 2012) that mediate how students coordinate around one another. The positional framing of *doing school* organizes roles for instructors as expert “knowers” and knowledge providers, and for students as novice “not-knowers” and knowledge receivers. What is striking is that this relationship is also replicated in interactions between students without an instructor present; that is, the positional framing of "knowers" versus "not-knowers," experts versus novices, is so powerful that it can recruit students who seemingly know more into the instructor position. As further evidence that *doing school* is at play during this lesson, I present an extended moment in which Navid easily slips into the role of knower-teller and recruits Carrie into the position of not-knower-receiver. This moment is particularly illuminating of how constrained both roles are for students due to the power imbalances they create.

As the scene below opens, students are ten minutes into the task. Both sets of partners have decided that bonded atoms want to be as far away as possible from one another, and they are now working out how to draw perspective drawings. Garrett and Arash are primarily drawing on

Garrett's prior knowledge of molecular shape names from high school to name and draw shapes. Uncertain if he is naming structures correctly, Garrett looks across the table towards Navid and asks: "What's the difference between molecular geometry and electron geometry?" Navid offers an explanation that Garrett accepts ("Alright, I get it. Thank you"). Then, without pause, Navid turns toward Carrie and explains to her why NH_3 would have a trigonal pyramidal geometry, though she has not asked him to do so.

Excerpt 3 – Knower-teller explains to not-knower-receiver

Navid:	(*to Carrie, pointing at an image of a tetrahedral structure she has generated in the Molecular Shapes simulation*) Um because, for example, imagine this is a lone pair right here, so that means you cancel out for the molecular geometry, and it's only this (*using his hand to cover one of the bonded atoms in the tetrahedral structure*), which is called a trigonal pyramidal.
Carrie:	Oka:::::y.
Navid:	It's like a pyramid
Carrie:	Okay, but the bond angle. I'm still at bond angle.
Navid:	Oh sorry, you're on this?
Carrie:	What were you – yeah
Navid:	I was on the next one. Yeah, so bond angle is 109.5 because, um, that's just the angle. I don't know how to explain it.
Carrie:	No, yeah, I get it.

It is interesting to note here that Navid is attempting to move out of his individual orientation to the task into a more collaborative orientation that includes Carrie, but unfortunately he does so in a way that does not invite her in as an equal participant. While he is doing his best to share understanding with Carrie in a way that is supportive of her, the highly constrained roles organized by the *doing school* frame do not offer Navid nor Carrie many options for how they should participate together. Navid could choose to hold on to what he knows and ignore Carrie, which leaves him working by himself, or he could explain what he knows to Carrie, which he does. His self-positioning as the more powerful knower-teller recruits Carrie into the less powerful position of not-knower-receiver.

Similarly Carrie's position as the not-knower-receiver offers her few options for participating. She can listen to Navid explain, even if it is not yet useful for her, or she can resist by indicating in some way that she does not welcome his explanations. In other words, she can participate as a listener or reject Navid's explanation and then be ignored. She chooses the latter by suggesting she is still working on bond angles and not ready for a mini lecture on molecular geometry.

As the scene continues, Navid shifts gears and tells Carrie what the bond angle is for CH_4. Notice, though, that while he knows the correct information, he cannot explain why the molecule takes on a particular shape with particular angles. In this *doing school* frame, it is sensible to have answers that are not yet justified with reasoning. For a third time, Carrie communicates that his explanations are unwelcome. For this moment, he accepts her pushback and returns to his own notes sheet. However just a few minutes later, the situation repeats. This time he initiates a teaching moment by posing a question to which he already knows the answer.

Navid:	So what do you think electron geometry is?
Carrie:	Probably not the same as this because there's a (inaudible) there. So what's even the molecular geometry? I don't even know the bond angle. Let's just (*holds up her hand*) slow down for a second.

Carrie begins to respond to his known-answer question, seemingly as a reflex to the familiar "initiate-respond-evaluate" participation structure Navid recruits her into. In doing so, she notices again that Navid is two steps ahead of her; she has not yet figured out the molecular geometry, let alone the bond angle, for this molecule. Clearly agitated, she holds up her hand and tells Navid to slow down.

I have pointed out several features of the classrooms scenes above that are consistent with a *doing school* frame (see Table 17 for a summary of this discussion). In analyzing these scenes, I do not wish to claim that interaction was being organized solely by *doing school.* What these scenes show us is that *doing school* is still sensible in the activity system of CHEM 101B. Research has established that *doing school* is entrenched in schools – it is the default frame students coordinate around. As such, it is easily cued. I suggest that even the act of entering a science classroom, or sitting at a desk, is enough to signal that *doing school* is at play. Though our design team did a lot of work to re-organize the classroom system to signal *collective investigation*, these examples reveal that there were still resources made available by the classroom system that align with the *doing school* frame. Hence, it is important to understand where course design is falling short of disrupting *doing school.*

Table 17. Content and Positional Framing of Doing School

	Doing school	
Frame Content	Figuring out answers to complete the note sheet Getting a lot done	
Positions and Roles	**Knower**	**Not-knower**
	Explainer Teacher	Asker Receiver of information
Sensible Forms of Participation	Asks know answer questions Evaluates responses Tells answers Offers explanations Working ahead of the group	Listens Asks for information Answers known-answer questions Resists being explained to

Elements of course design are consistent with doing school

The vignettes presented above illustrate students' participation organized through a *doing school* frame, and suggest that the classroom activity system was not yet sufficiently convincing students that the predominant schooling frame was no longer in play. In the sections below, I examine the ways that particular aspects of our task design, specifically the opening prompt and the note sheet, and instructor interactions make *the doing school* frame available for students to coordinate around.

Task design missing richness and interdependence

Though some aspects of the designed L6 task (i.e., question of day and task description) framed students' activity as a chemical investigation, the opening prompt on the L6 task card was missing the open-endedness required to support such activity. Chemical investigations are open-ended examinations carried out to construct new understanding about that which is currently unknown to investigators. Rather than supporting students to engage in investigatory practices (i.e. looking for patterns in data), the opening prompt directs students to produce Lewis dot structures, for which there are correct answers. The intention underlying the prompt was to provide students with an opportunity to practice a skill that is challenging and that requires time to develop. While the prompt does afford this practice, it does so at the expense of shutting down the investigation intended by the task. When students encounter questions for which there is only one correct answer, *doing school* gets cued and it becomes sensible to focus on producing correct answers.

Further, the activity of drawing Lewis structures for molecules that may be familiar to some students and not to others based on prior access to chemistry instruction gets in the way of *collective investigation*. For example, it is evident within the first few minutes of Garrett's and Arash's work together that Garrett already has knowledge about the names and 3D shapes of molecules that he can deploy to complete the note sheet. Such knowledge removes the need to turn to the Molecular Shapes simulation tool to investigate further. For example, Garrett quickly cites CH_4 as an example he has learned about in high school chemistry, and states out loud that it forms a shape he calls a tetrahedron.

Excerpt 4 – Employing chemical jargon

Garrett: So we have to draw the dot structures. So we have CH_4 – that's fairly simple. H (*Hunched over his note sheet writing. Quickly glances at Arash's note sheet*)
Arash: (*Hunched over paper writing, but glances at Garrett*) Is that right?
Garrett: (*looking down and continues drawing*) H, yeah, H
Arash: Perspective drawings?
Garrett: Oh! Okay, so CH_4 is that in a **tetrahedron**? Because it's a carbon and the hydrogens are going to want to be as far away from each other as possible? I would imagine it's gonna be C –
Arash: Hey, what's a tetrahedron?
Garrett: Tetrahedron is when I have my carbon in the middle, and ones up here, and then three are down here as far away from each other as possible
Arash: [Now there's three
Garrett: [So there's four of them and I don't know how to draw it in perspective
Arash: Right. I think this is…(*he trails off*)

Garrett's prior knowledge about the molecular shape and name of CH_4 recruits him to the position of knower and removes any need for the pair to actually investigate how the arrangement of molecular shapes relates to Coulomb's law. Instead of acting in the role of chemists as the task intends, Garrett and Arash participate within typical *doing school* roles as explainer and knowledge receiver respectively.

Finally, the fact that each student has a note sheet in front of them with opportunities to fill in blanks cues the *doing school* frame. Note sheets were intended to provide students with a way to organize their thinking from the day's tasks and to keep a record of their thinking as part of the notes they took for the course. In reality, the note sheet in this L6 excerpt functioned as a worksheet that begged to be completed. Years in school have taught students how to look at a worksheet, figure out what they need to do, and execute, rather than prompting learning in the form of asking questions and sense-making.

In the vignettes presented above, the column headings and blanks to fill in become Garrett's and Navid's guide for interpreting what they should do next. As such, they end up missing resources on the task card and in the online simulation tool meant to support *collective investigation* by requiring students to work together to model and make predictions about different molecular shapes. Further, individual note sheets make it available for each student to be siloed in their work, and for Navid and Garrett (as knowers) to forge ahead of their partners.

Instructors slip into roles consistent with doing school

Doing school is also cued when instructors take up roles as knowledge providers and answer-evaluators consistent with this frame. For example, in the excerpt below, Lee, an undergraduate student instructor, approaches Arash and checks in to see if he understands how to represent molecules using perspective drawings. The following conversation ensues:

Excerpt 5 – Evaluating and explaining

Lee:	K, now do you understand what um (*she trails off*)
Arash:	Oh yeah, I was – is this wrong? (*pointing to his drawing of* CH_4)
Lee:	You will never have more than three that you need, like you will never have two that are going to be out of dimension. The maximum that you can have pointing back and pointing forward are two.
Navid:	Oh really? I have three here
Garrett:	Oh does it have to point straight forward and straight back?
Arash:	(*pointing to Navid's paper*) That's what I did.
Navid:	(smiling) so this is not right?

In asking Arash if he understands how to represent perspective drawings, Lee positions herself as a "knower," a role instructors typically occupy within a *doing school* frame. Arash's response to Lee is evidence that *doing school* has been cued - he asks Lee to confirm whether his structure is correct. Lee then enacts a typical teacher role as knowledge provider, sharing what she perceives to be the "right" way to represent perspective drawings. In doing so, she implies what matters in this chemistry course – knowing how to draw correct structures (rather than understanding the reasoning underlying particular representations).

Notice that the activation of *doing school* has consequences for Navid's and Garrett's participation and learning as well. The algorithm for perspective drawings that Lee imparts to the team (i.e. two bonds in the plane, two bonds out) contradicts the sense Garrett and Navid had already made about perspective drawings. In an earlier discussion (prompted by Garrett in Excerpt 2), they accurately came to see there are multiple ways of representing perspective drawings, depending on the perspective the drawer takes. Lee's assertion here that there is one right way to represent molecules in 3D leads the team to a chemical misunderstanding and reinforces the notion that in chemistry there are "right" and "wrong" ways of thinking and doing.

What do we learn from these excerpts presented above? Consistent with Hand et al. (2012), these examples show us that *doing school* is hard to disrupt. Despite much work to rearrange the classroom system, particular tools and discourse practices aligned with doing school are still present within it. As I highlighted in my discussion above, task card prompts with expected answers, note sheets with spaces to fill in the blanks, both chemical jargon (i.e. molecular geometry) and examples commonly used in high school chemistry (i.e. CH_4) that tap into particular kinds of prior knowledge, and instructors playing the role of the knower-teller and evaluator of knowledge all continue to promote the sensibility of the *doing school* frame.

Framing battle in which *collective investigation* is successfully negotiated

While the sections above illustrate the persistence of the *doing school* frame, findings presented in Chapter 4 established that, largely, teams of students across the course did come to participate within a *collective investigation* frame in CHEM 101B. The question remains, what supported class-wide shifts into *collective investigation,* given the power of the *doing school* frame?

In the sections that follow, I turn to analyze an extended episode of classroom activity in which the *doing school* frame was contested and *collective investigation* was successfully negotiated within one team. Analyses lend insight into how students can accomplish *collective investigation* in moment-to-moment interaction. This moment comes from L7 in which Keyshia, Lucas, and Samuel are working on a task to investigate how the 3D shape of molecules relates to the property of smell and to make sense of this relationship in terms of Coulomb's law. The task card and note sheet for L7 are provided in Figure 19.

Figure 19. Task Card and Note Sheet for L7

L7: THINKING (ELECTRO)NEGATIVELY – *Polarity*

Today's Question: How are the properties of molecules related to the 3D distribution of electrons and Coulomb's law?

Your Task: Use the **Bare Essentials of Polarity** comic strip, the periodic table with **electronegativity** values, and the molecular models to develop a model to predict if a small molecule has a smell.

Small Molecules and Smell

Work with your team of 4. Divide the work so that each member draws and builds two molecules.

The human nose contains smell receptors that detect molecules in the air that we breathe in. The smell receptors contain positive and negative charges.

1. **Examine** the data below. Draw Lewis dot structures.
   - Molecules that have a smell: H_2S, HOF, CH_2F_2, NH_3
   - Molecules that do not have a smell: O_2, CO_2, CF_4, C_2H_6
2. **Build** three-dimensional models of each of these molecules with the model kit.
3. **Identify** differences between the molecules that do and do not have a smell.

Bringing It Together

Work with your team of 4. Make sure everyone is included.

4. **Develop** a model that relates smell with molecular structure. Use the concepts of polarity, electronegativity, and Coulomb's law in your model.
5. **Illustrate** on your Note Sheet how each of the polar molecules are attracted to a smell receptor with a + charge.
6. **Use** your model to predict which of the molecules below have a smell:

CH_2O, $C_2H_6O_2$, C_2H_4, SO_2

L7: THINKING (ELECTRO)NEGATIVELY – *Polarity* **Note Sheet**

LEARNING GOALS – Students should be able to:
- Explain electronegativity and polarity in terms of Coulomb's law.
- Use differences in electronegativity and shape to predict the charge distribution (polarity) of molecules.

Molecules that have a smell:

Molecule	H_2S	HOCl	CH_2Cl_2	O_3
Lewis dot structure				
Perspective drawing of the molecular shape				

Molecules that do not have a smell:

Molecule	O_2	CO_2	CF_4	C_2H_6
Lewis dot structure				
Perspective drawing of the molecular shape				

Keyshia, Samuel, and Lucas are presented with the molecular formulas of four molecules that have a smell and an additional four molecules that have no scent. They are each attempting to represent the 3D shapes of these molecules using the dashed and wedged perspective drawings they learned in L6 to indicate if a particular bond is moving in or out of the plane of the page. Keyshia opens up inquiry by asking her team, “So how do I know if [the bonds] go back and forward?” Samuel responds to her question by offering some information.

Excerpt 6 – A battle of frames

Samuel: In a triangular pyramid it will look like that. However you draw it, it doesn't matter. As long as it follows the octet rule and the 1-2-3-4 rule, you will be fine.
Keyshia: Is there a way for us to know by ourselves how they look?
Samuel: You pretty much have to memorize.

Consistent with a *collective investigation* frame, Keyshia poses an important question about how particular molecules take on distinct shapes. Samuel responds to Keyshia’s question with memorized information that is about executing a procedure to determine the shape. His focus on getting the answer rather than on understanding why his procedure works indicates that Samuel is coordinating around a *doing school* frame not aligned with Keyshia’s. At this point it might be sensible for Keyshia to accept Samuel’s answer, given that knowing information and getting answers quickly affords status within a *doing school* frame. Instead, she takes an intellectual risk and asks yet another investigation question. Samuel, however, does not take up the bid. His frame makes superficial engagement in chemistry learning (i.e. memorizing) sensible.

The framing wrestling match continues as Keyshia presses Samuel by asking for reasoning.

Excerpt 7 – Failed bids for the *collective investigation* frame.

Keyshia: Okay, but from these, how do we know [the shape]?
Samuel: Okay, because of bonds. The number of bonds. Okay, this one (*pointing to worksheet*), it has two bonds. I know it is linear, right, so I pretty much know the shape. Since this one has 4, I know it’s gonna look something like this (*pointing to 2D representation on his worksheet*). But then I have to put it in 3D. So it’s gonna look like…
Keyshia: How would you know if it’s gonna be bent or straight? (*pointing to molecule with two bonds)* Like would this one bent?
Samuel: No. That’s linear.
Keyshia: Then, is this one (*pointing to another molecule with two bonds)* would this one be bent or straight?
Samuel: No, this one is linear too. (*looking to Lucas for confirmation)* Right?
Keyshia: (*Keyshia raising her eyebrows)* When would it be bent?

Keyshia’s line of questioning presumes that there is important sense making to do around how and why molecules take on particular shapes that stretches beyond what Samuel’s procedural knowledge supports the team to understand. Her questions invite Samuel and Lucas to be co-investigators with her. Yet, Samuel's frame implies two kinds of actors linked to hierarchical positions of authority: the knower-teller and the not-knower-receiver. Hence, Samuel treats Keyshia's questions as needing an answer rather than investigation. We see him taking up the position as knower-teller as he explains his process for deciding whether a molecule will be linear or bent. Notice that his explanation does not include reasoning about *how* he knows, but merely *that* he knows (i.e., "it has two bonds. *I know* it's linear, right, so *I pretty much know* the shape"). At the risk of being interpreted as "not getting it," Keyshia persists in asking questions, insisting on understanding *why* molecules with the same 2D shape (i.e. A-B-A) might take on either a bent or a linear 3D shape.

As the scene continues, Keyshia makes yet another bid for *collective investigation*. This time, Lucas does something outside of the *doing school* frame – he recognizes Keyshia's question as an important contribution. Samuel's didactic response, though, does not leave space for investigation.

Excerpt 8 – Power and positioning in competing frames

Keyshia:	But why, why does it bend?
Samuel:	I mean-
Lucas:	That's a good question.
Samuel:	Do you remember bond angles? Do you know what those are?
Keyshia:	They want to get further apart if they are like more negative.
Samuel:	Yeah, yeah, that's the general idea, but there's a bit mo::::re than that. So for like H_2O, right, (*he begins to draw H_2O on his worksheet. Keyshia's eyes are on his paper)* you have two hydrogen atoms and one oxygen atom right here. What else are you missing? What's going on?
Keyshia:	There's lone pairs, right?
Lucas:	So (*pointing to Samuel's representation of H_2O*) this one would be bent because oxygen tends to bend.
Samuel:	(*looking to Keyshia and confirming Lucas' new rule*) So it tends to bend.
Keyshia:	(*smirks and leans back*) Oxygen tends to bend? So that's just a general rule?

Here, we continue to see the work this *doing school* frame does to unevenly distribute power among the students, and the ways in which it narrows opportunities for learning. Samuel positions himself as the knower-teller as he recruits Keyshia into an initiation-response-evaluation participation structure to scaffold her understanding of shapes and bond angles. While Keyshia's response to his question gets at the underlying chemical principle of electrostatics that governs why molecules form particular shapes, Samuel quickly brushes past her ideas and launches into a mini lecture about bond angles. Lucas interrupts and suggests a new algorithm to the team (i.e. "things with oxygen tend to bend"). Similar to Samuel's contributions, Lucas is proposing a rule that does not yet make chemical sense of what contributes to oxygen's "bendy" nature. Keyshia's smirk and change in body position reveal her exasperation.

It is remarkable that Keyshia persists in repeatedly asking her team for reasoning, particularly given that the *doing school* frame makes it available for her to be interpreted as "slow to understand." As the final scene opens, we see Keyshia buckling under the power of the predominant schooling frame, as she questions her own competence.

Excerpt 9 – The collective investigation frame prevails!

Keyshia: Am I asking a dumb questions, or what?
Lucas: No, I just don't know how to answer them, (*scratches his head)* because I don't know either. (*laughs*) You damn had good questions. (*He looks to the molecular shapes computer simulation.)* Oh okay, so this one's bent. The molecular geometry is bent.
Keyshia: What molecule is it?
Samuel: That's a tetrahedron.
Lucas: This is this one (*pointing to a molecule on Samuel's worksheet with 2 bonds and 2 lone pairs)*. But the electron geometry. (*he pauses and looks to the simulation, then back to the molecule on Samuel's worksheet)* And the molecular geometry is bent.
Keyshia: Okay, I understand now (*looks to Samuel, and claps her hands together*).
Samuel: Do you?
Keyshia: I do. (*pointing to the simulation)* It is tetrahedral because there are four different planes, including the lone pair. And then it's bent because of the two lone pairs, so the actual molecule has to make space for them.
Samuel: Oka:::::y.
Keyshia: You couldn't tell me that, but I told myself.

While Lucas has demonstrated some vulnerability up until this point, he has primarily played the role of the knower, confirming Samuel's answers and offering information of his own. Yet here, his response to Keyshia is entirely inconsistent with *doing school.* He makes three important moves that allow the *collective investigation* frame to prevail: (1) he joins Keyshia in taking the risky step of admitting that he does not know how to make sense of her questions; (2) he assigns competence to her questions, acknowledging them as important; and (3) he takes up her question and offers the Molecular Shapes simulation from L6 as a resource for investigating together.

I suggest that each of these moves serves to reorganize the hierarchical positioning connected to the *doing school* frame and to offer roles and new activity to the team. In admitting he does not know how to answer Keyshia's question, Lucas is newly aligning himself with Keyshia as a not-knower. He then moves to reposition Keyshia as a competent participant by suggesting she "had good questions." Finally, he recruits Keyshia into new activity as they coordinate together around the Molecular Shapes simulation as co-investigators of her questions and draw new conclusions about how and why lone pairs and the number of bonds collectively influence the shapes of molecules. As the scene ends, Keyshia contests the uneven relations of power organized through *doing school* as she remarks to Samuel: "You couldn't tell me that, but I told myself."

Keyshia's and Lucas' participation falls outside of what is typical for students within a *doing school* frame*,* suggesting that the classroom system of CHEM 101B is doing important work to make new activity sensible. The question is how did the classroom system support their participation? And more broadly, what can we as teachers, designers, and researchers do to make it possible for students to participate in ways that dislodge *doing school*? This is a large question for the field, and one that falls outside of scope of a single study. While I do not attempt to claim the answers to it, in the sections below, I share what our research team learned about the kinds of curriculum design, instructor interactions, and opportunities for reflection that shifted students' participation within teams in ways that supported *collective investigation.*

Designing to dislodge *doing school* and support *collective investigation*

We found that supporting the inquiry and interdependence that marks Keyshia's and Lucas' participation within a *collective investigation* frame, requires: (1) making it safe to take intellectual risks, and (2) fostering interdependence within teams.

Making it safe to take intellectual risks

Within a *doing school* frame, status and power are organized through knowing and correctness. By the time our college students arrive in CHEM 101B, they have learned how to hide what they do not yet understand. Their fear of being wrong or seen as not-knowing is a substantial barrier to engaging in rich chemical investigations. Doing good chemistry necessitates sharing uncertainty, asking questions, testing out multiple perspectives, and revising one's ideas. While the L6 and L7 vignettes make clear that the *doing school* frame is still available for students in CHEM 101B, Keyshia's and Lucas' participation in L7 suggests that there were resources already in the activity system that made it sensible to take such intellectual risks. For Keyshia, risk-taking meant repeatedly asking questions in the face of prolonged opposition and of being positioned as having less power. For Lucas, risk-taking meant admitting to his team that he did not know how to answer Keyshia's questions. I describe several interrelated strategies in the sections below that we as designers and instructors employed to foster intellectual risk-taking.

Positioning "asking questions" as a valued practice

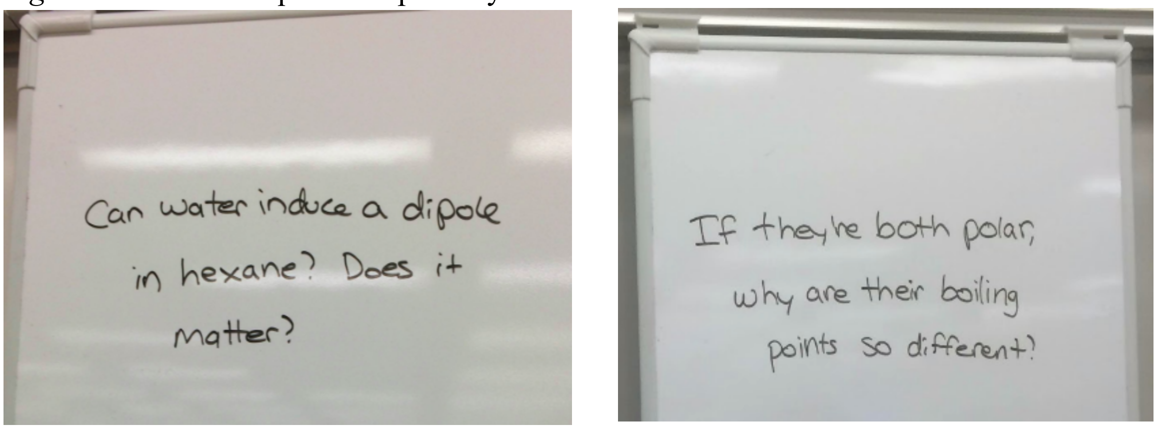
We sought to re-position "asking questions" as a valued practice in CHEM 101B by convincing students that doing chemistry is centrally about asking and investigating questions. In task launches, the professor often included *ask critical questions about data, ask for reasoning,* and *build on each other's questions* as "smart things" she expected students to do as they engaged in the task together. For example, in the "smart things" launch for lesson 12 the professor exhorted:

> And then definitely take some risks. I'm **hearing great questions**. And try to **engage each other with questions**. **Sometimes you think too quickly that you understand it all**. Trust me, I'm still trying to understand some of this stuff. Listen to what other people are asking because **it gives you good insights** into these things [emphasis added]. (Field Note for L12)

Professor S emphasizes that asking questions counts as an important intellectual contribution, in part because questions lead to new and deeper insights. She also warns against the pre-mature certainty that is sensible within a *doing school* frame, noting that certainty can get in the way of discovery. Further, she explicitly rejects the "instructor as knowledge-giver" model, instead positioning herself as someone who is still learning.

During class, instructors listened for and collected student-generated questions to share publicly on white boards surrounding the room (Figure 20). We did this to position students' questions as important intellectual contributions, and to support students to learn from the questions coming up in other teams.

Figure 20. Student's questions publicly recorded on whiteboards



Finally, to support students to expect and welcome unanswered questions, we included a prompt in both the note sheets and in homework that asked students to record any lingering questions they had following the task for the day (Figure 21).

Figure 21. Lingering questions prompt on note sheet

Lingering Questions: Record questions that your group was not yet able to answer, or that you are curious to explore further.

Altogether, these strategies were designed to communicate to students that asking questions is part of what it means to competently participate in chemical thinking and learning.

Valuing multiple perspectives and warning against pre-mature certainty

As illustrated in the case of Keyshia, Samuel, and Lucas, in and of itself getting students to ask rich questions is often insufficient for accomplishing *collective investigation.* We learned that we needed to foster a learning environment in which students felt safe being wrong or caught "not-knowing." In fact, we needed to proactively support students to take intellectual risks – to articulate out loud what they are wondering about, and to share with their teams what they notice in data, or what connections they are seeing, even when they are not sure if those ideas will turn out to be right. To foster intellectual risk-taking, we needed to design tasks that are rich and open-ended enough to make available multiple pathways for successful task completion, and we needed to convince students that doing chemistry is not about answer finding.

Learning to design open-ended tasks was an ongoing process for us as designers. Ultimately, we found that building tasks around analyzing and drawing new conclusions from data afforded the open-endedness we were aiming for. In curating data sets, we needed to include enough complexity such that there were lots of different things to see and notice in the data, but not so much as to overwhelm. We needed to generate data that would reveal clear patterns when students controlled for variables. We found that creating data cards (rather than data tables or graphs) afforded the most space for investigation because individual data cards allow student to test out an idea, and then to re-organize as they tried out a new perspective. Finally, in designing team products, we found that asking students to generate evidenced claims, explanations, arguments, and models worked well because they afford the possibility of making sense in different, but valid, ways.

Once we designed open-ended tasks, we needed to convince students to engage in the practices of chemical investigation. We did so in several ways. First, in the task launch and close, the professor communicated to students that rather than "right" or "wrong," chemists think in terms of "usefulness" - is this model useful, and what kinds of predictions can it help us make? Further, she tried to make visible to students that in chemistry there are often multiple valid ways of approaching problems and explaining phenomena. For example, in the "smart things" launch for L7, she explained:

> And you want to justify your thinking in ways that others can follow. And please ask others to explain their reasoning, because **I think as you're learning is that there's often multiple, valued ways of looking that things. There's not just one right answer.** So it's very useful to hear what other people have to say [emphasis added]. (L7 Field Note)

In addition to emphasizing that there are multiple ways of making sense in chemistry, she emphasized that doing good chemistry necessitates revising ideas, and that learners benefit from ideas that turn out to be partially correct:

> You should be open to revising your ideas. It's perfectly okay. This is a class where **you're allowed to have ideas that are partially correct and then you modify them. That's what science is about, so don't be afraid to do that** [emphasis added]. (L6 Field Note)

In addition to verbally communicating that revising models and ideas is a central practice in chemistry, we designed tasks that required students to develop, test, and finally revise models. For example, early on in the semester, students were introduced to a Shell model of the atom, in which electrons are represented in circular shells orbiting a nucleus. Though in many ways this model is outdated, it is actually quite useful for predicting structures of ionic and molecular compounds. Students relied on the Shell model for three units, then in the final lessons of the semester, students were given new data that the Shell model could not explain. They were asked to use this new data set to refine the Shell model of the atom (e.g., "Your task is to analyze trends in ionization energies and in photoelectron spectra to refine the Shell Model of the atom to account for the observations").

Finally, at the end of each unit students reflected on their participation in practices that we named as central to doing science, including intellectual courage, diligent skepticism, and bouncing back from setbacks. For the Science Skill reflection, we designed a series of Likert style questions that were intended to support students to consider their participation in class in relationship to these skills. They were then asked to describe a moment in class in which they engaged in the particular skill and reflect on how it felt to do so and what their engagement produced for the team. Students were also asked to consider how each member of their team, including themselves, was contributing to the team. Figure 22 depicts these open-ended prompts for "intellectual courage."

Figure 22. Selected prompts for "intellectual courage" from Science Skill reflections

Tying it Altogether: Reflect on Your Progress Towards Intellectual Courage*
Describe a moment in class where you felt nervous, but took an intellectual risk in class. How did you feel about it? How did your group respond to your idea or question?

Team Pulse*
For each of your teammates, describe their primary contribution(s) to your team. Include your own own contribution(s) as well. Be specific and include as many contributions as you'd like.

These prompts gave students an opportunity to make sense of their participation in relationship to new definitions of what it takes to be successful at chemistry. And it gave instructors an opportunity to learn what it felt like to be a student in CHEM 101B. After each reflection, I analyzed reflection responses and generated written class feedback that summarized themes in students' open-ended responses, and I reflected back to students what they named as areas of strength and growth in the Likert style questions. In generating feedback, my goals were to remind students: (1) that they are taking on intellectually challenging work, and (2) that all the things they are used to seeing as not-so-smart (i.e. asking questions, feeling lost, being wrong, etc.) are a normal and important part of doing chemistry. I share the excerpt below to illustrate what this feedback sounded like:

> Most of you said that sharing your ideas is scary business. Some of you said you don't want to feel responsible for leading the team to an incorrect understanding. Some of you said you perceive your teammates to know more and so you stay quiet. And yet, everyone who reflected on this skill shared moments in which sharing their thinking (even if it turned out to be wrong) led to deeper understanding for the whole team!
>
> *Strengths*: Many of you said you ask people about their ideas when you're not sure if you've understood something they've said. This is awesome for learning.
>
> *Areas of Growth*: Continue to push yourselves to think out loud, to share connections or questions even when you're not sure they will end up being correct. This is how understanding in chemistry happens for chemists - chemists put their ideas out to the intellectual community for critique, and those ideas get built upon, accepted, refuted, and refined.
>
> (Excerpt from class feedback for Science Skill Reflection #2)

As established in earlier chapters, students came to include “asking chemical questions” in their articulations of what it means to be “good at chemistry,” and they engaged in this particular practice most often during in-class investigations across the semester.

Fostering interdependence

Within a *doing school* frame, in which answer-finding and task-completion is the focus, working individually becomes sensible. Students often move at their own pace through their work and rely on one another only when they get stuck. And yet doing good chemistry requires the diverse perspectives, skills, and practices that are only available in diverse teams.

The L7 vignette suggests that while Keyshia’s individual risk-taking is important, the interdependence that emerges between Lucas and Keyshia ultimately disrupts *doing school* and accomplishes *collective investigation*. The collaborative practices that foster their interdependence are not typical in classrooms. For example, it is not typical for students to notice and publicly name the smart things other students are doing (as Lucas does when he names Keyshia’s questions as good), nor is it the norm for students to treat one another’s questions as worthy of further investigation (as Lucas does by taking up Keyshia’s question and offering a resource to investigate it together). Successful contestation of the *doing school* frame suggests that the activity system of CHEM 101B was creating the conditions in which it began to become sensible for students to investigate together. Below, I describe the work we did as designers and instructors to convince students that interdependence was necessary to doing good chemistry.

Rich and open-ended tasks foster interdependence

We learned that designing rich, open-ended tasks not only supported intellectual risk-taking, but that it also fostered the kinds of interdependence we were hoping to see. While this finding was not always true in the beginning of the semester (as evident in L6 and L7), as the semester went on, tasks centered around data and big chemical ideas that were unfamiliar to students. This meant the tasks were less so about tapping into the particular kinds of prior knowledge that could easily separate students into the “knowers” and “not-knowers.” All students started the task as a “not-knower” and as “co-investigators.” Further, our tasks were rich and complex enough that students needed to rely on the diverse contributions of the whole team in order make progress towards the team product. In this iterative process of learning to design good tasks, we came to realize that the “pair work” we had built into some of the tasks (e.g., in L6 students were directed to draw Lewis structures in pairs, and then come together as a team for the remained of the task) was a barrier to interdependence. Early on in unit two, we shifted to designing tasks for teams, rather than for pairs.

Instituting roles and norms that support interdependence

Given the dominance of the *doing school* frame and our early emphasis on pair work, we had a lot of work to do to support students to work together as a team. Further, recall that our instructional staff of undergraduate and graduate student are expert *doing-schoolers.* As such, they easily slipped into one-on-one interactions with individual students rather than engaging the entire team, and were often initiating initiate-respond-evaluate sequences typical in schooling. To support both students and instructional staff to foster interdependence, we instituted a norm called the “team question.” For students, this meant that teams had to discuss questions collectively before engaging an instructor. For instructors, this meant that the instructor could ask anyone in the team what the team question was. If that student could not answer, the instructor would ask them to discuss, leave, formulate their question, and come back. Instituting the team question norm was a messy process. Even towards the end of the semester, I observed instructors engaging in one-on-one interactions with individual students rather than engaging teams collectively. And in classroom video data the extent often to which instructors hold students accountable to the team question norm varies.

We also noticed early on that students were using the note sheet to guide their work rather than the task card. As such, we instituted a rotating team leader role. The primary responsibilities of the team leader were to get their team started by reading the task card out loud and to use the task card to move team along. We found that making someone responsible for using the task card did move teams away from merely completing the note sheet towards engaging in the investigation described by the task.

Positioning collaborative practices as valued

Finally, we then sought to encourage collaboration by convincing students that doing good chemistry necessitates the diverse perspectives of the team. In task launches, the professor emphasized that students' work together was collective, that students should articulate their ideas in ways that should make sense to their team, ask one another about their ideas, and engage each other's questions (e.g., "build on each other's ideas. That's really important today because there is a lot going on in the cards.")

Further, "collaboration" was included in the Science Skill reflections students completed at the end of each unit. Here, students were encouraged to reflect on the extent to which they (1) were aware of how much they spoke in their teams, (2) tried to learn from what others were suggesting, and (3) caught themselves when they dismissed other people's ideas. Then, in class feedback, we communicated that collaboration was central to doing science and engineering, and central to learning:

> Collaboration is another one of those skills that doesn't go away after college, and is a central practice in science and engineering.
>
> This course is organized around two central assumptions about teaching and learning: (1) every student has something to learn and something to teach, and (2) participation is the key to learning. Therefore, equal participation is essential in teams.
>
> Many of you are still catching yourselves missing opportunities to build on one another's ideas. Opportunities for learning chemistry are always richer when teams invest time in understanding how each person is thinking about a concept. Continue to ask for other people's ideas in the team, and to share ideas even if you're not sure that those ideas are correct.
>
> (Excerpt from class feedback for Science Skill Reflection #2)

Altogether, these interrelated strategies were meant to provide students with complex chemical work that relied on a diverse set of strengths to successfully complete, and then to support students to draw out and leverage one another's strengths.

Summary

A typical frame for classroom scenes is the *doing school* frame. I began this chapter by illustrating Arash's, Garrett's, Carrie's, and Navid's moment-to-moment interactions as they coordinate around *doing school.* These vignettes remind us that *doing school* is easily cued and challenging to disrupt. Doing the latter requires reorganizing all aspects of the classroom system such that they send explicit and implicit cues that *doing school* is no longer at play.

In the framing battle presented in the second section of this chapter, I demonstrate the interactional work students engage in to accomplish *collective investigation.* This extended vignette suggests that while *doing school* was available to students, the CHEM 101B activity system was in fact offering students resources that made the new forms of participation sensible for students. Given the predominance of *doing school,* it is clear that the work of dislodging this frame and accomplishing frames that are more productive for learning is never finished. *Doing school* will always be present, and designers and instructors need to be responsive to the ways that it is getting signaled within their classrooms.

I closed the chapter by sharing some promising and interrelated strategies we employed to support the intellectual risk-taking and interdependence that supported Keyshia and Lucas to contest *doing school* and accomplish *collective investigation*. These strategies included communicating that "asking questions" and "articulating what you don't yet know" are valued chemical practices and that chemistry benefits from the diverse perspectives available within teams. They also included designing tasks around new and big questions that students could not yet answer given the knowledge and understanding they initially brought to the day's task, and around data that students had never grappled with in their high school classes, such that all students within a team were recruited into new roles and positions as co-investigators.

Chapter 7: Conclusion

Scholars have called for the design of alternative educational spaces that counter dominant narratives about who is capable of learning science (Nasir et al., 2013) and what it means to be "good" at science (Carlone et al., 2011). This dissertation examined possibilities for learning and identity in an undergraduate general chemistry course re-designed to dismantle racialized, gendered, and classed hierarchies of competence in chemistry and to provide broad access to consequential chemistry learning and identities of competence for students. In this concluding chapter, I reflect on how findings presented in the empirical chapters contribute to our understanding of science learning and of identity construction in relationship to scientific thinking and learning. Further, I consider what these findings teach us about designing more equitable undergraduate learning environments that foster rich science learning and positive scientific identities. Finally, I discuss the questions this study raises and suggest directions for future research.

Disrupting common sense links between scientific competence and innate intelligence

Research has established that the overlap between racial narratives about math and science and discourses of intelligence make it sensible for students to read race into classroom practice and interaction with STEM courses (Shah, 2013). When racial narratives like "Asians are good at science" are cued or deployed in classrooms, they restrict some students from accessing positions as scientifically capable in ways that matter for participation, learning, and persistence in STEM majors (Nasir et al., 2012; Shah, 2013).

In line with Shah's findings (2013), this dissertation suggests that disrupting the link between science and the cultural commonsensical notions of innate intelligence is important for designing more equitable learning environments. In other words, disrupting the link between success in science and innate intelligence makes it less sensible for students and educators to believe and act as though only some people can be good at science. Analyses revealed that developing more authentic conceptions of chemistry as a social practice supported students to reject the notion that being "good at chemistry" requires innate intelligence. Giving students opportunities to participate in ways aligned with notions of authentic chemical practice supported students to develop identities as competent participants in chemical thinking and learning. These forms of participation engaged students in rich and rigorous chemistry learning.

Designing for alternative worlds is possible and complicated

Getting students to equitably participate in authentic chemical practice requires challenging work of designers and instructors. This work involves creating positions and forms of participation necessary for collectively engaging in chemical practice that are not sensible in the dominant figured world of school science that governs students' experiences in undergraduate general chemistry settings. Findings in this dissertation indicate that undoing the dominant world of school science is possible. The dissertation provides a robust picture of a new figured world that renders rich and risky forms of chemical participation available to students: asking chemical questions, sharing in precise terms what they are grappling with, proposing ideas for collective evaluation, taking up one another's questions, working hard to understand team members' points of view, and strongly resisting being done until the entire team is satisfied that conclusions drawn made chemical sense.

Design research shows that supporting rich and authentic participation in chemistry learning for students who have been steeped in the world of school science requires a significant restructuring of the classroom system around: (1) coherent content connected to core ideas, (2) engagement in collective investigation of big scientific ideas and relationships, (3) opportunities to be scientists as themselves and connect science to their lives, and (4) reflection that creates awareness of tensions between common sense notions and new conceptions of science. In this section I describe how restructuring the CHEM 101B activity system around these principles opened new possibilities for learning and identity.

Coherent content connected to core ideas

Recall from discussions in Chapter 3 that the course units of CHEM 101B build upon two interrelated core ideas, attractions (Coulombic potential energy) and motions (kinetic energy), to develop students' understanding of how molecular-level considerations of energy can be used to explain macroscopic properties and behavior of matter. Each task built from these core ideas, asking students to use ideas of molecular-level attractions and motions to develop new chemical explanations, arguments, and models. Hence, rather than feeling like a vast body of information to keep track of, chemistry became a core set of connected ideas and models that students could think with to explain the macroscopic world in terms of the molecular level. While this is a typical goal for chemistry instruction, it is rarely apparent to students.

Curricular tasks that support engagement in collective investigation

Second, across the vignettes presented in this dissertation, particular aspects of tasks were designed in ways that invited students to grapple with new chemical ideas that motivated and provided tools for further investigation. So what was the nature of the tasks – how were they part of supporting such new and risky participation? First, tasks were designed around new and big questions that students could not yet answer given the knowledge and understanding they initially brought to the day's task. Second, tasks were organized around data that students had never grappled with in their high school classes. Students' lack of ability to fall back on prior knowledge explicitly then positioned the students in the role of chemists, forcing them to engage with the kinds of questions that chemists ask (and do not have pre-conceived answers for), and the kinds of data or models chemists engage to build new explanations.

Third, while the questions for investigation were big and students often encountered "not-knowing," chemical resources were curated such that there were lots of different aspects of data to notice or consider (in L14: structural representations of molecules, bond length, bond strength) and patterns or exceptions to patterns to see and discover within data sets. The richness of the data meant that students could immediately experience themselves as "getting somewhere," and that many different kinds of contributions across the team could support this intellectual movement. Hence, everyone on the team had not only something to learn, but also something to contribute to the team's learning. The richness of the data sets also meant that students often experienced conundrums that pushed them to a point where they had to ask questions or articulate in precise terms what they were grappling with. For example, in the second vignette presented in Chapter 4, students are grappling with how two competing variables (electronegativity of atoms and atomic size) affect bond length and, subsequently, bond strength. When Kevin proposes H-Cl as an exception, he is focused on the effect the high electronegativity difference should have on bond length, and is not yet considering the opposite effect that the large atomic size of the Cl has. Or when Kehlani and Cadence are confused about solubility, it is because GeH_4 is an exception to an overgeneralized rule about polarity "like dissolves like." In summary, the richness of the data caused students to have to analyze competing effects of multiple variables and make sense of exceptions to patterns, thus creating conundrums that required the resources of the entire team to solve.

Finally, tasks then required that students link core chemical ideas learned during the course to the patterns or exceptions to patterns in data in order to develop new chemical explanations. For example, in the case of Kevin's proposal that H-Cl is an exception, his team draws on core ideas related to Coulombic attraction (i.e. magnitude of charges and the distances between them) to grapple with whether H-Cl is in fact an exception to the patterns they identified, and, if so, how they can newly explain the aberration. Similarly, Kehlani, Cadence, and Nora attempt to draw on ideas of attractions to make sense of why a seemingly non-polar molecule like GeH_4 could dissolve even to a small extent in a very polar substance like water. In sum, the richness of the questions and the power of the tools all grounded in a set of core chemical ideas lead to tasks that create appropriately sized conundrums. Students can investigate and solve these conundrums by drawing on the tools provided and the rich conceptual resources that members of the team contribute.

Communicating Chemistry Project allows students to bring themselves to science

The Communicating Chemistry project complemented students' chemical activity during class in how it required students to then synthesize and apply their newly developed understanding to teach two different audiences about the properties and behaviors of a new chemical substance (i.e. toxic metal salt or hormone). Analyses indicate that the emphasis on making chemistry relevant and sensible to an audience of friends and family created different kinds of identity opportunities for students from the ones created by participating in class activities. Recall that for Kehlani, the project allowed her to bring her own ways of talking and being to the work of doing chemistry. Moreover, it allowed for her strengths (i.e., applying chemical ideas to new contexts, making chemistry sensible to people who are not immersed in the discipline themselves) to count as important chemical work. Further, opportunities to write about connections between chemistry and issues of human health increased her feeling of connection to and enjoyment of chemistry.

Reflections that creates awareness of tensions

Since dominant cultural meanings about "good at chemistry" are ingrained into students' ways of making sense, Gutiérrez & Vossoughi (2010) suggested that students need opportunities to reflect on unexamined assumptions about science and to make sense of tensions that arise between new conceptions and common sense notions of science. The Science Skill reflections, course reflections, and even the interviews themselves were sense-making activities that made students' common sense assumptions visible so that they could be critiqued, disrupted, and remade by students themselves. Analyses revealed that for Kehlani to negotiate and momentarily resolve competing positioning of herself as "good" and as "not-so-good" at chemistry, she required opportunities to reconnect with expansive practice-based conceptions of chemistry and her own powerful participation in these practices within a semi-structured interview.

Instructional practices support collective investigation

While this dissertation contributes to our understanding of how to organize content and design curricular tools that support rich and collective chemical investigations, doing so is not sufficient for supporting the kinds of intellectual risk-taking and interdependence that marks participation with a *collective investigation* frame. Practices (i.e., asking chemical questions) that require students to make visible what they do not yet understand are risky given that being seen as "not-knowing" affords identities as not-so-smart in the dominant world of school science. Analyses suggest that particular instructional moves, such as framing participation within task launches and team norms, did important cultural work to successfully invite students into new roles as investigators and into collective participation in investigatory practices.

Task launches framed the nature of the scientific thinking and learning students would engage in that day. The professor used the launch to situate students' work in the larger context of the course, orient them to the chemical resources that would guide their work, and to name the "smart things" they could do to think together like chemists. Analyses revealed that three kinds of framing moves made by Professor S helped to establish the new positional and epistemological framings of *collective investigation*: (1) framing learning as ongoing and connected sense-making, (2) framing students as active sense-makers, and (3) framing competence as multidimensional and distributed. It was evident in interviews and course reflection data that the professor's framing of chemical participation in the launch mattered for students' developing conceptions of what chemistry is and what it means to be good at it.

To further support *collective investigation*, instructors listened for and collected student-generated questions and chemical connections to share them publicly on white boards surrounding the room. They also held teams accountable for thinking together by only engaging "team questions" that the team had articulated together.

Unintended and problematic aspects of design

The findings established that some aspects of the world of CHEM 101B made new meanings and new positions available to students and supported them to develop positive chemical identities. Nevertheless, exam-taking and exam grades tended to disempower students and invite them to construct themselves as not-so-good at chemistry. These findings raise important questions about how to design alternative assessments that offer students different kinds of opportunities to demonstrate competent participation in scientific practice beyond multiple choice and short answer exams. Or if exams are here to stay, how can instructors work towards mitigating the damaging effects of grades on students' developing senses of themselves in relationship to science? This study suggests that culminating assessments (such as the Communicating Chemistry project), which ask students to apply and synthesize chemical ideas, but do so without the pressure of a timed exam, are promising alternatives.

Ongoing questions and challenges

Ultimately, the burden lies on institutions of higher education and on the educators who inhabit them to reorganize undergraduate learning environments in ways that make it possible for all students to participate in rich and equitable science learning and to develop identities as capable scientific thinkers. This present study suggests that student-centered collaborative discussion-based models of instruction are promising approaches towards this goal. The question remains, what would movement towards implementing such models within institutions of higher education require?

Faculty themselves are situated in the dominant worlds of schooling that constrain their ways of making sense of students and that make a narrow set of instructional practices sensible. What kinds of support might faculty need to develop new sensibilities about learning, teaching, and students? Faculty learning communities about equity in STEM show promise for shifting faculty's conceptions and approaches to teaching and learning. However, such structures put the onus on faculty to improve their teaching in the context of university tenure structures that do not reward teaching innovation. To realize the goal of transformative science education, universities must both construct new incentive and reward structures with respect to teaching innovation and also develop programs for faculty professional development in this area.

Further, designing new curriculum is an enormous endeavor that individual faculty members should not be expected to undertake on their own. This present study benefited from a tenured chemistry professor who was able to volunteer time towards this project, alongside a graduate student and postdoctoral fellow whose full time work for three years included support for course design and curriculum development. Moving forward, institutions of higher education need ways of sharing curriculum more broadly. Future studies should investigate curriculum implementation across institutional settings. Design-based implementation research (Penuel & Fishman, 2012) has been suggested as a methodological approach for designing and studying scalable interventions.

Finally, given that many introductory science courses at large universities service 1000+ students per semester, future studies should consider how models like CHEM 101B might be scaled-up to serve more students. This work would require that universities invest in constructing larger active learning classrooms that can support collaborative work and in hiring additional instructional staff (i.e., teaching professors, full-time lecturers, graduate students) to support these courses. It is important to note that CHEM 101B would not have been possible apart from the seasoned undergraduate student instructors who facilitated collaborative work during class. We should continue to imagine, implement, and study new configurations of design that make it possible and sustainable to scale-up such practices.

To conclude, universities have a mandate to provide rich and equitable instruction for students. Equity demands that students have access both to the material resources and to ideational resources that support them to build strong identities as learners. Given that discourse in science limits these resources for students, it is vital that we work towards constructing learning settings that deconstruct and disrupt these hegemonic narratives and build more productive counter-narratives in their place. New meanings, activities, and discourses developed in the world of CHEM 101B demonstrate that re-figuring the world of general chemistry towards equity is both possible and powerful for students' learning and identity construction. And yet one course that imagines a different world is not enough to fully cement these new identities for students. Universities need to engage in the ongoing work of re-organizing STEM courses towards equitable and consequential learning.

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Appendix A: Interview Protocol

1. What's your major/ intended career? Why are you interested in this?
   - Has this changed at all since the beginning of the semester? If so, why?

2. Let's say an incoming Freshman was trying to figure out whether they should enroll in the larger lecture section or in CHEM 101B, how would you describe CHEM 101B to them?
   - Why do you think we do the tasks in class before watching the lecture?
   - To what extent do you think the kinds of things you do in this class are similar to or different from what chemists do?
   - And speaking about this more broadly, how do you think the thinking you did in class is similar to the ways that scientist think or approach questions
     - (ask for examples if not provided)

3. So overall, how is chemistry going for you this semester? Could you talk me through your experience in section 4 over the course of the semester?
   - Has chemistry always gone well/not so well for you?
   - How is section 4 similar or different from previous experiences learning chemistry, both high school (and if it applies) in college?
   - Do you feel like the overall structure of the class supported you to develop your understanding of the chemistry introduced in this class? What specific aspects of the course (did not) support(ed) this development?
   - How have you felt successful in CHEM 101B? Can you tell me about a moment in class when you felt really smart or really capable?
     - How often did you feel like that?

4. So I've heard people say "I'm good at chemistry" or "I'm not good at chemistry." What does it mean to be good at chemistry in this class?
   - Where do you see yourself fitting in there – do you see yourself as someone who is good at chemistry?
   - Do you think others see you that way? Why do you think so?
     - Do you think professor stacy sees you as someone good at chemistry?
     - Do you feel like your first team saw you as someone who is good at chemistry? What about your second team?
     - Describe any memorable interaction between yourself and any of these people.

5. Given the way the class is structured, what were you expecting the exam to be like?
   - Do you feel like the exams and quizzes gave you the opportunity to demonstrate ability to do chemical thinking and reasoning?

- Do you feel like the Communicating Chemistry project gave you the opportunity to demonstrate ability to do chemical thinking and reasoning in chemistry?
- How did grades support you to feel smart in chemistry or not.

6. We are curious to learn more about how you think more about science broadly. What does it mean to you to be a science person?

- Do you think of yourself as a science person?
- Do you feel that people in your personal life recognize you as a science person?
- Have we done anything in Section 4 this semester that has contributed to you feeling more connected to science?
- Thinking about where you were at the beginning vs. now, has participation shifted how you feel about being a science person?

Appendix B: Index of science practices codes

Location Key:

Lesson Number (e.g., L7)

Team Name (e.g., Na-B)

Time interval (e.g., 7-9 min)

Code #	Code Title	Location
SP1	Asking chemical questions	**L7** Na-B (7-9);(27-29) **L10**-NaA (14:30-16:30);(28:30-30:30) **L11**-BkB (8-10);(12-14); (14-16);(16-18); (18-20);(20-22);(22-24);(27-29);(33-37);(37-40:30); (40:30-42) **L12**-KA (10-12); (34-36); (38-40); (40-42) **L14**-GeB (8-10); (12-14); (16-18); (20-22); (22-24); (24-26); (26-28); (28-30); (30-32); (32-34); (38-40); (40-42); (42-44); (44-47) **L24**-BkA(2) (4-6); (12-14:30); (14:30-17:00); (14:30-17:00); (19-22); (19-22); (22-25); (35-37) **L29**-BkA (18-20); (22-24); (30-32); (42-44) **L30**-KA(2) (8:30-10:30); (8:30-10:30); (8:30-10:30); (10:30-12:30); (10:30-12:30); (16:30-18:30); (20:30-22:30); (20:30-22:30); (20:30-22:30); (26:30-28:30); (32:30-34:30); (32:30-34:30); (36:30-38:30); (36:30-38:30); (38:30-40:30) **L31**-BkA(2) (17:30-19:30); (19:30-21:30); (29:30-31:30); (31:30-33:30); (39:30-41:30); (43:30-45:30) L36-BkA(2) (10-12); (12-14); (16-18); (22-24); (34-36); (40-42); (42-44)
SP2	Identifying patterns or trends or in data and/or identifying exceptions; Identifying relationships between variables	L7 Na-B (13-15);(19-21);(19-21);(21-23);(21-23) L10-NaA (18:30-20:30), :30(18:30-20:30);(22:30-24:30);(24:30-26:30);(24:30-26:30);(26:30-28:30) L11-BkB; (27-29) L12-KA (10-12); (22-24); (26-28); (34-36); (48-50) L14-GeB (8-10); (16-18); (18-20); (20-22); (22-24); (24-26) L24-BkA(2) (4-6);(4-6); (12-14:30); (19-22) L29-BkA-none L30-KA(2) (6:30-8:30); (6:30-8:30); (18:30-20:30); (28:30-30:30); (36:30-38:30); (40:30-42:30); (44:30-46:30) L31-BkA(2) (15:30-17:30); (17:30-19:30); (17:30-19:30); (21:30-23:30); (21:30-23:30); (31:30-33:30); (35:30-37:30) L36-BkA(2) (8-10); (14-16); (16-18); (20-22); (40-42); (40-42); (44-46)
SP3	Justifying ideas with evidence	L7 Na-B (23-25);(25-27) L10-NaA (21:30-22:30)

Code #	Code Title	Location
	or reasoning,	L11-BkB (10-12);(10-12);(12-14);(20-22) L12-KA (12-14); (40-42) L14-GeB (10-12); (12-14); (20-22); (24-26); (28-30); (36-38); (42-44) L24-BkA(2) (10-12); (19-22); (19-22); (19-22); (22-25); (22-25); (22-25); (28:30-30) L29-BkA (16-18); (28-30); (40-42) L30-KA(2) (8:30-10:30); (12:30-14:30); (32:30-34:30) L31-BkA(2) (11:30-13:30); (29:30-31:30); (35:30-37:30); (37:30-39:30); (39:30-41:30); (39:30-41:30) L36-BkA(2) (10-12); (10-12); (10-12); (22-24); (28-30)
SP4	Challenging a claim/idea using evidence from data or scientific reasoning	L7 Na-B (19-21) L10-NaA-none L11-BkB (8-10);(10-12);(10-12);(10-12);(20-22);(31-33) L12-KA-none L14-GeB (16-18) L24-BkA(2) (14:30-17:00) L29-BkA-none L30-KA(2) None L31-BkA(2) None L36-BkA(2) None
SP5	Constructing causal explanations	L7 Na-B (21-23);(25-27) L10-NaA -none L11-BkB (6-8);(8-10) L12-KA (28-30); (30-32) L14-GeB (36-38); (42-44) L24-BkA(2) (12-14:30); (12-14:30); (14:30-17:00); (14:30-17:00) L29-BkA-none L30-KA(2) (8:30-10:30); (30:30-32:30) L31-BkA(2) (9:30-11:30) L36-BkA(2) (10-12); (10-12); (10-12); (10-12); (22-24)

Appendix C: Categorized list of "smart things"

Chemical Practices	Collective "learning together"	Socio-chemical norms
● Ask questions about data ● Justify your thinking and decisions ● Control for variables ● Recognize patterns/trends ● Considering relationships between variables and data sets ● Make connections across chemical representations ● Interpret symbolic and visual representations of solutions ● Reflect on the limitations of your model ● Synthesizing information from varied sources ● Make careful observations ● Organize many pieces of information clearly ● Making predictions before you do experiment	● Ask for or about other people's ideas ● Engage/build on each other's questions ● Rearticulate other people's thinking in your own words ● Take risks - be willing to offer ideas that might end up not being right ● Keep relating back to question of the day to guide your thinking ● Team leader should use the questions on the task card to keep moving the team's thinking forward ● Think out loud about what you're noticing or wondering about. ● Generate lots of ideas ● (...and synthesize those ideas) ● Keep cards in the middle space	● consider multiple ways of thinking ● ask for evidence and/or reasoning ● Apply/connect back to (specific knowledge) you generated in a prior class ● Connect back to Coulomb's Law ● Be open to revising your ideas ● Visualize molecular structure in 3D space ● Imagine/consider what's happening at the atomic scale ● Imagine how changes at the atomic level would translate the to macroscopic level ● Test out your rule after you write it - does it help you make predictions? ● Imagine what each substance looked like before it was added to solution. ● Consider when it would be appropriate to apply one method over another. ● Check that your argument includes: 1) a claim, 2) evidence, & 3) ● Determine what variable are most important, or most relevant ● Keep track of amounts