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Instructional decisions when teaching entropy: a case study on topic-specific pedagogical content knowledge

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Physical chemistry is a mathematically intensive course that requires students to integrate mathematical and conceptual understanding of abstract topics, with previous research exploring instruction on thermodynamics, quantum mechanics, and general approaches to the course. However, there has been limited work on the impact of instructors' pedagogical decisions related to student understanding of the topic of entropy. Within a larger research study exploring the cognitive resources activated by instructors when teaching entropy, the current case study aims to investigate how chemistry instructors' values, goals, and lived experiences inform their pedagogical decisions when teaching the topic of entropy. Using the refined consensus model of pedagogical content knowledge as a guiding framework, semi-structured interviews were conducted with undergraduate chemistry instructors from multiple institutions. Participants were asked to define and explain entropy, represent the topic through focused content questions, and describe their instructional approaches. Findings revealed that instructors primarily relied on their knowledge of students and pedagogical knowledge to guide instructional decisions related to their content knowledge, with minimal emphasis on and integration of assessment and curricular knowledge with the remaining professional knowledge bases. These results highlight the need for further research into the development of interconnections between the five knowledge bases of topic-specific pedagogical content knowledge to better inform instructional practices in undergraduate physical chemistry.

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Introduction

Previous work has reported that undergraduate physical chemistry students find the course difficult, due to its abstract nature and requirements of mathematical understanding (Hahn and Polik, 2004; Sözbilir, 2004; Bennett and Sözbilir, 2007; Bain *et al.*, 2014; Tsapalis and Finlayson, 2014; Bain and Towns, 2016). In connection to student understanding, prior research has specifically investigated physical chemistry instructional decisions related to the course curriculum (Sözbilir, 2004; Belt *et al.*, 2005; Becker *et al.*, 2015; Fox and Roehrig, 2015; Mack and Towns, 2016); quantum chemistry (Padilla and Van Driel, 2011); and thermodynamics (Bennett and Sözbilir, 2007; Bain *et al.*, 2014; Natalis and Leyh, 2024). Regarding instructional decisions related to the course curriculum, instructors' perceptions of student difficulties (Sözbilir, 2004), topic coverage (Fox and Roehrig, 2015), and instructional roles in teaching physical chemistry topics (Belt *et al.*, 2005; Becker *et al.*, 2015; Mack and Towns, 2016) have been explored. Padilla and Van Driel investigated quantum mechanical pedagogy through a

topic-specific approach, with findings demonstrating that instructors' beliefs on the goals of physical chemistry instruction impact instructional decisions for specific topics (Padilla and Van Driel, 2011). Additionally, Bennett and Sözbilir (2007) and Bain *et al.* (2014) explored how thermodynamics is taught within physical chemistry contexts, focusing on the three laws of thermodynamics and finding that students had challenges understanding the abstract topics, leading to alternative conceptions. These studies emphasized the need for instructors to better connect the particulate nature of matter and its concepts to the mathematical representations of thermodynamic properties (Bennett and Sözbilir, 2007; Bain *et al.*, 2014).

Of the foundational chemistry topics taught across the undergraduate curriculum, entropy is an abstract concept introduced in general chemistry contexts and further explored in upper-level courses, including physical chemistry. Previous research has provided evidence that entropy can be a confusing concept to students as they navigate the undergraduate chemistry curriculum (Sözbilir, 2004; Bain *et al.*, 2014; Abell and Bretz, 2018, 2019a, 2019b; Charles De Berg, 2022). Additionally, a systematic review was previously conducted, containing literature on instructional strategies and practices related to the concept of entropy (Natalis and Leyh, 2024). Although not focused on pedagogical

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decisions related to the concept, this review by Natalis and Leyh analyzed how instructional strategies and practices from the literature integrated the three components of the chemistry triplet – macroscopic, particulate, and symbolic (Johnstone, 2010; Taber, 2013). Beyond work conducted by the research team on cognitive resources activated by undergraduate chemistry instructors when teaching (England *et al.*, 2026), a focus on instructional decisions related to the topic of entropy in undergraduate physical chemistry settings is currently missing from the literature.

In addition to content knowledge (subject-matter knowledge) and pedagogical knowledge (knowledge of general instructional strategies), pedagogical content knowledge (PCK) has been posited as an essential component of instructors' expertise in teaching (Shulman, 1986). PCK is rooted in exploring instructional decisions, where five distinct types of knowledge (or professional knowledge bases) interact and inform an instructor's PCK: assessment knowledge, content knowledge, curricular knowledge, knowledge of students, and pedagogical knowledge (Shulman, 1986; Carlson and Daehler, 2019). PCK of preservice teachers in science contexts has been previously investigated, with a focus on the nature of science (Aydin *et al.*, 2013) and specific topics including translating between the macroscopic and particulate nature of chemical reactions (Van Driel *et al.*, 2002), physical and chemical changes (Bektas, 2015), ability to incorporate technology into instruction (Deng *et al.*, 2017; Cetin-Dindar *et al.*, 2018), and chemical equilibrium (Oztay *et al.*, 2023). In contrast, research leveraging PCK at postsecondary chemistry levels have focused on concepts of acid–base chemistry (Boothe *et al.*, 2023), kinetics (Akın and Uzuntiryaki-Kondakci, 2018; Rodriguez and Towns, 2019), and electrochemistry (Aydin *et al.*, 2014). Other studies at the undergraduate level of instruction have focused on PCK related to teaching specific chemical techniques including thin layer chromatography (Hale *et al.*, 2016) and ^1H NMR (Connor and Shultz, 2018; Fantone *et al.*, 2024).

Within the specific context of undergraduate physical chemistry instruction, previous work has leveraged PCK to explore how instructors approach teaching the course (Fox and Roehrig, 2015; Mack and Towns, 2016) as well as how they approach teaching specific quantum mechanical topics (Padilla and Van Driel, 2011). In a nationwide study, Fox and Roehrig (2015) investigated topic coverage, course delivery, assessment decisions, and faculty understanding of student perceptions. This study emphasized the need for a better understanding of how physical chemistry instructors make decisions between mathematical and conceptual explanations and how they present information to students (Fox and Roehrig, 2015). Mack and Towns (2016) further qualitatively explored instructional decisions across the undergraduate physical chemistry course *via* the lens of PCK. Findings from this work indicated that chemistry instructors believed that the purpose of teaching physical chemistry should focus on mathematical modeling to enhance conceptual understanding, following a hierarchical model with conceptual learning at the base, epistemic learning in the middle, and social learning at the top of the hierarchy (Mack and Towns, 2016). Additionally, in a topic-specific PCK

approach focusing on quantum mechanics, Padilla and Van Driel (2011) examined instructional decisions of postsecondary quantum chemistry instructors, focusing on topics of the model of the atom, wave-particle duality, and atomic orbitals. Findings from this work provided evidence that instructors used their beliefs about the purposes and goals for teaching quantum mechanics to shape their instructional decisions of specific topics related to their curricular knowledge, instructional strategies, student understanding of science, and how to assess scientific literacy (Padilla and Van Driel, 2011). To better understand instruction on the topic of entropy, this study aims to investigate the values, goals, and lived experiences that impact the pedagogical decisions of undergraduate general and physical chemistry instructors when reasoning about teaching entropy, using the refined consensus model (RCM) of PCK (Carlson and Daehler, 2019; Rodriguez and Towns, 2019).

Theoretical framing

Pedagogical content knowledge (PCK) was conceptualized by Shulman to frame how teaching decisions relate to and rely upon the content of the discipline (Shulman, 1986). To explicitly define PCK and related constructs, the refined consensus model (RCM) of PCK was established, shown in Fig. 1 (Carlson and Daehler, 2019; Rodriguez and Towns, 2019). The RCM posits three distinct realms or levels of PCK: (1) collective PCK (cPCK), or the cumulative knowledge held by a scientific community, informed by evidence within the field; (2) personal PCK (pPCK), or the personal compilation of knowledge held by an individual, informed by interactions with students, other instructors, and the community; and (3) enacted PCK (ePCK), or the application of knowledge within a given instructional environment (*i.e.*, specific classroom and/or laboratory), guided by student outcomes (Carlson and Daehler, 2019). In an interdependent and integrated fashion, cPCK is the knowledge base that guides an individual's pPCK, developed by previous experiences in learning environments and directly influenced by

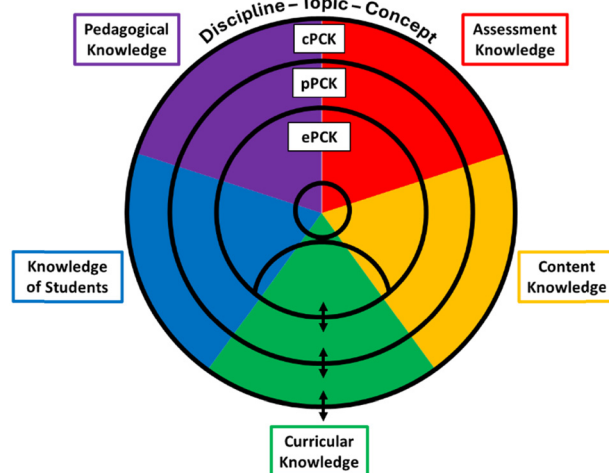


Fig. 1 Refined consensus model (RCM) of pedagogical content knowledge (PCK), adapted from Carlson and Daehler (2019) and Rodriguez and Towns (2019).



interactions with instructional colleagues, education researchers, course materials, and students. pPCK additionally shapes ePCK, an application of pPCK during planning, teaching, and reflecting (Carlson and Daehler, 2019).

Within each realm (cPCK, pPCK, and ePCK) of the RCM, five distinct types of knowledge (also referred to as professional knowledge bases) have been defined: assessment knowledge, content knowledge, curricular knowledge, knowledge of students, and pedagogical knowledge (Carlson and Daehler, 2019). Assessment knowledge is the knowledge of how to design formative/summative assessments, including how to format questions and evaluate assessment results to inform actionable steps. Content knowledge is the knowledge related to the subject matter, with emphasis on the key ideas and relationships needed for the instructional task. Curricular knowledge is an awareness of the structure, order, scope, and goals of the curriculum and impacts on instruction. Knowledge of students is the understanding of students' cognitive development, including prior knowledge. Finally, pedagogical knowledge is the general knowledge of theories of student learning, skills, and instructional principles related to teaching. These five types of knowledge develop through interactions between each of the three realms (cPCK, pPCK, ePCK) and the many different people associated with teaching: students, peer instructors, publications, and field experts (Carlson and Daehler, 2019). Additionally, three levels of grain size (discipline-specific, topic-specific, and concept-specific) are present within each of the realms (Carlson and Daehler, 2019). Discipline-specific PCK is the knowledge related to an entire discipline, like chemistry, physics, or biology. Topic-specific PCK explores the knowledge related to specific topics, like acid–base theory, enthalpy, or entropy. Concept-specific PCK is the smallest grain size that focuses on the knowledge associated with teaching individual concepts in the discipline, like calculating pH or electronegativity. Our current study investigates topic-specific personal PCK, investigating its impact on chemistry instructors' instructional decisions when reasoning about teaching entropy.

Research question

This research study uses the RCM of PCK to explore the pedagogical content knowledge used by chemistry instructors when teaching the topic of entropy, and is guided by the following research question: *How are the five professional knowledge bases of topic-specific personal pedagogical content knowledge leveraged by instructors when reasoning about teaching entropy?*

Methods

Instructional/pedagogical decisions when teaching the topic of entropy were examined through specific content questions, using a qualitative approach guided by the positionalities of the research team and the environment in which the study was conducted (Secules *et al.*, 2021). Within this qualitative work, critical reflection on biases is important for considerations of transparency, credibility, and trustworthiness (Foote and Gau Bartell, 2011; Gillborn

et al., 2018; Bayeck, 2022; Rodriguez and Navarro-Camacho, 2023). Via the researchers-as-instruments component of positionality (Secules *et al.*, 2021), we acknowledge our role in the research process, including impacts on study design, implementation, and analysis. Statements related to positionalities of the research team have been included in the respective sections below to directly acknowledge who this research has been done by and for.

Ethical considerations

This study was conducted at multiple R1 public institutions in the United States, with data collection occurring during Fall 2023 and Summer 2024. Institutional Review Board (IRB) approval was obtained prior to participant recruitment and data collection (IRB-23-110).

Participants and setting

As a part of a larger qualitative study (England *et al.*, 2026), instructors of general and physical chemistry courses were recruited to participate *via* a Qualtrics survey, which included questions related to instructors' teaching experience, research experience, and demographic information. Initial recruitment was conducted through purposeful sampling (Creswell and Poth, 2018) with volunteer and snowball sampling employed to produce a larger group of participants (Creswell and Poth, 2018). As a methodological choice, participant recruitment occurred by email, led by authors JE (a graduate student) and MBA (an assistant professor of chemistry). This recruitment strategy, *via* JE's and MBA's professional networks and relationships with instructors at institutions across the nation, potentially impacted decisions to participate in the study. Participants were selected for interviews ($N = 19$) in the larger qualitative study based on their survey responses to ensure representation from both general chemistry and physical chemistry instructors (England *et al.*, 2026). Of the 19 participants in the larger study, four participants were selected for the current case study due to their (1) wide range of teaching experience and (2) explicit explanations of their instructional decisions related to their values, goals, and lived experiences in connection with responses that elicited information related to topic-specific personal PCK. These four participants held a range of teaching experience (from 1–15 years), including experiences in secondary (high school) chemistry and postsecondary (undergraduate) general chemistry and physical chemistry contexts. All four instructors in the current case study teach the topic of entropy at least once per year, meaning that they had recently engaged with the material prior to the interview.

Interview protocol

The interview protocol was developed by authors JE and MBA to investigate decisions made by general and physical chemistry instructors when teaching the topic of entropy to undergraduate students. As a doctoral student at the time of the study with instructional aspirations and a strong foundation in physics, chemistry, and physical chemistry, this focus was informed and guided by JE's interest in how entropy is taught at the undergraduate physical chemistry level of instruction. After initial questions regarding instructors' experience with entropy in



teaching and research, the instructors were asked how they define and represent entropy when teaching. For a better understanding of instructional decisions and pPCK related to entropy, four content questions (Fig. 2) were included. Leveraging expert validation from a general and physical chemistry instructor who was not a participant in the study (Lincoln and Guba, 1985; Sandelowski, 1998), the four content questions were chosen to explore the main components of entropy taught at both the general and physical chemistry levels of undergraduate instruction. Each content question was prefaced by the following prompt: “We are interested in your instructional choices for the next few questions. How would you teach the following prompts to your students? Have you chosen to leave anything out in your explanations? Why?” Content Question 1 explored the entropy differences of phases, one of the first concepts introduced when teaching entropy. Content Question 2 included the entropy change of the Haber process and the combustion of ethanol. This question was included as a continuation of building on the ideas behind the entropy of phases to apply them to chemical reactions. Content Question 3 asked about the relationship between temperature and entropy and any chemical representations used by the instructors when teaching about this relationship. This question allowed for potential differences between representations used at the general and physical chemistry levels of instruction. Finally, Content Question 4 was chosen as a challenge question related to previously studied paradoxes in physical chemistry (Bartell, 2001) to

further elicit discussions of pedagogical differences between general and physical chemistry levels of teaching. Although the focus of the current case study investigates topic-specific pPCK of four instructors when teaching entropy, the larger study conducted by the research team (England *et al.*, 2026) explored cognitive resources activated by all 19 study participants when considering the four content questions. This data will not be reported in the present manuscript.

Data collection and analysis

Semi-structured interviews were conducted by author JE. All interviews were audio- and video-recorded and were approximately 25–45 minutes in length. Participants were asked to describe and explain their instructional decisions, as well as information related to the topic of entropy that they would choose to exclude from their explanations, based on the level of instruction. All audio/video recordings were transcribed using Otter.ai (Otter.ai, 2025). To ensure thorough transcription, audio and video data were transcribed and manually cleaned by JE. To remove any confidential information, transcripts were deidentified by assigning participant pseudonyms, and any writing from participants was scanned and saved under their respective pseudonyms. Qualitative data analysis used deductive coding (Braun and Clarke, 2021, 2023), leveraging the RCM of PCK and focusing on the five types of knowledge within personal PCK for the topic of entropy (Carlson and Daehler, 2019; Rodriguez and Towns, 2019). Data analysis was completed by both JE and SP, a senior undergraduate student concurrently enrolled in physical chemistry at the time of the study. SP additionally completed coursework in the science education teaching program (Teach North Texas, University of North Texas), directly applying his formal pedagogical training to data analysis in this work. Initial analysis was based on the five types of knowledge described by the instructors when discussing entropy. Once the types of knowledge (assessment, curricular, content, students, and pedagogical) were coded, instructors’ explanations of each type of knowledge were explored, using work from Rodriguez and Towns (Rodriguez and Towns, 2019). After thematic analysis of individual knowledge types and instructor explanations to determine themes among the codes, connections between the knowledge types were analyzed based on how participants elicited direct and explicit connections in their explanations. Data from the four participants were coded to complete consensus between the two independent coders, JE and SP, alongside discussion with MBA (Braun and Clarke, 2021). The full codebook, with codes, theme descriptions, and representative quotes, is shown in Appendix 1.

Results and discussion

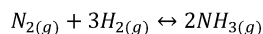
Participant responses were first analyzed based on the types of knowledge described by instructors as they explained defining/representing entropy and responded to the four content questions. These types of knowledge identified within the four

We are interested in your instructional choices for the next few questions. How would you teach the following prompts to your students? Have you chosen to leave anything out in your explanations? Why?

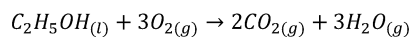
Content Question 1: Put the phases (solid, liquid, and gas) in order of increasing entropy. Why did you choose this order?

Content Question 2: How does the entropy change, or not change, for the following reactions? Explain your reasoning.

Haber Process:



Combustion of Ethanol:



Content Question 3: As the temperature of a system is increased, what happens to entropy? Why is there an increase/decrease? Can you represent this using an equation or image?

Content Question 4: Is the change in entropy positive, negative, or zero when two identical gases are spontaneously mixed? Explain your thought process.

Fig. 2 Content questions posed to participants within the present study. (Reproduced from ref. England *et al.*, 2026 with permission from the Royal Society of Chemistry.)



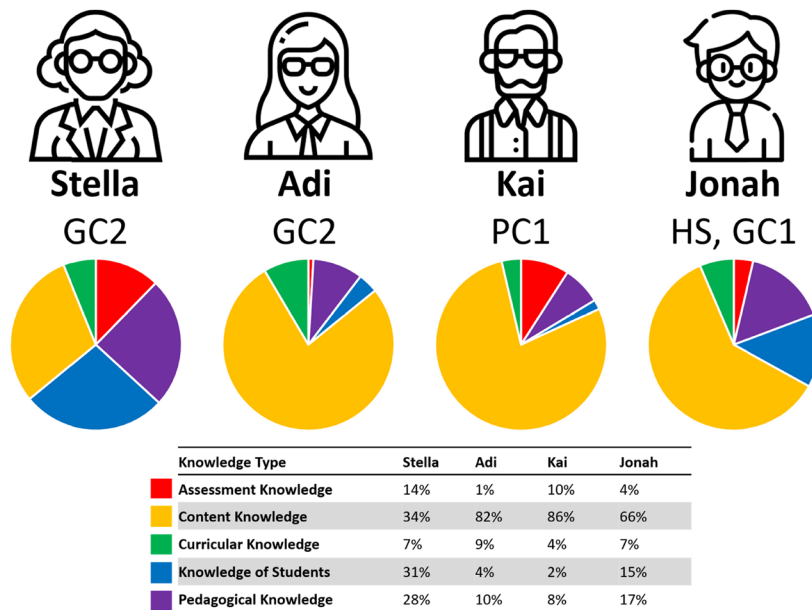


Fig. 3 Topic-Specific Personal PCK (TS-pPCK) types of knowledge (professional knowledge bases) identified within instructors' responses are indicated. Courses taught by participants include General Chemistry I (GC1), General Chemistry II (GC2), Physical Chemistry I (PC1), and High School AP Chemistry (HS).

instructors' topic-specific personal PCK (TS-pPCK) are shown in Fig. 3. Although qualitative approaches intend to provide context and insights that numbers alone cannot offer (Creswell and Poth, 2018), pie charts have been used to represent the qualitative data in this study, as these representations allow for effective visualization of how the knowledge types were elicited in varying proportions among participants. While the types of knowledge were often interconnected among the four instructors, each knowledge type has initially been individually described below.

Content knowledge

For all four instructors, the proportion of responses related to content knowledge (knowledge of subject matter, including key ideas and relationships) was highest in comparison to all other types of knowledge. This is likely due to the nature of the interview guide, which required participants to discuss their instruction through four content questions related to entropy. Several specific themes of content knowledge were described in the instructors' responses to the entropy content questions: mode/depth of presentation, defining critical concepts, and facilitating connections to additional concepts.

The most prevalent way instructors' responses elicited information related to content knowledge was in how they described presenting the topic of entropy to their students while teaching (mode of presentation), with all four instructors generally discussing how they worked through content specific problems in instructional settings. Adi described explaining the change in entropy for the Haber process (Content Question 2) to students, focusing on the change in number of moles of gas in the reaction:

"I would say, now you have three gases or three substances that are gases. Now we are going to consider – or we are going to add up the coefficients of the reactants on each side. So, on the left,

there are one and three, four in total. On the right, there are just two. So that means on the left, you start with four moles of gases, then they – somehow, they combine to make two because the moles of the gases decrease and so we know gases, they are random, they are disorderly, they go everywhere. Because the number of moles of gases decrease, we say the randomness decreases. It becomes more orderly, so S decreases. We use the number the sum of the coefficients."

Instructors also defined the aspects of entropy that they determined were "critical concepts" for understanding entropy, as well as how these concepts connected to additional concepts. These critical concepts included instructors' acknowledgement of required student learning objectives and/or important knowledge components to convey during instructional practice when teaching the topic of entropy. For example, after describing how they presented ideas related to impacts of temperature change on entropy in response to Content Question 3, Adi stated, *"This is what I tell them, and [the Maxwell distribution] graph is in my notes. This is something they need to know."* Adi noted that knowing the relationships between kinetic energy, gas particle velocity, temperature and their impact on entropy are critical concepts, as the students are expected to understand them and apply them during assessments.

Additionally, instructors described how they might facilitate connections between critical aspects of entropy by showing relationships to other content. When considering Content Question 3 related to temperature and entropy, Kai facilitated making connections between several critical concepts: the third law of thermodynamics, phase diagrams, and the temperature difference of the phases. Kai stated:

"Let's look at this phase diagram [draws phase diagram for Content Question 3]. This basically shows that some liquid goes to gas as temperature increases, and... the third law tells us, in this process, entropy always increases. Raising temperature



always gives higher entropy, so we can see that [the gas] phase would have a higher entropy than [the liquid] phase."

In addition to mode of presentation, depth of presentation was also a theme within the responses related to instructors' content knowledge. Within this theme, instructors explicitly described their reasoning for specific material they would intentionally include and/or exclude from their explanations when teaching entropy at the undergraduate level. With experience in both secondary and postsecondary instructional contexts, Jonah described introducing the idea of microstates to undergraduate general chemistry students, using a particulate representation of air molecules in two gas chambers. In contrast, Jonah noted an emphasis on using representations that depict disorder, like the breaking down of molecules and substances, when teaching at the secondary (high school) level. Stella also described excluding specific representations of entropy when teaching undergraduate general chemistry in comparison to undergraduate physical chemistry, like the Boltzmann relationships. Stella described that, while recognizing the technical definition of entropy as the number of microstates, they choose to describe/represent entropy as the dispersal of energy or matter when teaching general chemistry students:

"The more technical way [to define entropy] is the number of microstates. Right? So higher entropy, greater number of microstates, most students don't understand what that means in gen chem. So, the definition that I favor very heavily is that entropy is a dispersal of energy, which is also a dispersal of matter... I don't usually use the Boltzmann relationships. So, that's entropy is the Boltzmann constant times the natural log of the number of microstates. I don't usually use that for my class because it's a freshman chemistry class. And it just feels like another equation to memorize."

Pedagogical knowledge

While instruction on this knowledge type typically occurs through formal coursework included in secondary teaching programs of study, pedagogical knowledge is not a current emphasis in postsecondary chemistry graduate programs of study. Previous literature has posited that this phenomenon contributes to a potential lack of training/experience for new postsecondary chemistry instructors beginning their career (Committee on Professional Training, 2015; Donkor *et al.*, 2024). Defined as general knowledge of theories of student learning, skills, and instructional principles related to teaching, evidence of pedagogical knowledge in instructors' responses when teaching entropy were categorized into three main themes: instructional medium, teaching preferences, and theoretical assumptions from previous teaching and research.

Within the theme of instructional medium, instructors described decisions of varied use of presentations, simulations, videos, problem-solving packets, and images. Stella discussed choosing to provide videos prior to class in a flipped approach, with students then working in small groups on a set of questions during class. Kai described choosing to use computational simulations when teaching undergraduate physical chemistry, as well as writing/drawing equations and graphs related to entropy on the board. Additionally, Adi discussed choosing to

use PowerPoint presentations, animations, and images to show movement when considering differences in the entropy of phases:

"In my lecture notes, I have little animations... I borrowed from the internet. It's like, if you look through a window, then you have the solid, they're highly aligned. And then they move a little bit, teeny tiny bit about where they are, they move around on the PowerPoint slides. And for the liquids, they are still close to each other, but they're not highly aligned, structured. They still move around, but they [move] a little more than the solid. And... gases, through the same window, you see the gas particles just flying through."

Within the theme of teaching preferences, instructors described their decisions to frame content based on the specific type of classroom layout or pedagogical approach used in alignment with their course learning outcomes. Stella described the setting of her course as a flipped classroom, where the students watch videos outside of class time and work in small groups on problem-solving while in class:

"So, with my class, we have these mini lecture videos, where I sort of give them that information through [the LMS]. And then when they come to class, they're working in their teams on questions or activities that I've created to align with our learning outcomes that were covered in the videos."

Additionally, instructors explicitly described framing their content *via* scaffolding during explanations of entropy. Scaffolding is an educational tool used to aid a student in completing a task that is typically beyond their ability, in an effort to guide the students to independently solving tasks by removing the scaffolds over time (Wood *et al.*, 1976; Rosesshine and Meister, 1992; Reiser, 2004). Jonah specified scaffolding during instruction by first discussing students' previous knowledge about the entropy of phases and the number of moles of reactants and products. Jonah then subsequently guided student understanding of the entropy change of reactions as students solved Content Question 2 for the entropy change in the combustion of ethanol, leveraging their prior knowledge: *"My instructional choice would be to break it down into the two ways that we've learned so far: solid liquid gas, and then gas number of moles, and we see they both agree to each other."* Jonah's discussion focused on the ways they scaffold student understanding based on their knowledge of students' challenges and responses.

Within the theme of theoretical assumptions from previous teaching and research, instructors explicitly explained how their instructional decisions when teaching entropy were related to previous experiences in teaching and/or research. For Content Question 2, Kai reported initially using a qualitative approach in instruction, but then subsequently using a mathematical approach to ensure accurate qualitative understanding: *"It makes more sense to me, so I introduce it that way. But then I say, well, uh let's do some calculations, and, you know, double check on our intuition to see this is true... One thing I do emphasize to my students is, you know, always back your reasoning by rigorous math."* Stella described choosing to allow students to cultivate their own understanding and reasoning of the material, without immediately correcting for different strategies of problem solving. Stella



recognized that there are many ways of knowing, allowing students to leverage their own prior knowledge in the learning process:

"I don't correct. Like, I don't say, oh, no, you need to think of it this way. If it's something that makes sense for them, and it's accurate, it does have to be accurate. But as long as it's not inaccurate, I'm just like, Yeah, awesome. I don't want to mess with that. So, a lot of my instructional choices are based on supporting the students in developing their own ways of understanding and reasoning. And it doesn't have to be the way I think of it."

Knowledge of students

When explaining instructional decisions for entropy, knowledge of students (knowledge of students' cognitive development and the variation of approaches and prior knowledge) was elicited in their responses. Instructors explained their knowledge of students through several themes: considerations of student responses to specific tasks, challenges for students, and prior knowledge of students.

Each of the four instructors discussed how students would respond to the specific content question prompts, as well as how students would approach solving general problems on entropy. Based on experience in interacting with previous students, Stella explained their choice to use the dispersal of energy or matter when defining entropy, due to student response to the disorder definition: *"Disorder – they [students] think chaos... And they think the end of that movie, Event Horizon... They think it means chaos."* Kai also had many instances of how students would respond directly to the prompts presented while teaching entropy. When thinking about instructional decisions for Content Question 4, Kai conveyed thoughts on student responses based on previous student discussions in class: *"And most of the students will correctly predict, well the gases [are] still gonna mix together, and I asked them to think about, well, is this a spontaneous process, reversible process, or a irreversible... process? ... Yeah, this is a spontaneous process."*

Instructors also elicited specific challenges for students when thinking about the specific content questions, as well as general challenges students have in the conceptual understanding of entropy. In continuation of Stella's discussion about confusion between disorder and chaos, they additionally reported that disorder is less helpful, as students face challenges in applying this definition to chemistry problems. Many of Stella's discussions included remarks on the relationship between how students respond to content questions on entropy and what specifically makes conceptual understanding of entropy challenging. For Content Question 1, Stella began by explaining that increasing or decreasing can be confusing to students, before outlining experiences with student responses:

"So, sometimes my students don't really understand what I mean by increasing or decreasing. And so, I'll draw the wedge like, okay, it's getting bigger or less negative, in some cases with entropy. So that's something that I would scaffold if they're not sure about that part. Then I would allow them to rank them, and then if they are in order or out of order, I would ask, you know, what made you do this? And what they would usually respond would be... solid < liquid < gas, because gas is spread out more. Right, so that's a really common one. Sometimes they

use the term disorder. And they'll say, oh, the gases are more disordered than the liquid, than the solid. But usually, it's a spreading out kind of thing."

Jonah noted student challenges with the entirety of thermodynamics, also describing their own challenges as a student with entropy, enthalpy, and Gibbs free energy:

"You know, thermodynamics in general, to anyone who's approaching chemistry for the first time, high school or college, that's just a very tough part of chemistry. And I mean, thermo is probably the hardest thing, and... from my own perspective, you can go an entire undergrad degree without understanding what entropy and enthalpy are. And Gibbs free energy. These are things that you could just have an idea of in your head, and you go a whole undergrad degree without understanding it."

Within the theme of prior knowledge of students, Stella detailed students' use of prior knowledge on gas laws and the dispersal definition of matter when solving Content Question 4: *"So, most of them would kind of go back to gas laws and be like, 'oh', and again, our definition of the dispersal of matter, and be like, 'oh, it spreads out more.'" Jonah emphasized students' prior education experiences, rather than entropy-specific prior knowledge. In response to how entropy changes when temperature increases (Content Question 3), Jonah communicated that they knew their current students were logic-minded, and thus, able to understand a logic model explanation (Fig. 4). In this explanation, Jonah related kinetic molecular theory and the motion of particles to temperature and the order of molecules,*

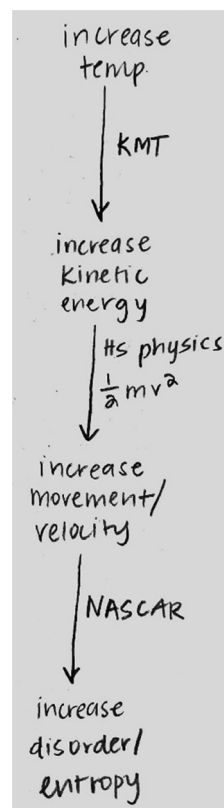


Fig. 4 The logic model described by Jonah when explaining their instructional decisions while working through Content Question 3 with students.



using a real-world example. Jonah chose to draw arrows between each point of the logic model:

“Like you could tell in the student body that I had, they were a little bit more logic-minded. They were taking the higher-level math classes. They sort of had that approach in their head already. So, I was just appealing to that logic component.” Jonah also recognized that the instructional choice to use a logic model was only applicable to this specific set of students. Jonah explained that they *“would probably not try that approach on students that were a little more creative-minded, a little less logical.”*

Assessment knowledge

This type of knowledge (knowledge associated with designing assessments and actions needed based on the assessment data) was less prevalently elicited in instructors' responses, likely due to the content-specific focus of the interview. However, this could also be due to the lack of accessible training resources for development of instructors' assessment knowledge, as previously reported in the literature (Aydin *et al.*, 2013; Rodriguez and Towns, 2019). When the instructors in our study did bring up assessment knowledge, their responses were categorized into three themes: assessment item modification, assessment scaffolding, and addition of assessment prompts for students.

Within the themes of assessment item modification and scaffolding, instructors included ways they would change the content questions for their students (*i.e.*, changing the chemical reaction presented, changing the wording for clarity). While also aligning knowledge of students with assessment knowledge to better measure student understanding of entropy (Padilla and Van Driel, 2011), Stella stated that the wording of Content Question 4 would be confusing to students. Stella suggested the use of different language and scaffolding of the question in parts/components for the purpose of assessment:

“I would draw a picture for them, and I probably wouldn't even specify positive, negative, or zero. I would probably just say, is there a change in entropy? Number one. And then number two, how do you think it changes? Do you think it increases or decreases? And because if they say, no, it doesn't change, then that would be zero. So, I would draw the picture for them, because the phrasing ‘two identical gases mixed’ is a little confusing. So, if I draw a picture, and I say you have, you have the same gas in two different flasks that are... separated by a tube with like a stopcock, and then you open it. So how would that change?”

Within the theme of proposed additional prompts for students to further student understanding of the topic of entropy, Jonah used assessment knowledge to develop additional prompts for Content Question 2 to aid in students' qualitative understanding of how entropy changes during a reaction:

“Where you break this [Content Question 2] into a third question, and you say, well, I've got a liquid, and a gas, goes into a gas. And you count the number of gas molecules with the liquid, and you have more, so that those two rules disagree. And you have to think about – Well, which rule takes priority? ... I'm gonna break it down into rules. Say, well, here's a rule: solid, liquid, gas. Here's a rule, you know: gas, moles. Well, let's look at which one has priority, and that's probably the next question.”

Curricular knowledge

This type of knowledge (awareness of goals, structures, scope, and sequence) as described by the four instructors in this study was categorized into the following themes: considerations of knowledge from previous courses, considerations of longitudinal curriculum, and modification of the curriculum.

For previous courses, instructors' responses within this theme were distinct from discussions of students' prior knowledge (knowledge of students) based on the context given by the instructors. Curricular knowledge of previous courses included instructor knowledge expectations from previous course levels of instruction overall, rather than explicitly thinking of the prior knowledge students hold from their perspective. For example, when describing the relationship between temperature and entropy, Kai stated, *“Your entropy always increases. As a matter of fact, this is determined by accumulation of prior knowledge, such that the entropy always increases with temperature, and that is part of the third law.”* As an instructor of physical chemistry, Kai used his knowledge of instruction in previous courses of the undergraduate chemistry curriculum to make an assumption of the knowledge that students should hold.

Within the theme of considerations of longitudinal curriculum, instructors communicated specific understanding that students need to know for future instruction within their own course, as well as in later coursework within the chemistry curriculum. Stella detailed instruction on entropy in relation to previous and future topics within the undergraduate General Chemistry II course:

“We talk about entropy twice. Initially, we talk about it kind of briefly when we talk about gases dissolved, like solutions with gases and dissolved in a liquid solvent. And we're just like, Oh, hey, it's a thing and um, that it affects, you know, the – the favorability because we talked about solutions and solubility in the first – the order I use, it's the first chapter um in [General Chemistry II]. But we don't really get into it until the thermo chapter. And so, we're like, oh, remember, H, H for heat is what I like to say, enthalpy and then introduce entropy, second law, third law, and then we tie that together in uh spontaneity and free energy.”

For responses related to modification of the curriculum, instructors illustrated the initial format of instruction relevant to entropy, as well as details on how they incorporated changes within the curriculum. Jonah elicited thoughts on instructional changes for thermodynamics to account for the abstract nature of some of the topics: *“I formatted my thermodynamics lessons from the...idea that these things that we're learning, enthalpy, entropy, Gibbs, these are slightly abstract topics.”* Jonah first taught general chemistry, subsequently becoming a high school chemistry instructor. Because of this, Jonah acknowledged the abstract nature of entropy, choosing to introduce simplistic definitions in the context of secondary teaching, with the option to consider more technical definitions based on their knowledge of students in the class. Of the limited current research focused on curricular knowledge, studies have shown that the opportunity for instructors to collaborate (collective PCK) is needed to help build an individual instructor's curricular knowledge within their personal PCK (Andrews, *et al.*, 2022; Fantone, *et al.*, 2024).



Professional knowledge base integration

Instructors commonly discussed more than one knowledge type during their explanations for each of the content questions, and this often occurred in an integrated manner. In addition to the previously described individual knowledge type analysis, our work investigated connections between the five knowledge types for each participant (Fig. 5). Specific examples of integration are described below.

Stella prevalently discussed their knowledge of students and pedagogical knowledge in connection with their content knowledge, explicitly describing how knowledge of their students guides their pedagogical decisions and the specific content/representations that they choose to present. In response to Content Question 3, Stella first described theoretical assumptions from previous research and teaching on helping students develop mental models (pedagogical knowledge) in connection with their knowledge of student thinking (knowledge of students) and their own thinking (content knowledge) related to phases:

“Atoms are invisible. They’re so tiny. So, we have to imagine, right, we have to have these representations in our head. So, I would probably ask them, What are they thinking relating to temperature and entropy? . . . Usually, they’ll [the students] go to phases. . . I think gases, I just go to gases. . . [But the students] think phases. And so they’re like, Well, usually, they’ll say, Well, I know solid is less than liquid, and that’s less than gas. And when you heat up like an ice cube, it melts, and you heat up even more, it’s a gas. So, they [the students] usually say the entropy increases as temperature increases.”

Stella then additionally connects pedagogical knowledge and knowledge of students in consideration of the depth of presentation of the content knowledge: *“Students are not thinking about higher energy populating the higher energy microstates, they’re not thinking of that, they’re just thinking of like a physical connection that they have.”* Reflected by the highly integrated

chord diagram (Fig. 5), Stella’s values, goals, and lived experience in reasoning with the teaching of entropy interact in meaningful ways across each of the five knowledge types, with those connections shaping how Stella describes their instructional decisions when teaching entropy. This aligns with findings from previous work indicating that teaching experience can influence how PCK develops (Friedrichsen *et al.*, 2009; Oztay *et al.*, 2023). In contrast, Adi focused their responses on connections between content knowledge and curricular/pedagogical knowledge. However, Adi did not explicitly integrate ideas related to curricular and pedagogical knowledge. Regarding connections between content and curricular knowledge, Adi described topics as *“this is something they need to know”*, with an emphasis on content understanding required in subsequent courses within the undergraduate curriculum. Adi’s content knowledge and pedagogical knowledge were used in an integrated manner when describing decisions related to presenting material, with an aim to use specific teaching strategies to represent the phases at the particulate level so students better understand foundational chemical principles related to entropy:

“In my lecture notes, I have um little animations, I borrowed from, I think borrowed from the internet. Um. It’s like if you look through a window, then you have the solid, they’re highly aligned. And then they move a little bit teeny tiny bit about where they are, they move around on the PowerPoint slides.”

Like Stella, Kai elicited many connections between knowledge types, particularly between assessment knowledge and content knowledge, as well as between pedagogical knowledge and content knowledge. Many of the connections between assessment and content knowledge relied on Kai’s ideas for additional assessment prompts for students, subsequently describing their own content knowledge related to these developed assessment items. For example, Kai described how they:

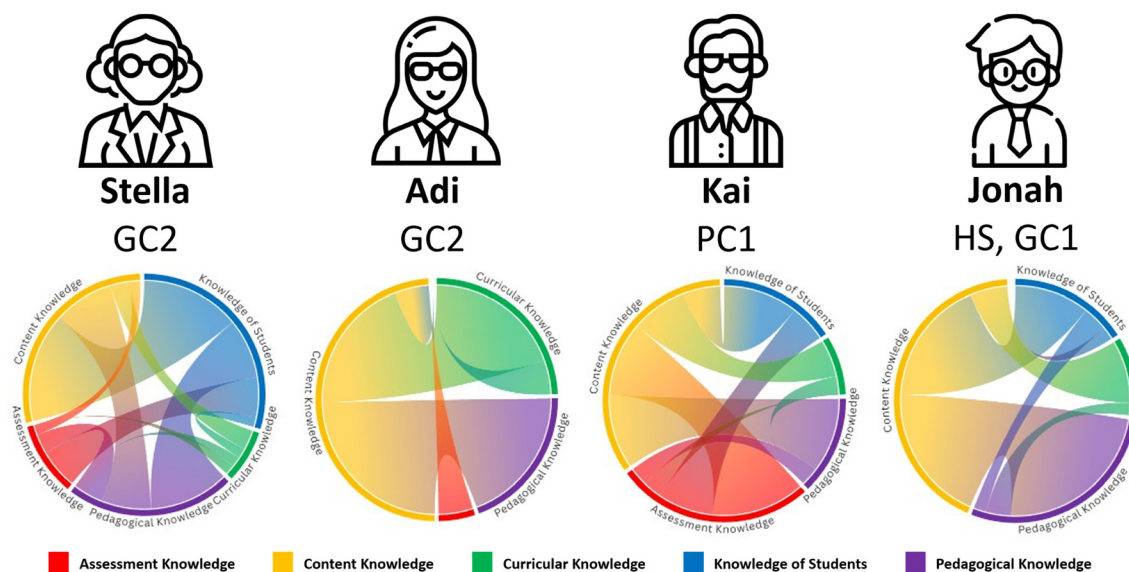


Fig. 5 Chord diagrams showing how the five types of knowledge were integrated by each participant. Within the chord diagrams, thicker arcs between knowledge types indicate more connections used throughout their responses in the interview.



“Raise the question, you know, if you take say um helium, deuterium mixing together, what is the change of entropy? . . . Now, if you say change, say the para hydrogen to uh to the anti para hydrogen, uh mix them together, how does that change the entropy? So eventually it comes down to the realization that information is also a form of entropy reduction.”

As another example, Kai responded specifically to Content Question 3 by (1) answering the original question and (2) modifying the question and describing their own content knowledge required to solve the new problem through understanding the relationship between temperature and entropy:

“Let’s say we don’t have a phase transition. Let’s just take a gas, heat it up, and there, we can very rigorously write down the equation. How does entropy change with temperature at constant pressure? And that can be related to the heat capacity, and I just tell the students, well, heat capacity has to be a positive number. We’ve never had a substance where you give it heat, and it drops in temperature. So, that tells us mathematically that entropy increases with temperature. And then I say, well, as it is found out, this is true, not only within a single phase, but also across phase boundaries when you go from liquid to solid, from solid to gas, or going from different phases of solid, even. Your entropy always increases.”

Like Adi, Kai elicited connections between content knowledge and pedagogical knowledge by describing the use of whiteboards and mathematical representations, then subsequently describing the content knowledge related to the mathematical equations. While pedagogically Kai described the use of a qualitative for instruction on mathematical representations of entropy, they also described emphasizing *“to students [to] always back your reasoning by rigorous math.”* Additionally, Kai was the only participant to elicit ideas integrating knowledge of students and assessment knowledge. Kai described how students would respond to the additional assessment prompts they presented while discussing how they would teach Content Question 4:

“Most of the students will correctly predict, well the gases still gonna mix together, and I asked them to think about, well, is this a spontaneous process, reversible process, or a irreversible or a um impossible process. Mostly, they can correctly derive that, yeah, this is a spontaneous process.”

Jonah prevalently connected pedagogical knowledge, knowledge of students, and content knowledge. Jonah described their instruction on entropy *via* two main rules: the entropy of phases and the difference in the number of moles in the products/reactants. While Jonah leveraged assessment knowledge, they did not readily connect this to other knowledge types: *“[For Content Question 2, I would] break this into a 3rd question, and you say, Well, I’ve got a liquid, and a gas, goes into a gas. And you count the number of gas molecules with the liquid, and you have more, so that those 2 rules disagree, and you have to think about. Well, which rule takes priority?”*

Conclusions

Within topic-specific personal PCK (TS-pPCK), three of the four instructors most often elicited information related to content knowledge within the five types of knowledge (or professional knowledge bases) when considering their reasoning with the

context of teaching entropy. While these three instructors less frequently described the remaining knowledge bases, all five bases were present within the interview data. For one instructor, Stella, a balanced distribution of content knowledge, knowledge of students, and pedagogical knowledge was demonstrated in response to the entropy content questions. Stella also prevalently integrated the knowledge bases when they were leveraged. As the most experienced instructor within this study, this is potentially due to Stella’s level of teaching experience in connection with experience in using evidence-based strategies and instructional approaches for the topic of entropy. In contrast, Jonah, despite having the least amount of teaching experience, exhibited a relatively high amount of pedagogical knowledge and knowledge of students compared to Kai and Adi. However, Jonah made fewer connections between knowledge types in comparison to Kai. This suggests that teaching experience alone does not directly correlate with the development of instructors’ personal PCK, shown in previous literature to be slightly correlated but continuously changing (Friedrichsen *et al.*, 2009; Oztay *et al.*, 2023). However, future work should be conducted on the relationship between teaching experience and ability to elicit connections between the five knowledge types.

For all four instructors, assessment knowledge and curricular knowledge were the least discussed knowledge types, consistent with other studies conducted at the undergraduate physical chemistry level of instruction (Padilla and Van Driel, 2011). Additionally, integrating assessment knowledge with the other knowledge types was less prevalent. As our interview protocol was structured in a way to collect data related to instructional choices in response to topic-specific questions on entropy, it was expected that a large portion of the pPCK discussed was content knowledge. Course level did not appear to significantly influence how the knowledge types were distributed or integrated in instructors’ responses. However, general chemistry instructors discussed curricular knowledge more frequently than the physical chemistry instructor (Kai), emphasizing the importance of preparing students for future topics. This aligns with the role of general chemistry courses in providing foundational knowledge necessary for students to progress in their undergraduate degree. Although previous literature has also emphasized the need to connect particulate-level representations to mathematical representations of thermodynamics (Bennett and Sözbilir, 2007; Bain *et al.*, 2014), our findings indicate instructors’ emphasis of either particulate or mathematical representations, with fewer explicit connections between the two.

In general, content knowledge, knowledge of students, and pedagogical knowledge were interconnected in guiding instructional decisions. In our work, evidence suggests that instructors who placed a strong emphasis on their knowledge of students were more likely to incorporate pedagogical knowledge alongside content knowledge when making instructional decisions. This supports the model proposed by Veal and MaKinster (1999), identifying knowledge of students as a critical component in the development of PCK. Our study additionally provides evidence that each knowledge type within pPCK plays a crucial role in teaching entropy due to its abstract nature, which necessitates different instructional approaches, supported in previous literature (Mack and Towns, 2016).



Implications for research and practice

As chemistry instructors within the collective PCK, it is important to continuously develop our dynamic personal PCK towards the shaping of our enacted PCK. Beyond knowledge of content, it is critical to know our students, anticipate knowledge required for their future educational/career trajectories, and apply evidence-based pedagogical and assessment practices towards measurement of student understanding of the content. Particularly, knowledge of students was shown to be vital in integrating multiple knowledge types within instructors' topic-specific personal PCK in our work. As Stella eloquently stated: "My instructional choices are based on supporting the students in developing their own ways of understanding and reasoning. And it doesn't have to be the way I think of it."

As a mechanism to better integrate the five knowledge bases, we encourage instructors to continue to consider the following questions when reflecting on how their instruction informs each of the five knowledge types, inspired by previous work by Rodriguez and Towns (Rodriguez and Towns, 2019):

(1) Content knowledge: what content is needed to support students in facilitating connections between entropy-related concepts? What information about entropy should be explicitly described? Should specific information be excluded from instruction on entropy within this context, and why?

(2) Pedagogical knowledge: what medium should be used to facilitate the learning of entropy? What strategies and representations can be used to enhance student learning of entropy?

(3) Knowledge of students: what are specific strengths/challenges students may hold when considering the topic of entropy? What prior knowledge of entropy do students bring to the learning context?

(4) Assessment knowledge: what should (and should not) be assessed for the measurement of student understanding of entropy? How can assessment items be modified to better measure student understanding of entropy?

(5) Curricular knowledge: what prior knowledge will students need when they consider entropy in future learning contexts? What specific entropy concepts are relevant for future learning and career trajectories?

Based on our findings, we encourage upper-level undergraduate chemistry instructors to deeply consider students' knowledge requirements as they continue their academic and professional careers (curricular knowledge), as this was not prevalently evidenced in our work. To enhance curricular knowledge in instructors' personal PCK (which ultimately can impact enacted PCK), our work provides evidence that instructors should continue to reflect on the following question: How might instruction on entropy within upper-level undergraduate physical chemistry impact students' future learning beyond this course and/or degree pathway?

For chemistry education researchers, further investigation of instructional decision-making when teaching specific topics in the context of undergraduate physical chemistry is warranted. As Jonah described: "To anyone who's approaching chemistry for the first time, high school or college... Thermo is probably the hardest thing... You can go an entire undergrad

degree without understanding what entropy and enthalpy are." Research should explicitly target the development of context-specific resources to help educators integrate the five knowledge bases when teaching the topic of entropy through enacted PCK, with emphasis placed on integration of assessment and curricular knowledge with content, student, and pedagogical knowledge. Future research on the development of physical chemistry instructors' PCK should also extend beyond individual perspectives to include group discussions (to provide information related to instructors' collective PCK) and classroom observations (to provide insight into enacted PCK).

Limitations

This research is a part of a larger qualitative investigation of the cognitive resources activated and used by instructors and graduate students when teaching and tutoring the topic of entropy. As this study was focused on instructional decisions related to content questions, content knowledge was prevalently elicited by participants, which could have led to a lower emphasis on responses related to the remaining four knowledge bases. Initial development of the interview protocol was focused on eliciting a wide variety of cognitive resources, without explicit framing of pedagogical content knowledge initially guiding the design of the study. Thus, specific questions relevant to each of the five knowledge bases were not included in the interview guide. This means that the four instructors in the present case study elicited information related to the five knowledge bases in an unprompted manner. Finally, this work collected data on instructors' personal PCK, without exploring enacted PCK or collective PCK. Although distinct, these three realms are considered to be integrated along a continuum of PCK within the RCM. Thus, the decision to focus on instructors' personal PCK is inherently limited in scope of connections to the additional realms.

Author contributions

In an effort to normalize the practice of transparency in the preparation of this work, the specific contributions of all authors are described as follows: study design – JE, MBA; data collection – JE; development of data analysis plan – JE, MBA; data analysis – JE, SP; interpretation of results – JE, SP, MBA; writing – JE, SP, MBA; editing – JE, MBA; funding and resources – MBA.

Conflicts of interest

There are no conflicts of interest to declare.

Data availability

Data within the current manuscript has been collected from human participants. Thus, under IRB regulations at the institution of study for IRB-23-110, data are not available due to confidentiality reasons to maintain anonymity.



Appendix 1

Types of knowledge (professional knowledge bases) have been included in the codebook below, as well as descriptions of themes and corresponding representative quotes from participants.

Types of knowledge	Themes and descriptions	Representative quotes
Content knowledge	Critical concepts and facilitating connections: Explicitly stating a critical concept or connecting material with other concepts	“Let’s look at this phase diagram. This basically shows that some liquid goes to gas as temperature increase, and... the third law tells us, in this process entropy always increases. Raising temperature always gives higher entropy, so we can see that [the gas] phase would have a higher entropy than [the liquid] phase.” (Kai)
	Depth of presentation of topic: explicitly explaining decision to include or exclude specific content material	“I don’t usually use the Boltzmann relationships. So that’s entropy is the Boltzmann constant times the natural log of the number of microstates. I don’t usually use that for my class because it’s a freshman chemistry class. And it just feels like another equation to memorize.” (Stella)
Pedagogical knowledge	Mode of presentation: General discussion about how they teach and/or present the topic and work through the problems in instructional settings	“I would say now you have three gases or three substances that are gases. Now we are going to consider- or we are going to add up the coefficients of the reactants on each side. So, on the left, there are one and three, four in total. On the right, there are just two.” (Adi)
	Theoretical assumptions from previous teaching/research: explicitly stating that their instructional decisions are related to previous experiences in teaching and/or research	“My instructional choice would be to break it down into the 2 ways that we’ve learned so far solid liquid gas, and then gas number of moles, and we see they both agree to each other.” (Jonah)
Knowledge of students	Teaching preferences: choosing to frame the content based on type of classroom or pedagogical approach (<i>i.e.</i> , flipped <i>versus</i> traditional formats); additionally, using scaffolding during explanation that are distinct from assessment scaffolding	“So, with my class, we have these mini lecture videos, where I sort of give them that information through [the LMS]. And then when they come to class, they’re working in their teams on questions or activities that I’ve created to align with our learning outcomes that were covered in the videos.” (Stella)
	Instructional medium: choosing to use specific medium of instruction (<i>i.e.</i> , PowerPoint, simulations, videos, problem solving, images)	“In my lecture notes, I have little animations... I borrowed from the internet. It’s like if you look through a window, then you have the solid, they’re highly aligned. And then they move a little bit teeny tiny bit about where they are, they move around on the PowerPoint slides.” (Adi)
Assessment knowledge	Prior knowledge of students: explicitly stating what students know and how this shapes instructional decisions	“So most of them would kind of go back to gas laws and be like, ‘oh’, and again, our definition of the dispersal of matter, and be like, ‘oh, it spreads out more.’” (Stella)
	Challenges for students: recognizing where students may struggle and/or how to facilitate student understanding of difficult content	“You know, thermodynamics in general, to anyone who’s approaching chemistry for the first time, high school or college, that’s just a very tough part of chemistry. And I mean, thermo is probably the hardest thing, and... from my own perspective, you can go an entire undergrad degree without understanding what entropy and enthalpy are. And Gibbs free energy. These are things that you could just have an idea of in your head, and you go a whole undergrad degree without understanding it.” (Jonah)
Curricular knowledge	Considerations of student responses: explicitly describing how a student would respond to a specific prompt/task	“Disorder they think chaos... And they think the end of that movie, Event Horizon, where people start eating each other or something. I don’t know... They think it means chaos.” (Stella)
	Addition of assessment prompts for students: adding context to the content questions within the interview guide, or adding questions to the interview guide, in order to promote student understanding	“Where you break this into a 3rd question, and you say, well, I’ve got a liquid, and a gas, goes into a gas and you count the number of gas molecules with the liquid, and you have more, so that those 2 rules disagree, and you have to think about. Well, which rule takes priority?” (Jonah)
Curricular knowledge	Assessment scaffolding: explaining how they would scaffold, or that they would scaffold, items/questions within assessments	“So, I would draw the picture for them, because the phrasing, two identical gases mixed, is a little confusing. So, if I draw a picture, and I say you have, you have the same gas in two different flasks that are... separated by a tube with like a stopcock, and then you open it. So how would that change?” (Stella)
	Assessment item modification: describing how they would ask an assessment question/item in a different way	“I would draw a picture for them, and I probably wouldn’t even specify positive, negative or zero. I would probably just say, is there a change in entropy? Number one.” (Stella)
Curricular knowledge	Modification of curriculum: describing initial format of class and how they incorporated changes to the curriculum; includes ideas related to explicitly stating components they do not teach within the curriculum	“I formatted my thermodynamics lessons from the id- like the idea that these things that we’re learning, enthalpy, entropy, Gibbs, these are slightly abstract topics.” (Jonah)
	Considerations of Longitudinal Curriculum: explicitly stating that certain components of the topic are needed for future understanding of topics	“[This is] something I require them to know.” (Adi)
	Considerations of knowledge from previous courses: explicitly stating what students should know about a topic from previous discussions or courses	“Your entropy always increases. As a matter of fact, this is determined by accumulation of prior knowledge, such that the entropy always increases with temperature, and that is part of the third law.” (Kai)



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References

- Abell T. N. and Bretz S. L., (2018), Dissolving salts in water: Students' particulate explanations of temperature changes, *J. Chem. Educ.*, **95**(4), 504–511, DOI: [10.1021/acs.jchemed.7b00845](https://doi.org/10.1021/acs.jchemed.7b00845).
- Abell T. N. and Bretz S. L., (2019a), Development of the Enthalpy and Entropy in Dissolution and Precipitation Inventory, *J. Chem. Educ.*, **96**(9), 1804–1812, DOI: [10.1021/acs.jchemed.9b00186](https://doi.org/10.1021/acs.jchemed.9b00186).
- Abell T. N. and Bretz S. L., (2019b), Macroscopic observations of dissolving, insolubility, and precipitation: General chemistry and physical chemistry students' ideas about entropy changes and spontaneity, *J. Chem. Educ.*, **96**(3), 469–478, DOI: [10.1021/acs.jchemed.8b01007](https://doi.org/10.1021/acs.jchemed.8b01007).
- Akin F. N. and Uzuntiryaki-Kondakci E., (2018), The nature of the interplay among components of pedagogical content knowledge in reaction rate and chemical equilibrium topics of novice and experienced chemistry teachers, *Chem. Educ. Res. Pract.*, **19**(1), 80–105, DOI: [10.1039/C7RP00165G](https://doi.org/10.1039/C7RP00165G).
- Andrews, T. C., Speer, N. M. and Schultz, G. V., (2022), Building bridges: a review and synthesis of research on teaching knowledge for undergraduate instruction in science, engineering, and mathematics, *Int. J. STEM Educ.*, **9**(1), 66, DOI: [10.1186/s40594-022-00380-w](https://doi.org/10.1186/s40594-022-00380-w).
- Aydin S., Demirdöğen B., Muslu N. and Hanuscin D. L., (2013), Professional journals as a source of PCK for teaching nature of science: an examination of articles published in the science teacher (TST) (an NSTA Journal), 1995–2010, *J. Sci. Teacher Educ.*, **24**(6), 977–997, DOI: [10.1007/s10972-0139345-0](https://doi.org/10.1007/s10972-0139345-0).
- Aydin S., Friedrichsen P. M., Boz Y. and Hanuscin D. L., (2014), Examination of the topic-specific nature of pedagogical content knowledge in teaching electrochemical cells and nuclear reactions, *Chem. Educ. Res. Pract.*, **15**(4), 658–674, DOI: [10.1039/C4RP00105B](https://doi.org/10.1039/C4RP00105B).
- Bain K. and Towns M. H., (2016), A review of research on the teaching and learning of chemical kinetics, *Chem. Educ. Res. Pract.*, **17**(2), 246–262, DOI: [10.1039/C5RP00176E](https://doi.org/10.1039/C5RP00176E).
- Bain K., Moon A., Mack M. R. and Towns M. H., (2014), A review of research on the teaching and learning of thermodynamics at the university level, *Chem. Educ. Res. Pract.*, **15**(3), 320–335, DOI: [10.1039/C4RP00011K](https://doi.org/10.1039/C4RP00011K).
- Bartell L. S., (2001), Apparent Paradoxes and Instructive Puzzles in Physical Chemistry, *J. Chem. Educ.*, **78**(8), 1067, DOI: [10.1021/ed078p1067](https://doi.org/10.1021/ed078p1067).
- Bayeck R. Y., (2022), Positionality: The Interplay of Space, Context and Identity, *Int. J. Qual. Methods*, **21**, 16094069221114745, DOI: [10.1177/16094069221114745](https://doi.org/10.1177/16094069221114745).
- Becker N., Stanford C., Towns M. and Cole R., (2015), Translating across macroscopic, submicroscopic, and symbolic levels: the role of instructor facilitation in an inquiry-oriented physical chemistry class, *Chem. Educ. Res. Pract.*, **16**(4), 769–785, DOI: [10.1039/C5RP00064E](https://doi.org/10.1039/C5RP00064E).
- Bektas O., (2015), Pre-Service Science Teachers' Pedagogical Content Knowledge in The Physics, Chemistry, and Biology Topics, *Eur. J. Phys. Educ.*, **6**(2), DOI: [10.20308/ejpe.05030](https://doi.org/10.20308/ejpe.05030).
- Belt S. T., Leisvik M. J., Hyde A. J. and Overton T. L., (2005), Using a context-based approach to undergraduate chemistry teaching – a case study for introductory physical chemistry, *Chem. Educ. Res. Pract.*, **6**(3), 166–179, DOI: [10.1039/B5RP00007G](https://doi.org/10.1039/B5RP00007G).
- Bennett J. M. and Sözbilir M., (2007), A study of Turkish chemistry undergraduates' understanding of entropy, *J. Chem. Educ.*, **84**(7), 1204, DOI: [10.1021/ed084p1204](https://doi.org/10.1021/ed084p1204).
- Boothe J. R., Zotos E. K. and Shultz G. V., (2023), Analysis of post-secondary instructors' pedagogical content knowledge of organic acid–base chemistry using content representations, *Chem. Educ. Res. Pract.*, **24**(2), 577–598, DOI: [10.1039/D2RP00253A](https://doi.org/10.1039/D2RP00253A).
- Braun V. and Clarke V., (2021), One size fits all? What counts as quality practice in (reflexive) thematic analysis? *Qual. Res. Psychol.*, **18**(3), 328–352, DOI: [10.1080/14780887.2020.1769238](https://doi.org/10.1080/14780887.2020.1769238).
- Braun V. and Clarke V., (2023), Toward good practice in thematic analysis: Avoiding common problems and be(com)ing a *knowing* researcher, *Int. J. Transgender Health*, **24**(1), 1–6, DOI: [10.1080/26895269.2022.2129597](https://doi.org/10.1080/26895269.2022.2129597).
- Carlson J. and Daehler K. R., (2019), The Refined Consensus Model of Pedagogical Content Knowledge in Science Education, in *Repositioning Pedagogical Content Knowledge in Teachers' Knowledge for Teaching Science*, Hume A., Cooper R. and Borowski A. ed., Springer Nature Singapore, pp. 77–94.
- Cetin-Dindar A., Boz Y., Yildiran Sonmez D. and Demirci Celep N., (2018), Development of pre-service chemistry teachers' technological pedagogical content knowledge, *Chem. Educ. Res. Pract.*, **19**(1), 167–183, DOI: [10.1039/C7RP00175D](https://doi.org/10.1039/C7RP00175D).
- Charles De Berg K., (2022), Student thinking profiles within a small group addressing problems in thermodynamics as part of a physical chemistry unit: reflections for students and instructors, *Chem. Educ. Res. Pract.*, **23**(3), 628–643, DOI: [10.1039/D1RP00336D](https://doi.org/10.1039/D1RP00336D).
- Committee on Professional Training, (2015), *Committee on Professional Training Report on PhD Recipient Survey*, American Chemical Society.
- Connor M. C. and Shultz G. V., (2018), Teaching assistants' topic-specific pedagogical content knowledge in ¹H NMR spectroscopy, *Chem. Educ. Res. Pract.*, **19**(3), 653–669, DOI: [10.1039/C7RP00204A](https://doi.org/10.1039/C7RP00204A).
- Creswell J. and Poth C., (2018), *Qualitative Inquiry and Research Design: Choosing Among Five Approaches*, 4th edn, SAGE Publications.
- Deng F., Chai C. S., So H.-J., Qian Y. and Chen L., (2017), Examining the validity of the technological pedagogical content knowledge (TPACK) framework for preservice



- chemistry teachers, *Australasian J. Educ. Technol.*, **33**(3), DOI: [10.14742/ajet.3508](https://doi.org/10.14742/ajet.3508).
- Donkor B., Collini M. A. and Harshman J., (2024), The Goal of Doctoral Education in Chemistry: Faculty Perspectives, *J. Chem. Educ.*, **101**(8), 3050–3061, DOI: [10.1021/acs.jchemed.4c00087](https://doi.org/10.1021/acs.jchemed.4c00087).
- England, J., Proo, S., Weber, R. and Atkinson, M. B., (2026), Investigating the Productivity and Integration of Cognitive Resource Use when Teaching Entropy, *Chem. Educ. Res. Pract.*, in review.
- Fantone R. C., Geragosian E., Connor M. and Shultz G. V., (2024), Exploring post-secondary chemistry instructors' knowledge for teaching ^1H NMR spectroscopy, *Chem. Educ. Res. Pract.*, DOI: [10.1039/D4RP00003J](https://doi.org/10.1039/D4RP00003J).
- Footo M. Q. and Gau Bartell T., (2011), Pathways to equity in mathematics education: how life experiences impact researcher positionality, *Educ. Stud. Math.*, **78**(1), 45–68, DOI: [10.1007/s10649-011-9309-2](https://doi.org/10.1007/s10649-011-9309-2).
- Fox L. J. and Roehrig G. H., (2015), Nationwide Survey of the Undergraduate Physical Chemistry Course, *J. Chem. Educ.*, **92**(9), 1456–1465, DOI: [10.1021/acs.jchemed.5b00070](https://doi.org/10.1021/acs.jchemed.5b00070).
- Friedrichsen P. J., Abell S. K., Pareja E. M., Brown P. L., Lankford D. M. and Volkmann M. J., (2009), Does teaching experience matter? Examining biology teachers' prior knowledge for teaching in an alternative certification program, *J. Res. Sci. Teach.*, **46**(4), 357–383, DOI: [10.1002/tea.20283](https://doi.org/10.1002/tea.20283).
- Gillborn D., Warmington P. and Demack S., (2018), QuantCrit: education, policy, 'Big Data' and principles for a critical race theory of statistics, *Race Ethn. Educ.*, **21**(2), 158–179, DOI: [10.1080/13613324.2017.1377417](https://doi.org/10.1080/13613324.2017.1377417).
- Hahn K. E. and Polik W. F., (2004), Factors influencing success in physical chemistry, *J. Chem. Educ.*, **81**(4), 567, DOI: [10.1021/ed081p567](https://doi.org/10.1021/ed081p567).
- Hale L. V. A., Lutter J. C. and Shultz G. V., (2016), The development of a tool for measuring graduate students' topic specific pedagogical content knowledge of thin layer chromatography, *Chem. Educ. Res. Pract.*, **17**(4), 700–710, DOI: [10.1039/C5RP00190K](https://doi.org/10.1039/C5RP00190K).
- Johnstone A. H., (2010), You Can't Get There from Here, *J. Chem. Educ.*, **87**(1), 22–29, DOI: [10.1021/ed800026d](https://doi.org/10.1021/ed800026d).
- Lincoln Y. S. and Guba E. G., (1985), *Naturalistic Inquiry*, SAGE.
- Mack M. R. and Towns M. H., (2016), Faculty beliefs about the purposes for teaching undergraduate physical chemistry courses, *Chem. Educ. Res. Pract.*, **17**(1), 80–99, DOI: [10.1039/C5RP00148J](https://doi.org/10.1039/C5RP00148J).
- Natalis V. and Leyh B., (2024), Improving the teaching of entropy and the second law of thermodynamics: a systematic review with meta-analysis, *Chem. Educ. Res. Pract.*, DOI: [10.1039/D4RP00158C](https://doi.org/10.1039/D4RP00158C).
- Otter.ai, (2025), <https://otter.ai/> (accessed April 27, 2025).
- Oztay E. S., Ekiz-Kiran B. and Boz Y., (2023), Revealing the development of interaction among components of pedagogical content knowledge in teaching chemical equilibrium, *Chem. Educ. Res. Pract.*, **24**(2), 624–636, DOI: [10.1039/D2RP00159D](https://doi.org/10.1039/D2RP00159D).
- Padilla K. and Van Driel J., (2011), The relationships between PCK components: the case of quantum chemistry professors, *Chem Educ Res Pract.*, **12**(3), 367–378, DOI: [10.1039/C1RP90043A](https://doi.org/10.1039/C1RP90043A).
- Reiser B. J., (2004), Scaffolding Complex Learning: The Mechanisms of Structuring and Problematizing Student Work, *J. Learn. Sci.*, **13**(3), 273–304, DOI: [10.1207/s15327809jls1303_2](https://doi.org/10.1207/s15327809jls1303_2).
- Rodriguez A. J. and Navarro-Camacho M., (2023), Claiming Your Own Identity and Positionality: The First Steps toward Establishing Equity and Social Justice in Science Education, *Educ. Sci.*, **13**(7), 652, DOI: [10.3390/educsci13070652](https://doi.org/10.3390/educsci13070652).
- Rodriguez J.-M. G. and Towns M. H., (2019), Alternative Use for the Refined Consensus Model of Pedagogical Content Knowledge: Suggestions for Contextualizing Chemistry Education Research, *J. Chem. Educ.*, **96**(9), 1797–1803, DOI: [10.1021/acs.jchemed.9b00415](https://doi.org/10.1021/acs.jchemed.9b00415).
- Rosesshine B. and Meister C., (1992), The Use of Scaffolds for Teaching Higher-Level Cognitive Strategies, *Educ. Leadersh.*, **49**(7), 26–33.
- Sandelowski M., (1998), The call to experts in qualitative research, *Res. Nurs. Health*, **21**(5), 467–471, DOI: [10.1002/\(SICI\)1098-240X\(199810\)21:5<467::AID-NUR9>3.0.CO;2-L](https://doi.org/10.1002/(SICI)1098-240X(199810)21:5<467::AID-NUR9>3.0.CO;2-L).
- Secules S., McCall C., Mejia J. A., Beebe C., Masters A. S., Sánchez-Peña L. M. and Syvantek M., (2021), Positionality practices and dimensions of impact on equity research: A collaborative inquiry and call to the community, *J. Eng. Educ.*, **110**(1), 19–43, DOI: [10.1002/jeec.20377](https://doi.org/10.1002/jeec.20377).
- Shulman L. S., (1986), Those Who Understand: Knowledge Growth in Teaching. *Educ. Res.*, **15**(2), 4, DOI: [10.2307/1175860](https://doi.org/10.2307/1175860).
- Sözbilir M., (2004), What makes physical chemistry difficult? perceptions of Turkish chemistry undergraduates and lecturers, *J. Chem. Educ.*, **81**(4), 573, DOI: [10.1021/ed081p573](https://doi.org/10.1021/ed081p573).
- Taber K. S., (2013), Revisiting the chemistry triplet: drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education, *Chem Educ Res Pract.*, **14**(2), 156–168, DOI: [10.1039/C3RP00012E](https://doi.org/10.1039/C3RP00012E).
- Tsaparlis G. and Finlayson O. E., (2014), Physical chemistry education: its multiple facets and aspects, *Chem Educ Res Pract.*, **15**(3), 257–265, DOI: [10.1039/C4RP90006E](https://doi.org/10.1039/C4RP90006E).
- Van Driel J. H., Jong O. D. and Verloop N., (2002), The development of preservice chemistry teachers' pedagogical content knowledge, *Sci. Educ.*, **86**(4), 572–590, DOI: [10.1002/sce.10010](https://doi.org/10.1002/sce.10010).
- Veal W. and Makinster J., (1999), Pedagogical Content Knowledge Taxonomies, *Electron. J. Sci. Educ.*, **3**, 1–17.
- Wood D., Bruner J. S. and Ross G., (1976), The Role of Tutoring in Problem Solving, *J. Child Psychol. Psychiatry*, **17**(2), 89–100, DOI: [10.1111/j.1469-7610.1976.tb00381.x](https://doi.org/10.1111/j.1469-7610.1976.tb00381.x).

