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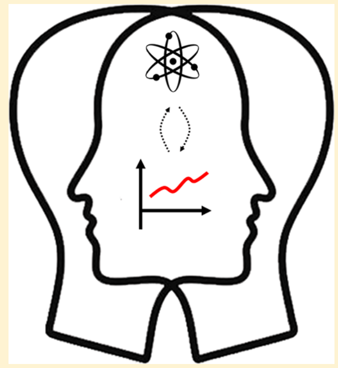
Interpreting Data: The Hybrid Mind

Kimberly Heisterkamp and Vicente Talanquer*

Department of Chemistry and Biochemistry, University of Arizona, Tucson, Arizona 85721, United States

ABSTRACT: The central goal of this study was to characterize major patterns of reasoning exhibited by college chemistry students when analyzing and interpreting chemical data. Using a case study approach, we investigated how a representative student used chemical models to explain patterns in the data based on structure−property relationships. Our results elicited various reasoning challenges: undifferentiation of concepts, overreliance on surface explicit features, oversensitivity to contextual features, unconstrained application of ideas, hybridization of chemical and intuitive knowledge, and overreliance on nonmechanistic explanatory schemas. Our findings also revealed several affordances in student thinking: cognitive flexibility, responsiveness to probing and scaffolding, rich knowledge base, and pragmatism in the search for explanations. Our investigation provides insights into curriculum design and teaching and assessment strategies that can better leverage students' cognitive resources to scaffold learning.



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FEATURE: Chemical Education Research

INTRODUCTION

Recent reform efforts in science[1−4] and chemistry[5−8] education have emphasized the need for developing curricula and implementing teaching methods that help students learn and integrate discipline content knowledge and science and engineering practices in relevant contexts. Students are expected to actively engage in the following:[1,2] asking questions, developing and using models, planning and carrying out investigations, analyzing and interpreting data, and building arguments from evidence. Understanding the challenges that students face when confronting such types of tasks is critical for supporting learning in reformed classrooms and laboratories.

Aligned with the goals of current educational reform efforts, in this contribution, we summarize the results of a case study approach to explore college general chemistry students' reasoning when engaged in the analysis and interpretation of chemical data. We present an in-depth analysis of the reasoning patterns of a student who completed two semistructured interviews involving the analysis and interpretation of different sets of experimental results. We paid particular attention to how this student used chemical models to explain patterns in the data based on structure−property relationships. We recognize the limitations of our case study approach concerning the generalizability of findings. However, our goal is to highlight major challenges and affordances in the reasoning of a typical student who actively engaged in the assigned tasks and very openly verbalized ideas. The analysis of this case provides valuable educational insights into curriculum design and teaching and assessment strategies that can better leverage students' cognitive resources to scaffold learning.

INTERPRETING AND EXPLAINING PHENOMENA

A student's ability to analyze, interpret, and explain natural phenomena has been investigated in the different science areas. A significant fraction of this type of research has sought to characterize the nature of the explanations built by students at different developmental or educational levels.[9−16] These investigations reveal that many students struggle to build causal mechanistic explanations of natural phenomena,[12−14] generating instead, descriptive or relational accounts in which actions or events are justified using teleological arguments (i.e., based on the needs and wants of the agents involved).[15,16] When students engage in mechanistic reasoning, it is common for them to build sequential causal stories in which a single active agent acts on one or more passive components to achieve a particular goal.[12,13] Research findings suggest that students' explanations of complex phenomena are often based on implicit schemas that assume inappropriate causal mechanisms.[17,18]

Research in chemistry education has elicited several of the challenges that students face in building explanations about the properties of chemical substances and processes using chemical models.[19−21] College students, for example, often rely on heuristic reasoning when comparing chemical substances and explaining or inferring their relative properties.[19] Instead of applying model-based reasoning to infer the properties of chemical compounds, students tend to engage in some sort of "mental rolodexing", searching for known cases in their minds that match surface characteristics of the target problem.[20] In general, students express chemical knowledge about structure−property relationships that comes across as fragile

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and fragmented, and many individuals struggle to apply it in a meaningful manner.[21]

THEORETICAL FRAMEWORK

Research on students' ability to productively engage in sense-making activities such as interpreting data is closely related to investigations on the structure and development of people's knowledge in different domains.[22] This type of work is often framed within one of three major theoretical perspectives frequently referred to as the "framework theories" approach,[23] the "knowledge-in-pieces" standpoint,[24] and the "ontological categories" stance.[25] Within the framework theories perspective, student reasoning is assumed to be guided by a network of interrelated knowledge and beliefs (framework theory) about the natural world. From the knowledge-in-pieces viewpoint, intuitive knowledge about the world is more fragmented, including a diverse collection of phenomenological ideas (phenomenological primitives or p-prims). In the ontological categories approach, human reasoning is seen as influenced by the categories in which people mentally place the different components of the systems under analysis.

Studies in science education often portray the above perspectives as competing theories.[26,27] However, they can be seen as complementary viewpoints when students' conceptions are conceived as emergent structures that dynamically arise from the interactions of diverse types of cognitive resources (e.g., conceptual, epistemological, ontological, procedural, affective).[28−31] Some of these emergent structures can be robust enough to resemble coherent schemas in a domain; other structures may be more labile, generated on the spot when an individual faces a particular task in a specific context. Conceptualizing student knowledge as a dynamic complex system allows us to explain both the existence of naïve frameworks in some areas and the fragmented nature of student knowledge in others.[30]

In our own research, we have sought to better characterize the nature of basic cognitive elements that support student thinking in chemistry.[32,33] In particular, we have paid attention to two types of cognitive resources:

(1) Implicit assumptions about the properties and behavior of the entities and phenomena in the domain.
(2) Tacit heuristics to make judgments and decisions under conditions of uncertainty.

We have claimed[33] that these implicit cognitive elements[34] not only guide, but also constrain the dynamic mental constructs and reasoning strategies that enable novice students' sense making, decision making, and inferential reasoning. Different cognitive elements are likely to be triggered and interact in particular ways in an individual's mind depending on prior knowledge, past experiences, motivation, and the specific nature of a task. The constructs and strategies that emerge from these interactions allow students to make inferences and decisions that are satisficing (provide what are perceived as satisfying and sufficing answers)[35] but may result in systematic biases and errors.[36] The present study was guided by this theoretical perspective and was designed to further explore the constraints and affordances of student reasoning in chemical contexts.

RESEARCH GOALS AND METHODOLOGY

This investigation is part of a larger research project focused on the characterization of patterns of reasoning exhibited by college chemistry students when analyzing and interpreting chemical data. In particular, we seek to understand how students use chemical models to explain patterns in the data based on structure−property relationships. In this contribution, we report on the results of a case study involving a student enrolled in the second semester of a one-year general chemistry course for science and engineering majors at our institution.

Kai (code name), our study participant, could be characterized as an average science major in the freshman year at our university. This student was a prehealth major who had earned a grade of 78.3% in the first semester of the general chemistry course (the average final grade in this class was 71.0 ± 12.9). Prehealth majors account for over one-third of the students taking general chemistry courses at our institution. At the time of the study, Kai was a few weeks into the second semester of general chemistry where this student got a final grade of 78.5% (the average final grade in this class was 71.8 ± 13.2). In general, Kai received average grades in the different midterm exams, completed most homework assignments, and performed satisfactorily in the laboratory associated with the course. We have purposely chosen a gender-neutral name to refer to this study participant and avoided gender-specific pronouns in the description of findings to emphasize the typicality of the subject.

Kai volunteered and consented to participate in our study, which involved two different semistructured interviews that lasted close to 30 min each. Kai was selected for this case study for various reasons. First, Kai's performance in the chemistry courses was representative of that of average students who complete the course satisfactorily, neither excelling nor constantly struggling. Second, this student actively engaged in all the interview tasks, openly expressing ideas and making underlying thinking quite visible. More importantly, this study participant expressed diverse patterns of reasoning that made explicit many of the challenges that motivated novice chemistry students face in applying chemical thinking to data analysis and interpretation as well as the various affordances in their thinking.

In each of the two interviews, Kai was presented with a set of experimental data and prompted to analyze it and interpret it. The general semistructured interview protocol is included in Box 1. Besides the general guiding questions listed in this textbox, the interviewer (first author of this paper) asked specific questions as needed to clarify ideas expressed by Kai and to ensure the student followed up with justifications and further explanations.

Box 1. General Interview Protocol

Initial Prompt: During this interview, I am going to show you some experimental data and ask you some questions about it. I am interested in learning about how students interpret experimental data in chemistry. I do not expect you to necessarily know the right answers. I just want to learn more about how you would think about it.

Data Are Introduced

Guiding Questions:

(1) Have you seen these data before?
(2) Could you talk aloud about what you think the data represent?
(3) Do you see any trends in the data?
(4) How would you explain these trends?

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The experimental data presented during the interviews were chosen to explore Kai's ability to analyze and interpret data using structure−property relationships at two different scales. In the first interview, the data included a graph showing the ionization energy (in kJ/mol) of neutral atoms in the second period of the periodic table as a function of their atomic number (see Figure 1). Interpretation of these data demands thinking about relationships between structure at the electronic level and properties at the atomic level. In the second interview, the data included three separate tables listing the boiling points (in °C) of linear hydrocarbons, alcohols, and amines composed of molecules with one to three carbons (see Table 1). Kai was asked to analyze each of the data tables first separately and then as a group. Interpretation of these data demands the application of relationships between structure at the molecular level and properties at the macroscopic level. The core understandings required for completing both data analyses are introduced in the first semester of the general chemistry course, and thus this student was expected to apply prior chemistry knowledge to complete the tasks.

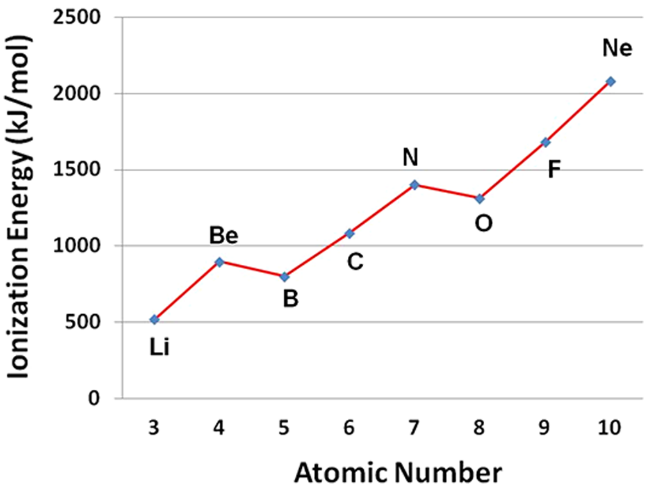

Figure 1. Data presented for interpretation and analysis in the first interview.

Both interviews were audiotaped and later transcribed. The transcripts were analyzed using a constant comparison method looking for emerging codes and themes.[37] Initially, each of the statements made by Kai during each interview was coded in narrative form to capture major actions, ideas, and ways of reasoning expressed by the participant. The following paragraph illustrates this type of narrative code: "Referring to the data, Kai states that negative values are difficult to analyze. Then, labels each substance in order of high to low BP and says that the ordering makes sense because something will require most energy to change into a gas when it has the most mass." Subsequently, each of the narrative codes was analyzed to identify the type of normative ideas (i.e., valid chemical knowledge) and non-normative ideas (e.g., intuitive knowledge) expressed by this student throughout the interviews. Given that Kai expressed a variety of ideas when analyzing the data, we also sought to identify the features or events that triggered switches in student reasoning. The narrative codes, types of ideas, and reasoning switching triggers identified in this first level of analysis served as a basis for a second analytical round focused on the identification of major patterns in student reasoning within and across interviews. At all levels of analysis, the two authors of the paper independently analyzed the interview transcripts, compared and discussed their codes, and worked together to build shared descriptions and interpretations. Given the nature of the investigations (case study), all coding differences were analyzed and discussed until a consensus was reached.

■ FINDINGS

The analyses of Kai's interview transcripts revealed several patterns of reasoning depicted in Figure 2 and summarized in the following paragraphs. These patterns illustrate the major challenges that this student faced in analyzing and interpreting both sets of data. However, they also highlight affordances in the expressed reasoning.

Undifferentiation of Concepts

In both interviews, Kai spent a significant amount of time trying to make sense of the quantities represented in the experimental data (i.e., ionization energy, boiling point). In particular, this student struggled to differentiate between sets of concepts related to one another in the following ways:

(1) By surface features such as similarity in their naming (e.g., atomic mass versus atomic number).
(2) By similarity in their patterns of behavior (e.g., electronegativity versus ionization energy).
(3) By similarity in underlying mechanism (e.g., producing a gas by separating atoms via breaking bonds versus producing a gas by separating molecules via overcoming intermolecular forces).

In some cases, Kai was able to differentiate concepts independently after initial confusion, but in other situations, the differentiation demanded probing and guidance by the interviewer (**I**). Consider, for example, the following exchange:

I: *Okay, so what causes something to boil?*
Kai: *It would be the energy going into it...when something boils does the whole, does all of this become a gaseous molecule (circles whole methane molecule)? Or is it like parts of it break off and it becomes into gas (gestures at H atoms breaking off)?*
I: *So, what would happen?*
Kai: *So like with this, it does not have as many pieces as this one, so when energy goes into it...would this break off? And then become a gas (motions to H leaving the molecule of methane)?*
I: *So, if that broke off, what would you get?*
Kai: *It would be CH_3 minus.*
I: *And when you boil something, do you form something new?*
Kai: *No, you do not. So, that whole thing would. Got it.*

This interview excerpt illustrates how Kai struggled to make sense of the meaning of boiling by considering two potential

Table 1. Data Presented for Interpretation and Analysis during the Second Interview

Substance	Bp (°C)	Substance	Bp (°C)	Substance	Bp (°C)
Methane (CH_4)	−161.5	Methanol (CH_3OH)	64.7	Methylamine (CH_3NH_2)	−6.3
Ethane (CH_3CH_3)	−89	Ethanol (CH_3CH_2OH)	78.5	Ethylamine ($CH_3CH_2NH_2$)	16.6
Propane ($CH_3CH_2CH_3$)	−42	Propanol ($CH_3CH_2CH_2OH$)	97.4	Propylamine ($CH_3CH_2CH_2NH_2$)	48.6

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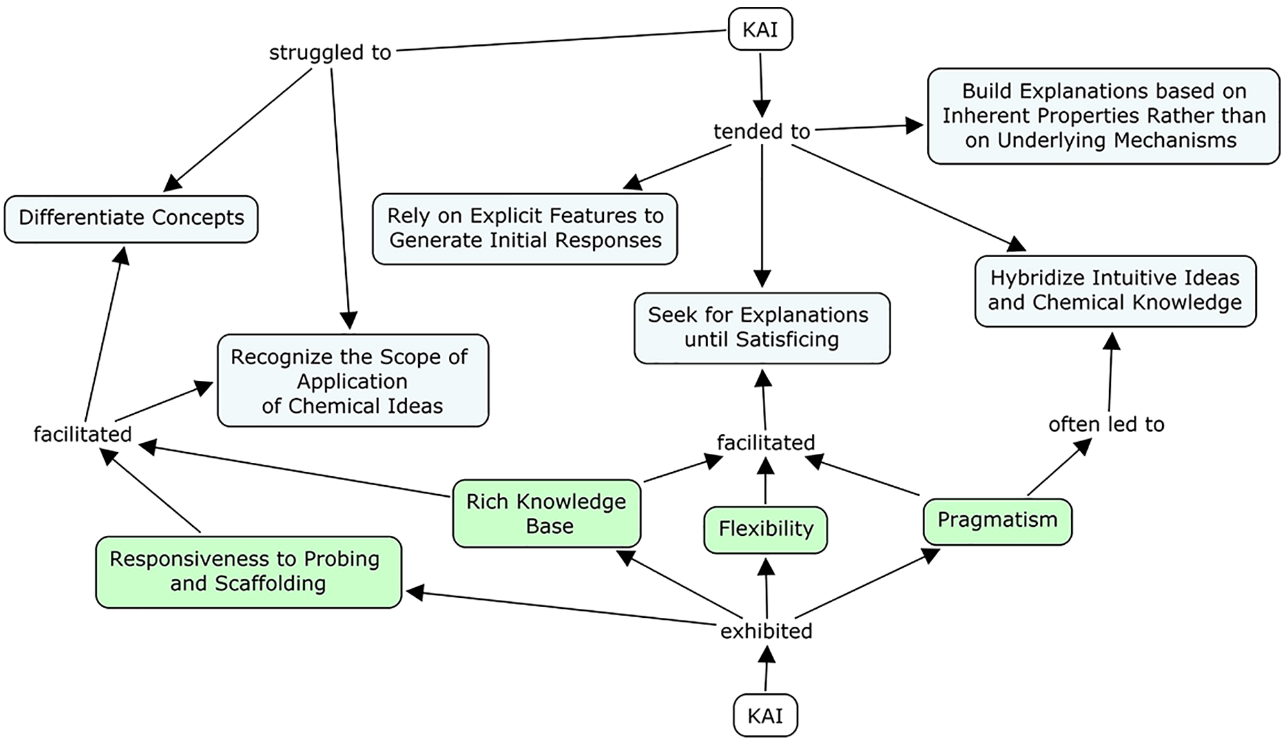

Figure 2. Major challenges (blue) and affordances (green) in Kai's reasoning while interpreting data.

mechanisms that could lead to the formation of a gas. Kai's reasoning was actually sophisticated in the understanding of the potential effects that an energy input may have at the molecular level. Kai also seemed to have the pieces of knowledge necessary to associate boiling with its actual molecular mechanism (e.g., no new substances are formed in the process). However, Kai required support to integrate such knowledge. Similar instances of confusion between different concepts and ideas were observed throughout the two interviews, several of them resolved by guiding Kai to elaborate ideas and providing formative scaffolding. Undifferentiation of concepts has been previously identified as a major barrier to conceptual change.[38]

Initial Reliance on Explicit Features

Kai's initial attempts to explain trends or variations in the experimental data were frequently based on the identification of explicit similarities or differences between the chemical species under analysis. This focus on surface similarity by novice learners has been discussed by several authors.[39] To illustrate this reliance on explicit features, let us analyze how Kai attempted to first explain the decrease in ionization energy between beryllium and boron in Figure 1:

> ***I***: *Okay, so why do you think when we go from Be to B it decreases in ionization energy?*
> ***Kai***: *Well, there is a big gap there (points to the spatial gap between the symbols of Be and B in the periodic table). That is my best guess. But then it does the same thing for nitrogen to oxygen. Um...okay, so then there's the transition metals right there...mhm...So that means it is easier to take the electron away from boron than from beryllium. Okay, that is a good question. Alright, so, these are like highly um, what's the word...reactive (points to the alkali metals in the periodic table). Are these highly reactive too? (points to the alkaline earth metals) But wait...this is a metalloid right? (points to boron) What phase is it normally in?*

Initially, Kai sought to associate the deviation in the increasing trend in ionization energy between beryllium and boron to the existence of the very explicit spatial gap between the symbols of these two elements in the periodic table. However, Kai recognized that such gap was not present between the symbols of nitrogen and oxygen where the other deviation was observed. That led Kai to abandon the initial line of reasoning to seek for other potential sources of difference such as the reactivity of the two elements or their states of matter. Similarly, in the analysis of the boiling point data, Kai first paid attention to differences in number of atoms present in the condensed chemical formulas of the represented chemical compounds and sought to explain the experimental trends based on differences in molecular masses.

In many cases, Kai was able to move beyond the consideration of surface explicit features in the interpretation of data either independently, by recognizing the limitations of the proposed ideas, or with the help of the interviewer, who constantly asked Kai to justify claims and redirected this student's attention to the existing data.

Dynamic Search for Explanations until Satisficing

Kai exhibited great flexibility in the interpretation of data, switching from one idea to another whenever an explanatory attempt was unsatisfactory to this student or was questioned by the interviewer. For example, as we described in the previous subsection, Kai began the interpretation of deviations in the ionization energy data by referring to the spatial location of the elements in the periodic table. When that explanation failed, Kai began a search for other potentially relevant differences. These included, in sequence, element reactivity, state of matter, number of occupied electron shells, presence of unpaired electrons, and existence of full shells. Kai was able to connect the observed experimental behavior with differences in electron configurations, but through a highly idiosyncratic application of concepts and ideas. Consider this exchange:

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J. Chem. Educ. XXXX, XXX, XXX−XXX

I: *Okay, so what's happening as you go from beryllium to boron? Like how are they different?*

Kai: *Well this has one more electron in the shell. Wait, wait...so the number of shells. So it would have...um. This is Be, and the first shell can hold two, and the second shell can hold six? (Begins to draw Bohr's model of Be).*

I: *Eight if you are talking about the Bohr model.*

Kai: *Yeah so...two...and that is like happy. Well not happy, but it has four. Alright, then boron would be the same thing, but it'd be right here. Okay so this electron does not have a pair. So that would be easier to take away (points to B) than this one (points to Be) because it has a pair to it.*

I: *So, because it has a pair...it is...?*

Kai: *Well this one, what is that? It is easier to delocalize like this. Because it does not have, it is not as restricted in the atom. Okay.*

I: *So when you have a pair, they're restricted to be with each other? Is that what you are trying to say?*

Kai: *I do not know. Are they?*

I: *I do not know.*

Kai: *Um, okay because this one is going around here. Well okay, this one is trying to find a pair. So...it would be easier to take this away because it is trying to find a pair. That is is my final answer.*

I: *Okay, so electrons want pairs?*

Kai: *Right yeah.*

I: *Why does an electron want a pair?*

In this example, we see Kai seeking to explain why the presence of an unpaired electron in a boron atom would result in a lower ionization energy compared to that of a beryllium atom. This student dynamically proposed different ideas, such as electron delocalization and an electron's search for a pair, to try to rationalize the lower energy cost of removing the lone electron. These ideas were often replaced by others when Kai was asked to justify them and failed to generate a satisfactory answer. However, that does not imply that such ideas were discarded, as some of them (e.g., the tendency of lone electrons to seek for a pair) resurfaced later in the interview when Kai interpreted different data (e.g., ionization energies for N and O).

Kai's construction of explanations was very dynamic and pragmatic, using a variety of ideas in the search for an answer and stopping the search when a first plausible interpretation was generated (satisficing). When this interpretation was questioned, however, Kai reinitiated the search usually introducing newly remembered ideas triggered by different factors such as the specific type of data analyzed, a question or comment made by the interviewer, or the simple act of talking more about the system under analysis. This dynamic search for explanations has been reported by education researchers exploring student reasoning in different domains.[40,41] Nevertheless, our results suggest that the nature of the data under consideration may play a major role on the extent to which this dynamic "explanation switching" is observed.

The presence of anomalies in the data for atomic ionization energies seemed to challenge student reasoning not only because it led Kai to expand the number of variables considered when trying to explain the behavior of the system, but also because the source of such anomalies was not equivalent, and different causes had to be invoked. As a result, dynamic explanation switching was prevalent throughout the first interview. On the other hand, when analyzing and interpreting the data for the boiling points of different chemical compounds, Kai generated an initial explanation that, although nonnormative, allowed this student to rationalize all of the data (i.e., the larger the molecular mass, the higher the boiling point). Consequently, explanation switching was minimal for most part of the interview. Toward the end of this second interview, however, when the interviewer asked, "Is there anything else you want to say about any of the data?", Kai stated, "Okay, they have like stronger intermolecular forces" and started building a rather well-structured and well-founded normative interpretation based on differences in intermolecular interactions.

Kai's behavior during the second interview suggests that although this student had developed the normative understanding needed to interpret the data (differences in intermolecular forces cause differences in boiling points), the intuitive response (the heavier molecules require more energy to move into the gas phase) triggered by surface features (differences in number of atoms in the molecular formulas) dominated student reasoning and seemed to coexist with the normative explanation that was deployed toward the end of the interview as an afterthought. This result aligns with findings from recent research in cognitive psychology that suggests that initial ideas are not erased but continue to exist and are activated more easily and faster than the more recently acquired scientific concepts.[42]

Unconstrained Application of Ideas

Kai applied a variety of ideas to the interpretation of experimental data, many of them relevant and some of them irrelevant for the tasks at hand. In the search for explanations, this student seemed to freely apply ideas triggered by association, without much awareness or consideration for their relevance or actual context of application. For example, during the first interview, Kai was trying to justify why it would be more stable for valence electrons to singly occupy all 2p orbitals in a nitrogen atom rather than to form electron pairs. Kai claimed that single occupancy would create a more stable charge density:

Kai: *It creates a more stable charge density.*

I: *And that is good?*

Kai: *Yeah. Do not ask me why.*

I: *Why?*

Kai: *...Okay let us see mmm...okay so, more charge distribution is good. Okay now we're actually talking about this in class. Charge distribution is good because...oh okay let us say if it were in water and they are gonna ionize. Then, the negative charge would it be more or less? It would react with water and a negative charge reacts...not that has to do with ion size too...what was the question again?*

I: *You are saying delocalizing the charge around the atom is better...*

Kai: *Well because it is not as restricted, so yeah. Because they're not as close to the atom, so the delocalization allows the electrons to be less restricted so they can. I remember reading something with water...ahh okay. So they delocalize and then it was less of an organizing effect on water, and that would make the entropy go down.*

In this excerpt, Kai associates the greater stability of electrons distributed in different orbitals in an atom with ideas that had just been discussed in the general chemistry class concerning the increased stability of aqueous conjugate bases in which electron charge is more delocalized. Although certainly a connection may be built between these two phenomena in

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J. Chem. Educ. XXXX, XXX, XXX−XXX

terms of electron repulsion and electric potential energy, Kai seemed to build the association based on surface similarities rather than on underlying mechanisms. Ideas about the effect of charge distribution on the stability of conjugate bases were available in this student's mind, and Kai tried to apply them without much consideration for the similarities or differences between the targeted system (electrons in an atom) and the potential analog (electrons in a conjugate base dissolved in water). This unconstrained application of ideas may be associated with the tendency of the human mind to overgeneralize[43] and to reduce the number of variables considered when making decisions or solving problems.[44]

Hybridization of Intuitive Ideas and Chemical Knowledge

To a great extent, the ideas expressed by Kai during the two interviews were a blend of chemical knowledge and intuitive assumptions about the properties and behaviors of entities and processes. This hybridization of ideas manifested in two main forms. In some situations, Kai seemed to think of the submicroscopic components of matter (e.g., electrons, atoms, molecules) as macroscopic objects, using common sense knowledge about these objects to infer or justify the proposed properties of submicroscopic particles. Consider, for example, the following two excerpts from different moments in the first interview in which Kai was justifying the trend of increasing ionization energy with atomic number:

> ***I***: *So why do you think it happens (referring to the overall trend in Figure 1)?*
> ***Kai***: *...So, the more electrons it has, it would have that pull toward the nucleus so, the more electrons that pull would take more energy to like take it away from it.*
> ***I***: *Okay...*
> ***Kai***: *Because it would have a lower potential energy in the shell. Because it is closer to the nucleus...So it'd be the electron density, and then it would take more energy to pull that electron away from more electrons compared to less electrons.*
>
> ***I***: *So, if something is more spread out and it is easier to take it away then, why does that make sense?*
> ***Kai***: *Because okay, I do not know for some reason I was just thinking of materials. Like cotton let us say is not as dense as like a rock so it is easier to pull apart a piece of like cotton because it does not have like a lot of density. So, like electron density, so if it is spread out, it would be easier to give one away and then let us say a rock. So you can easily take apart a piece of a rock and give it to something else.*

In this case, Kai blended chemical ideas about electron density in atoms with intuitive knowledge about density of macroscopic materials to justify the overall trend in the ionization energy data.

In other occasions, hybridization of knowledge seemed to involve the attribution of inherent goal-oriented properties to submicroscopic particles based on regular patterns in their behavior. For example, the common arrangement of electrons in pairs in chemical systems seemed to lead Kai to believe that electrons "want" to pair up because: "...they spin in opposite directions or something like that...so it's like to like balance the, it's so that um, atoms will be stable." Consequently, Kai thought that lone electrons require less energy to be removed (they are less stable). Similarly, the common presence of a full valence shell in atoms of stable molecules and ions seemed to justify Kai's expressed beliefs that atoms "want" full shells to become more stable and the emptier the shell the easier to remove the electrons in it. Additionally, Kai expressed that the single occupancy of atomic orbitals (Hund's rule) resulted from the atoms "wanting" to utilize all shells because a uniform electron distribution would be more stable and would allow atoms to more easily bond with other atoms. The central role that hybrid (synthetic or mixed) constructs play in learning has been discussed by other authors.[23]

Explanation Focused on Inherent Properties Rather than on Underlying Mechanisms

Although Kai expressed a great variety of ideas, particularly when engaged in the analysis of ionization energy data, most of these ideas shared implicit features. In particular, they came across as blends of chemical knowledge with the intuitive belief that the properties and behaviors of compound systems result from inherent properties of their components. These inherent properties determine how components react to external intervention (e.g., how much they move when energy is provided to the system) or their natural "wants" and "needs" (e.g., electrons want to pair up, occupy full shells, and be spread out in space to be more stable). This reliance on inherent properties to explain the properties or behaviors of a system seems to be a common human bias.[18]

In very few occasions, Kai spontaneously built interpretations or offered explanations that were mechanistic in character. These mechanistic explanations were based on the description of the interactions between diverse agents and the effects of such interactions. These types of explanations also rely on the assumption that components possess inherent properties that govern their behavior (e.g., electric charge, spin), but they are built using causal rather than teleological arguments.[45] During the first interview, for example, Kai never referred to attractions and repulsions between atomic components in building explanations. This student relied, instead, on known patterns of behavior (e.g., electrons arrange in pairs, spread out in space) to assume natural goals and intentions that served as short "explanatory heuristics" in the analysis and interpretation of data.

■ DISCUSSION

The analysis of Kai's interviews revealed patterns of reasoning that illustrate the challenges that college students face to meaningfully apply and integrate their chemical knowledge to explain trends in experimental data (see Figure 2). These challenges include: undifferentiation of concepts, overreliance on surface explicit features in guiding reasoning, oversensitivity to contextual features in building explanations, unconstrained application of ideas, hybridization of chemical and intuitive knowledge, and overreliance on nonmechanistic explanatory schemas. Our findings, however, also highlight several affordances in student thinking and understanding such as cognitive flexibility, responsiveness to probing and scaffolding, rich knowledge base, and pragmatism in the search for explanations.

It would be tempting to reduce Kai's challenges in the interpretation of data to the presence of a set of fixed misconceptions that needed to be elicited and eradicated. However, our findings suggest that student reasoning was highly dynamic and that many of the misconceived ideas expressed by Kai were actually constructed on the spot in the attempt to resolve the interpretive tasks at hand. We could also claim that Kai's problems mainly stemmed from lack of chemical knowledge or limitations in this student's ability to think abstractly using chemical models. However, our results

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indicated that Kai could engage in sophisticated reasoning both independently and with proper probing and scaffolding depending on the context.

Kai's reasoning in several instances during the two interviews revealed the type of fragmented knowledge structure described in "knowledge-in-pieces" accounts of students' understanding.[24,26,27] This would explain the lack of coherence in some of Kai's expressed ideas and the high sensitivity of some this student's answers to the information provided in each of the tasks. However, many of Kai's interpretations also revealed features commonly associated with the "framework theory" perspective on knowledge structure.[22] For example, Kai consistently built explanations that invoked the existence of inherent properties and relied on teleological accounts to justify behaviors, as if guided by a naïve theory of causality. We would thus claim that Kai's reasoning can be better described by adopting a "dynamic complex system" view, which allows for the coexistence of diverse types of emergent cognitive structures.[28−31]

■ IMPLICATIONS

We believe that Kai's case actually elicits core issues in curriculum, instruction, and assessment in chemistry at the college level. Kai is an intelligent and motivated individual who successfully completed the general chemistry courses but likely ended these classes with what can be characterized as a "hybrid" chemical mind. In this type of mind, chemical knowledge is loosely connected and tends to have a lower cueing priority than competing intuitive ideas. When actually cued, such knowledge is applied without much understanding of its meaning and scope, guided by implicit intuitive schemas that support the development of hybrid cognitive constructs highly sensitive to context as they are dynamically built when facing a particular task.

How can we help students like Kai finish their general chemistry courses in a more desirable and productive "state of mind"? The results of our study provide insight into strategies that may help remedy the situation. For example, students' difficulties differentiating concepts and recognizing the scope of their application may be alleviated by creating more opportunities for students to compare and contrast different chemical concepts and ideas in the classroom. Different research studies have demonstrated the benefits of explicitly engaging students in the identification, analysis, and reflection of variations between related systems, concepts, and ideas, asking them to create representations and explanations for such variations.[46,47] These compare−contrast−invent activities may involve, for example, the analysis of different data sets using a given model or the application of different models to the interpretation of the same data.

Strategies to help students recognize intuitive schemas that are likely to interfere with their thinking, as well as to help them develop alternative ways of reasoning, may depend on the specific course content. For example, strengthening understanding of structure−property relationships may require engaging students in the analysis of the different scales at which these relationships manifest (e.g., electronic → atomic, atomic → molecular, molecular → molar), working with data and models at each of these scales, and scaffolding mechanistic reasoning by helping students identify, describe, analyze, and reflect on the different agents acting at each level, their properties, their interactions, and the constraints on their behavior.

Our findings suggest that students possess a variety of cognitive resources that can support the development of more meaningful understandings with proper scaffolding and formative feedback. However, those resources need to be tapped into in a purposeful manner by creating opportunities in the classroom for students to engage in the application, construction, evaluation, and revision of models while trying to make sense of data. The implementation of these types of instructional strategies would demand major changes in the curriculum as well as in teaching and assessment practices. It would be unrealistic to expect that the same amount of content could be covered in a one-year general chemistry course where students actively engage in the types of model-building, model-application, and model-evaluation activities suggested above. Similarly, it would be impossible to use a lecture format to provide the type of scaffolding and formative feedback that would benefit students as they work on those tasks. As existing research indicates, teaching approaches that facilitate active engagement and guided inquiry would be more effective.[48,49] Assessments would need to be diversified to better capture student reasoning, which, as our study shows, is rich, complex, and sensitive to context. Maintaining the status quo in the face of existing evidence would rob students like Kai of opportunities to transcend their hybrid minds.

■ LIMITATIONS AND FUTURE RESEARCH

The findings of our study are limited by the qualitative nature of our "case study" approach. The generalizability of our results is affected by the extent to which our study participant was actually representative of the majority of general chemistry students. Additionally, our interpretation of the qualitative data is influenced by our prior knowledge and beliefs about the nature of student knowledge and learning. Nevertheless, our investigation elicited a set of challenges and affordances in student reasoning that will guide our analysis of data collected through interviews with a larger set of students. We are particularly interested in characterizing the prevalence of the different challenges and affordances in students' reasoning, identifying the conditions under which they tend to manifest (reasoning triggers), and exploring the extent to which different kinds of scaffolding informed by our research support students' ability to use chemical models of structure−property relationships to interpret chemical data.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: vicente@u.arizona.edu.

Notes

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J. Chem. Educ. XXXX, XXX, XXX−XXX

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J. Chem. Educ. XXXX, XXX, XXX−XXX