8-11-2020

Student Understanding in Acid-Base Concepts in Chemistry: Conceptualization from General Chemistry II through Biochemistry

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Recommended Citation
Kilpatrick, Nancy A., "Student Understanding in Acid-Base Concepts in Chemistry: Conceptualization from General Chemistry II through Biochemistry." Dissertation, Georgia State University, 2020.
doi: https://doi.org/10.57709/18642035

STUDENT UNDERSTANDING IN ACID-BASE CONCEPTS IN CHEMISTRY: CONCEPTUALIZATION FROM GENERAL CHEMISTRY II THROUGH BIOCHEMISTRY

by

NANCY KILPATRICK

Under the Direction of Suazette Mooring, Ph.D.

ABSTRACT

The acid ionization constant, K_a, is a fundamental acid-base equilibrium concept that is taught in US post-secondary general chemistry II and threaded through later chemistry courses as pK_a. It is essential that students' have prior knowledge of acid-base models, acid strength, equilibrium, and K_a to comprehend pK_a fully. However, many students possess unstable and incoherent ideas regarding these topics. Therefore, more effective teaching strategies and assessments are needed to provide support for this network of linked concepts. Think-aloud interviews with twenty undergraduate students across general chemistry, organic chemistry, and biochemistry were used to investigate students' explanations and reasoning about equilibrium and acid ionization constant. Students' reasoning was examined through the lens of meaningful learning and the resources framework.

It was found that, with prompting, most students were able to define at least one acid-base model, generally the Bronsted-Lowry model. Students were placed into five levels of sophistication based on their reasoning about acid strength, equilibrium, K_a and pK_a. Upper-level students were less coherent and stable than lower-level students for acid strength. Interestingly, most students were unable to define equilibrium for a reaction and had an incoherent understanding. A trend was observed for upper-level students to converge on describing equilibrium in terms of equal amounts. Furthermore, it was found that students did not attribute more than reversibility to a double-headed arrow. Approximately one-quarter of the students used the concept of K_a coherently in multiple contexts throughout the study; however, a trend of incoherency was observed for students in organic chemistry II. Most students did not utilize pK_a beyond a mathematical entity involving K_a, without regard to the actual concept.

These findings suggest that instructors need to provide opportunities for students to make meaningful connections between K_a and pK_a and the underlying prior knowledge that is required to understand this complex topic. Instructors need to provide clarity to students in the meaning of words and the symbols used in acid-base chemistry. Additionally, when conducting assessments, students need to be assessed in more than one context to assure comprehension.

INDEX WORDS: Acid-base chemistry, Acid Equilibrium Constant, Acid Strength, Chemistry Education Research, K_a, pK_a, Resources framework, Undergraduate, Undergraduate Chemistry

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A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

in the College of Arts and Sciences

Georgia State University

2020

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Georgia State University
August 2020

DEDICATION

I would like to dedicate this work first and foremost to my children: Evan, Fiona, and Adeline. All of you have encouraged me to pursue my dreams, even though it was not always easy for us. As each of you, in turn, goes out into the world, I hope I can provide you with the courage and the faith you have given me. I know that you can achieve whatever you set your mind to.

I would also like to acknowledge my family and friends for their unwavering support. For the countless conversations when I needed to think about my research with someone. I appreciate that all of you believed I could get here. Without you, I could not have done all of it. Thank you from the bottom of my heart for allowing me to reach this goal in my life.

ACKNOWLEDGEMENTS

I would like to acknowledge my advisor Dr. Suazette Mooring who provided me with the opportunity to broaden my vision in my academic career. I have learned how to be a better chemistry educator while I have been in your lab. You have provided me with the opportunity to improve myself and the learning experience for my students. Thank you for your guidance and support.

I would like to thank my committee, which includes Dr. Suazette Mooring, Dr. Kathryn Grant, and Dr. Renee Schwartz, for helping me with this achievement. I would like to particularly thank Dr. Schwartz for including me in her cohort of students to learn how to critique and write my review of the literature. I appreciated the opportunity. I felt included in your group of students. The feedback from you and the other students helped me produce a better review than I could have done on my own. I will strive to provide mentorship and leadership to my students like you have given to me. Finally, Dr. Kathryn Grant, you have been a mentor to me since my days here at GSU as an undergraduate. I will always remember your voice in my head during our inorganic lectures. You wanted us to make sure not to forget about those that came before us and the learn about “the people.” I will make sure to continue that tradition and teach my students about “the people.” You made a big impression on me in your teaching, and I will always remember you.

I would like to acknowledge my undergraduate and graduate assistants in the lab that helped with this research: Maria Tran, Tarik Prince, Jordan Foster, and Jason Boyne. Thank you for attending lectures to help take notes and the endless hours of transcribing interview data for this project. Your efforts were all appreciated.

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LIST OF ABBREVIATIONS

ACCM	Anchoring Concept Content Map
ACS	American Chemical Society
ACS-EI	American Chemical Society Exams Institute
AQ	Aqueous
BC	Biochemistry I
CA	Conjugate acid
CB	Conjugate base
CLUE	Chemistry, Life, the Universe, and Everything
ESL	English as a Second Language
DISSOC	Dissociation
F	Female
F, C	Flexible, Coherent
GCII	General Chemistry II
ICE	Initial, Change, Equilibrium
K	Equilibrium Constant
K_a	Acid Ionization Constant, Acidity Constant, Acid Dissociation Equilibrium
K_b	Base Dissociation Constant
K_c	Equilibrium Constant
K_{eq}	Equilibrium Constant
K_p	Equilibrium constant with partial pressures
K_{sp}	Solubility product constant

M	Male
NB	Non-Binary
OCI	Organic Chemistry I
OCII	Organic Chemistry II
SPI	Student Principal Investigator
S, C	Stable, Coherent
S, I/C	Stable, Incoherent/Coherent
TA	Teaching Assistant
U, I	Unstable, Incoherent
U, I/C	Unstable, Incoherent/Coherent

1 INTRODUCTION

Students, in college undergraduate general chemistry courses, learn foundational concepts in acid-base chemistry that are important (Duis, 2011; Ferguson & Bodner, 2008; Villafañe, Bailey, Loertscher, Minderhout, & Lewis, 2011; Watters & Watters, 2006) for understanding more difficult concepts in organic chemistry (Ferguson & Bodner, 2008; Stoyanovich, Gandhi, & Flynn, 2015) and biochemistry (Wood, 1990). However, it has been suggested that students do not always learn these foundational concepts (Nakhleh, 1992; Villafañe, Bailey, et al., 2011), and instructors have indicated that they have to reteach these foundational concepts to students (Duis, 2011).

Duis (2011) published an exploratory study of twenty-three organic chemistry educators at twenty-one different institutions in the United States that investigated their perspectives on topics that had to be reviewed or retaught in organic chemistry from general chemistry. This study also included fundamental concepts in organic chemistry, difficult concepts in organic chemistry, and organic chemistry concepts that faculty believed were needed for further learning in chemistry. The study found that the most commonly retaught or reviewed topic was acid-base chemistry, and 35% of the organic chemistry educators sampled cited it as a concept that was needed for later learning in chemistry. Acid-base chemistry was ranked third, after reaction mechanisms and the correlations of structure to properties/reactivity, as a fundamental concept in organic chemistry. Approximately half of the educators that participated in the study indicated that acid-base chemistry was one of the most difficult topics in organic chemistry, second only to reaction mechanisms (Duis, 2011).

Undergraduate students who take a series of chemistry courses will utilize pK_a in a variety of ways after they are introduced to the concept of the acid dissociation constant, K_a, during most second-semester general chemistry courses. The underlying concept of pK_a is about the equilibrium of the acid dissociation, which provides information about the amount of the protonated and the deprotonated states of the molecule (Raker, Holme, & Murphy, 2013). The usefulness of pK_a extends to making buffers in the laboratory, providing information on which hydrogen will be reactive during a proton transfer reaction, deciding whether reactants or products are favored and whether biomolecules are protonated or deprotonated. These concepts are delineated as foundational concepts by the American Chemical Society Exams Institute through the anchoring concepts content maps for general chemistry and organic chemistry (T. Holme, Luxford, & Murphy, 2015; T. Holme & Murphy, 2012; Murphy, Holme, Zenisky, Caruthers, & Knaus, 2012; Raker et al., 2013).

The anchoring concept content maps (ACCM) were developed by the American Chemical Society (ACS) Exams Institute (ACS-EI) using various focus groups at the ACS National and Regional meetings, Biennial Conference for Chemistry Education, and Exam Institute Offices. The purpose of the ACCM is an all-encompassing listing of chemistry content that would typically be covered in a general chemistry course (Murphy et al., 2012). Four levels organize the anchoring concept content map, with each level becoming more detailed in the topic. The first level is the framework, or the “big ideas” called the anchoring concepts. The second level is the enduring understanding, which represents the essential foundational concepts. The third level is the subdisciplinary articulations. This level is related to how the second level is associated with a subdiscipline. The fourth level is the content details, which are the finer details of the course content (T. Holme & Murphy, 2012). The anchoring concept in general chemistry for equilibrium is that “all physical and chemical changes are, in principle, reversible and often reach a state of dynamic equilibrium.” The enduring level indicates that K, an equilibrium constant, can characterize the equilibrium and that it has applications in the subdiscipline of acid-base chemistry. At the subdiscipline level for acid-base systems, in water, it specifies that students should have conceptual as well as a quantitative understanding of this equilibrium system. Additionally, they indicate that pH is used in the quantitative descriptions of acid-base chemistry for equilibrium systems (T. Holme et al., 2015; T. Holme & Murphy, 2012).

For organic chemistry students, the anchoring concept and the enduring understanding are the same. The subdiscipline level indicates that pK_a is a measure of equilibrium between the protonated and deprotonated forms of the molecule. The content level details include the acidic nature of s-character hybrid orbital (sp), acidity due to resonance of phenols and enolates, and ability of certain atoms to carry a negative charge better to make them more acidic (Raker et al., 2013). It is important to note that ACS exam items are written to encompass content detail (level 4) understanding of the material (T. Holme et al., 2015).

In addition to the concepts from the ACCM, Stoyanovich et al. (2014) analyzed twenty-eight reactions in eleven different organic chemistry textbooks to determine intended specific acid-base learning outcomes for introductory organic chemistry students that were needed to be successful in analyzing more complex reactions in organic chemistry. These outcomes, which were deemed essential by experts who evaluated them, included concepts such as definitions of the models for acids and bases - Arrhenius, Bronsted-Lowry and Lewis, the protonation state of the molecule, identification of the acid, base, conjugate acid and conjugate base, reaction mechanisms, acid strength, equilibrium predictions, and predominant form of a molecule based on pK_a and pH. Furthermore, it was noted that memorization of periodic trends is insufficient to consider the learning outcome achieved, it requires further explanation of how factors affect the stability of the base, such as electronegativity, atom size, inductive effects, resonance, and hybridization (Stoyanovich et al., 2015).

Currently, there is no ACCM for biochemistry. However, Villafañe et al. (2011) identified foundational concepts necessary before taking biochemistry and Loertscher and colleagues (2014) have developed threshold concepts considered to be central to understanding biochemistry (Loertscher, Green, Lewis, Lin, & Minderhout, 2014). In 2011, Villafañe et al. developed an instrument to assess biochemistry students understanding of foundational concepts that are needed before taking the course as part of a larger project comprised of twenty experienced biochemistry faculty collaborators. The assessment is a twenty-four-question distractor-driven multiple-choice assessment with four answer choices per question that cover eight concepts, with three questions per concept. The set of three questions for each concept was designed based on a change in the stem of the question as a direct statement, inverse statement, or applied statement. Therefore, student understanding is indicated if they answer all three of the questions on a given topic correctly. The assessment was analyzed to ensure content and construct validity along with reliability. One of the eight concepts in this assessment was the relationship between pH and pK_a. The concept of pH and pK_a is central in biochemistry (Villafañe, Loertscher, Minderhout, & Lewis, 2011), which agrees with one of the acid-base learning outcomes for organic chemistry students designed by Stoyanovich et al. (Stoyanovich et al., 2015). For example, students need to be able to determine the ionization state of a substance with a given pK_a in an aqueous solution with a given pH value (Villafañe, Bailey, et al., 2011). Since these foundational concepts are needed before biochemistry, Loertscher, and colleagues developed the biochemistry thresholds (Loertscher et al., 2014).

The biochemistry thresholds are the “big ideas” that underlie the foundational concepts in biochemistry that create a web of interrelated central concepts. In general, threshold concepts provide a framework to link student learning to curricular design. These concepts are essential for the learner to progress but are characteristically troublesome. These threshold concepts were identified through a five-phase process. Initially, a pilot study was performed with two focus groups of recent biochemistry students of possible threshold concepts for equilibrium, as it had been previously identified in biology. The list of the concepts was developed by a group of more than seventy interdisciplinary life sciences and biochemistry faculty members that participated in workshops during the summer of 2013. The highest rank concept was equilibrium, while pH and pK_a were ranked in the top five. The workshops were followed by focus group interviews with forty-six undergraduates at five diversely different college-level institutions to refine the concepts and define the knowledge statements. However, they only did this for three of the nine concepts; six of the concepts had the knowledge statements based on well-documented literature of students’ alternative conceptions. The working list of five threshold concepts was determined after the analysis of the data in conjunction with an advisory panel of members and participants from the life sciences workshop. After that, the knowledge statements for each of the concepts were created based on interview data from the students. A survey was sent to the participants of one of the workshops to verify the knowledge statements. The threshold concepts include steady state, which encompasses the concept of equilibrium for biochemistry students (Loertscher et al., 2014).

There have been a multitude of research studies that catalog student conceptions related to acids and base, as well as alternative conceptions, where an alternative conception is defined as anything different from a scientifically accepted definition or principle (Nakhleh, 1992;

Villafañe, Bailey, et al., 2011). This study is intended to capture the sophistication of student understanding in acid-base equilibrium concepts, as has been called for by researchers (M. M. Cooper, Kouyoumdjian, & Underwood, 2016). The scope of these studies have encompassed various concepts related to acid-base equilibrium including: acid-base models (Cartrette & Mayo, 2011; Cros et al., 1986; McClary & Talanquer, 2011a), classifying acid-base reactions (M. M. Cooper et al., 2016), acid-base strength (Bretz & McClary, 2015; Maeyer & Talanquer, 2010; McClary & Bretz, 2012; McClary & Talanquer, 2011a, 2011b), buffers (Orgill & Sutherland, 2008), and microscopic representations of acid-bases (Jasien, 2005; Smith & Metz, 1996). None of these studies focused on the student understanding related to the concepts of the acid equilibrium constant and pK_a. This research focuses on a cross-sectional study of students from general chemistry II, organic chemistry I and II, and biochemistry. This current study focuses its attention on student understanding about the concepts of the acid equilibrium constant (K_a) and pK_a, as well as the application of these concepts in problem-solving. There is a clear need to probe further why students have difficulty in this topic. While evaluating the second-semester organic chemistry students' understanding of curved arrow formalism in reaction mechanisms, Ferguson and Bodner (2008) revealed that students' lack of conceptual knowledge of pK_a would present an obstacle in their ability to complete a correct reaction mechanism. To the researchers' surprise, none of the participants in the study invoked the usage of pK_a, or any acid-base principles for the reaction mechanisms during the think-aloud interviews (Ferguson & Bodner, 2008). In McClary and Talanquer's 2011 study, they indicated that students' struggled with the meaning of pK_a (McClary & Talanquer, 2011a). Additionally, this finding is supported by the results of Villafañe, et al., where only 30% of biochemistry students were able to answer questions about the charge of a molecule with a given pK_a at a particular pH after a semester of study (Villafañe, Loertscher, et al., 2011). While this work did not focus on buffers, in particular, Orgill's research provides a meaningful connection between student understanding pH and pK_a (Orgill & Sutherland, 2008).

1.1 Research Questions

- How do general chemistry, organic chemistry, and biochemistry students connect and relate ideas of acid-base equilibrium?
- How do students' ideas and explanations of acid-base equilibrium transition as they proceed from general chemistry through biochemistry?
- How do students use acid-base equilibrium concepts in problem-solving for acid-base equilibrium scenarios?

1.2 Theoretical Frameworks

The following sections will review the theoretical frameworks for the basis of this research, followed by a review of relevant literature to understand the foundation for this research into how students understand acid-base equilibrium concepts in chemistry. The theoretical frameworks of meaningful learning and resources framework are discussed.

1.2.1 Meaningful Learning

A theoretical framework is the lens by which this study will be viewed and evaluated. One of the theoretical frameworks for this research is meaningful learning, which is derived from constructivism. Constructivism is a learning theory (or learning philosophy) that views knowledge as being constructed in the mind of the learner. Students do not gain knowledge just by being told. The learner is actively involved in the processing and constructing new knowledge with their prior knowledge (Resnick, 1983; Von Glasersfeld, 1984). Meaningful learning was a refinement to the constructivist viewpoint by David Ausubel, an American psychologist. It is learning at a deeper level by which the learner deliberately seeks to integrate and organize new knowledge with existing knowledge to create relational frameworks. Meaning learning contrasts with rote learning, in which learning occurs with memorization of definitions or facts with no regard for the actual meaning of the individual of the words and no connection with their prior knowledge.

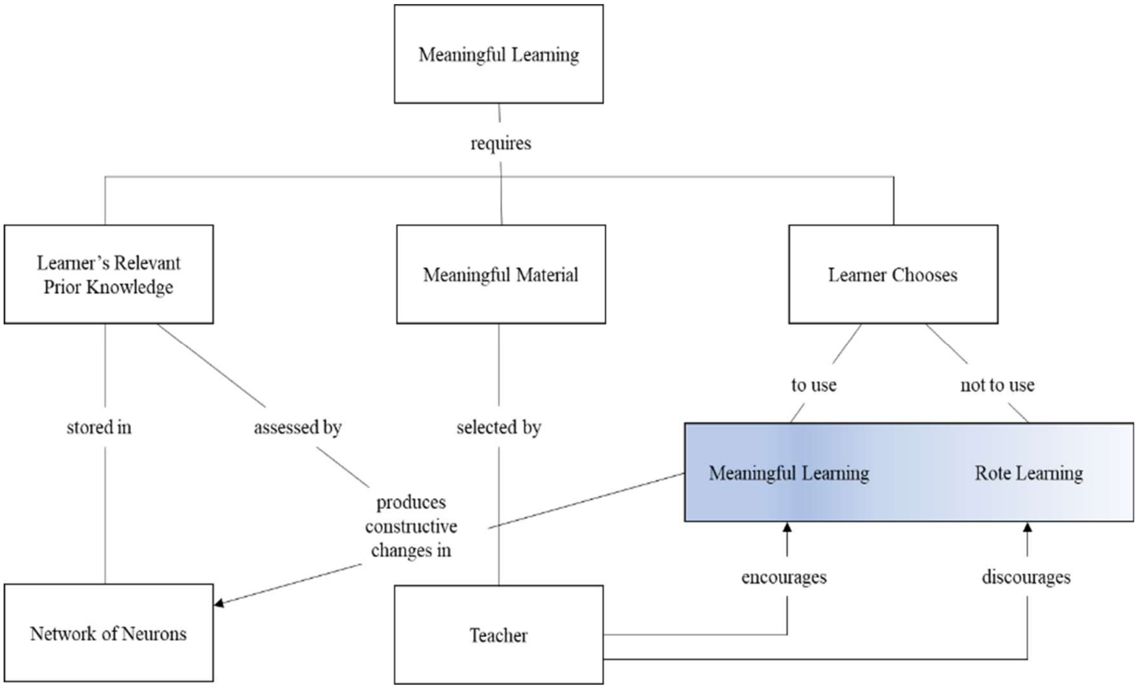


Figure 1. Concept map for prerequisite conditions for meaningful learning. Adapted with permission from Bretz, S. L. (2001). Novak's Theory of Education: Human Constructivism and Meaningful Learning. Journal of Chemical Education, 78(8), 1107. doi:10.1021/ed078p1107.6. Copyright (2020) American Chemical Society

Consequently, for meaningful learning to occur, students must possess adequate prior knowledge, determine what new knowledge is relevant to their prior knowledge, and consciously make connections between these two (Ausubel, 1963, 1968). A concept map of these prerequisites for meaningful learning is outlined in Figure 1. It should be noted that this is a continuum from rote to meaningful learning (Ausubel, 1963). An example to illustrate this continuum is presented by Ebenezer, in which a high school student is describing a solute and solvent as follows: “Solute is the stuff that dissolves in another stuff. Solvent is the stuff that dissolves the stuff” (Ebenezer, 1992). Instructors, as experts, think in scientific terms and would like the student to use this terminology; however, a student may use their own language and would be on the continuum from rote to meaningful learning as the student progresses in their knowledge (Ebenezer, 1992).

1.2.2 Resources Framework

This research is approached from the perspective of the resources framework that views that cognitive structures are based on a network of fine-grained resources that may, or may not be activated for use in a specific context (Hammer, Elby, Scherr, & Redish, 2005). This contrasts with frameworks that see knowledge as being transferred as a single, stable, intact cognitive structure that can be applied from one situation to another, such as the transfer skills framework (Dori & Sasson, 2013). Some of the key influences of this framework are diSessa and Sherin’s phenomenological primitives (diSessa & Sherin, 1998) and Minsky’s computational model of the mind, in which there are a “society” of “agents” that work together to make up the processes in the mind (Minsky, 1986). These available resources are built from prior knowledge and students' beliefs, their epistemology (Hammer et al., 2005).

In the resources framework, the context of the resource is important. Firstly, that resources are not considered to be merely right or wrong, just context-dependent, in the sense that they may be productive in one context and non-productive in another context. Secondly, that the learner may respond differently in different contexts, to illustrate the nature of a resource that is productive in one context, but unproductive in another context, we can utilize the words “strong” and “weak.” In chemistry, the words strong and weak are used in different concepts to convey different contextual meanings that are in opposition to each other. In the concept of acid-base chemistry, a “strong acid” does not completely dissociate, whereas a “weak acid” can partially dissociate. In the concept of bonding, a “strong bond” stays together and does not break apart, whereas a “weak bond” comes apart easily. If a learner is utilizing a resource of “strong stays together” and “weak comes apart,” this would be an unproductive resource in the context of acid-base chemistry, but a productive resource for bonding.

The context for the learner can be viewed in terms of the “frame.” The frame is the learner’s view and expectations of a specific scenario, which affects what they pay attention to and how they act. Thus, the frame ques different resources to be activated or not activated. It is this aspect of the resources framework that can provide explanatory power when novice students seem to offer contradictory responses to what experts would consider the same concept. Inconsistent responses can be within the same task when the learner’s understanding is challenged, or in a different task when the same concept is presented. When the learner’s understanding is challenged, they will often go through “frame negotiation” and may shift their frame to alter their selection of resources. For example, this research probes student understanding with think-aloud interviews that use clarifying and probing questions that can challenge a student’s understanding; that challenge can, in turn, shift the student’s response to utilize a new set of resources. However, this “frame negotiation” does not always occur; some frames most resistant to change, and learners will not alter their choices. When students use the same concept for different tasks, the resources framework does not involve “transferring” an intact, single knowledge structure. It involves actively generating at the moment, fine-grained resources based on the cues of the frame, therefore different tasks for the same concepts can elicit different responses for students based on the task at hand (Hammer et al., 2005).

The resources framework allows for the development of novice learners to more expert-like thinking through more sophisticated levels of understanding that become less context-dependent (Louca, Elby, Hammer, & Kagey, 2004). Once a set of mutually consistent and reinforcing resources begin to activate as a well-established set, they can become a resource in their own right (Hammer et al., 2005). Novice learners progress towards experts who have developed networks of complied resources that are not context-dependent, as demonstrated by their articulate nature, consistency, and stability across multiple contexts (Louca et al., 2004).

2 REVIEW OF RELEVANT LITERATURE

Based on the resources framework, many fine-grained context-dependent resources can be activated when a student tries to understand a concept. For acid equilibrium constants and pKa, students may have to activate an array of resources including: the three levels of Johnstone's triangle (M. M. Cooper, Grove, Underwood, & Klymkowsky, 2010; Johnstone, 1982, 1993, 2000, 2010; Taber, 2013), acid-base models (Cartrette & Mayo, 2011; Cros et al., 1986; Jasien, 2005; McClary & Talanquer, 2011a; Nakhleh, 1994; Nyachwaya, 2016; Smith & Metz, 1996), acid-base reactions (Bhattacharyya & Bodner, 2005; M. M. Cooper et al., 2016; Crandell, Kouyoumdjian, Underwood, & Cooper, 2019; Dood, Fields, & Raker, 2018; Ferguson & Bodner, 2008; Grove, Cooper, & Rush, 2012; Strickland, Kraft, & Bhattacharyya, 2010), nucleophiles and electrophiles (Anzovino & Bretz, 2015, 2016; Bhattacharyya, 2013; Bhattacharyya & Bodner, 2005; Cartrette & Mayo, 2011; Ferguson & Bodner, 2008; Strickland et al., 2010), equilibrium (Banerjee, 1991; Camacho & Good, 1989; Gorodetsky & Gussarsky, 1986; Hackling & Garnett, 1985; Johnstone, 2000, 2010; Loertscher et al., 2014), acid strength (Cartrette & Mayo, 2011; Maeyer & Talanquer, 2010; McClary & Bretz, 2012; McClary & Talanquer, 2011a, 2011b), rates and rate laws (Bain, Rodriguez, & Towns, 2019; Banerjee, 1991;

Becker, Rupp, & Brandriet, 2017; Camacho & Good, 1989) pH and pK_a (Cros et al., 1986; Orgill & Sutherland, 2008; Villafañe, Loertscher, et al., 2011; Watters & Watters, 2006). However, there are no previous studies that directly inquire into students' conceptual understanding of acid equilibrium constants and pK_a. Students often learn these concepts based on how they are assessed (Momsen et al., 2013; K. M. Scouller & Prosser, 1994), which often culminates in an examination. Whereby the instructors feel that examinations reflect student comprehension (Cassels & Johnstone, 1983; M. M. Cooper et al., 2016; Cornog & Colbert, 1924; T. A. Holme, Luxford, & Brandriet, 2015; Johnstone & Cassels, 1978; Nakhleh & Mitchell, 1993; National Research Council, 2011, 2013; Reed, Brandriet, & Holme, 2017; Stowe & Cooper, 2017). Finally, the advantages and distinctions of expert versus novice solve problems are addressed (Bhattacharyya & Bodner, 2005; Bodner & Domin, 2000; Bodner & McMillen, 1986; Cassels & Johnstone, 1983; M. M. Cooper et al., 2016; Cowan, 2010; Crandell et al., 2019; Ferguson & Bodner, 2008; Grove et al., 2012; Halford, Cowan, & Andrews, 2007; Hayes, 2015; Jasien, 2005, 2010; Johnstone, 1982, 1991, 2010; Johnstone & Al-Naeme, 1991; Johnstone & Selepeng, 2001; Kozma & Russell, 1997; Markic & Childs, 2016; Miller, 1956; National Research Council, 2000; Nyachwaya, 2016; Smith & Metz, 1996; Stowe & Cooper, 2017; Strickland et al., 2010; Taber, 2013; Talanquer, 2011).

2.1 Johnstone's Triangle: Macroscopic, Microscopic and Symbolic

In the 1960s, the chemistry curriculum went through a significant redesign that encompassed content knowledge with three different components or levels. These levels included macroscopic, microscopic, and symbolic (Johnstone, 1991). The macroscopic content knowledge includes tangible items and visual objects that one can encounter in daily life. In contrast, the microscopic content knowledge includes such things as molecules and atoms, which are not able to be visualized with the naked eye in daily life. The symbolic content knowledge is the symbols, equations, stoichiometry, and accompanying mathematics that represent chemistry. These three basic components are interlinked and represented by Johnstone's triangle, Figure 3. Johnstone has argued that the creation of chemical knowledge is different from the "normal world" in that there is an added complication of encompassing these three levels of thought. No one level is superior to another; they are complements to each other (Johnstone, 2000). However, Taber (2013) argues that the symbolic level "facilitates shifting between levels" (Taber, 2013).

Furthermore, experts have the ability to move through the triangle utilizing the different levels when necessary. However, for students, this is a difficult task to move between these various levels with ease (Johnstone, 1982, 1993). Once more, when students are taught, the instructors often shift seamlessly through the triangle, and the student is unaware that the shift has occurred and is left confused and unable to connect concepts (Johnstone, 2010). Furthermore, research has shown that students not only have trouble navigating the triangle but also being able to construct and utilize the representations (M. M. Cooper et al., 2010). The ability to utilize different levels and shift more seamlessly through the different levels provides this research an indication that students are developing towards a more expert-like understanding.

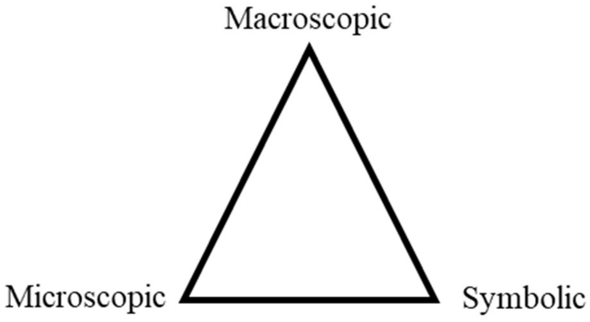


Figure 2. Johnstone's Triangle

2.2 Students' Interrelated Conceptions

2.2.1 Acid-Base Models

There have been a variety of studies that investigated student conceptions of the underlying models of acids and bases. Research has shown that students describe acids and bases with more naïve descriptions, such as pH, to models resembling acid-base theories (Cartrette & Mayo, 2011; Cros et al., 1986; McClary & Talanquer, 2011a). Cros et al. (1986) investigated first-year undergraduate students' conceptions of matter and acids and bases, in France, with an open-ended questionnaire, where students were asked to define an acid and a base. Overall, 23% of students described it in terms of pH value, where an acid had a $pH < 7$, 14% utilized the Arrhenius definition, where H^+ is produced in an aqueous solution, and 47% defined an acid in terms Bronsted-Lowry, as a proton transfer (Cros et al., 1986).

Cartrette and Mayo (2011) had similar findings with semi-structured interviews of fourteen second-year organic chemistry students, where all but one student provided a definition consistent with the Bronsted-Lowry definition that acids would lose a proton. This single student described acids in a naïve way, in that, acids have a pH less than 7. To probe the students further, they were prompted for the Lewis acid-base theory explanation, and less than 50% of students were able to define it (Cartrette & Mayo, 2011). However, not all studies have simply asked students to define acids.

McClary and Talanquer (2011) probed nineteen undergraduates in first-year organic chemistry to understand their mental models of acids expressed when engaged in prediction, explanation, and justification tasks about relative acid strength. From this study, they found that students seemed to fall into four different categories of mental models that are not necessarily hierarchical (Table 1). These categories included whether acidity was an intrinsic property of the compound, that acids donate protons, or that acids accept electrons. The most simplistic was Model A, which was an undeveloped conceptualization that viewed acidity as an intrinsic property of the molecule, due to some atom or functional group being present and that the presence of these atoms made the acid assume some of its features. Model B represented a mental model of acids that included the idea that acids lose hydrogen atoms or protons. These students did not reference conjugate base stability; therefore, they still attribute the acidity as an intrinsic property of the compound. Model C extends Model B to recognize that the acid that loses the proton, or hydrogen, then itself becomes a charged species. Although these students recognize the stability of the conjugate base, they did not necessarily distinguish between the inductive effect and resonance stability of the conjugate base. McClary and Talanquer noted that these students relied on the fact that more resonance structures meant a more stable conjugate base. Model D was related acids as electron acceptors, which "resembles the concept of a Lewis acid," which was only used as a secondary model for two students (McClary & Talanquer, 2011a). This lack of usage of the Lewis acid theory echoes the results found by Cartrette and Mayo (Cartrette & Mayo, 2011).

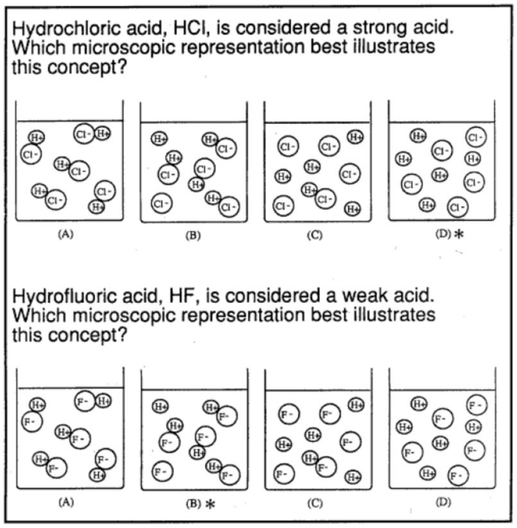
Table 1. Mental model of acids and acid strength. Adapted with permission from McClary, L., & Talanquer, V. (2011). College chemistry students' mental models of acids and acid strength. Journal of Research in Science Teaching, 48(4), 396-413. doi:10.1002/tea.20407. Copyright (2020) John Wiley and Sons

Model A: Acidity as an intrinsic property of substances. Acid strength determined by the presence of certain types of atoms or functional groups in the molecule (composition/structural features). Lack, or very underdeveloped, sense of mechanism for acid behavior. Acids perceived as unstable substances
Model B: Acids as substances that lose hydrogens or protons. Acid strength determined by intrinsic properties of the acid, some explicit (# of H atoms) some implicit (polarity), some molecular (molecular polarity), some local (bond polarity)
Model C: Acids as substances that donate protons. Acid strength determined by implicit properties of the molecule (mostly electronic; mostly local) that help stabilize the conjugate base
Model D: Acids as substances that accept electrons. Acid strength determined by the number of lone electron pairs or empty orbitals

McClary and Talanquer indicated that some of the students utilized multiple models, and this was dependent on two different contexts, either the task trigger or a trigger by a feature of the molecule. Most of the students that were feature-triggered used only Model B and Model C in conjunction with each other. During the ranking task, some of the rankings required the use of the conjugate base stability for the determination of the model, and these students shifted their model usage. The authors noted that, on average, these students were using multiple sets of criteria and struggled to pick out salient features relevant to the ranking. When these students used Model B, it appeared that they were utilizing differences in electronegative or atom size for their decision making. In contrast, when they used Model C, they were making decisions based on whether unsaturated bonds or conjugated systems were involved. However, one student used three different models that appeared to be guided by the salient features of the specific ranking task, which allowed him to differentiate between the substances (McClary & Talanquer, 2011a).

The task-triggered shifts came as part of the explanation and justification steps, which seemed to assist them in their explanation or justify their decisions. In the explanation task, students seemed to struggle with the meaning of pK_a, which seem to trigger a shift. When students tried to justify their ranks, some shifted their models to accommodate the explanation, or even had a revelation of previously undiscussed factors. The authors pointed out one student that had a difficult time reconciling the different models from the viewpoint of a proton donor to the electron acceptor, in which they indicated that it is the use of multiple models at play (McClary & Talanquer, 2011a).

Mental models are not the only way that we can understand students' conceptions of acids, models can be visual models that students either developed (Nakhleh, 1994; Nyachwaya, 2016), or interpreted (Jasien, 2005; Smith & Metz, 1996) at the microscopic level. As part of a more extensive study, Nakhleh (1994) presented four models of matter that emerged from interviews with secondary students on their understanding of acid-base concepts on the molecular level. Although the analysis included verbal dialogue and drawings, Nakhleh indicated that many students had a difficult time verbalizing their thoughts while utilizing molecular models. Furthermore, most showed poorly formed concepts of acid solutions at the molecular level. The analysis of the drawings confirmed the verbal descriptions, and students fell on a spectrum of nonparticulate, where these solutions were drawn as bubbles, or waves to partial ionic conceptions (Nakhleh, 1994). Findings like this continue to be revealed in a more recent study by Nyachwaya (2016) in which students were unable to develop appropriate particulate level depictions of acid-base systems at different stages of a neutralizations (Nyachwaya, 2016).



Hydrochloric acid, HCl, is considered a strong acid. Which microscopic representation best illustrates this concept?

Hydrofluoric acid, HF, is considered a weak acid. Which microscopic representation best illustrates this concept?

Figure 3. Acid Strength Questions. Reprinted with permission from (Smith, K. J., & Metz, P. A. (1996). Evaluating Student Understanding of Solution Chemistry through Microscopic Representations. Journal of Chemical Education, 73(3), 233. doi:10.1021/ed073p233). Copyright (2020) American Chemical Society

Due to growing concerns of students' algorithmic learning approaches, Smith and Metz (1996) interviewed undergraduates, graduate students, and faculty while they performed a multiple-choice assessment for two microscopic representations, a strong acid and a weak acid, to examine the conceptually understanding based on microscopic representations, Figure 3. For the representations of the strong acid, approximately half of the undergraduates chose the correct answer, and approximately half chose one of the incorrect choices. The most often wrong choice picked was the representation that none of the acid had dissociated. When probed, the most common reason students selected this representation was the belief that strong acids contain a strong bond and do not dissociate. This same finding was seen in the 2005 study by Jasien when he performed a study of undergraduates chemistry students' conceptual understanding of numerical and pictorial representations of acid-base concepts (Jasien, 2005). Smith and Metz were also offered reasons that included that acids accept the hydrogen from bases, strong acids are not soluble and that the representation that was completely dissociated represented a strong base, therefore the opposite picture must be a strong acid. Interestingly, the authors noted that many of the students successfully defined that a strong acid dissociates completely; however, this knowledge did not translate to the microscopic pictorial representations (Smith & Metz, 1996).

Smith and Metz reported that the representations for the weak acid had a slightly lower success rate for undergraduates and more varied responses for incorrect choices. Some students chose a representation that was the direct opposite of what they chose for the strong acid. When probed, students indicated that they felt that weak acids were able to be pulled apart more easily, which has been seen in other studies (Jasien, 2005). Furthermore, many students admitted to simply guessing their answer. Interestingly, the graduate students and faculty performance dropped on the weak acid microscopic pictorial representations to 60% and 82% success rates, respectively. Graduate students' reasoning ranged from surprise that HF was a weak acid to trying to recall the K_a value or claims that it had been too long since they study the topic. Smith and Metz claimed that when students simply memorize definitions without being able to visualize them at a molecular level (Smith & Metz, 1996), they are not truly able to comprehend them entirely. This finding aligns with Johnstone's contention that for students to learn chemical knowledge, they must be able to integrate the microscopic definition along with a symbolic representation (Johnstone, 2000).

2.2.2 Acid-Base Reactions

The symbolism in acid-base chemistry is not only related to the basic definitions and microscopic representation of acids and base, but students have to consider the identification of acids and bases in reactions which can be difficult for them (Bretz & McClary, 2015; Cartrette & Mayo, 2011; Cros et al., 1986; Ferguson & Bodner, 2008; Orgill & Sutherland, 2008; Stoyanovich et al., 2015). Students must also be able to interpret the conceptual meaning behind the curved arrow formalism, or electron pushing formalism, used in reaction mechanisms (Bhattacharyya & Bodner, 2005; M. M. Cooper et al., 2016; Dood et al., 2018; Ferguson & Bodner, 2008; Grove et al., 2012). When engaged in evaluating reactions students may invoke concepts of basicity, nucleophilicity, electronegativity, and stability through resonance (Ferguson & Bodner, 2008), however, it is noted by the researchers that these concepts may only be understood at a superficial level (Bhattacharyya & Bodner, 2005; Ferguson & Bodner, 2008; Grove et al., 2012; Strickland et al., 2010). Grove and colleagues (2012) explored organic chemistry students' development of the understanding of organic reaction mechanisms over two semesters by engaging students in using the reaction mechanism to predict the products. Unfortunately, many students only provided the products without showing the reaction mechanism, or would write out the products, then fill-in the reaction mechanism, indicating little connection to the use of the curved arrow notation, or even any usefulness of the process in the student's mind (Grove et al., 2012). This finding was not unique; previous research has found that students seem to be more concerned with what the product is over what is the process of getting to the products (Bhattacharyya & Bodner, 2005; Ferguson & Bodner, 2008). It should be noted that in the previous study performed with graduate students by Bhattacharyya & Bodner (2005), the students were able to construct the mechanism with curved arrow formalism; however, they were unable to explain the chemical context behind them, including the "how" and "why" of the reaction.

Cooper et al. (2016) developed an assessment task to characterize student reasoning in acid-base reactions in which students in a transformed general chemistry course constructed explanations about "what" happens, "why" it happens, and "how" it happens. The assessment task was a reaction of HCl with water forming the hydronium ion and chloride ion, where the Lewis structures were provided with all the lone pairs present. It was presented in this manner to focus the students' attention on the area of interest, which was the reaction occurring and draw their attention to the structures by providing the lone pairs of electrons (M. M. Cooper et al., 2016), which has not been done in previous work (Bhattacharyya & Bodner, 2005; Grove et al., 2012). The "what" of the acid-base reaction can be described by either the Bronsted-Lowry model, through the transfer of a proton, or the Lewis model, through the attraction of the electrons to the electron-deficient area. However, to describe "how" a proton is transferred, a student must utilize the Lewis model. Cooper and colleagues clarify that although the arrow formalism can describe the "how" and "why" of the reaction, the mechanistic reasoning is associated with "how" happens, and the causal mechanism is associated with "why" the reaction occurs. The responses were evaluated by categorizing varying levels of sophistication that progressed from no response to descriptive to Bronsted type models terminating at the Lewis Causal Mechanistic, where they provided the "what," "why" and "how" in their explanation. The initial assessment did not elicit that desired response from students, so instead of "Please explain your answer…," the task prompts were altered to say, "Describe in full detail what is happening…" and "explain why this is happening." The final iteration also asked for students to provide the reaction mechanism. Most students were able to convey that the reaction was between an acid and a base. It was noted that some of the students used mixed models that incorporated Bronsted-Lowry and Lewis by utilizing protons and electrons in their explanations. Students who invoked the Lewis model and drew the mechanism for the reaction were more likely to get the mechanism correct (M. M. Cooper et al., 2016). This finding was corroborated by Dood et al., who utilized a slightly modified form of this same assessment in a lexical analysis study of organic chemistry students (Dood et al., 2018). Furthermore, within the same acid-base model, those who utilized the causal explanation of "why" had a higher rate of success on providing the correct reaction mechanism. Therefore students who used the Lewis causal model had the best chance of success (M. M. Cooper et al., 2016).

In an extension of Cooper and colleagues' 2016 study, Crandell and colleagues (2019) evaluated student understanding of acid-base reactions using causal and mechanistic reasoning by examining students during two semesters of traditional organic chemistry, who were previously enrolled in either a traditional or transformative general chemistry course. At the beginning of organic chemistry, the traditional chemistry students tended to use Bronsted-Lowry model explanations for the task on HCl and water, when compared to the transformative general chemistry curriculum who tended to use more of the Lewis model, which invoke the causal mechanistic reasoning. Interestingly, the traditional general chemistry course students cited the use of electrons in the context of the second task, where only Lewis was applicable (Crandell et al., 2019), which is in contrast to the findings of Cartrette and Mayo when students tried to force the use of the Bronsted-Lowry model where only the Lewis model would be appropriate (Cartrette & Mayo, 2011). The researchers indicated the reaction of NH_3 and BF_3 was often presented in the context of the Lewis model, and it prompted the "activation of resources aligned" with that model.

Crandell et al. reported that after two semesters of organic chemistry, all the students showed improvement in their causal mechanistic reasoning. However, students that had been in the transformative general chemistry curriculum were more likely than other students to provide a Lewis causal mechanistic explanation. Furthermore, the transformative general chemistry students were better at drawing mechanistic arrows for the reaction even though they were all enrolled in the same organic chemistry course with the same instructor. These findings indicate that the transformative general chemistry curriculum had an impact on the students' success. However, the gap in mechanistic explanations that were present at the beginning of organic chemistry I between the students with a traditional general chemistry background and the transformed general chemistry background disappeared by the end of organic chemistry II (Crandell et al., 2019). This study reaffirmed Cooper's earlier finding that students that invoke the Lewis causal mechanistic model are more likely to draw the correct reaction mechanism (M. M. Cooper et al., 2016).

2.2.3 Nucleophiles and Electrophiles

One of the prerequisites for understanding reaction mechanisms is the role of nucleophiles and electrophiles (Bhattacharyya, 2013). Research has shown that students have confusion in the ability to distinguish a Bronsted-Lowry base and a nucleophile (Bhattacharyya & Bodner, 2005; Cartrette & Mayo, 2011; Ferguson & Bodner, 2008; Strickland et al., 2010), which indicated a lack of process-oriented thinking, also termed as mechanistic reasoning

(Strickland et al., 2010). Students can often define and point out attributes of a nucleophile and an electrophile but are unable to explain the underlying concepts such as polarizability, resonance, or inductive effects (Anzovino & Bretz, 2015, 2016; Cartrette & Mayo, 2011; Strickland et al., 2010), which is reminiscent of surface-level understanding in reaction mechanisms. When Cartrette and Mayo (2011) interviewed students, and they were asked to define a nucleophile and an electrophile, only twelve of the fourteen students were able to define them correctly. However, only eight were able to support their definitions with characteristics. Then, when students were prompted about any correlation of nucleophiles and electrophiles to acids and bases, only four students were able to draw the correct connections between them. Although students were able to define nucleophile and electrophile, they inappropriately used Bronsted-Lowry acid-base theory to reason through their explanations. Therefore, students are not making meaningful connections for these concepts to Lewis acid-base theory. Although one student who had more meaningful, deeper connections was able to explain the relationships between the terms of electrophiles being electron loving and acids are accepting electrons (Cartrette & Mayo, 2011).

Interestingly, in a study by Anzovino and Bretz, students again exemplified the rationale of structure over function, where they relied mostly on the charges of the molecules to determine whether they were nucleophiles or electrophiles after they had completed their reaction mechanisms (Anzovino & Bretz, 2015). This study arrived at results similar to Cartrette and Mayo, in that most students were able to define nucleophiles and electrophiles concerning charge and the etymology of the word, while less than half associated them with an acid-base theory (Anzovino & Bretz, 2016). Furthermore, this same result has been seen in a study of graduate students, Strickland et al. (2010) reported that about half of the students provided superficial definitions of nucleophiles and electrophiles by utilizing the etymology of the words (Strickland et al., 2010).

2.2.4 Equilibrium

Symbolism in reactions is not only presented in the mechanism by the curved arrow formalism but in the acid-base reactions to indicate the direction(s) of the reaction and the extent of the reaction, in which the symbolism communicates necessary information to the student. Research has shown that students do not understand the symbolism presented in equilibrium reactions (Gussarsky & Gorodetsky, 1990; Hackling & Garnett, 1985). It is worthwhile to note that some general chemistry textbooks represent the dissociation of hydrochloric acid in water, which is a strong acid dissociation that goes to "completion" represented by a single arrow (Tro, 2010). Then students enter organic chemistry, and the textbook presents a reaction for the dissociation of HCl in water as a reversible reaction that goes "mostly to completion" (McMurry, 2016). Research has shown that students struggle to differentiate the concepts of completion reactions and reversible reactions (Hackling & Garnett, 1985).

The word equilibrium elicits the intuitive notion from students that equilibrium will mean equal (Loertscher et al., 2014). It has been suggested that the misuse of language may be a root of some of these student views of equilibrium (Loertscher et al., 2014). Johnstone has suggested that the everyday use of the context of equilibrium is at odds with the chemistry concept of equilibrium. The everyday equilibrium that is utilized when riding bicycles or carrying baggage requires that masses are equal on each side, and if you add something to one side, it will go toward that side (Johnstone, 2000, 2010). Additionally, students have used words to describe equilibrium in terms of being "balanced" (Gussarsky & Gorodetsky, 1990), "stable," or "just right" (Loertscher et al., 2014). This conception of balance has been demonstrated in a study by

Hackling and Garnett, where students most often connected the idea that the equilibrium indicated that the concentration of the reactants and products were equal, which they suggested was based on the reaction stoichiometry (Hackling & Garnett, 1985). Students have described the equilibrium system in a more anthropomorphic manner that everything is happy (Loertscher et al., 2014).

The nature of the reaction for chemical equilibrium has been shown to be problematic for students (Banerjee, 1991; Gussarsky & Gorodetsky, 1990; Loertscher et al., 2014). Research has shown that the incongruity for students' minds for the ideas of that equilibrium reactions move back and forth and yet can still favor one side (Loertscher et al., 2014). Gorodetsky and Gussarsky (1986) found that both high and low achieving students struggled to understand the underlying features of chemical equilibrium, concerning its dynamic and reversible nature of two reactions occurring at the same rate. Furthermore, students have difficulty with the concept that this is a dynamic equilibrium that is a continual process and not a static system (Gussarsky & Gorodetsky, 1990). It has been evidenced that upper-level biochemistry students think that equilibrium applies differently to biological systems than it did in general chemistry or organic chemistry (Loertscher et al., 2014).

Additionally, equilibrium concepts are often taught in conjunction with mathematical problem solving that students will often apply rote methods of algorithmic problem solving without comprehension of the underlying concept (Gussarsky & Gorodetsky, 1990). Johnstone (2010) suggests that students working memory are already burdened by merely learning the concept of equilibrium without the addition of calculations, which leads to “chaos” (Johnstone, 2010).

The extent of the reaction is measured by the equilibrium constant, which has been investigated for general types of equilibrium. In a study by Hackling and Garnett (1985) of Year 12 students in Australia, students struggled with the idea that the equilibrium constant value would not change with change conditions of concentrations in the system. However, some students inappropriately applied the concept that equilibrium constants do not change when temperature changes occur (Hackling & Garnett, 1985). During the development of the biochemistry thresholds, some students had already completed biochemistry that still lacked the foundational understanding of equilibrium constants to be able to apply it in biochemistry (Loertscher et al., 2014).

Research has indicated that ionic equilibrium concepts present more difficulties for students compared to other equilibrium concepts (Banerjee, 1991; Camacho & Good, 1989). In a think-aloud study of problem solving and equilibrium by Camacho and Goode (1989), the participants were comprised of thirteen novices and ten experts. The novices included five high school students and eight undergraduate students, both majors and non-majors, while the expert group included six doctoral students and four faculty members. The gas-phase problem-solving had the same number of unsuccessful problem solvers, whereas the number of unsuccessful problem solvers increased with the ionic equilibria problems. Interestingly, the doctoral students in the "expert" group with less teaching experience performed less successfully than their peers. Camacho and Goode found that the significant difference in successful and unsuccessful problem solving was the amount of specific content knowledge utilized by the participant. One particular issue that was brought to the attention of the researchers was the lack of all novice learners and two of the experts to be able to have the appropriate knowledge to distinguish between the various chemical equilibrium constants: K_c, K_p, K_a, K_b, and K_{sp}. Some of these subjects had further complications due to the inability to write out the appropriate names and symbols for molecules. The failure to successfully solve problems related to equilibrium constants also stemmed from the fact that all the novices and some of the experts could not recall the mathematical relationships for determining the equilibrium constants. One interesting finding that Camacho and Goode noted was the lack of the novice learner to make the connection between K_a and K_{sp}, as equilibrium constants (Camacho & Good, 1989).

Jasien (2005) performed a study of conceptual understanding of acids that utilized a paired format of numerical and pictorial items in a distractor driven multiple-choice instrument. The participants included undergraduates in chemistry in general chemistry I, II, and biochemistry at four higher education institutions, a community college, a public university, and a selective private university. One pair of questions was associated with the acid ionization constant, K_a. It was found that most students were able to select the proper numeric values related to K_a. Interestingly, the biochemistry students performed the worst on this task. The corresponding task for the pictorial question showed a decrease in performance for all courses in their ability to select the appropriate molecular level representation of the weakest acid. Again, there was an almost 20% drop in performance from the general chemistry II course to biochemistry course at the select private university.

2.2.5 Acid Strength

K_a is not the only way students determine acid strength. Relative acid strength can be determined by observation of composition, structural and electronic features of compounds. Research has shown that students rely on heuristics (McClary & Bretz, 2012; McClary & Talanquer, 2011a, 2011b) and inappropriate models (Cartrette & Mayo, 2011) for reasoning in tasks associated with relative acid strength.

Maeyer and Talanquer (2010) performed a study on general chemistry II students' ability to rank chemical substances, which included acids and bases. In general, the students who were interviewed used heuristics, or short cut reasoning, to arrive at their answers. As a result, a more extensive qualitative study was designed to promote the use of heuristics, including recognition and one-reason decision making. The recognition heuristic is where students select an answer since they feel like they have seen it more, therefore it holds more value. For example, when students were ranking acids, 79% used the recognition heuristic when ranking HCl, H_2S, and HI, since many of them recognized HCl. However, the recognition heuristic was task-dependent and not utilized as much for the melting point and boiling point tasks. The one-reason decision-making heuristic is where selections are made by using simple rules based on cues to decide of this over that one. Maeyer and Talanquer noted that students often used this decision-making tool without regard to the whole task, they would isolate choices and choose between these two and then those two neglecting the use of different decision-making factors for the ranking choices. Students made choices of acid strength based on the number of hydrogens, that more hydrogens in a compound indicated a stronger acid. The study also reported that students would use atomic properties over molecular properties by isolating atoms in the structure to explain their reasoning, rather than viewing the entire structure (Maeyer & Talanquer, 2010). This same isolation of surface-level features have been observed in organic chemistry I and organic chemistry II (McClary & Bretz, 2012; McClary & Talanquer, 2011b).

Following Maeyer and Talanquer's study on ranking, McClary and Talanquer (2011) performed a similar ranking study. However, it only included acid strength ranking concepts, and it was designed for more advanced students in organic chemistry with more structural and composition knowledge than general chemistry students would possess (McClary & Talanquer, 2011b). The study utilized seven ranking tasks with three compounds in each set to probe students' ability to rank relative acid strength based on compositional, structural, and electronic features, such as the inductive effect and resonance. The study identified three main heuristics at use by the student, including reduction, representativeness, and lexicographic. The reduction heuristic is where the commonality of the compound can be observed and therefore discard because they are alike. However, it was noted by the authors that lead to cases where students did not pay attention to the structural feature of interest. The representativeness heuristics is utilized to determine whether a molecule belongs to a group. This heuristic led students to make wrong choices only looking at functional groups such as the carboxylic acid group, or the hydroxyl group to determine relative acid strength.

Additionally, as was seen in Maeyer and Talanquer's previous study (Maeyer & Talanquer, 2010), students judged acid strength on the idea of more of "this" is present, so it is more acidic (McClary & Talanquer, 2011b). The lexicographic heuristic is a type of one-reason decision making. This heuristic often led to the correct ranking if appropriately used. This heuristic included using the electronegativity of the atom attached to the acidic proton, the type of substituents attached to the compound, and resonance structures. However, it was noted that students struggled when they relied on only a single factor when making decisions. The study revealed that students often failed to understand the unpinning mechanism of the concept and relied on the heuristic to rank acid strength. Additionally, students utilized the concept of more resonance forms means more acid strength, without any considerations of stability, or even any visualizations of the resonance structures (McClary & Talanquer, 2011b).

McClary and Bretz (2012) extended the research on the acid strength ranking tasks by utilizing the prior work of McClary and Talanquer (2011) to create a multitier multiple-choice diagnostic instrument designed to evaluated misconceptions and determine the strength of misconceptions (McClary & Bretz, 2012). The instrument was designed with three deep structured prediction tasks that would elicit the student's confidence in their answer. The data revealed two misconceptions related to functional groups and stability (McClary & Bretz, 2012). In agreement with previous research (McClary & Talanquer, 2011b), students relied on the functional group to determine acid strength, which can lead to overgeneralization and neglect molecular properties (McClary & Bretz, 2012). McClary and Bretz also noted that although students could draw on the diagnostic tool, none of the 104 participants drew the conjugate base to verify which hydrogens on the molecule of interest would be the most acidic (McClary & Bretz, 2012). This is an important skill, as research has shown that student's inability to determine the most acidic hydrogen on a molecule has been shown to impede their progress on developing correct reaction mechanisms (Ferguson & Bodner, 2008). The misconception related to stability is that some students indicated that an increase in stability decreases acid strength, not recognizing that the decrease in strength is for the conjugate base rather than the original acid. An interesting finding on this instrument was that students who answered incorrectly in their ranking of acid strength were, on average, very confident in their answers, indicating an unawareness of their lack of knowledge (McClary & Bretz, 2012).

Cartrette and Mayo (2011) utilized an acid strength rank activity to study students' connections between conceptual and procedural knowledge for acids (Cartrette & Mayo, 2011). The students were asked to rank acid strength by structural features of several compounds as strong, moderate, or weak acids and justify the answers. One set of compounds was able to be deciphered utilizing Bronsted-Lowry acid-base theory, while the second set was only capable of being interpreted using Lewis acid-base theory. The performance on this first set of compounds was low with little variation. Students were unable to predict acid strength correctly or provided only part of the reasoning, aside from one chemistry major and one pre-professional who utilized structural factors such as polarity, resonance, induction, and orbital hybridization.

In the second set of compounds, in which the students had to use the Lewis acid-base model, students were confused about whether the acid would accept or donate electrons. When discussing boron trifluoride, a student suggested it would donate electrons because of all the electrons around the fluorines. While another, used indicated she was using Bronsted Lowry acid-base theory to determine that boron trifluoride was an acid because it could not accept an H^+, since it was stable and not charged. Another molecule present was ammonia, while many of the students answered correctly; they utilized the improper acid model for their reasoning. When a positive charge was present on a molecule, students were better able to identify its' strength correctly. Many of the incorrect responses were based on students forcing the Bronsted-Lowry model to fit their needs (Cartrette & Mayo, 2011).

2.2.6 Rate and Rate Laws

Although chemical kinetics may not initially seem related to acid-base equilibrium concepts, research has shown that students have confused rates and equilibrium (Bain et al., 2019; Banerjee, 1991; Becker et al., 2017; Camacho & Good, 1989). Camacho and Goode (1989) noted in their study of problem-solving and chemical equilibrium, almost all the novice students "confused the extent, or completeness of the reaction with the rate of the reaction in achieving equilibrium" (Camacho & Good, 1989). This same result was seen in other studies of chemical equilibrium (Banerjee, 1991; Hackling & Garnett, 1985). Additionally, Banerjee found that participants interpreted a large value of an equilibrium constant to be a very fast reaction (Banerjee, 1991). Students have used principles that are applied to constructing equilibrium constants to construct rate laws (Bain et al., 2019; Becker et al., 2017). Bain, et al. (2019) a quarter of their sample of 36 general chemistry, five physical chemistry, and three engineering students confused rate constants with equilibrium constants. In the semi-structured interviews, these students seemed to struggle with the surface-level features of both constants. They both begin with the letter "k" and have a similar mathematical form, where k is proportional to some concentration of the products represented by brackets possibly raised to an exponent (Bain et al., 2019).

2.2.7 pH and pK$_a$

Students are taught the concept of pH during most general chemistry courses. In a study of first-year university students, Cros et al. (1986) found that only 17 % of students were able to provide a qualitative description of pH as measuring the degree of acidity. In contrast, almost half defined pH with its mathematical formula of $pH = -\log [H_3O^+]$, and the other 15% misremembered it (Cros et al., 1986). One source of confusion with pH was revealed in Orgill and Sutherland's (2008) study on students' perceptions of buffers, where many of the general chemistry, but some biochemistry students confused the hydronium ion concentration, used for pH, with the concentration of the weak acid (Orgill & Sutherland, 2008).

Many students are hampered not only by the basic content knowledge concerning pH but the associated mathematical concepts of exponents and logarithms (Camacho & Good, 1989; Orgill & Sutherland, 2008; Watters & Watters, 2006). Camacho and Goode (1989) found that problem-solving was hindered by the inability to utilize the logarithm laws in pH to connect with the concentration of protons and to make connections between K_a and pK_a (Camacho & Good, 1989). Watters and Watters (2005) interviewed biochemistry students to ascertain their understanding of pH and pK_a as it is an important concept in biochemistry for understanding the ionization state of biomolecules. None of the students in the study were able to utilize pH appropriate in a problem with sound conceptual understanding. Almost half of the students had naïve concepts of pH, which included ideas such as the concept if a solution contains HCl, it must be acidic, not taking into consideration the concentration of the acid, and lacked necessary math skills to calculate the pH. Students who were able to calculate the pH were unable to apply appropriate content knowledge of very dilute acids. It was noted that most of the students could not manually calculate the logarithm. It required the assistance of a calculator (Watters & Watters, 2006), where the dependence of a calculator caused additional complications. Some students inappropriately used the wrong button on the calculator for the logarithm, using the natural logarithm instead of log base 10 (Orgill & Sutherland, 2008).

In general chemistry, students generally learn to connect the concepts of pH and pK_a in terms of the Henderson-Hasselbalch equation. However, research has shown that upper-level students lack basic content knowledge of pH, pK_a, and ionization and are unable to make coherent links between these concepts (Orgill & Sutherland, 2008; Villafañe, Loertscher, et al., 2011; Watters & Watters, 2006). In a study by Watters and Watters (2005), biochemistry students would rely on retrieval of fragments of knowledge from their memory and disconnected concepts, which ultimately did not lead them to success in trying to analyze data. Interestingly, the researchers point out that what the students were retrieving was a sentence from their study guide about the relationship of pH and pK_a that stated, "when the pH is less than pK_a, the proton is on, and when the pH is greater than pK_a, the proton is off." Primarily from the memorization of these facts, all of the students except one made no meaningful connection to the Henderson-Hasselbalch equation (Watters & Watters, 2006). Orgill and Sutherland (2008) reported that upper-level students had a difficult time understanding how and why buffers work because they failed to make connections to other necessary concepts like pH, ionization, and the molecular structures. Furthermore, in the study, while working through problem-solving, students approach them as if they were solving math problems and manipulating numbers without regard to the chemical species involved in the buffer system. Some students had issues distinguishing pK_a from K_a, as well as equating pH with pK_a (Orgill & Sutherland, 2008).

In 2011, Villafañe et al. utilized the Biochem Diagnostic Assessment Instrument to assess the biochemistry students understanding of foundational concepts that are needed before taking the course as a pretest and posttest for an introductory biochemistry course at a Midwestern United States public research institution. The sample was $N = 125$ students, which completed both the pretest and posttest assessments. The three distractor items were included in the multiple-choice assessment. The first was that when pH equals pK_a, the ionizable group is all protonated or all deprotonated. The second was that when pH is less the pK_a, the predominate species is deprotonated (or pH is greater than pK_a the predominate species is protonated). Lastly, that pH does not affect ionizable groups. After a semester of biochemistry, there was a statistically significant average gain score of 0.13 ($p < 0.01$), which indicates that there was an increase in students' pretest and posttest scores. Focusing on the pH and pK_a question set, only 12% of students correctly answered on the pretest, and 30% of students answered correctly on the posttest. Of note, students in this study would have likely completed at least two semesters in general chemistry and two semesters of organic chemistry before this instruction, and only one-third of students were able to get this right (Villafañe, Loertscher, et al., 2011).

2.3 Assessments

Assessments convey to students what is important about a course and, as such, will tailor their learning to examinations (Momsen et al., 2013; K. Scouller, 1998). In a study of organic chemistry assessments, Stowe and Cooper (2017) note that students will learn pattern recognition and simple algorithms by utilizing methods such as flashcards if all that is expected on exams is a simple recall from their notes rather than conceptual understanding. To their dismay, 93% of the exam items that were assessed did not use any of the eight scientific practices (Stowe & Cooper, 2017) as outlined by *The Framework for K-12 Science Education (National Research Council, 2011)*. These science practices include:

1. Asking questions
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations
7. Engaging in arguments from evidence
8. Obtaining, evaluating, and communicating information (National Research Council, 2011)

Many instructors feel that classroom assessments will indicate whether students have understood a concept. Still, often, in reality, students may not as the assessment may not be testing at the level of conceptual understanding. Research suggests that it cannot be assumed that although students select an appropriate response that they have a deep understanding of the concept (Stowe & Cooper, 2017). The ACS-EI conducted an open-ended survey of 1,395 recent general chemistry instructors to define conceptual understanding in chemistry education. "In chemistry, there are core chemistry ideas that include theories, practices, patterns, and relationships. A student who can demonstrate conceptual understanding can:

- Transfer – apply core chemical ideas to chemical situations that are novel to the student
- Depth – reason about core chemistry ideas using skills that go beyond mere rote memorization or algorithmic problem solving
- Predict – expand situational knowledge to predict and/or explain the behavior of a chemical system
- Problem Solving – demonstrate the critical thinking and reasoning involved in solving problems including laboratory measurement
- Translate – translate across scales and representations (T. A. Holme et al., 2015)"

The ACS-EI indicates that at least one of these five categories must be present in an assessment item for it to be considered to be testing at the level of conceptual understanding (T. A. Holme et al., 2015). As noted by Crandell and colleagues (2019), that although students are shown to have a superior understanding of reaction mechanisms at a causal mechanistic level, which indicates mechanistic reasoning about "what," "why" and "how" a reaction is occurring, it is not currently reflected in their grades, as even such "elite" testing sources, such as the ACS examination does not test knowledge at this level (Crandell et al., 2019). This finding is in agreement with ACS-EI's findings that acknowledge, for the ACCM anchoring concept for the concepts of structure and function and equilibrium; it currently lacks testing students on constructing explanations on ACS general chemistry exam items (Reed et al., 2017). These findings concurred with research by Stowe and Cooper (2017), who analyzed an assortment of organic chemistry exams from elite universities. The analysis utilized *The Framework for K-12 Science Education* for scientific and engineering practices (National Research Council, 2011) as a guideline. Stowe and Cooper found that when students are asked to draw the reaction mechanism, they are not asked for any explanation of how or why it is occurring (Stowe &

Cooper, 2017). This assumption is an example of the underlying problem that if the student can reproduce the curved arrow movement in a reaction mechanism, that indicates an understanding of the mechanism, which the research has shown is not the case (Bhattacharyya & Bodner, 2005; M. M. Cooper et al., 2016; Crandell et al., 2019; Ferguson & Bodner, 2008; Grove et al., 2012).

Many instructors do not align assessments with the expected content knowledge in mind (Cornog & Colbert, 1924; Momsen et al., 2013; Stowe & Cooper, 2017). Momsen (2013) points out that assessments do not always assess the learning outcomes for courses as instructors are not properly trained to develop assessments. They will make assessments similar to what they experienced, content that can be assessed easily, and basic facts and concepts without the requirement of more complex cognitive skills (Momsen et al., 2013). For instance, in 1923, in some of the earliest stages of chemistry education research, Cornog and Colbert surveyed twenty-seven college and university chemistry instructors to find out what was being taught to first-year college students by use of a questionnaire, review of the texts and inspection of final exam questions. The study found that approximately 70% of instructors emphasized theory, whereas the textbooks had almost the exact opposite emphasis. Additionally, they found “sharp contraindications” of the material covered on the exams that did not coincide with the instructor's focus during instructions. Cornog and Colbert point out that students will inevitably find old exams and learn only as much as they need to pass an exam (Cornog & Colbert, 1924).

Almost a hundred years later, in a study of organic chemistry examinations by Stowe and Cooper noted similar findings to Cornog and Colbert. Stowe and Cooper indicated that the rhetoric used to promote organic chemistry is that it will encourage “scientific ways of thinking.” However, it did not align with what is presented on examinations. The examination items required algorithmic problem-solving and pattern recognition. (Stowe & Cooper, 2017).

Furthermore, research has shown that problem solving by algorithmic methods does not equate to conceptual understanding (Nakhleh & Mitchell, 1993).

Research has suggested that words can control the extent of the ability of a student to provide an answer, and it is not necessarily dependent on their chemical knowledge (Cassels & Johnstone, 1983; Johnstone & Cassels, 1978). Therefore, it is crucial to make sure the task prompt in an assessment can elicit the desired response without providing too much information to the student (M. M. Cooper et al., 2016; Stowe & Cooper, 2017). Research has shown that even a change of one or two words in a task prompt can greatly improve outcomes in an assessment by reducing "linguistic noise" (Cassels & Johnstone, 1984; M. M. Cooper et al., 2016; Johnstone & Cassels, 1978). Cassels and Johnstone (1984) found that the simple substitution of simpler words improved student performance on assessments, such as removing negative terms. Terms that referred to amounts of a substance in an implicit and contrary way, such as "most dilute" or "least abundant," were also difficult for students to decipher. The substitution of more formal phrases in assessment tasks, such as "tendency to predominate," also increased student performance. Lastly, extensively wordy sentence structure impeded student performance on assessment items suggesting that short, concise task prompts on assessment items would improve performance (Cassels & Johnstone, 1984). Other research has indicated that increased cognitive demand does not equate to the increased difficulty of the content of the task (Momsen et al., 2013).

Research suggests that the words used in task prompts may not elicit the intended response. In a study by Cooper et al. (2016), they found that the initial assessment task prompt, which asked students to "please explain your reasoning," was insufficient to elicit the desired depth of response. The final iteration of the task prompt asked students to "describe in full detail what you think is happening" and "please explain why you think this is happening." The 1st group of students few students provided merely descriptive rather than any reasoning on what, why, or how compared to the 2nd group of students, with a statistically significant difference between the two groups of students ($\chi^2 = 48.55$, $p < 0.001$, $\varphi = 0.46$).

In a study by Stowe and Cooper (2017) of organic chemistry assessment items, they indicate that prompts should include "explicit" science practices as outlined by *The Framework for K-12 Science Practices* to help ensure assessment at a deeper level of learning. Furthermore, they suggest that the method of "everything is important" and "testing for everything" leads students to utilize less than desirable methods of learning, like rote memorization. In this situation, students can provide answers with more insight into their understanding of important topics, rather than simple "trivia." One of the underlying threads in their suggestions of adding science practices to assessment items was the concept of student justification of their answer, rather than simple analysis (Stowe & Cooper, 2017).

Momsen (2013) points out that how a task is framed rather than a simple lack of content understanding can impact student success on exams. The framing in task prompts can cause students to activate resources in an inappropriate context. (Momsen et al., 2013). Assessments are often written as selected-response items or multiple choice (Cassels & Johnstone, 1984). In multiple-choice tests, students often use strategies of rote learning to prepare by memorizing facts and formulas, where this surface-level learning impacts the students' ability to learn in the future as they progress to upper-level courses (Momsen et al., 2013; K. Scouller, 1998). Research indicates that students' perceptions were to prepare for multiple-choice examinations by surface-level strategies, whereas they utilized deeper level strategies when confronting essay style assessments (K. Scouller, 1998). Momsen (2013) notes that students' ideas about science practices and knowledge are “shaped and reinforced” by assessments (Momsen et al., 2013). Stowe and Cooper (2017) note that when designing selected-response items, instructors should make sure that the items include science practices. Still, all types of assessment should encompass all three dimensions of The Framework for K-12 Science Education, including the science practices, cross cutting concepts, and core ideas to ensure strong evidence of student competence (National Research Council, 2013; Stowe & Cooper, 2017). Furthermore, the National Research Council states that selected-response items should not solely assess students.

2.4 Expert versus Novice

Unfortunately, it is often assumed that novices can solve problems in the same manner as experts (Stowe & Cooper, 2017), but that is not necessarily true (Bhattacharyya & Bodner, 2005; M. M. Cooper et al., 2016; Grove et al., 2012). According to the National Research Council (2000), experts have several distinct advantages over novices. Experts have a better ability to notice features and develop patterns compared to novice learners. By way of being “experts,” they have attained a great deal of organized content knowledge that they can flexibly retrieve and apply to a variety of new situations. Furthermore, experts can contextualize their knowledge into appropriate circumstances. (National Research Council, 2000).

Research has shown that improved capacity in the working memory improves performance in science (Johnstone & Al-Naeme, 1991). Working memory is used to temporarily store and processing information, such as understanding language, deciphering information, and making plans (Cowan, 2010; Johnstone, 2010). Although working memory reaches a maximum capacity around the age of 16, Johnstone (2010) suggests that experts learn to use their working memory more efficiently due to their interest and expertise in the content area. Johnstone notes that the amount of information that can be comfortably stored and processed in the working memory is approximately five pieces of information plus or minus two (Johnstone, 2010). Rather than Miller's magical number of seven plus or minus two (Miller, 1956), as that would only be feasible when no processing would be required (Johnstone, 2010). That is in agreement with Cowan's assertion that the working memory can process roughly four meaningful "chunks" of information (Cowan, 2010). Interestingly, Johnstone shared a list from 1971 in areas of common difficulty experienced by chemistry students that his group researched, which included the concept of equilibrium, where the common thread among the topics was the required amount of information that needed to be manipulated in order for learners to understand the topics, which incidentally was more information than the researchers anticipated (Johnstone, 2010).

The working memory capacity can be utilized better by using strategies to control the cognitive processing load in the working memory (Halford et al., 2007; Johnstone & Al-Naeme, 1991; Miller, 1956). One technique is called chunking, which involves recoding and reorganizing smaller pieces of information into a unit called a chunk (Miller, 1956). Research indicates that larger chunks are built up by practice and expertise, in turn providing an advantage to the expert problem solver over the novice by improved utilization of the working memory (Halford et al., 2007; Kozma & Russell, 1997; Miller, 1956). A second technique is called segmentation, which is the ability to process information in serial sequence rather than trying to performing them in parallel is an advantage for experts over novice learners (Halford et al., 2007). Furthermore, the cognitive load can be reduced by the ability of experts to control what information makes it to the working memory, where the relevant is attended to, and the irrelevant is ignored. Johnstone and Al-Naeme (1991) suggest that as experts, the instructors are better able to filter out the irrelevant information and reduce cognitive load compared to the novice learner freeing up space in the working memory for other activities. They suggest that this "signal" to "noise" issue can be a real problem in lectures where "on average the lecturer will deliver over 5000 spoken words in 50 minutes, but the student will record 1500 of these" (Johnstone & Al-Naeme, 1991).

Another part of the cognitive processes that utilize the working memory is the processing of language. Chemistry has its language, which can be unfamiliar, having a variety of meanings in different circumstances, or prompt students by nature of the word to activate improper resources (Cassels & Johnstone, 1983; Johnstone & Selepeng, 2001). It is important to note that the expert, the instructor, has mastered the language and possibly forgotten his/her struggles to develop that language skill (Markic & Childs, 2016). Furthermore, research has shown that in the instances where English is a second language for the student, they can lose up to 20% of their working memory capacity to process language-related information. The researchers suggest that these students would have more difficulty developing syntax and context for words within every day and scientific uses and therefore have difficulty extracting meaning from the words, leading to possible rote learning (Johnstone & Selepeng, 2001). For example, Johnstone (2010) points out that one of the topics that is prone to developing language barriers for students is the word "equilibrium" as they learn it in chemistry and physics with the same language, but in entirely different contexts which are counterintuitive to each other (Johnstone, 2010). Experts in chemistry can appropriately apply context when the same words are utilized in sometimes counterintuitive ways (National Research Council, 2000). It has been found in research that a word in a scientific context was more challenging to understand than in everyday context for students (Cassels & Johnstone, 1983; Johnstone & Selepeng, 2001).

In chemistry, the word 'strong' is used to represent strong bonds, in a sense that a larger amount of energy is needed to be input to break a bond. Whereas the word strong is used concerning dissociation of acids when a strong acid dissociates more easily. These two concepts can confuse students, let alone the everyday use of the word ‘strong.’ Smith and Metz (1996) investigated microscopic representations with undergraduates students, which included representations of a strong acid and a weak acid. For the representation of the strong acid, 46.6 % selected the representation in which none of the acid had dissociated. When probed during a think-aloud interview, the most common reason students selected this representation was the belief that strong acids contain a strong bond and do not dissociate (Smith & Metz, 1996). There was a similar finding in a study by Jasien (2005) that included both numerical and pictorial representations of the acid ionization constant, K_a; the students were more successful at the numerical representation of K_a. Still, they showed a decrease in the ability to select the appropriate pictorial representation of the stronger acid (Jasien, 2005). This difference in ability may indicate that the students are not clear on the meaning of the words for weaker versus stronger acid. Furthermore, the students struggle to move within Johnstone’s triangle as then representations are presented in different representations, whereas as experts can freely move around the triangle to decipher and translate the different representational levels into a coherent picture (Johnstone, 1991, 2010; Taber, 2013; Talanquer, 2011).

In a follow-up study by Jasien (2010), undergraduate students that ranged from second-semester general chemistry to upper-level chemistry participated in one-on-one structured interviews to classify the meaning of the word ‘neutral’ (Jasien, 2010). In chemistry, we use the word ‘neutral’ to represent uncharged molecules, something that is not acidic or basic, and use it when describing the pH scale that a pH of seven is neutral. Jasien found that eight out of twenty students at some point in the interview associated neutral with being unreactive. Additionally, students mixed the ideas of being uncharged, with the concept of being acidic or basic.

Additionally, the word ‘neutral’ was associated with equal amounts of hydrogen and hydroxide ions in a solution (Jasien, 2010). This finding was echoed in Nyachwaya’s (2016) study with second-semester general chemistry students with acid-base titrations (Nyachwaya, 2016).

In a study of language fluency during an acid-base titration activity with second-semester general chemistry students, Nyachwaya (2016) found students struggled with the meaning of a variety of scientific vocabulary words involved in acid-base chemistry, including the meanings of the words such as aqueous, dissolves and dissociated. He suggests that merely knowing the terminology is not enough, that students must understand the underlying meaning behind the words as applied in chemistry. Furthermore, students would often use slang for descriptions of scientific processes, such as “they are kinda chilling in there.” Nyachwaya also points out that language fluency in chemistry includes the syntax, which he defines as the ability to translate written words into symbols, in which students had difficulty translating simple chemical names into formulas to create the initial reaction with the correct products (Nyachwaya, 2016).

According to research, there is a distinction between problems and exercises, although they are closely related. A problem is when you know where you are and where you want to go, but you do not know how to get there, whereas, in an exercise, you know how to get there (Bodner & Domin, 2000; Bodner & McMillen, 1986; Hayes, 2015). Therefore, a major difference in any chemistry course is that the instructor, the expert, will be performing exercises, while the student, the novice, is solving problems. However, to keep things simple, this research will utilize the word problem solving for both aspects with the understanding that for experts, it is an exercise, and for a novice, it is a problem. As experts, instructors must consider that students are “novice” learners, and as such, the novices will approach problem-solving is a different way due to less experience and limitations within their knowledge (Taber, 2013).

Problem-solving, as defined by Hayes (2015) involves six steps, which includes deciphering the problem, representing the problem, making a plan to arrive at the solution, carrying out the plan, evaluation of the answer and reflection on the experience of solving that problem (Hayes, 2015). According to research, problem-solving involves disembedding information contained in the problem and translating it into a structure that the individual understands (Bodner & Domin, 2000; Bodner & McMillen, 1986). Bodner and McMillen (1986) suggest that instructors, the experts, disembed crucial information at the beginning of problems, that may not be disseminated to their students. The expert may forget in performing an exercise that the information in the problem needs to be disembed and restructured to solve the problem, and the novice cannot reach the end of problem-solving if they cannot get through this step. Furthermore, they found that students will higher spatial ability had higher success on both multiple choice and open ended questions in chemistry, suggesting that they can disembed information better than students with a lower spatial ability (Bodner & McMillen, 1986).

According to Bodner and Domin (2000), successful problem solvers can translate between a variety of different representations of the same chemical systems. The representations include both internal representations and external representations. The internal representations are how pieces of the problem are stored within the mind of the learner. In contrast, the external representations are the “physical manifestations,” such as the drawings, or equations (Bodner & Domin, 2000). They are confirming Bodner and McMillen’s assertion that the spatial reasoning ability of the learner has an impact on problem-solving. Spatial reasoning is the ability of a learner to disembed information and restructure it (Bodner & McMillen, 1986). For instance, some novices have had problems disembedding information from the symbolic structures in chemistry, such as moving from a linear conformation to a cyclic product (Ferguson & Bodner, 2008). Bodner and Domin (2000) indicate that poor performance in some organic students is due to the fact they are unable to assign any meaningful value to the symbolic representations of letters, lines, and numbers in chemical equations or formulas because they do not represent anything to them. In contrast, for an expert, they would assign physical meaning to these symbols by disembedding the information. As was also seen in Nyachwaya's study were students were unable to disembed chemical equations from the written text (Nyachwaya, 2016). They suggest that until students are able to assign meaning to these symbols they will continue to create absurd products for the reactions (Bodner & Domin, 2000).

For experts, processes in chemistry, the macroscopic and microscopic are connected by symbols (Johnstone, 1982, 1991, 2010), but for the novice learned who does not move easily through the triangle may not disembed this information. This lack of ease of movement can lead novice students not to make appropriate use of symbols in chemistry. Bhattacharyya and Bodner (2005) went as far as to express the idea that to students, curved arrows in reaction mechanisms are not even symbols to them (Bhattacharyya & Bodner, 2005). Crandell suggested that we call the process "electron pulling" instead of "electron pushing" when explaining it to students, as that may be more meaningful to the actual process (Crandell et al., 2019). Ferguson and Bodner called the process "arrow pushing formalism" as students see the use of arrows differently from practicing chemists (Ferguson & Bodner, 2008). This finding was previously seen in a study of graduate students with Strickland et al., where they described the students' usage of "arrows as the agents of change as opposed to the electrons" (Strickland et al., 2010).

Researchers found that students used curved arrows as a means to get to the product and would with force make the arrows fit, with little chemical meaning of the representation of the arrows (Bhattacharyya & Bodner, 2005; Ferguson & Bodner, 2008). In contrast, an expert would think at a level of the flow of electrons (Ferguson & Bodner, 2008) and understand that arrows represent how interactions begin and the movement of electron density throughout a reaction (M. M. Cooper et al., 2016). Therefore, the students do not understand that the curved arrow formalism is a means of explanation of "how" and "why" the reaction is occurring (Bhattacharyya & Bodner, 2005; M. M. Cooper et al., 2016; Crandell et al., 2019; Strickland et al., 2010). Furthermore, Bhattacharyya and Bodner noted that in students rush to obtain the answer, they would often skip preparatory steps in reactions because it did not lead them straight to products (Bhattacharyya & Bodner, 2005). This finding suggests that the students may not be appropriately disembedding the information presented in problems.

Grove et al. (2012) studied students' usage of arrows for mechanisms in organic reactions over an academic year, where even as students became more familiar to functional groups continued to approach all mechanisms in the same fashion regardless of the functional groups involved. Furthermore, at some time points in the study upwards of 75% of these students were not utilizing mechanisms in reactions, indicating that they had little use for them as a tool for solving the problem to produce the correct products (Grove et al., 2012).

Research has shown where other representations in reactions have a different meaning for novices and experts. A notable difference observed between novice and expert problem solvers by researchers was that novice problem solvers see molecules involved in reactions as something that are static rather than something dynamic (Bodner & Domin, 2000; Ferguson & Bodner, 2008; Strickland et al., 2010). Furthermore, many students simply see the Lewis structure of the molecule as mere representations of the molecules, not as the valuable symbols are embedded with information about molecular structure, polarity, and properties that experts would visualize (M. M. Cooper et al., 2010).

In summary, experts have several advantages to novices in their ability to solve problems due to novices' lack of experience. Experts can use strategies to increase the capacity of their working memory that are not available to novice learners, which include the ability to develop patterns. Experts are more familiar with the language of chemistry and can disembed information presented in problem-solving. Experts can move freely through Johnstone's triangle and make meaningful connections between the symbolic, the macroscopic, and microscopic levels by understanding the underlying principles and function behind the structures. In contrast, novices favor the surface features of the structure over the function.

In general, the studies presented in the literature review have focused on a single aspect of a concept. This current study seeks to understand how students reason about acid equilibrium by probing students' understanding of the prior knowledge necessary for understanding the concepts. An example of these connections is illustrated for the concepts of K_a and pK_a in a concept map (Figure 4). The concept map begins with the concept of equilibrium, then applies the equilibrium constant to acids, which connects to the acid-base models. The acid equilibrium constant, K_a, is connected to pK_a.

This study further seeks to take a more in-depth look at the stability of the students' knowledge by probing their understanding in different contexts. These contexts include open-ended verbal questions, molecular level thinking, and problem-solving tasks. This study synthesizes the findings to evaluate students based on the stability of their knowledge across multiple contexts and student understanding of concepts related to acid equilibrium constants.

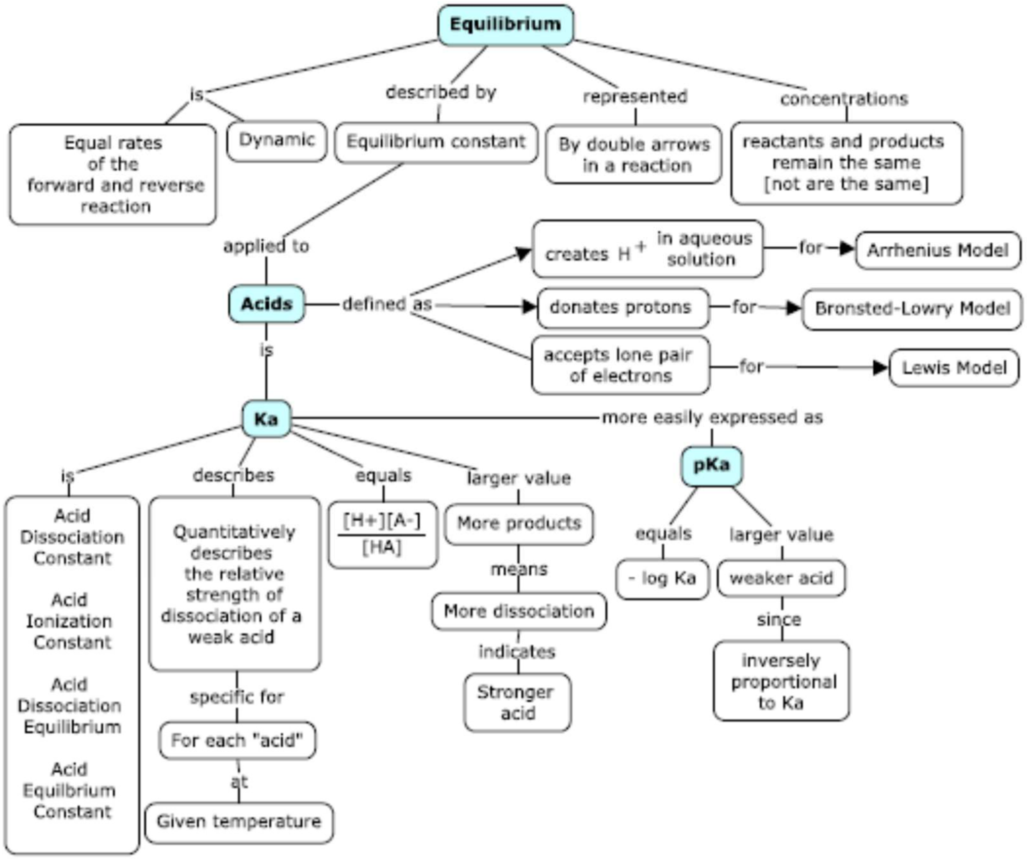


Figure 4. Concept map to illustrate the connection of resources from equilibrium to pK$_a$

3 Methodology

3.1 Participants

This study was a cross-sectional study. It included participants from four university chemistry courses in a progressive series. The courses included general chemistry II, organic chemistry I and II, and biochemistry I. The research was conducted at a large, urban public research university with undergraduate and graduate degree programs in the southern United States during the Fall semester of 2018. The ethnicities of the entire student population for the institution in the Fall semester of 2018 were 40% Black, 16% Asian, 33% White, 7% two or more races, and 4% not reported. The entire student population had 40 % males and 60% females.

Twenty college chemistry students (13 [65%] females, 6 [30%] males and 1 [5%] non-binary) participated in the cross-sectional study during the Fall semester 2018, located in Table 2. The participants included (6) general chemistry II students, (6) organic chemistry I students, (4) organic chemistry II students, and (4) biochemistry I students. The course grades for the participants ranged from A+ to D. It should be noted that five of the students had previously taken the course that they were interview for without successful completion - Gwen, Frances, Louise, Carrie, and Clara. Gwen previously attempted organic chemistry I and received a “W,” however, covered the acid-base material before withdrawing. Frances previously attempted organic chemistry I with a grade of a C-. During Frances’ interview, she indicated that she was an English as a second language (ESL) learner. She struggled with the language barrier in her studies, but especially in chemistry. Louise previously attempted organic chemistry I four times receiving grades of F, F, C- and C-. Carrie withdrew from organic chemistry II before covering the acid-base material. She received a “W.” Clara previously attempted biochemistry four times with course grades of D, D, C, and F. Seventy-five percent of the participants were under the age of twenty-four. The participants' majors included biology (9), biomedical (1), chemistry (4), mathematics (1), neurosciences (3), psychology (1), and sociology (1). The ethnicity of the participants was diverse, with 55% (11) African American/Black, 20% (4) Asian, 20% (4) Caucasian/White, and 5% (1) Hispanic.

Table 2. Cross-sectional study - participants by course, grade, gender, age, major and ethnicity

Name	Course	Grade	Gender	Major	Ethnicity
Sam	GCII	A+	M	Chemistry and Physics	Caucasian/White
Bill	GCII	A	M	Neurosciences	Asian
Gladys	GCII	B	F	Biology	Caucasian/White
Chester	GCII	C	M	Biology	African American/Black
Kim	GCII	B	F	Mathematics	African American/Black
Marie	GCII	B+	F	Biology	African American/Black
Alex	OCI	A	NB	Biology	Caucasian/White
Gwen	OCI	B+*	F	Chemistry	African American/Black
Kent	OCI	B	M	Chemistry	African American/Black
Annie	OCI	A+	F	Biology	Asian
Frances	OCI	C*	F	Neurosciences	Hispanic
Louise	OCI	B*	F	Psychology	Caucasian/White
Jack	OCII	B+	M	Neurosciences	African American/Black
Carrie	OCII	C*	F	Biology	African American/Black
Kelly	OCII	A	F	Biology	African American/Black
Quinn	OCII	A	F	Biomedical Sciences	African American/Black
Clara	BC	D*	F	Biology	African American/Black
Mitch	BC	A+	M	Sociology	African American/Black
Sylvia	BC	A	F	Chemistry	Asian
Emily	BC	C+	F	Biology	Asian

* Indicates that this course has been attempted more than once by the participant

3.2 Classroom Settings

The participants were taken from over the four courses with seven different instructors. Most of the courses were taught in a traditional format, with the instructor primarily lecturing to the class. The general chemistry course had 150 minutes of instruction per week, either two or three days of lecture per week. The general chemistry courses required online homework, exams, and an ACS final exam. The exams were multiple choice formatted questions. The organic chemistry I and II courses had 150 minutes of instruction per week, with three days of lecture per week. The organic chemistry I and II courses required homework, quizzes, exams, and an ACS final exam. The exams were a mixture of multiple choice and short answer formatted questions. The biochemistry course had 270 minutes of instruction per week, with three days of lecture per week. The biochemistry course required exams, quizzes, and a final exam. The exams were multiple choice formatted questions.

3.3 Student Recruitment

For the cross-sectional study, the student principal investigator (SPI) obtained permission from the instructors of general chemistry II, organic chemistry I, organic chemistry II, and biochemistry courses in the Fall of 2018 to present the study during the lecture course. The study was described to the students following the recruitment protocol in Appendix A.1. The students were asked to voluntarily participate in a single 1 to 1 ½ hour one-on-one semi-structured interview. The students were informed that they would receive a $10 gift card as compensation for their participation in the study. During recruitment, students indicated their interest in the study by providing their name and email address to the researcher. The student principal investigator contacted all students who provided their contact information, via a follow-up email, in Appendix A.2, to set up interviews. All students who responded to the email and were able to meet with the researcher at a mutually convenient time were interviewed.

3.4 Classroom Observations and Field Notes

The student principal investigator received permission from the course instructor to attend the lecture course to make classroom observations. During the lectures, field notes were recorded in written form, and audio recordings were made of the lectures. The student principal investigator reviewed all field notes and recordings for the material covered during the lecture. Additionally, the student principal investigator read all course textbooks associated with the assigned reading material for the courses per the syllabi for the acid-base concepts related to this research. Classroom observations and readings provided insight into the course material presented to the students in each course in this study.

3.5 Student Interviews

Semi-structured interviews were used to determine what students understand about acid-base concepts in the courses and their acid-base problem-solving strategies. The concepts were initially probed with open-ended questions, and then the interview progressed to a think-aloud problem-solving section. During the think-aloud problem solving, students verbalized their thought processes as they solved the problems in real-time. This protocol provides a clearer view of how the student is processing information about the problem as they solve it and not in retrospect when they have had time to collect their thoughts. The think-aloud protocol allows the researcher to probe the student with clarifying questions, such as “What do you mean by that?” or “Why did you do this?”, which can provide more in-depth knowledge of the information being processed by the student that is not necessarily initially communicated (Bowen, 1994; Ericsson & Simon, 1998).

For each course, the students were interviewed after the topic was presented, to ensure that students would be at their optimal level of knowledge. The interview immediately followed the assessment of the acid-base material. In general chemistry II, the interview was conducted after their third exam, by which time they had covered general equilibrium concepts, acid-base equilibrium, and buffers. In organic chemistry I, the interview was conducted after their first exam, after which they had covered the chapter on acid-base topics. In organic chemistry II, the interview was conducted after their third exam, by which time they had covered carbonyl chemistry. In biochemistry, the interview was conducted after the first exam, as the course reviews acid-base chemistry in the initial weeks of the course.

The interview was conducted in a private room to maintain the privacy and confidentiality of the participant. The interview was audio and video recorded. Students' faces were not shown in the video recording, only their written work. The Livescribe^{TM} Echo (Livescribe, 2018) was used to record the paired written and spoken responses. A digital recording device recorded a backup of the audio. The video was used to capture nonverbal gestures with the participant's hands and provided a backup of the written and spoken responses of the participant.

At the beginning of each interview, the researcher provided the participant with the IRB approved Informed Consent Form (see Appendix B.1, B.2, B.3). The researcher ensured that the participant understood that the entire interview was a voluntary process, that they may stop at any time, and this included any specific question during the interview. After the participant signed the informed consent, the researcher explained to the participant the technology that was being used to record the interview, including the Livescribe pen, digital recorder, and video camera. The researcher also presented the tools available for the participant to use during the interview, which included the Livescribe^{TM} pen and paper, a calculator, and a periodic table. The participant was given instructions to freely utilize these tools in whatever way that they felt necessary. For example, it was suggested that they could use the paper to write down anything that would help them with their thought processes, such as words, drawings, or equations. The students were given instructions on how a think-aloud interview works. The students were asked that “as you solve each problem, I would like you to verbally describe what you are doing and what you are thinking.” It was explained to students that during the interview, the researcher might prompt them for what they are thinking if they are not speaking or may ask for clarification. It was further added that the clarifying questions did not indicate that it was right or wrong, just merely for understanding the student’s words, or actions.

The interview proceeded by using the prescribed IRB # H18262 approved interview protocol (Appendix C.1). The interview protocol was developed by utilizing multiple resources. One source for the protocol development included reviewing current standards in the literature. These included the anchoring concepts content maps (ACCM) presented in the literature by the ACS for General Chemistry and Organic Chemistry (T. Holme et al., 2015; T. Holme & Murphy, 2012; Murphy et al., 2012; Raker et al., 2013), the acid-base learning outcomes for organic chemistry students (Stoyanovich et al., 2015), and the foundational concepts for biochemistry students (Villafañe, Loertscher, et al., 2011). A second source for protocol development included reviewing current courses at the institution, which included the current texts for the courses (Berg, Tymoczko, Gatto Jr., & Stryer, 2015; Karty, 2018; McMurry, 2016; Tro, 2010), classroom observations, and interviews with chemistry faculty. The faculty interviews were used to determine what they felt were important foundational acid-base concepts for success in higher-level chemistry courses. After the initial interview protocol was designed, a pilot study, structured similarly to the method described herein, was conducted in Spring 2018 (N = 9) to refine the questions and problem-solving protocol, however, the interviews were not utilized further than that purpose. The interview protocol contains both the semi-structured open-ended questions and contextual problems. The interview began with an introduction to the purpose of the interview. Then, the participant completed a demographic survey (Appendix D). The interview proceeded with a series of introductory questions about the student's major, plans, and current experience in chemistry. The next section of the interview was the open-ended questions on acid-base chemistry, followed by a series of problems (Appendix C.2).

It should be noted that with each progressive level of chemistry, additional problems were added to include course level-appropriate content. All students were asked questions # 1 – 6, # 7 was added organic chemistry I students, # 8 was added for organic II students, and # 9 – 10 were added for biochemistry students. Problems # 9 – 10 will not be reported in the findings in section 4 as they did not any additional information to the study. It was found that some of the students struggled with the wording of the two questions. Students struggled with the meaning of the word "predominant" in problem #9. In problem #10, the structure was a word problem. Some students were unable to extract the provided information about the solubility of the molecule. The ability to read a word problem was not the intent of this research. At the end of the interview, participants completed the Student Evaluation Form from the IRB, in Appendix E. Students were then issued a $10 gift card, for which they signed a participant record of payment or gift card, in Appendix F.

Once the interviews were completed, all identifiable information, such as names, were removed and replaced by a pseudonym. The student participants were assigned a unique identification number based on the initial interview date and the course and pseudonym. All identifiable information, including the participants' consent forms and demographic surveys, were stored in a locked filing cabinet. The code key for participants' pseudonyms was stored on a separate firewall-protected computer separate from any other electronic documents that pertained to this study.

The student's grades were obtained with their consent from the Office of Institutional Research for all chemistry courses that pertained to this study, not just the specific course the student participated in for the interview. These included grades from general chemistry II, organic chemistry I and II (including the separate lab sections), and biochemistry.

3.6 Data Analysis

All interviews were transcribed verbatim. The transcribed interviews had all steps in the problem solving added to the transcript as they occurred, as well as any necessary hand gestures, or clarification available from the videos added to the transcript to provide a complete record of the interview. Each transcription was reviewed and manually coded for themes by each open-ended question (Appendix C.1) or problem-solving task (Appendix C.2). The specific questions and problem-solving tasks for each of the ideas related to acid-base equilibrium are described in more detail in the corresponding findings section for acid-base models (4.1), acid-strength (4.2), equilibrium, K_a and pK_a (4.3).

The constant comparative method was used for coding (Johnson & Christensen, 2017). First, open coding was applied, which examined the data by naming and categorizing discrete elements in the data and labeling important words and/or phrases in transcribed data. This initial coding allowed the transcriptions to be pared down to include the data that is pertinent to the research and remove extraneous tangents. The pared-down transcript was entered in NVivo software for additional coding. The text that was manually coded was coded in the NVivo software.

The next step in the constant comparative method was axial coding. In this step, the themes are developed by combining concepts into categories, which are slightly more abstract than the previous groupings, organizing the categories, and developing the relationships in the categories. Selective coding puts the story together and develops the central idea (Johnson & Christensen, 2017). The qualitative coding was done by more than one researcher on a selected group of interviews to ensure consistency in coding, which is called interrater reliability. Using the NVivo software, a Kappa of 0.7 was reached for the interrater reliability, which indicates moderate agreement (McHugh, 2012). The differences in coding were discussed by researchers as a group to develop a consistent method of coding. The themes were compared within each course for general chemistry II, organic chemistry I, organic chemistry II, and biochemistry, as well as across courses. This comparison identified similarities and differences within the courses and provided the ability to contrast the themes across the courses.

The themes developed from the coding of the open-ended questions and the problem-solving tasks determined the students' ideas and explanations of acid-base equilibrium concepts. The themes were assessed for how well they aligned with scientifically acceptable explanations. The themes in the open-ended questions and problem-solving tasks were compared for similarities and differences to assess the stability of the concept across contexts. By combining the analysis of scientifically acceptable explanations and stability, students were categorized on levels of sophistication for each concept. The levels of sophistication for each concept were combined graphically to reveal an overall relationship of the students’ ideas and connections of acid-base equilibrium concepts from general chemistry to biochemistry.

4 FINDINGS

This research study hopes to unveil difficulties in student learning and reasoning of foundational acid-base chemistry concepts taught in general chemistry II and developed in higher level chemistry courses. This study pays particular attention to concepts related to acid-base equilibrium and pK_a. The themes developed from the student interviews provide insight into this understanding from a student perspective, as they are currently immersed in the course material. It is the hope of this research study to provide instructors with more insightful knowledge of what makes learning these concepts so difficult for their students and to help instructors employ the best strategies to help improve student outcomes.

The findings for the cross-sectional study are presented in the following subsections, which will discuss acid-base models, acid strength, and the relationship between K_a and pK_a. The section on acid-base models (4.1) explores how students verbally define acids and bases in open-ended questioning and their responses to a task in which they had to label components of an acid-base reaction. The section on acid strength (4.2) explores how students verbally define strong and weak acids, how they draw a molecular level representation, and how they interpret molecular level pictures to choose the representations for a strong and weak acid. The next section (4.3) explores how students describe the relationship between K_a and pK_a. More specifically, this section will describe students' understanding of the concept of equilibrium, K_a, and the relationship between K_a to pK_a.

4.1 Acid-base models

Participants in all courses were asked, “From a chemistry perspective, what is an acid?” This question was followed up by the same question for the definition of a base from a chemistry perspective. After these questions, students were asked if they could recall any other acid-base definitions from their chemistry courses, which allowed ample opportunity for participants to provide any possible answer they desired. Some of the students struggled to respond in a manner consistent with an acid-base model, so they were further prompted by the student principal investigator (SPI) with “Can you think of any acid or base models that you have learned in chemistry class?”. If the student was unable to respond, they were further prompted with “Do you remember learning about Bronsted-Lowry, or Lewis?” A couple of students continued to struggle and were further prompted with “How can you identify an acid?” In the problem-solving section, a task was designed to have students apply their knowledge of acid-base models to a reaction by labeling the acid, base, conjugate acid, and conjugate base (Appendix C.2 #3). Students in the organic chemistry I course and above were asked to provide curved arrow mechanisms for the task.

4.1.1 Verbal Descriptions – Acid-Base Models

The responses were analyzed to determine the acid-base models that the participants employed to define an acid or a base. The acid and base models are reported together to avoid reporting redundant data, as the students provided the corresponding responses for an acid and a base for each of the models that they described. For example, Mitch, in biochemistry, succinctly stated, “acid - electron acceptor, proton donor” and alternatively for a base - “electron donor, proton acceptor.” The responses were coded to the appropriate acid-base model according to the features in the students’ descriptions, not if they mentioned the name of the model. Although, if students named a model, it was coded to confirm that the model and the corresponding features described agreed. Some students stated the name of the model, but the features they described disagreed with the model they named (Table 3). The disagreement of name and model was most evident for the Lewis model, especially with general chemistry II students. However, general chemistry II students at this institution have minimal exposure to the Lewis acid-base model in their courses. However, none of the students who mentioned the Lewis model by name and provided features of the model were provided any additional prompting.

Table 3. Acid-base model named and features correspondence by course

Model named	Name & Features	GC II	OC I	OC II	BC	Total
Arrhenius	Agreed	2	-	-	-	2
Bronsted-Lowry	Agreed	1	1	-	2	4
	Disagreed	1	-	-	-	1
Lewis	Agreed	1	2	-	1	4
	Disagreed	3	2	1	-	6

All three acid-base models were utilized by the participants (Table 4). Only three participants, who were in lower-level courses, provided responses consistent with the Arrhenius acid-base model. For example, Kent, in organic chemistry I, stated, "… the last version that I don't think we're going to use anymore is the one that, it [an acid] creates H^+ when it reacts with water." Across all courses, most participants utilized a Bronsted-Lowry acid-base model, as stated by Bill, "…Bronsted-Lowry is when an acid is a proton donor or a hydrogen ion donor." Interestingly, the Lewis acid-base model was mentioned by most of the organic chemistry I and biochemistry students, but not by organic chemistry II students. Sylvia exemplified this model in biochemistry, where she stated an acid is "an electron-pair acceptor." Of further interest, three participants, Marie, Jack, and Carrie, did not utilize any acid-base models when defining an acid, or a base, with two of those participants in organic chemistry II.

When students struggled to produce a response, they were provided additional prompts. Six of the twenty participants required additional prompting to elicit a definition of an acid or a base consistent with a model (Table 4). By explicitly prompting the student for a "model," half of these students were able to respond consistent with an acid-base model. Even with the additional prompts explicitly asking about the models by name, the remaining three were still unable to respond consistently with an acid-base model. Two of these students, Jack and Carrie, were in organic chemistry II and, by this level, would have received instruction on acid-base models at least twice, if not three times, in their college chemistry curriculum.

Table 4. Acid-base models described by student and course

Courses	Name	Arrhenius Model	Bronsted-Lowry Model	Lewis Model
GC II	Sam	X		X
	Bill	X	X	
	Gladys		X	
	Chester*		X	
	Kim*		X	
	Marie*			
OC I	Alex		X	X
	Gwen		X	X
	Kent	X	X	X
	Annie		X	X
	Frances		X	
	Louise			
OC II	Jack*			
	Carrie*			
	Kelly*		X	X
	Quinn		X	
BC	Clara		X	
	Mitch		X	X
	Sylvia		X	X
	Emily		X	X
Summary of Courses	GC II	2	4	1
	OC I	1	5	4
	OC II	-	2	1
	BC	-	4	3
		3	15	9

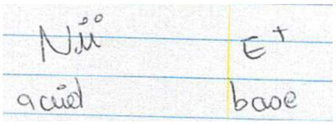
* Required additional prompting to elicit responses for models

For general chemistry II students, three out of six defined an acid and a base from the context of at least one of the three acid-base models without prompting (Table 4). Two additional students were able to provide one theoretical definition from the perspective of acid-base models after prompting, having defined an acid initially with respect to pH and macroscopic properties. One student, Marie, persisted in her use of macroscopic descriptions after prompting, she stated, “Uh, other than that, I know from lab - I just know that acids are harsh. That they come with – they usually come with hydrogen, included in them.”

This research is not about delineating misconceptions. It is about understanding how students reason about acid-base concepts and to provide instructors with information to help scaffold students learning in the classroom. For instance, Bill indicated that the Lewis acid model was “pretty much the *opposite* of Bronsted-Lowry. So, the acid is the proton acceptor, and then the base is the proton donor, I believe.” Firstly, Bill did not recognize the contradiction in what he just described, as he stated, “Bronsted-Lowry is when an acid is a proton donor or a hydrogen ion donor” and “Bronsted-Lowry [for a base], it’s when it’s a proton acceptor.” He used a resource he attributed to the word “opposite” for the Bronsted-Lowry and the Lewis models but only applied it to reversing the definitions. His idea is part of the Lewis model, but he does not make the distinction between electron and proton in his definition. An interesting question an instructor might pose to build on the resources that this student already has to aid in his learning is: would he consider the idea of the electron and proton as “opposites” – the negative and positive charge to help him develop his concept of acid-base models.

All the organic chemistry I students that utilized acid-base models without any prompting provided definitions based on one to three of the theoretical acid-base models. Although Louise had an idea of acid-base models, she applied the idea of the proton acceptor to the acid and the proton donor to the base. She is flawed in her understanding. However, the resources framework is not about being right or wrong; she does have a useful resource in the idea that acids and bases function as a result of a transfer of a proton. It should be noted that another student, Frances, initially used the concept of nucleophiles and electrophiles to decipher acids and bases but struggled with it and abandoned it. The following excerpt from Frances illustrates her struggle in her organizing her prior knowledge. She is unable to associate the base to the nucleophile and the acid to the electrophile, using a symbolic heuristic.

> ***SPI:*** *So, from a chemistry perspective, how would you define an acid?*
>
> ***Frances:*** *Uh. Oh gosh. It's a proton donor or proton acceptor?*
>
> ***SPI:*** *And like I said if it helps you to write anything out.*
>
> ***Frances:*** *Uh, ok. Yeah. So, one kind of little thing is like this (writes out Nü and* E^+*) - this is the base (labels* E^+ *as the base), and this is the acid (labels Nü as the acid). Oh, gosh, I feel on the spot. I don't know if I'm doing this right.*



Nü	E^+
acid	base

> ***SPI:*** *Ok. That's all right. And so, what have you drawn here?*
>
> ***Frances:*** *So, those are the Lewis acid-bases conformations. I don't know why it's easier for me to remember that, but I'm not sure if I'm doing that correctly.*

Frances utilized a symbolic heuristic. She does not appear to attribute meaning to the two dots above the "u" in the "Nü." For her, the dots are not representative of the electrons, which are donated in the reaction. Furthermore, Frances acknowledges her confusion about using this shortcut. Still, she does not attempt to try to make any connections with the Bronsted-Lowry acid-base model definitions of an acid or a base to try to clarify her understanding. This lack of meaning attributed to the symbolism was further explored with Frances to confirm her understanding.

SPI: *And so, what you drawing over the nucleophile there?*

Frances: *What do you draw over the nucleophile?*

SPI: *What is that? What are those representations there? (SPI pointing out the electrons in the picture of Nü)*

Frances: *Oh, no. It's nothing, I'm sorry.*

Overall, Frances seems unaware of any meaning concerning the two dots over the "u," and she associates the Nü to the acid and the E^+ to the base. She appears to have simply memorized this information. This line of reasoning is important to note because although she has been able to define an acid and a base by the Bronsted-Lowry model, she adopts this symbolic heuristic in the task presented in section 4.1.2.

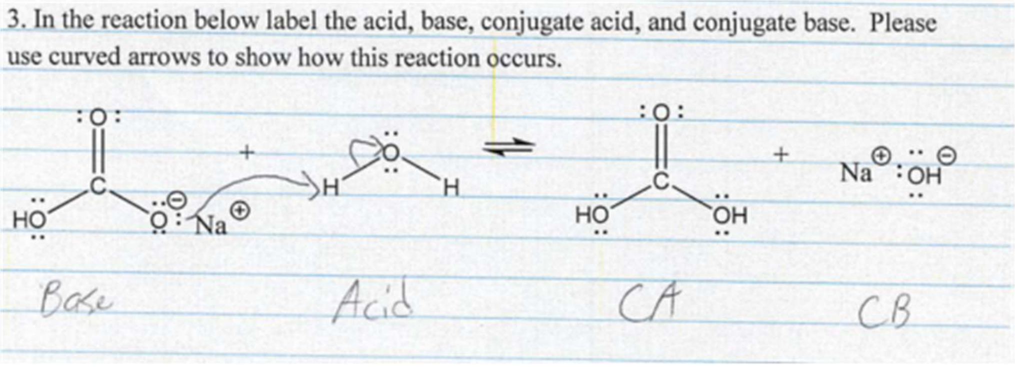
All the organic chemistry II students initially used definitions ranging from pH, conjugate base stability, and functional groups to define an acid, rather than using the acid-base models. Only one student, Kelly, was able to provide a rudimentary understanding of acids and bases without specific prompting for theories. She provided an illustrative example in which she described how the acid and base reacted using the appropriate language for Bronsted-Lowry and Lewis acids and bases. However, she was not able to explicitly define an acid or a base model. Another student, Quinn, was able to define an acid and a base for the Bronsted-Lowry acid-base model upon prompting by describing it as "… [an acid is] a proton donor." The other two organic chemistry II students, Jack and Carrie, could not provide definitions based on acid-base models, preferring to utilize features such as conjugate base stability and pH for acids and bases.

Three of the biochemistry students were able to provide two models for an acid and a base, which included the Bronsted-Lowry and Lewis models, without any prompting. The fourth student, Clara, was able to discuss two models. However, she only clearly defined the Bronsted-

Lowry model as "… [an acid is] something that's able to, I believe, donate a hydrogen," while she indicated that the Lewis acid-base model was "dealing with electrons."

Overall, students who named an acid-base model were more likely to disagree with the name and features of the model for the Lewis model. Seventy-five percent of the students defined an acid and base consistent with the Bronsted-Lowry model. These results are similar to Cartrette and Mayo's findings that students more successfully utilize the Bronsted-Lowry acid-base model (Cartrette & Mayo, 2011). Almost half of the students provided more than one acid-base model. Surprisingly, organic chemistry II students required more additional prompting to respond, and only half were successful in providing a response based on an acid-base model.

4.1.2 *Application of Acid-Base Model to a Task*



3. In the reaction below label the acid, base, conjugate acid, and conjugate base. Please use curved arrows to show how this reaction occurs.

Figure 5. The task to apply acid-base models as illustrated by Mitch's response from biochemistry

The responses were analyzed for the participant's success in the labeling task, the initial step performed by the student, the reasoning used, and the curved arrow mechanism success. An example of the task is in Figure 5. Sixteen out of twenty students were able to successfully label the acid, base, conjugate acid, and conjugate base in the reaction (Table 5). The students used various ways to initiate their problem-solving steps. Some students jumped right in with a curved arrow mechanism or labeling immediately without any verbal reasoning. In contrast, some students describing structural feature changes, such as hydroxyls, hydrogen, electrons, charges, the nucleophile, or the electrophile. Since the resources framework views reasoning at a smaller grain size, structural features observed by the students were recorded. For example, if a student used language, such as charges or lone pair electrons, it was coded as such. Alternatively, if a student used terms such as nucleophile and electrophile, it was coded as such.

For students, the initial step was more varied, but the reason for their labeling was more consistent. One student, Kim, initially began by looking at the changes in hydrogens, but quickly started to look at changes in "OH's." This result is not surprising, as the reaction was intentionally loaded with "OH" groups to see if it activated students' tendency to use functional groups or to activate the use of the Arrhenius acid-base model. Unfortunately, Kim was unable to apply any acid-base models when she defined models verbally; she only indicated her knowledge of the features of the Bronsted-Lowry model. Although she did not verbally define the Arrhenius model, the context of the problem brought the features of it to the forefront of her mind. She stated, "I'm thinking about the H… and seeing where I can find that… I know that for water, uh, water can be an acid or a base. I'm also looking for OH, which would be the base." Although Kim was trying to use features from acid-base models, her problems laid deeper in her lack of understanding that an acid reacts with a base, as illustrated in Figure 6, where she labels both reactants as acids.

Ten out of twenty students utilized the Bronsted-Lowry model in describing the gain or loss of hydrogens, or protons, all of which successfully labeled the reaction correctly. As described by Sylvia, in biochemistry, "So, there's water here, so this [water] loses hydrogen. This [sodium hydrogen carbonate] gains a hydrogen, so this [carbonic acid] is protonated, and this [sodium ion] gets a base, a hydroxide. This [water] gets deprotonated."

Table 5. Results for the task to label acid, base, conjugate acid and conjugate base by initial step, labeling success, and reasoning by students and course

Courses	Name	Labeled Successfully	Initial step								Reasoning						
						Variations											
			Curved Arrow Mechanism	Label	General structural setup	OH's	H's	Electrons	Charges	Nucleophile & electrophile	Arrhenius	Bronsted-Lowry	Lewis Model	Charges	Nucleophile & electrophile	Functional Groups	More hydrogens, more acidic
GC II	Sam	X							X					X			
	Bill	X					X					X					
	Gladys	X				X						X					
	Chester*				X												X
	Kim*						X				X						
	Marie*	X		X								X					
OC I	Alex	X					X					X					
	Gwen	X							X					X			
	Kent	X				X						X					
	Annie	X						X				X				X	
	Frances*							X	X						X	X	
	Louise	X	X													X	
OC II	Jack	X								X				X	X		
	Carrie	X	X											X			
	Kelly	X					X					X				X	
	Quinn	X		X								X		X			
BC	Clara*	X		X								X					
	Mitch	X						X	X				X	X			
	Sylvia	X					X					X					
	Emily*			X									X				
Summary of Courses	GC II	4	-	1	1	1	2	-	1	-	1	3	-	1	-	-	1
	OC I	5	1	-	-	1	1	2	2	-	-	3	-	1	1	3	-
	OC II	4	1	1	-	-	1	-	-	1	-	2	-	3	1	1	-
	BC	3	-	2	-	-	1	1	1	-	-	2	2	1	-	-	-
		16	2	4	1	2	5	3	4	1	1	10	2	6	2	4	1

* Required additional prompting

Two students utilized the Lewis model, one unsuccessfully and one successfully. Emily only had a surface-level understanding of the model in which she described, “It [water] can give off, um, the electron to go, um, bind what the carbon.” For Emily, in Figure 6, another resource was activated that indicated to her that the carbonyl was where “the attack” was to occur, and the OH group would be the leaving group from the sodium hydrogen carbonate.

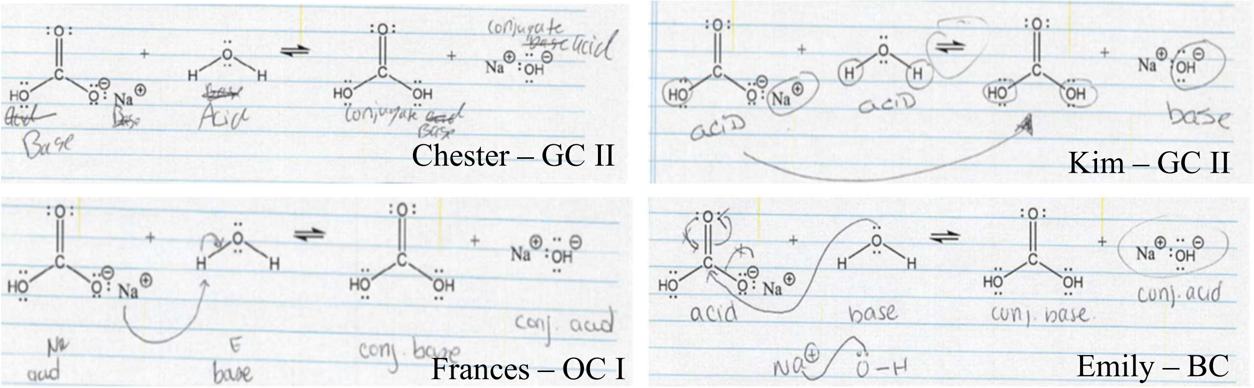


Figure 6. Unsuccessful samples for the task, problem # 3, for Chester, Kim, Frances, and Emily

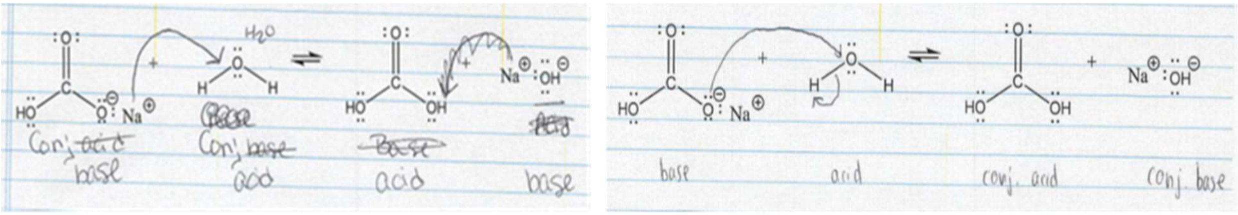
On the other hand, Mitch properly utilized the Lewis model to reason through the task. He successfully integrated his reasoning with his curved arrow mechanism as he described it,

> *I’m looking at this [sodium hydrogen carbonate]… it has a negative charge on the oxygen and an extra-lone pair. So, I’m gonna label that as the base. Um, and so this water is gonna be the acid. So, since this [sodium hydrogen carbonate is a base, it’s gonna donate electrons. So, I’m gonna draw an arrow from the lone pair on one of the oxygens, uh, taking a hydrogen, and then I’m gonna show that bond breaking onto the oxygen. And then that’s gonna leave me with the base turning into the conjugate acid [carbonic acid].*

From this excerpt, Mitch initially identified the acid and base from the negative charge and the lone pairs on the molecule to reason through the task. Five other students, mostly in organic chemistry II, utilized this reasoning, and all were successful in the task. One example is Jack, an organic chemistry II student, who did not describe any of the three theoretical acid-base models verbally. He reasoned through the task by using surface-level characteristics without describing the underlying acid-base models. Jack made connections in his reasoning from the negative charge and the lone pair electrons to his concept of nucleophile and electrophiles to arrive at the correct answer. Frances also tried to use the concept of the nucleophile and electrophile without success in the task. She did not understand the underlying components, as she was using a symbolic heuristic, Nü, and E^+ that she did not clearly understand, as described in section 4.1.1. Although, when Frances checked her work, she felt it looked wrong based on the functional groups involved as seen in the following excerpt:

> ***Frances:*** *So that would make this [carbonic acid] the conjugate base and the conjugate acid [sodium hydroxide]. But now that I think about this, this doesn't make sense. This should be the acid [carbonic acid].*
>
> ***SPI:*** *And so, why should that be the acid?*
>
> ***Frances:*** *Because its carboxylic acid.*
>
> ***SPI:*** *Ok. Are there any definitions of acids you can think of that you could use, you know, besides the fact that that is a carboxylic acid functional group?*
>
> ***Frances:*** *Yeah, no, there's none other definitions I mean.*

Louise, in organic chemistry I, who did not describe any theoretically appropriate acid-base models, attempted to use her verbal definitions for an acid and a base, where an acid is a proton acceptor, and a base is a proton donor. However, the discrepancy in her definitions became clear to her final answer on the task. She shifted her use of this line of reasoning to merely using the functional groups for reasoning through her answer selecting the acid and base in the products then proceeding to the selections in the reactants based on the conjugates (Figure 7).



Louise – OC I

Annie – OC I

Figure 7. Incorrect curved arrow mechanism for the task for Louise and Annie (OC I)

The task asked for students to include a curved arrow mechanism to see if this would activate students to utilize reasoning that was consistent with the Lewis model more than the Bronsted-Lowry model. If students failed to provide arrows, they were prompted to add them. The results for the curved arrow mechanism are presented for organic chemistry I, II, and biochemistry, as this is not taught in general chemistry II (Table 6). The results (Table 5) indicate that only two students used terms that discussed donating and accepting electrons in terms of reasoning to provide labels for their reactions. This suggests that simply asking for curved arrow mechanisms did not activate any reasoning for these students to use a Lewis acid-base model. When these students provided their curved arrow mechanism, while many of them did talk about electron movement, they did not use this to provide the actual labels for the task. The curved arrow mechanisms were an afterthought for most of the students, as has been seen in the literature (Grove et al., 2012).

Table 6. Curved arrow mechanism for labeling task for students and courses from organic chemistry I and above

Courses	Name	Curved Arrows		
		Complete, correct	Incorrect	Unable
Organic chemistry I	Alex		X	
	Gwen	X		
	Kent	X		
	Annie		X	
	Frances		X	
	Louise		X	
Organic chemistry II	Jack	X		
	Carrie	X		
	Kelly	X		
	Quinn	X		
Biochemistry I	Clara			X
	Mitch	X		
	Sylvia	X		
	Emily		X	
Summary of courses	OC I	2	4	-
	OC II	4	-	-
	BC	2	1	1
		8	5	1

General trends indicated that the majority of students in organic chemistry I, who are just learning mechanisms, provided incorrect mechanisms. All the organic chemistry II students provided correct mechanisms, and the biochemistry students had mixed performance. Overall, most students used mechanisms independently of the acid-base model. The students were performing an independent step without connection to the model. One interesting notation was revealed by two students in organic chemistry I.

For example, Annie and Alex, both verbally defined two acid-base models, the Bronsted-Lowry and the Lewis acid-base models. They then verbally used the Bronsted-Lowry model to reason about the labels for the reaction, but during the curved arrow mechanism reasoning, there was a discrepancy in their molecular-level understanding of electron movement during the reaction. In Figure 7, Annie's response to this task illustrates that the electrons are donated from the oxygen in the base to the oxygen in the acid, and the bond breaks between the hydrogen and the oxygen, giving the electrons to the hydrogen to bring with it back to the oxygen who donated its electrons. From Alex's description, she knows something is wrong with this as she constructs it:

> *Um so, in this case, we definitely – yeah, this [hydrogen carbonate ion], um, is gonna be losing a pair of electrons to make room for that hydrogen, it feels like. Feels wrong to say. Um, but I mean, it's, um – yeah, and you end up giving – yeah, so I think I'd end up saying like –and you just want movement of electrons here?*

This use of mixed models by students to explain the curved arrow mechanism should be noted by instructors to make sure to provide clarity to students who may not appropriately translate all the information in a symbolic reaction mechanism.

4.2 Acid strength – Strong vs. Weak Acid

All participants were asked to define a strong acid, followed by a weak acid, immediately followed by a task to draw a molecular level representation of each in an aqueous system (Appendix C.2 problem #1). After completing the remaining open-ended questions on K_a, pK_a, and pH, the initial task in the problem-solving section, problem # 2 in Appendix C.2, asked the students to select the correct molecular level representation for a strong acid, then followed the task to select the representation for a weak acid. When students struggled to respond to the initial question on defining a strong acid, the SPI further prompted the student to "compare a strong acid to weak acid." The responses were analyzed to determine how students reasoned about the terms "strong acid" and "weak acid" and the properties they attributed to those terms.

1.1.1 Verbal definition - Strong acid

The responses were analyzed for the various ways in which students described a strong acid (Table 7). Some students attributed more than one feature to a strong acid. General chemistry II and organic chemistry I students were more likely to describe a strong acid as completely dissociated when compared to the upper-level courses. For example, Sam, in general chemistry II, states, "It [a strong acid] is something that completely deionizes in water." When the concept of a strong acid is introduced in general chemistry, it is often introduced as a reaction that goes to completion with a single arrow (Tro, 2010), but in more advanced organic chemistry courses the concept is revised to indicated that it is an equilibrium reaction that goes almost to completion (Karty, 2018; McMurry, 2016). This concept builds on the prior knowledge of the students, which can improve their sophistication in understanding; however, it can introduce more complexity as they build their understanding. For example, Alex, in organic chemistry I, stated, "in solution [the acid] dissociates… completely, or near completely and does not tend to sit in a heavy equilibrium reforming its original acid form, and mostly… becoming its conjugate base." Here, Alex extends the definition of a strong acid but added a slightly conflated concept of Le Châtelier's principle in describing which side of the reaction is favored by using the term "heavy equilibrium." Three students described strong acids in a comparative manner that described "how easy" it would be for the strong acid to lose the proton or hydrogen. This was classified as a less sophisticated way of describing the dissociation process. Surprisingly, organic chemistry II students, unlike organic chemistry I students, relied on the rote memorization of the list of six (seven) strong acids: HCl, HBr, HI, $HClO_4$, $HClO_3$, H_2SO_4, HNO_3. When the concept of a strong acid is presented in general chemistry II, it is was noted that instructors suggested to students to learn this short list of strong acids.

Table 7. Verbal descriptions of a strong acid by student and course

Courses	Name	Tricks $(> 10^{-4})$	pH	More reactive	More hydrogens in compound	Conjugate base	Lower pKa	Not heavy equilibrium	List of strong acids	Easier to lose a proton	Completely dissociated	Nearly complete dissociation
GC II	Sam										X	
	Bill								X		X	
	Gladys									X		
	Chester*	X										
	Kim										X	
	Marie								X			
OC I	Alex							X				X
	Gwen										X	
	Kent										X	
	Annie		X									
	Frances				X		X					
	Louise		X				X					
OC II	Jack					X						
	Carrie		X	X								
	Kelly								X			
	Quinn								X	X		
BC	Clara*		X				X			X		
	Mitch						X					
	Sylvia										X	
	Emily		X									
Summary by course	GC II	1	-	-	-	-	-	-	2	1	3	-
	OC I	-	2	-	1	-	2	1	-	-	2	1
	OC II	-	1	1	-	1	-	-	2	1	-	-
	BC	-	2	-	-	-	2	-	-	1	1	-
		1	5	1	1	1	4	1	4	3	6	1

* Required additional prompting to compare strong and weak acids

Four students, two each in organic chemistry II and biochemistry, sought to describe strong acids by a lower pKa, which on the surface appears to an expert to be a comparative way to describe acid strength. An expert would understand that the relative strength of an acid can be described by pKa: that is a stronger acid has a lower pKa versus a weaker acid has higher pKa. However, all but one of these students had conflated reasoning associated with a strong acid. These encompassed the idea that strong acids have more hydrogens, either in solution (lower pH) or in the structure of the compound.

One student, Jack, in organic chemistry II, persisted in describing acid strength by the nucleophilicity of the conjugate base as illustrated by the following:

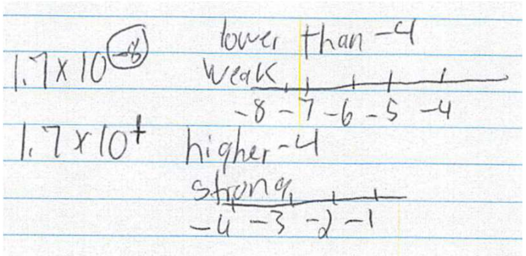
Jack: *A strong acid is usually… dependent on the conjugate base. So, if the conjugate base is pretty nucleophilic, then that would determine the strength of an acid.*

SPI: *And how would that determine it – would it be stronger, or weaker?*

Jack: *It would be stronger.*

Chester, in general chemistry II, described a method his teaching assistant (TA) provided as a trick for figuring out when an acid is a weak acid or a strong acid that pivoted around the value of 10^{-4}. This use of heuristic can be helpful; however, he had no idea what concept that value belonged to as illustrated below:

Chester: *The way I would do is cause of my SI tutor. She gave us a little trick or something, so basically, the way it is, if the, you know, how it goes like … (writes as he speaks)* 1.7×10^{-8}*, for example, she use to tell us that if the exponent was lower… than negative 4 … then it would be considered a weak acid… In order to determine if it was a strong acid if you write it like this, but this was like … Because if it's higher than 1, if it's higher than -4, then it would be a strong acid.*



SPI: *And when you, when you think about this, besides these numeric things, um, what is, what is this value for [pointing to the 1.7 x* 10^{-8}*]?*

Chester: *Those are usually like Ksp, or …maybe sometimes the pH… that's what you try to look for that to see if that's a strong or weak acid. Cause they'll give you this number (student pointing to the 1.7 x* 10^{-8}*) according to the acid, and they'll make you find like what's the concentration of this, or what's the concentration of a certain formula…Uh, it's – usually, it's when you're trying to calculate for pKa basically, or pH. Because doing this, it was supposed to help determine if you're using the quadratic formula or not.*

Overall, ten students had descriptions of a strong acid based on dissociation on a spectrum from more easily losing a proton to near completely dissociating. As students progressed from general chemistry II, they progressed away from the definition of a strong acid based on dissociation. Five students used shortcuts, by using the list if strong acids, or tricks. Four students had ideas that were based on pKa, most of which had additional conflated ideas associated with strong acids. Five students had conflated ideas associated with strong acids, including a low pH, including two that also had conflated ideas about pKa and strong acids (Table 7). The conflation of pH with acid strength has been seen in the literature (Orgill & Sutherland, 2008).

4.2.1 Verbal definition – Weak Acid

The responses were analyzed for the various ways students described a weak acid (Table 8). Most students described weak acids using the same type of terminology they used to define a strong acid. Furthermore, most of the students used an idea that was consistent with a "complementary" concept. For example, Bill described both weak acids and strong acids in terms of the degree of dissociation. He stated that a strong acid "can ionize completely," whereas a weak acid "doesn't dissociate completely, and it's in equilibrium." All the students that described weak acids in terms of the degree of dissociation described it as partial dissociation, except one. Gwen, in organic chemistry I, indicated that a weak acid does not dissociate. She used an idea that was the opposite of her strong acid response, which was that of complete dissociation. This idea of using complete opposites to define strong and weak acids has been seen before in the literature (Smith & Metz, 1996). These ideas are important to note for instructors as they need to convey that strong and weak acids are complementary, but not opposites. The everyday meaning that students attribute to these words may confound their reasoning.

In efforts to avoid redundant findings, an overview of the ideas used will be presented for those covered in section 4.2.1 to focus on the newly activated ideas. All the general chemistry II students used the same types of ideas to define a weak acid in a manner that was complementary to their idea of a strong acid. Three students (Sam, Bill, and Kim) used partial dissociation. One student, Gladys, used the idea that the acid is less able to lose the proton. One student, Marie, indicated that if it is not on the list of strong acids, it must be a weak acid. One student, Chester, utilizes the trick taught to him by his TA that "values" under 10^{-4} are weak acids. Interestingly, only one student, Bill, mentioned that weak acids were at equilibrium.

Table 8. Verbal descriptions of a weak acid by student and course

Courses	Name	Tricks ($<10^{-4}$)	Distribution of electron from H	pH	Less hydrogens in the compound	Less Reactive	Conjugate base	No dissociation	Higher pKa	Not on List of Strong Acids	Equilibrium	Less able to lose a proton	Partial Dissociation
GC II	Sam												X
	Bill									X	X		X
	Gladys											X	
	Chester*	X											
	Kim												X
	Marie									X			
OC I	Alex										X		X
	Gwen							X					
	Kent										X		X
	Annie			X							X		X
	Frances				X				X				
	Louise			X					X				
OC II	Jack						X						
	Carrie					X							
	Kelly*		X										
	Quinn											X	
BC	Clara*											X	
	Mitch								X				
	Sylvia												X
	Emily			X									
Summary by course	GC II	1	-	-	-	-	-	-	-	2	1	1	3
	OC I	-	-	2	1	-	-	1	2	-	3	-	3
	OC II	-	1	-	-	1	1	-	-	-	-	1	-
	BC	-	-	1	-	-	-	-	1	-	-	1	1
		1	1	3	1	1	1	1	3	2	4	3	7

* Required additional prompting

Organic chemistry I students utilized complementary concepts, except for Gwen, as noted above. Annie utilized both a concept that complemented her strong acid definition and activated an additional idea to describe a weak acid. Annie stated, “So, a weak acid will have a higher pH and, mmm, in their environment, uh, it will not dissociate completely, their proton, but have the equilibrium state on the acids and the conjugate base.” She begins by describing a weak acid in the same terms as she has described a strong acid by using pH. Then, something is activated for her to describe a weak acid in terms of dissociation, which was not present for a strong acid. Furthermore, she indicated that the reaction of the weak acid was in equilibrium, whereas the idea of completion was not activated for the strong acid. Additionally, Kent and Alex noted the equilibrium nature of the reaction. However, Alex had activated the idea of equilibrium for the strong acid, but Kent did not.

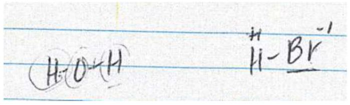
In organic chemistry II, Quinn, Carrie, and Jack used a complementary definition for the weak acid. For a weak acid, Quinn indicated it was less able to lose a proton when compared to a strong acid. Carrie indicated that a weak acid was less reactive than a strong acid. Jack continued to utilize ideas based on the nucleophilicity of the conjugate base. However, when prompted, Kelly tries to activate a new set of resources to develop an idea of a weak acid when contrasted with a strong acid. Recalling, Kelly had no definition of a strong acid other than being on the list of strong acids. Her excerpt illustrates how she tries to explain how the charge of hydrogen is distributed differently in a strong acid versus a weak acid:

SPI: *So, in chemistry, how would define a weak acid?*

Kelly: *Um. Water, I know that is a weak acid.*

SPI: *So, maybe if you compare the difference, what would be the difference between a strong acid and a weak acid?*

> **Kelly:** *I guess I look at it (writes out H-O-H and H-Br) because the most negative atom in water is the oxygen, but the most negative atom in the strong acid is the Br. So, this would have a plus one (writes +1 on hydrogen in HBr), and this would have a minus one (writes a -1 on the Br in HBr), not really, but. This one [Br in HBr] would have a negative charge on here, like a full negative charge, but then this [O in* H_2O*] negative here, this has to be - what is it? Split up between these two H's, while this one [HBr] only has one extra thing [HBr has one hydrogen], and this one [*H_2O*] has two [hydrogens] next to the negative [oxygen].*



From an instructor's perspective, Kelly has some useful resources at her disposal. However, this is not entirely an inaccurate picture of a weak and strong acid that can be compared. She selects a strong acid and a weak acid, but this concept is more complicated than a simple charge distribution of one hydrogen on this one and two on that one. Nevertheless, she is activating an idea that is suggesting this to her. The reasoning for acid strength does have to do with the charge and the atoms involved, and that could be built upon to help develop Kelly's reasoning.

All the biochemistry students were consistent in using the same ideas for their weak acid and strong acid definitions. Clara described that a weak acid was less able to lose its proton compared to a strong acid. Sylvia described a weak acid in a complementary manner to her strong acid definition by utilizing an idea of partial dissociation for a weak acid. Mitch described that "the higher the pK_a, the weaker the acid." When Emily persisted in using pH to described weak acids, she was prompted to describe the difference in diluted and concentrated acids to see if it would activate any resource to alter her descriptions. The following excerpt indicates that it did not alter her perspective:

SPI: *How would you define a weak acid?*

Emily: *Weak acid would be around - has a pH around 7. So, like at, or closer to 7 like 4.2 compared to 1.1.*

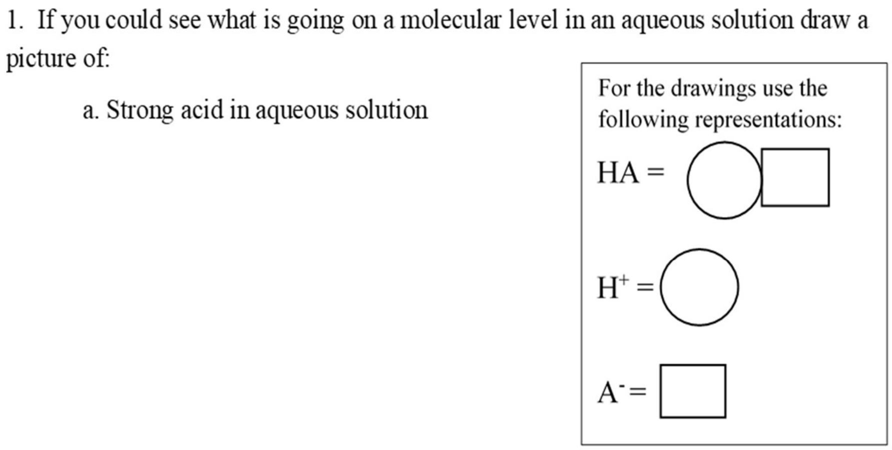
SPI: *And what about dilute versus a concentrated acid? What would be the difference in those?*

Emily: *Diluted and concentrated acid, I guess… um, has like, water. Um, addition of water to make it diluted.*

Overall, ten students had descriptions of a weak acid based on dissociation on a spectrum from being less able to lose a proton to partial dissociation. The same trend was seen in weak acid descriptions as for the strong acids, that as students progressed from general chemistry II, they progressed away from the definition of a weak acid based on dissociation. An interesting finding was that a couple of students activated additional resources with the weak acid definition that explained the process in terms of dissociation. In contrast, they did not use dissociation with a strong acid.

4.2.2 Application of Strong Acid in a Molecular Level Drawing Task

Students' responses were analyzed to evaluate their conception of a strong acid at a molecular level (Figure 8) and whether their explanation of their drawing was consistent with their verbal definition (Table 9).



1. If you could see what is going on a molecular level in an aqueous solution draw a picture of:

a. Strong acid in aqueous solution

For the drawings use the following representations:

Figure 8. The task to draw a strong acid at the molecular level

Ten students out of twenty students produced molecular level drawings consistent with a strong acid at the molecular level. Nine students, four each in general chemistry II and organic chemistry I and one in biochemistry, had only products present in their molecular level drawing of representations of H^+ and A^-. Students varied in their language to describe the process of dissociation from the idea of “separate” and “break” to a more scientifically appropriate “dissociate” term. Gladys, in general chemistry II, had not used the term dissociation to verbally define or explain her molecular level drawing, choosing to use words such as “it can break these bonds and separate these guys [HA].” Therefore she was prompted:

SPI: *What would you call that process?*

Gladys: *In my mind, I keep saying dissociation.*

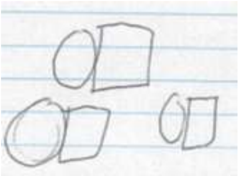
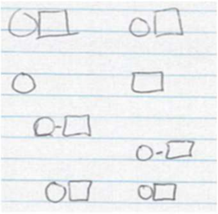
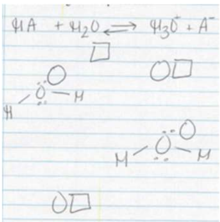
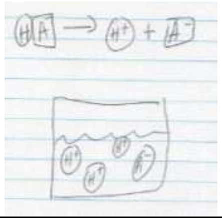
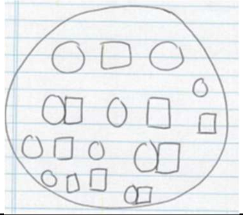
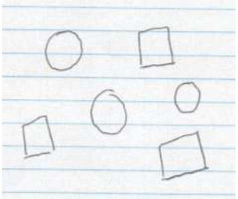
An interesting finding is that Alex used the idea of near-complete dissociation in their verbal description but did not apply this to the molecular level drawing. In contrast, Mitch, who relied only on lower pKa values to discuss strong acids, did draw the strong acid to show nearly complete dissociation. His drawing (Table 10) and explanation follow:

Table 9. Student interpretation of a strong acid at a molecular level by drawing and reasoning

Courses	Name	Strong acid, strong bond All HA	Harder to dissociate more HA >> $H^+ = A^-$	Almost equal amounts HA, H^+, A^-	More H^+ Concept	Nearly completely dissociated $H^+ = A^- >> HA$	All products $H^+ = A^-$	Previous verbal strong acid definition
GC II	Sam						X	Complete dissociation
	Bill						X	Complete dissociation
	Gladys						X	Easier to lose
	Chester	X						Tricks (> 10^{-4})*
	Kim						X	Complete dissociation
	Marie	X						List of strong acids*
OC I	Alex						X	Nearly complete dissoc.*
	Gwen						X	Complete dissociation
	Kent						X	Complete dissociation
	Annie						X	pH*
	Frances				X			More hydrogens & pH
	Louise				X			pH & lower pK_a
OC II	Jack		X					Conjugate base*
	Carrie				X			pH & more reactive
	Kelly				X			List of strong acids*
	Quinn			X				List & easier to lose*
BC	Clara				X			pH & lower pK_a
	Mitch					X		Lower pK_a*
	Sylvia						X	Complete dissociation
	Emily				X			pH
Summary by course	GC II	2	-	-	-	-	4	
	OC I	-	-	-	2	-	4	
	OC II	-	1	1	2	-	-	
	BC	-	-	-	2	1	1	
		2	1	1	6	1	9	

* Molecular level drawing explanation not based on activation of a similar set of resources as the verbal definition

Table 10. Sample of molecular level drawings of a strong acid

Category of Molecular Level Strong Acid Drawing	Sample	Student Course
Strong acid, strong bond (All HA)		Chester GC II
Harder to dissociate (more HA >> $H^+ = A^-$)		Jack OC II
Almost equal amounts (HA, H^+, A^-)		Quinn OC II
More H^+ Concept		Clara BC
Nearly completely dissociated ($H^+ = A^- >> HA$)		Mitch BC
Completely Dissociated ($H^+ = A^-$)		Kent OC I

> *"So, I, um, drew more of the H^+ and A^- dissociated than I did the HA because, I guess if you were looking at the equation, the HA, like the HA is a reactant and then H^+ and A^- as the products. If it's a stronger acid, it should that would move the equilibrium to the right so, you would end up having more of the products."*

Mitch activated a different set of resources when prompted to explain the molecular level reasoning of a strong acid in an aqueous solution compared to his verbal definition. It is findings such as this that instructors should take special note of, as experts whose resource activation is stable across contexts. Students, as novices, may use different sets of resources, which are activated depending on the context of the questions: one verbal and one reasoning at the molecular level.

Another example of a different resource activation was Annie in organic chemistry I. When she defined a strong acid verbally, she based it on a low pH. However, when she drew her molecular level drawing, she based it on complete dissociation to only H^+ and A^-. However, this is not to say she does not attribute a low pH to a strong acid; she simply did not mention a low pH. She simply activated ideas that produced an answer consistent with the idea that "the proton and then the conjugate base separate. Multiple of them. A lot of them."

Three students, two in general chemistry II and one in organic chemistry II, activated the idea"stronger acids have stronger bonds." The students in general chemistry II, Chester and Marie, adopted ideas of no dissociation with drawings of all HA. In contrast, Jack, in organic chemistry II, indicated, "…the way I kinda see it, that strong acid[s] are going to be harder to dissociate in an aqueous solution." Jack's drawing had mostly HA with a few H^+ and A^-.

The second-largest subset of representations for the molecular level is for a concept denoted as the "More H^+ concept." All the students using this concept were upper-level chemistry courses, including organic chemistry I, organic chemistry II, and biochemistry. The drawings all included a feature of more H^+ representations compared to the A^-. First and foremost, these students failed to consider conservation of atoms in the reaction; the A^- simply disappeared in favor of more H^+. Interestingly, Clara, in biochemistry, even wrote out the reaction for a strong acid dissociating, but her drawing (Table 10) failed to consider it. She activated the resource of how a strong acid dissociates to its components on some level. However, Clara did not make use of the reaction for what to include in her drawing. In this case, it was not simply a problem of "not thinking of about it" since she did not conserve the atoms. All but one of these students, Kelly, who recalled a list of strong acids, had a verbal definition of a strong acid based on the idea that strong acids have more hydrogens, either using pH or in the compound itself. Another interesting aspect of these drawings for this group of students is that most of these drawings represented complete dissociation or nearly completely dissociated systems. Although these students drew the strong acid completely dissociated, when compared with their weak acid drawings in the following subsection, they draw them completely dissociated as well. This comparison indicates that they do not understand the underlying concept of dissociation as applied to acid strength.

Carrie used the concept of more H^+ in a strong acid and combined it with an idea of more reactive, as well. As illustrated by the following:

> ***Carrie:*** *A strong acid, it would be a lot more of the $H^{+'}$s. Ok, so here's the beaker with solution. And then, it's like, a lot of H^+s. (draws the beaker with a line for the solution with five circles for H^+ representations) Because it's strong, it's more reactive, so it's going to react with solution.*
>
> ***SPI:*** *Ok. And is there anything else in that solution?*

Carrie: *Yeah, there might be like a couple of A^-s. (draws in four squares for the A^- representations, which are not connected to the circles for the H^+ representations)*

SPI: *Ok. And when you look at that, you have – H and A separated, um, why did you do that?*

Carrie: *Just how I drew it like it could be actin' mixed together, possible, depending on what it is.*

SPI: *Ok. And what makes that difference? Why would, why would sometimes it would be together, what's the difference?*

Carrie: *It depends on like what you're mixing it with… cause, I know, like everything doesn't necessarily mix with like a strong acid.*

Carrie is not able to explain what she means by more reactive, but this is important to point out this concept of "more reactive" will reoccur with in the following subsections 4.2.4 molecular level drawing for a weak acid and 4.2.5 strong acid molecular level picture.

Quinn, in organic chemistry II, drew an interesting representation (Table 10). She was one of a couple of students who wrote out any representation for the water, and she also wrote out the reaction. However, she also utilized the double-headed reaction arrows for a reversible reaction. When she explained the strong acid representation, she indicated that it would be "easier for the hydrogen to leave, but it will also want to go back because it's attracted to the negative, negative charges as opposed to like the lone pairs as well." When she verbally described a strong acid, Quinn described how a strong acid could lose a hydrogen easier. However, she neglected to explain her idea that the reaction was reversible and went in reverse easier as well. This additional reasoning from the problem-solving task provided more information on the student's understanding by reasoning through the task, not simply a verbal explanation.

Overall, half of the students properly represented a strong acid at a molecular level, in which all but one student was consistent with their verbal definition. Six students utilized a concept of more H^+ in their molecular drawing, and five of these students verbally defined strong acids based on more hydrogens, either with pH or more hydrogens in the compound. Three of the students represented strong acids at the molecular level by utilizing the idea that a strong acid has a stronger bond and cannot dissociate as easily, where these students had not verbally defined a strong acid with an appropriate definition. Lastly, one student seems to conflate the idea that it is easy to lose the proton and just as for it to be regained because of the charge it left.

4.2.3 Application of Weak Acid in Molecular Level Drawing Task

Students' responses were analyzed to evaluate their conception of a weak acid at a molecular level (Appendix C.2 #1b.), how it complemented their strong acid definition, and whether the explanation of their drawing was consistent with their verbal definition (Table 11). Nine students (Sam, Bill, Gladys, Kim, Alex, Kent, Annie, Quinn, and Sylvia) all described and drew representation consistent with their verbal weak acid definitions. Some of them drew more HA representations than H^+ and A^-, whereas some drew equal amounts of HA, H^+, and A^-. This representation is interesting, as discussed later in this study in section 4.3.1, some students will define the idea of equilibrium as "equal amounts." Another student, who used the idea of equal amounts of HA, H^+, and A^- was Quinn, a student in organic chemistry II. Quinn also writes out the dissociation reaction in both the weak acid and strong acid molecular level drawing tasks (Figure 9), which were incidentally on the same piece of paper. Furthermore, Quinn described the weak acid in the molecular level drawing in terms of the ability of the weak acid not being the same as the strong but not as "easy" when she said, "And we're gonna have – I feel like it would be the kind of like the same thing, but if this was like [a] weaker acid, then I don't feel like it would be that easy."

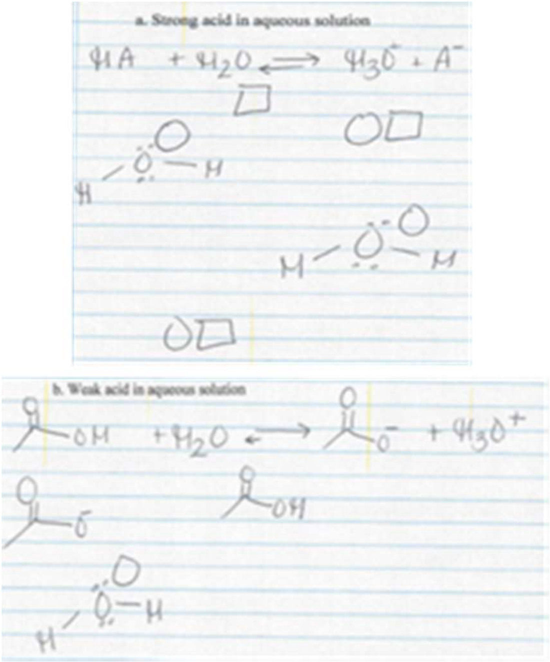


Figure 9. Quinn's molecular level drawings of a strong acid and weak acid

Quinn used the double-headed arrows in both reactions for the strong acid and weak acid. She verbally acknowledged the nature of the reversibility of the reactions. Recalling in section 4.2.3, Quinn's response to the strong acid molecular level drawing, she indicated that the strong acid could more easily go in the forward as well as the reverse direction. Her reaction here indicated that the reverse reaction is much less likely to occur, and she indicated that with her dialogue that "this [acetate ion] and that [hydronium ion] would now go back into [acetic acid and water] … but I mean it is, but it's less – so I'll write a small arrow." Incidentally, comparing the two representations, Quinn has drawn ratios of roughly the same amount HA, $H^{+,}$ and A^{-} in both drawings, the only difference was in her verbal explanations and reactions.

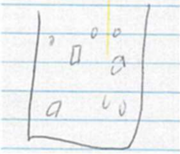
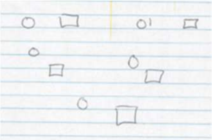
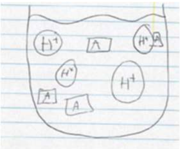
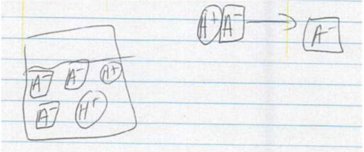
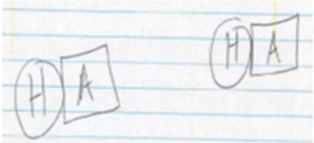
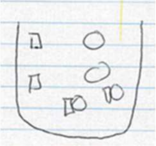
Mitch did not mention dissociation ideas at all in his verbal description of weak acids but rather relied on a higher pKa value to describe weak acids. He drew and reasoned about the concept of a weak acid at the molecular level by using equilibrium shifting to the left compared to the strong acid, as described in section 4.2.3. Mitch stated, “Because I would expect the, um, equilibrium to, well I would expect there to be more reactants than products. I would expect the equilibrium, the equilibrium to shift it to the left.”

Five out of the six students (Frances, Louise, Kelly, Clara, and Emily) who used the “more H^+” concept to describe strong acids used a “more A^-” concept to describe weak acids. These students indicated that a weak acid would have more A^- or conjugate base in solution compared to H^+. All these students drew their representation of a weak acid as completely or nearly completely dissociated solutions. This representation would indicate that students do not understand the underlying difference in the amount of dissociation of a weak acid versus a strong acid. This assertation was posited in section 4.2.3 for those students who used the “more H^+” concept that presented their representations of a strong acid as completely dissociated. Based on the idea of meaningful learning, these students display a lack of understanding of underlying concepts, which will impede their progress to more complex topics. They do not appear to understand the concept of dissociation. Furthermore, they are neglecting the idea of the conservation of atoms. Although conservation of atoms was not a concept that was the focus of this study, it is of great concern. Particularly, when upper-level students are displaying this lack of understanding of a fundamental concept that is presented in general chemistry.

Table 11. Student interpretation of a weak acid at a molecular level by drawing and reasoning

Courses	Name	Easy to break ($H^+ = A^-$)	More Products ($HA < H^+ = A^-$)	Faster Rate, weaker bond ($H^+ = A^-$)	Mostly not reacted ($H^+ = A^- >> HA$)	More A^- Concept	Not dissociated (All HA)	Equal Amounts ($HA = H+ = A^-$)	Reactants > Products ($HA > H^+ = A^-$)	Previous verbal weak acid definition
GC II	Sam								X	Partial Dissociated
	Bill							X		Partial Dissociated
	Gladys								X	Less able to lose
	Chester		X							Tricks ($< 10^{-4}$)
	Kim								X	Partial Dissociated
	Marie	X								Not on list of strong
OC I	Alex							X		Partial Dissociated
	Gwen						X			No dissociation
	Kent								X	Partial Dissociated
	Annie							X		Partial Dissociated
	Frances					X				Less H & higher pK_a
	Louise					X				pH & higher pK_a
OC II	Jack			X						Conjugate base
	Carrie				X					Less reactive
	Kelly					X				Distribution of electron
	Quinn							X		Less able to lose
BC	Clara					X				Less able to lose
	Mitch								X	Higher pK_a
	Sylvia								X	Partial Dissociated
	Emily					X				pH
Summary by course	GC II	1	1	-	-	-	-	1	3	
	OC I	-	-	-	-	2	1	2	1	
	OC II	-	-	1	1	1	-	1	-	
	BC	-	-	-	-	2	-	-	2	
		1	1	1	1	5	1	4	6	

Table 12. Sample of molecular level drawing for weak acids

Category of Molecular Level Weak Acid Drawing	Sample	Student Course
Easy to break ($H^+ = A^-$)		Marie GC II
Faster Rate, weaker bond ($H^+ = A^-$)		Jack OC II
Mostly not reacted ($H^+ = A^- >> HA$)		Carrie OC II
More A^- Concept		Clara BC
Not dissociated (All HA)		Gwen OC I
More Products ($HA < H^+ = A^-$)		Chester GC II
Equal Amounts ($HA = H^+ = A^-$)		Bill GC II
Reactants > Products ($HA > H^+ = A^-$)		Sylvia BC

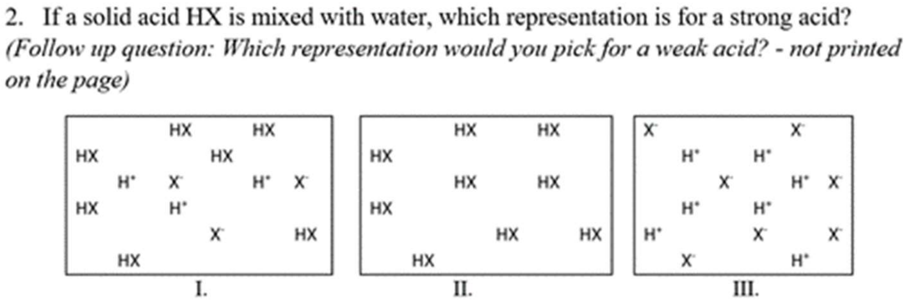
The remaining four students did not have any appropriate verbal definition for a weak acid. Both Chester and Marie based their weak acid molecular level drawing on the idea that the weak acid would be apart since they have a weaker bond. Chester did not utilize the idea of complete dissociation, whereas Marie did. Other students activated the idea that acid strength and bond strength are associated with the rate of reaction. For example, Jack explained his molecular level drawing for a weak acid this way: "A weaker acid would dissociate faster because there's not – the bond isn't as strong cause it's a weaker acid." When describing his molecular level ideas of a strong acid, Jack also said that a strong acid is hard to dissociate. Again, this is different from his verbal definition of a strong acid based on the nucleophilicity of conjugate bases. Another student, Carrie, who previously used the idea of pH and "less reactive" to verbally define weak acids, also used the idea of the "less reactive nature of weak acids" to draw them at a molecular level. Carrie drew separated H^+ and A^- with a few HA together. She explains that H^+ and A^- are not as reactive, so they would not be bonded (Table 12). As illustrated by her description below:

> ***Carrie:*** *Cause, that [weak acid] wouldn't be like as reactive because it's weak. And there wouldn't be as many bonds in this one [the weak acid], I don't think.*
>
> ***SPI:*** *When you say "not as many bonds," what do you mean?*
>
> ***Carrie:*** *Because it's less reactive since it's a weak acid. So, it's not going to react as much. Like, it's, like… (student starts to point at the HA representation in the key then goes back to the weak acid drawing)*
>
> ***SPI:*** *Would there be other things in there besides the H^+ and A^-?*
>
> ***Carrie:*** *Like the - like, the H and the A wouldn't be, it wouldn't be as many together in the weak acid.*

First, Carrie described a strong acid at a molecular level as “more reactive” in section 4.2.3. This idea was not a clearly formed concept in her drawing, the H^+ and A^- were dissociated, and the atoms were not conserved when she used the more H^+ concept for the strong acid. However, Carrie’s explanation has some useful resources. Other concepts utilize relative acid strength, like pK_a, that can be used to explain how “reactive” one compound is compared to another. If an instructor had Carrie in their class, they could use her current reasoning to provide her with assistance to improve her understanding. They could help her more appropriately structure her reasoning about the individual components of the reaction. So, she could understand how reactivity applies, as it currently appears to be confounding her understanding.

Overall, as in the verbal definitions provided by students, the molecular level drawings provided by students for a weak acid were complementary to their strong acid drawings in some aspect. For those that had a more developed understanding of a weak acid in terms of partial dissociation, their molecular level drawings more appropriately reflected this. Alternatively, students who had verbal descriptions that utilize pH or less hydrogens produced drawings with features of both more A^- representations and complete dissociation in their drawings.

4.2.4 Application of Strong Acid in Molecular Level Picture Selection Task



2. If a solid acid HX is mixed with water, which representation is for a strong acid?
(Follow up question: Which representation would you pick for a weak acid? - not printed on the page)

Figure 10. The task to select the representation for the strong acid and explain the reasoning

Students were asked to select the representation that depicted the strong acid (Figure 10) and provide their reasoning for making that selection. Students' responses were analyzed to evaluate their conception of a strong acid at the molecular level and consistency with students' previous molecular level drawing (Table 13). The data is presented on frames shifts during the interview caused by the interviewer, the number of representations discussed by their features before answer selection, and if the student wrote out the dissociation reaction during the task to provide additional information on student reasoning (Table 13).

Twelve students of out twenty (Sam, Bill, Gladys, Kim, Alex, Gwen, Kent, Annie, Jack, Kelly, Mitch, and Sylvia) selected and reasoned about a representation consistent with their strong acid at the molecular level drawing from the section 4.2.2. Ten of these twelve students reasoned based on the idea that strong acids completely dissociate. Jack selected a representation based on his previous drawing. However, he chose an incorrect representation of a strong acid because he continued reasoning that a strong acid would be harder to dissociate. Another student, Kelly, selected the correct response and reasoned by looking for the "how many separated Hs" in the solution. Her language was consistent with her use of "more H^+" in a strong acid. Of note, Kelly's strong acid at the molecular level drawing had two more H^+ than A^-, but there was no representation available in this task for her to select that concept.

Nevertheless, her reasoning did not change. This reasoning, along with her other contextually definitions of a strong acid, could offer insight into scaffolding Kelly's understanding of strong acids. She has verbally defined a strong acid based on a list of strong acids, then used a concept of "more H^+" in her molecular level drawing and representation. Indeed, strong acids would have more H^+, but they should have a corresponding amount of A^-.

Table 13. The response, reasoning, comparisons, and consistency for strong acid molecular level representation, when picture provided as a multiple choice

Courses	Name	Response			Frame shifts with prompting	Reasoning						Writes dissociation reaction	Compares			Consistent with drawing
		No. I	No. II	No. III		Interactions of H & X	Strong stays together	Dissociation Reaction	More products, based on Ka	Partial dissociation	Complete dissociation		No comparison selects 1	Compares features of 2	Compares features of 3	
GC II	Sam			X							X		X			X
	Bill			X							X	X			X	X
	Gladys			X							X				X	X
	Chester			X				X				X	X			
	Kim			X							X			X		X
	Marie		X		X	X						X	X			
OC I	Alex			X							X		X			X
	Gwen			X							X				X	X
	Kent			X							X			X		X
	Annie			X							X				X	X
	Frances	X					X			X					X	
	Louise		X				X								X	
OC II	Jack	X					X			X			X			X
	Carrie		X			X							X			
	Kelly			X		X									X	X
	Quinn			X					X				X			
BC	Clara		X			X							X			
	Mitch			X							X				X	X
	Sylvia			X							X				X	X
	Emily			X		X							X			
Summary of Courses	GC II	-	1	5	1	1	-	1	-	-	4	3	3	1	2	4
	OC I	1	1	4	-	-	2	-	-	1	4	-	1	1	4	4
	OC II	1	1	2	-	2	1	-	1	1	-	-	3	-	1	2
	BC	-	1	3	-	2	-	-	-	-	2	-	2	-	2	2
		2	4	14	1	5	3	1	1	2	10	3	9	2	9	12

The other five students, who previously used the idea of "more H^+" on their molecular level drawings, used two different methods of reasoning to select the molecular level representation for a strong acid. Frances and Louise, in organic chemistry II, reasoned that a "strong acid stays together," however, this reasoning led each of them to select different representations. Louise selected representation no. II, because the "acid stayed together throughout the mixture." Frances selected representation I that had some dissociation, which she discussed when she compares features of all three of the representations. An interesting aspect that becomes apparent for Frances, who is an ESL learner, is that she is not just struggling with the concept of the strong acid or weak acid, she is unsure about what happened to the water since it is not represented in the picture. This confusion about the water is illustrated below:

> *... I don't see any water, so there has to be in my head a residue of water. Because there is absolutely no way that the acid is going to consume all the water molecules like there will be no water so this one cannot be it… So, I don't know, maybe there is not oxygen, because the acid actually consumed the oxygen, so there is only residue of hydrogen.*

This finding is interesting since both molecular level drawing and representations were about acids in an aqueous system; however, they were contextually different. The molecular level drawing task simply indicated that this was as a "strong acid in an aqueous solution," which requires a student to translate the word aqueous to mean "in water." In contrast, the molecular level picture task was written as "a solid acid HX added to water," a generic representation of an acid added to water, in which a student must consider what happens as a solid becomes an aqueous solution. For Frances, it appears that the task prompt that included the word "water" activated something for her to utilize water in her representations. However, she did not make a connection that H^+ is often used instead of H_3O^+.

A few students (Carrie, Clara, and Emily) used the interactions of H and X to reason through their selections for a strong acid, no. II, II, and III, respectively (Figure 10). Carrie continued to use her same line of reasoning based on the idea that strong acids are "more reactive." However, when Carrie drew the molecular level drawing, she did not connect the H^+ and A^-, whereas when she selected the picture, she choose one based on the most H and X together. It appears that something was activated to indicate that they were together. Recalling the dialogue from section 4.2.3, Carrie was not clear why the H^+ and A^- were separated in her concept of "more H^+." She said, "It depends on like what you're mixing it with… cause, I know like everything doesn't necessarily mix with like a strong acid." This an unstable concept for Carrie, which has some useful resources that need to be scaffold towards an appropriate scientific understanding of a strong acid. Clara, in biochemistry, has an unstable conception for a strong acid, when reasoning for the selection of the strong acid picture she indicated that "an acid has, basically the proton attached to it, so this [no. II] has more protons involved with X." She activates an idea of more protons again. However, interestingly this time, she attaches the proton to the X rather than dissociating it as she did in her drawing of the strong acid at the molecular level. Emily, in biochemistry, uses the "number of H's in each box," which is similar reasoning to her molecular level drawing of more H^+. However, then she adds, "and how they are interacting with the X's," something was not activated in her molecular level drawing, as there were no A^-'s present in her drawing.

Chester began his task by writing out the dissociation reaction of HX and water with double-headed arrows to H^+ and A^-, which led him to select no. III for complete. His dialogue provides surface-level reasoning that the products of the reaction are H^+ and X^-, so that is the representation that he is selecting. Chester stated, "if you were to do a formula, you would get

H_3O^+ or H^+, and X and they are both like separated. They're not, well, they're not together." However, this was in complete opposition to how he responded when he drew out his molecular level drawing, and none of the HA was dissociated. Also recalling that Chester verbally defined strong acids by using tricks that his TA taught him, all these surface-level learning techniques are lending to an unstable conception of strong acid for Chester.

Marie initially selected representation no. II, where all of the acid (HX) "would be paired together." However, during the task, Marie had written out the dissociation reaction, and the interviewer challenged Marie's understanding based on this discrepancy:

> ***SPI:*** *And when you wrote this here, you actually wrote* H_3O^+ *and* X^-*, um, when you look at this what's on the left side?*
>
> ***Marie:*** *The reactants.*
>
> ***SPI:*** *And what are these (SPI points to products)?*
>
> ***Marie:*** *The products.*
>
> ***SPI:*** *Ok. And so, when you mix it [HX] with water, you have an* H^+ *here [in the products of the reaction], but there aren't any be any H pluses here [no. II]?*
>
> ***Marie:*** *Uh, I didn't even think about that part. Hmm… I'm guessing it wouldn't be that [no. II], it would probably be, wait. No, it would probably be this one [no. III] because it only has H pluses, and this one doesn't have any H pluses, just H's alone, and this (*H^+ *and* X^-*) is the product now, so.*

This challenge from the interviewer shifted Marie's response, which may help improve her understanding if she remembers this connection. However, like Chester, this is a surface-level connection to the products without a connection to the extent of the dissociation in the reaction. This exchange between the interviewer and Marie was important to note as it affected Marie's response to the weak acid representation and demonstrated a way to help scaffold a student's reasoning as they were processing the information with the resources that they were currently using.

4.2.5 Application of Weak Acid in Molecular Level Picture Selection Task

After students completed their reasoning for their selection of the strong acid at the molecular level picture task, students were asked to select which representation would be for a weak acid at the molecular level (Figure 10) and provide their reasoning. Students' responses were analyzed to evaluate their conception of a weak acid at a molecular level and whether the reasoning of their selection was consistent with their previous molecular level drawing (Table 14). The data is presented on the number of representations that were discussed by their features before answer selection to provide additional information on student reasoning.

Ten students (Sam, Bill, Gladys, Kim, Alex, Kent, Annie, Jack, Quinn, and Sylvia) were consistent in their selection and reasoning of weak acid molecular level representations when compared to their drawings (Table 14). Nine of those ten students used reasoning based on partial dissociation. Jack incorrectly selected representation no. III, with his continued use of weak acids being able to dissociate easier than strong acids.

Mitch, in biochemistry, indicated that he felt that representation no. II would be the "weakest" acid, even when challenged by the interviewer, although he momentarily shifts as illustrated below:

Mitch: *Um, I guess I would choose… I would choose two, the like weaker between the all three of them, the weakest of the three of them.*

Table 14. The response, reasoning, comparisons, and consistency for weak acid molecular level representation, when picture provided as a multiple choice

Courses	Name	Response			Reasoning								Compare		Consistent with drawing
		No. I	No. II	No. III	Stays together	Weaker bonds	H involved with X	Most dissociated	Less separated H's	Reversible, both present	Partially dissociates	Really weak acid cannot dissociate	No comparison selects 1	Compares features of 2	
GC II	Sam	X									X		X		X
	Bill	X									X		X		X
	Gladys	X									X			X	X
	Chester*		X		X								X		
	Kim	X									X		X		X
	Marie*	X								X			X		
OC I	Alex	X									X			X	X
	Gwen	X									X		X		
	Kent	X									X		X		X
	Annie	X									X			X	X
	Frances			X		X							X		
	Louise			X		X								X	
OC II	Jack			X				X					X		X
	Carrie			X			X						X		
	Kelly	X							X					X	
	Quinn	X									X		X		X
BC	Clara	X					X							X	
	Mitch		X									X		X	
	Sylvia	X									X		X		X
	Emily	X					X							X	
Summary of Courses	GC II	5	1	-	1	-	-	-	-	1	4	-	5	1	4
	OC I	4	-	2	-	2	-	-	-	-	4	-	3	3	3
	OC II	2	-	2	-	-	1	1	1	-	1	-	3	1	2
	BC	3	1	-	-	-	2	-	-	-	1	1	1	3	1
		14	2	4	1	2	3	1	1	1	10	1	12	8	10

> ***SPI:*** *The one that is a weak acid in solution, that is still an acid and would be representative of what a weak acid in solution would look like?*
>
> ***Mitch:*** *Ok. So, I would choose, I guess I would choose one.*
>
> ***SPI:*** *Ok. And why would you choose one?*
>
> ***Mitch:*** *Because it's, um, kind of half and half, so it's, it's not really, um, it's not strong because it's not completely dissociating, but it's not, um, - the conjugate base also, isn't. Oh, I guess if it's a weak acid, it's a strong conjugate base. So, I would actually choose two. I would choose two. Because, so I, um, would choose two, becaus-, because, um, if I, if it's a weak acid, it's not gonna be in the dissociated form. But if it's a weak acid, then I would assume the conjugate base is - it's a strong conjugate base so it would be more like to go in the reverse going back to the, the aci-, the, the HA form. So, I would choose two for that one.*

Something has been activated for Mitch that indicates that the "weakest" acid will not dissociate. Although his molecular level drawings were some of the more sophisticated, he did lack a verbal definition based on dissociation rather than relying on pKa values.

Chester selected a weak acid representation based on the idea that was the exact opposite of his selection for a strong acid, in that "weak acids would stay together." Chester previously wrote and reasoned with the dissociation reaction for the strong acid, section 4.2.5, but he did not use it for the weak acid. Although, notably, he previously utilized the reaction with reversible arrows and reasoned as if it were a single arrow for reaction completion.

Marie had selected the correct response for a weak acid based on the idea that the weak acid would have a reversible reaction, and both the reactants and products would be present. This reasoning is an improvement towards more scientific thinking for Marie. Recall during the previous strong acid portion of this task, Marie was prompted by the interviewer to utilize the reaction to help her reason through the task.

Gwen, in organic chemistry I, has some different activation of resources when she selects her representation of a weak acid than when she drew her representation. When she reasons to select her representation, she states, “there’s some dissociation, but it’s not complete.” However, when she drew it in the previous weak acid at the molecular level task, she drew all as HA combined (Table 12), not dissociated at all. This concept appears to be developing for Gwen and dependent on the context of the problem. Furthermore, that context does not necessarily need to be a difference in molecular level thinking as both tasks asked for thinking at the molecular level.

Several students used reasoning for a weak acid that complemented their strong acid reasoning. Frances and Louise indicated that weak acids have weaker bonds, and both selected representation no. III. Kelly continued to use the idea of the number of separated H’s, in the case of a weak acid, she looked for less H’s and selected no. I. Carrie, Clara, and Emily used the interaction of H with X to reason through their selections of weak acid representations, with Carrie selecting a completely opposite representation from the others. Carrie used the idea that a weak acid was “less reactive” and selected the representation with all the H^+ and X^- separated, whereas Clara felt that a weaker acid would have less protons attached to the acid, and Emily felt that in the X^- in no. I “could still act as a base.” Emily’s quote is interesting as she is one of the students who used the concept of more A^- in her weak acid drawing, which was not utilized as a resource in this task often as there was no choice for more A^-. This reasoning perhaps provides an insight that Emily envisions the X^-, or A^-, as the “base component” of the weak acid. Emily may be relating that idea to her verbal definition of a weak acid based on pH, which means more

A^- in the solution, which would make the solution more basic. This idea might be also be intertwined with ideas associated with the base definition in the Arrhenius acid-base model.

Overall, throughout the three tasks about strong acids, eight students were consistent in their responses across multiple contexts (Sam, Bill, Gladys, Kim, Alex, Gwen, Kent, and Sylvia). This trend was also seen with weak acid across multiple contexts for eight students, incidentally not the same eight students (Sam, Bill, Gladys, Kim, Alex, Kent, Annie, and Sylvia). Furthermore, inconsistent students lacked an appropriate verbal definition of a strong acid or weak based on the concept of the extent of dissociation related to each.

4.3 Relationship of K_a and pK_a

4.3.1 Equilibrium

Based on the idea of meaningful learning, students construct their knowledge on prior knowledge and make connections to that prior knowledge. The concept of equilibrium is an underlying concept of the acid ionization constant, K_a. Therefore, students in all courses were asked to explain what it means for a reaction to be in equilibrium. The responses were analyzed for the ideas that students associated with this concept (Table 15).

Only four students (Sam, Bill, Kim, and Annie) out of twenty participants described the concept of a reaction at equilibrium as a reversible reaction that occurs at the same rate in both the forward and reverse directions. Three students in general chemistry II and one in organic chemistry I. For example, Sam, in general chemistry II, stated:

> *It means that, um, it's in a constant state between the products and the reactants continually going back and forth, such as the products rate of turning into the reactants is equal to the rate of reactants turning into products.*

Table 15. Ideas used to define reaction equilibrium by course

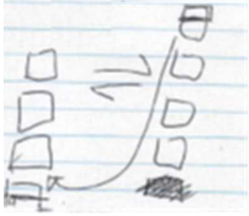
Courses	No response	Equal amounts	pH = 7 [H$^+$] = [OH$^-$]	Problem-solving tricks	Stoichiometrically balanced	Lack of understanding of arrows	Completely reacts	Reversible	Reversible and same rate	Double-headed arrows
GC II	-	1	-	1	-	2	1	1	3	3
OC I	-	3	-	1	-	3	1	3	1	-
OC II	-	2	1	-	2	1	-	1	-	1
BC	1	3	-	-	-	-	-	-	-	-
	1	9	1	2	2	6	2	5	4	4

Interestingly, none of the upper-level students in organic chemistry II or biochemistry defined equilibrium as reversible and at the same rate. Five additional students (Gladys, Alex, Kent, Frances, and Quinn), from each course except biochemistry, described the reversible nature of the equilibrium reaction without any discussion of the reactions occurring at the same rate. However, all but one student, Kent, also provided additional conflated ideas that did not pertain to defining reaction equilibrium. Most of these conflated ideas were the idea of equal amounts of “things” in the reaction. These “things” being the reactants and products, the dissociated and undissociated forms, or the acid and base. One of the students, Frances, acknowledged the reversible nature of the equilibrium reaction but was confounded by the idea that all the reactants completely react, then the reverse reaction also occurs.

Eleven students did not provide any appropriate ideas to describe a reaction at equilibrium, but instead used a variety of conflated ideas, from general chemistry II through organic chemistry II. However, all the biochemistry students appeared to converge on the same conflated idea that equilibrium indicated equal amounts of "things." The conflated idea of equal "things" was seen across all courses in nine students. Sylvia, in biochemistry, defined equilibrium as "When there's an equal amount of the dissociated and undissociated." This interpretation of equilibrium has been seen in the literature (Hackling & Garnett, 1985). Carrie, in organic chemistry II, extended this idea of equal things to encompass the concepts of pH being equal to 7 at equilibrium, where $[H^+] = [OH^-]$.

One interesting description of equal amounts was from Gladys, in general chemistry II. She described it in terms of balancing out pieces on the left and right sides of the reaction. She stated:

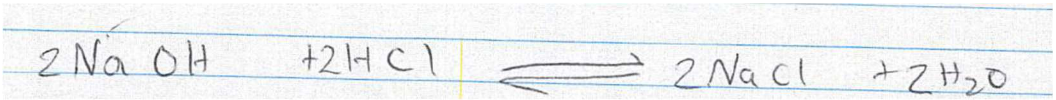
> *That usually means it can go forward and backwards to stay at like constant stability sort of. It's like so, kind of a metaphor, there's four blocks on one side, three blocks on another side. They're gonna try to like half a block, so they can both kind of be a little bit more stable with each other [She splits one block in half and draws an arrow to the other side to show it sharing that portion].*



Gladys appears to understand that the reaction is reversible, but she is using this to even out the quantities of the reactants and products to equal amounts to achieve equilibrium.

Two students (Jack and Kelly) in organic chemistry II, described equilibrium in terms of balancing an equation by demonstrating how to balance the stoichiometry. Furthermore, Jack used a strong acid (HCl) and strong base (NaOH) reaction for his example to explain equilibrium, although he used the double-headed reaction arrows for equilibrium. As illustrated by this passage from Jack's interview:

> ***Jack:*** *Well, for a reaction to be in equilibrium, that means that both sides have to be balanced out… So, I'll say NaOH (writes NaOH +), and then you have HCl (writes HCl). Then in order for you to have equilibrium (writes double-headed arrows), then you would get … Na and Cl together and then the H and the OH together. So, you would get NaCl and then* H_2O *(student writes NaCl and* H_2O*). But usually, sometimes they'll have like more compounds, so if there's like a 2 (writes a 2 in front of the HCl) in front of the HCl, then you would have to try balance out the equation. So, usually, you'd put a 2 to balance the Cl here (writes a 2 in front of NaCl) and because there's two OHs you'd have to try to balance out the H on this side and so you would end up adding another two here (writes a 2 in front of the* H_2O*), and then there would be two O s, and you'd have to add a two here (writes a 2 in front of NaOH) to try to balance it out.*



$2NaOH \quad +2HCl \rightleftharpoons 2NaCl \quad +2H_2O$

Recall that Jack had no models for an acid or base, he was unable to define a strong acid, or weak appropriately, and now conflates the idea of equilibrium. In meaningful learning, students have prior knowledge to build on and make deliberate connections with for a deeper learner. Jack's inability to construct an appropriate explanation of equilibrium, distinguish strong and weak acids or use acid-base models had a cascading effect.

Recalling, in section 4.2.4 on weak acids at a molecular level, both Alex and Quinn drew equal amounts of HA, $H^{+,}$ and A^{-} for their weak acid molecular level drawing. However, based on the resources activated by Alex in the following dialogue about the weak acid at the molecular level drawing task, at some level, Alex is aware of the need to not be at equal amounts. It appears that different resources are being activated in different contexts for Alex:

> *But you know, just you have a fair bit of the actual, uh, acid in its original form and then also some of it separated [H^+ and A^-]. And that'll, that sort of – how,* ***how much of each kind of depends upon, um, your, uh, pKa and your pH and whatnot****.*

Chester, in general chemistry II, continued to use problem-solving heuristics, or shortcuts, throughout his interview. He described equilibrium as "something like the 5% rule, that's what he told us in class. It was like if it's at equilibrium if it's lower than 5%." He seemed to be conflating some amount of percent ionization for describing weak acids with equilibrium. Alex, in organic chemistry I, used a rule for problem-solving that seemed to conflate her understanding of equilibrium as it relates to strong acids and weak acids:

> *…like equilibrium not really mattering and the acid being considered strong if it was to the point where there were… if it was… something, um, to like a magnitude of 100, uh, the difference between whether it favors the left or the right side of the, the equation.*

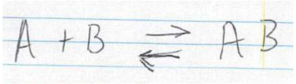
Alex appeared to be conflating the idea equilibrium and a strong acid with the idea of a weak acid and whether its change in concentration matters during ICE table calculations. The ICE table is a typical problem covered in the general chemistry II acid-base chemistry curriculum. The textbook used at the institution in this study focused heavily on this task. Several lectures were spent reviewing and practicing this type of problem in general chemistry II. For an ICE table problem, the student is given the initial concentration of a weak acid. Then some change in concentration is applied to the system. The student then calculates the new equilibrium concentrations using the equilibrium constant. To simplify the problem and omit using the quadratic equation, the student can use the "magnitude of 100 rule". When the molarity of the weak acid is 10^2 or magnitude of 100 greater than the equilibrium constant, then the change in initial weak acid (HA) is not going to affect the calculation. It can be omitted, thereby simplifying the calculation.

Mitch, in biochemistry, provided no response when he was asked to define equilibrium except to say, "I'm not sure honestly." However, in section 4.24, in the context of the weak acid molecular level drawing, he used the idea of equilibrium as part of his reasoning to describe whether the reaction laid more towards the reactants or the products. Interestingly, he used this resource in the context of the task before this equilibrium question, yet he was unable to give a verbal description of equilibrium.

Some students utilized the symbolic reaction arrows to reason about equilibrium. Four students, three in general chemistry II (Bill, Gladys, and Chester) and one in organic chemistry I (Jack) attributed the appropriate meaning to the double-headed arrows that are representative of the reversible nature of the equilibrium reactions. However, six students (Kim, Marie, Alex, Frances, Louise, and Kelly) demonstrated discrepancies in the proper usage of and meaning of reaction arrows. For example, Kim, in organic chemistry II, understands that equilibrium is represented by the double arrows, which is appropriate. However, the meaning she attributed to the symbolism was not sophisticated enough to reflect the reversible nature of the system when contrasted to her understanding of a single arrow. Her language reflects that double-headed arrows indicate that all the reactants have reacted to make products for an equilibrium reaction and that for a reaction with a single arrow, the reactants have not completely reacted yet.

SPI: *What does it mean for a reaction to be in equilibrium?*

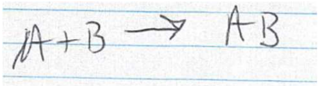
Gwen: *It means that all of the reactants have reacted to, uh, produce the products. And…. um, it's - there's just balance on both sides of the, um, I don't wanna say* *equation, but it's just… Like I, I know if I had A plus B, and then when all of the A had mixed with all of the B, and you just maybe have AB – I that's, I guess that's in equilibrium (student writes out A + B double arrows AB). All of the atoms… all of the A atoms have reacted with the B atoms, and they…. um, basically the, the reaction is, is no longer sort of one-sided. It, it's…. um…. I'm doing a terrible job of explaining this.*



$A + B \rightleftharpoons AB$

SPI*: Is there anything that helps express equilibrium?*

Gwen: *Well yeah, this symbol, these symbols here (student indicates the double arrows). It, as opposed to if it was just, like, A plus B and there was just one yield sign (student writes out A+B with a single arrow to AB). That [a single arrow] would denote that it's not quite finished reacting.*



$A + B \rightarrow AB$

A developing concern here is that equilibrium is an underlying resource for understanding the acid equilibrium constant, K_a, and more than fifty percent of the sample is unable to describe it appropriately. This lack of understanding has the potential to have a cascading effect on students' ability to interpret K_a fully. Overall, students who indicated that a reaction at equilibrium would be reversible and have the same rate did not provide additional unrelated resources. Whereas, students that indicated equilibrium reactions were simply reversible, generally provided additional unrelated resources. The most often utilized alternative resource was the idea that there are equal amounts of "things." Furthermore, a general lack of ascribing the appropriate meaning to arrows indicates that simply utilizing double-headed arrows does not imply an understanding of that reactions are reversible.

The idea of "equal amounts" for students in this study could develop from a couple of different contexts related to equilibrium and acid-base chemistry. Students that discussed equilibrium in terms of "equal amounts" used equal amounts of reactants and products, dissociated and undissociated, acid and base, protonated and deprotonated, and H^+ and A^-. If you take into consideration that at equilibrium, the concentrations of the reactants and products remain the same, students may be misinterpreting this language as equal amounts. As students progressed to biochemistry, they converged to describing equilibrium as equal amounts. In this biochemistry course, they utilize pK_a and pH to determine the ionization states of amino acids by comparing the ratio of the acid and conjugate base forms. When Emily, in biochemistry, was asked to explain what happens when $pH = pK_a$, she responded, "if they are equal to each other, they will be in equilibrium." Therefore, students may be conflating the concept of equal amounts of acid and base when $pH = pK_a$ from the relationship in the Henderson-Hasselbalch.

4.3.2 K_a – Acid Ionization Constant

Participants were asked a series of questions to elicit their overall understanding of K_a, the acid ionization constant, which may include a description of K_a, mathematical expression, and/or a descriptive evaluation of the expression. These were further categorized to determine the level of sophistication of the student based on their ability to integrate these features.

4.3.2.1 Abbreviation - K_a

The initial question posed to the students was simply, "What is K_a?" The question was structured and analyzed to determine the meaning ascribed by the students to the abbreviation K_a (Table 16). When students struggled with their response, they were further prompted with "Do you remember other K's, like K_{eq}, K_a, K_b?" There was no need to provide the general chemistry II students with this additional prompting as they had been presented this material at length in this course just before the interview. In contrast, organic chemistry I and biochemistry have minimal refreshers on the material covering concepts related to K_a.

Table 16. Meaning ascribed to the abbreviation K_a by student and course

Courses	Name	I do not remember	For acids/acidity	Rate/Kinetics	Connects to pKa	Products over reactants	Mathematical Expression	Names constant
GC II	Sam							X
	Bill							X
	Gladys				X	X		X
	Chester					X		
	Kim							X
	Marie		X					
OC I	Alex*							X
	Gwen*				X			
	Kent		X					
	Annie*						X	
	Frances	X						
	Louise*						X	
OC II	Jack*		X	X			X	
	Carrie	X						
	Kelly				X			
	Quinn*							X
BC	Clara			X				
	Mitch							X
	Sylvia				X			X
	Emily							X
Summary by course	GC II	-	1	-	1	2	-	4
	OC I	1	1	-	1	-	2	1
	OC II	1	1	1	1	-	1	1
	BC	-	-	1	1	-	-	3
		2	3	2	4	2	3	9

* Required additional prompting

Seven out of twenty students were able to provide an answer without any additional prompting. Two students were able to provide a name for K_a with additional prompting. Altogether, these nine students used a variety of names for K_a, which included the acid constant, acid ionization constant, acid equilibrium constant, and acid dissociation constant. This variety is not a surprise since K_a has many names. In general, it is an equilibrium constant for acids. It is also called the acid ionization constant (Tro, 2010), the acidity constant (Karty, 2018; McMurry, 2016), and the acid dissociation equilibrium (M. M. Cooper & Klymkowsky, 2019). Two of these nine students described other aspects of K_a before arriving at the name of the constant. Gladys connected K_a to the idea of products over (divided by) the reactants and its connection to pK_a, whereas Sylvia only mentioned the latter.

When students failed to produce the name of the constant, it was provided to them. Most of these students were in organic chemistry I or II. The failure to produce a name is especially interesting for organic chemistry I students since it is one of the first topics that is discussed in organic chemistry I and one of the last topics that is discussed in general chemistry II. Three of these students attempted to arrive at the name of K_a by utilizing a mathematical expression. One of these students, Chester, used products over reactants, and he called it the "concentration formula." He stated, "K_a, that is – I think that's prod-, that's products over reactants. So, that's how you - that's' the that's the concentration. K_a is the concentration of the formula." Gwen and Kelly, students in organic chemistry I and II respectively, made connections between K_a and pK_a, but could not name K_a. Also, Clara conflated K_a with Michaelis-Menten kinetics (K_m), a topic she was currently learning in biochemistry. Marie and Kent, students in general chemistry II and organic chemistry I respectively, were only able to conjure up the idea that K_a is related to acidity. Frances and Carrie, in organic chemistry I and II, respectively, admitted that they were unable to describe anything related to K_a.

4.3.2.2 Description of K_a

Students were asked to describe K_a to understand what meaning they ascribe to the concept (Table 17). Seven out of twenty students (Marie, Gwen, Frances, Carrie, Kelly, Clara, and Emily) were unable to provide any description of what they thought K_a described. Three students, Sam and Bill, in general chemistry II and Annie in organic chemistry I, described K_a in terms of acid dissociation. Sam stated, "… how well an acid dissociates."

Four students, three in organic chemistry I and one in biochemistry, described K_a according to the acid, conjugate acid and conjugate base. For instance, Louise stated, "how much of the [conjugate] acid and its conjugate base is in there compared to the acid." Gladys, in general chemistry II, simply stated, "K_a describes for the acids, like the concentrations of each amounts and how that is represented like in the solution." Kim, in general chemistry II, similarly described K_a as "the ratio of the concentration of the products to the concentrations of the reactants." Chester continued to use his problem-solving strategies in his descriptions when he stated, "it describes what, uh, kinda describes what you're trying to find. Like, kinda like, kinda like the ICE [initial, change, equilibrium] table."

Interestingly, four students indicated that it describes the "equilibrium." Sylvia, in biochemistry, stated, "the point at which the acid will be in equilibrium." These students previously described equilibrium in section 4.3.1. However, Sylvia previously described this as "When there are equal amounts of dissociated and undissociated." There is no indication here when she describes K_a that she intends that meaning in her description of K_a. Did the other students who simply mentioned the word equilibrium in passing attribute their original meaning,

Table 17. Ideas used to describe K_a by student and course

Courses	Name	Unable	Rate	Problem-solving	Equilibrium	Ratio of products to reactants	Concentrations in solution	How much acid to conjugate acid & conjugate base	How well acid dissociates
GC II	Sam								X
	Bill				X				X
	Gladys						X		
	Chester			X					
	Kim					X			
	Marie	X							
OC I	Alex				X			X	
	Gwen	X							
	Kent		X					X	
	Annie				X				X
	Frances	X							
	Louise							X	
OC II	Jack		X						
	Carrie	X							
	Kelly	X							
	Quinn		X						
BC	Clara	X							
	Mitch							X	
	Sylvia				X				
	Emily	X							
Summary by course	GC II	1	-	1	1	1	1	-	2
	OC I	2	1	-	2	-	-	3	1
	OC II	2	2	-	-	-	-	-	-
	BC	2	-	-	1	-	-	1	-
		7	3	1	4	1	1	4	3

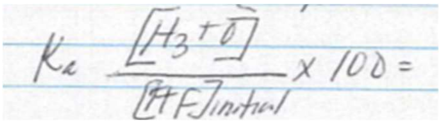
or some alternative meaning? Or could it be that they have heard equilibrium associated with this definition before, so are using it? With this research, the question arises "when words are expressed, what is the meaning attributed to them?"

Three students conflated K_a with rates. Kent in organic chemistry I stated, that "K_a describes the rate in which the weak acid would dissociate." However, he also described it as "how much of it dissociates," so he has useful resources for describing K_a, along with his conflated ideas. Jack and Quinn, in organic chemistry II, described it with respect to the "rate." However, when Quinn was asked to describe K_{eq}, she described it in terms of the ratio of the concentrations.

4.3.2.3 General Expression for K_a

Students were also asked to describe a general form of the K_a expression (Table 18). When students struggled to produce an expression, the SPI suggested that they write out a dissociation reaction. The responses were analyzed based on the construction of the expression. Previously, Frances, Carrie, Kelly, Clara, and Emily were not able to verbally describe K_a, and none of these students successfully provided a mathematical expression for K_a. Additionally, Quinn, who utilized rate to describe K_a, was unable to provide any mathematical expression for it. Gwen and Marie previously could not verbally describe K_a but provide some mathematical expressions that could be scaffolded towards understanding.

Gwen mathematically expressed it as reactants over products, which is an inverted simplification of the K_a. Marie, in general chemistry II, provided the following expression:



$$K_a \frac{[H_3{}^{+}O]}{[HF]_{initial}} \times 100 =$$

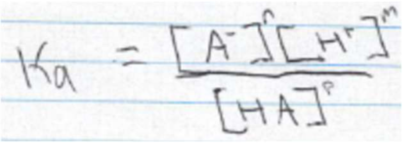
Table 18. Mathematical expressions for K_a by student and course

Courses	Name	Unable	Percent ionization	Reactants over products	[Products]/[Reactants]	K_{eq} with subscripts, not superscripts	$[H^+][A^-]/[HA]$ Coefficients from rate order	[H][A]/[HA] no charges	$[H^+][A^-]/[HA]$ some charges	$[H^+][A^-]/[HA]$ all charges
GC II	Sam							X		
	Bill*									X
	Gladys									X
	Chester									X
	Kim*				X					
	Marie		X							
OC I	Alex*								X	
	Gwen*			X						
	Kent						X			
	Annie*									X
	Frances	X								
	Louise*									X
OC II	Jack					X				
	Carrie	X								
	Kelly	X								
	Quinn	X								
BC	Clara	X								
	Mitch									X
	Sylvia*								X	
	Emily	X								
Summary by course	GC II	-	1	-	1	-	-	1	-	3
	OC I	1	-	1	-	-	1	-	1	2
	OC II	3	-	-	-	1	-	-	-	-
	BC	2	-	-	-	-	-	-	1	1
		6	1	1	1	1	1	1	2	6

* Required additional prompting

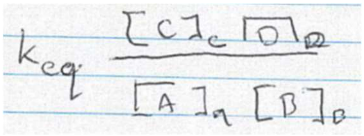
Marie's expression is conflated with percent ionization; however, the K_a expression is structured similarly. When Marie was asked to describe what this is used for in-class, she stated, "To find the percent ionization." Then she was asked to describe percent ionization, and she replied, "I'm not 100% sure how to explain ionization." Her understanding is not only conflated, but she does not seem to understand the underlying concept of ionization, which is also important for Ka. Percent ionization is presented simultaneously with K_a for these students in general chemistry II. This conflation, based on mathematical similarity, has been seen by other researchers with rate laws and K_a (Bain et al., 2019; Becker et al., 2017). Conflation with rate laws was observed in Kent's mathematical expression, where he stated:

> *So, K_a is equal to H^+ and A^-, which means the equilibrium constant would be…and then HA… that's concentration (indicates the brackets), and there is certain variables that would go here (indicates superscripts) depending on the rate order, I believe.*



$$K_a = \frac{[A^-]^n[H^+]^m}{[HA]^p}$$

Jack, in organic chemistry II, developed a mathematical expression based on K_{eq} rather than K_a; however, his general form used subscripts in place of superscripts. He explained that he could multiply the subscripts to arrive at the outcome. His mathematical expression is illustrated below:



$$K_{eq} \frac{[C]_c[D]_D}{[A]_a[B]_B}$$

When Jack was asked about what K_a would be compared to the K_{eq}, he stated, "Um, I guess, it would be for the first half of the reaction." Although Jack produced a generic mathematical expression for K_{eq}, he does not make a meaningful connection between the two concepts. This lack of connection is interesting as previously, Quinn was not able to make connections when she described K_a inappropriately but appropriately described K_{eq}.

Five out of six general chemistry II students had appropriate mathematical expressions for K_a. Kim described it in an oversimplified manner as products over reactants. Bill, Gladys, and Chester described it appropriately as $[H^+][A^-]/[HA]$ with all charges present, whereas Sam had the appropriate form but omitted writing in the charges on the ions. While this delineation between students who have omitted some, or all the charges may seem insignificant and students may have incidentally forgotten to write them, this research is exploring the real-time usage by the students in the different contexts.

Three out of six organic chemistry I students had appropriate mathematical expressions for K_a. Annie and Louise provided the expression $[H^+][A^-]/[HA]$, whereas Alex provided it as $[A^-][H]/[HA]$. None of the organic chemistry II students had an appropriate mathematical expression for K_a. Two out of four biochemistry students provided appropriate mathematical expressions for K_a, Mitch, and Sylvia. Mitch provided a complete K_a, whereas Sylvia omits a charge.

Overall, ten students provided a mathematical expression for Ka; however, some of these were missing charges in the overall format. None of the organic chemistry II students provided a mathematical expression for K_a. Five of the seven students who were unable to describe K_a were unable to express it mathematically.

4.3.2.4 Descriptive Evaluation for K_a values

Students were asked to evaluate a larger value of K_a indicated compared to a smaller value of K_a. Students provided variety in their descriptive evaluations, as well as their actual number of evaluations by each student (Table 19). Five out of twenty students were unable to provide any evaluation of the meaning of a larger value of K_a. Three of those were organic chemistry II students, who continue to struggle with the overall concept of K_a. Interestingly, Jack provided an expression for K_{eq}, but his lack of connection to K_a impaired his ability to utilize it as a resource to interpret values.

The most often used descriptive evaluation of a larger value of K_a was that it meant a "stronger acid." However, only ten out of twenty students (Sam, Bill, Chester, Alex, Kent, Annie, Louise, Quinn, Mitch, and Sylvia) indicated that a larger value of K_a meant it was a "stronger acid." Eight out of these ten (Sam, Bill, Chester, Alex, Kent, Annie, Mitch, and Sylvia) students utilized other descriptors to justify their choice. The students used a combination of justifications. Two students in organic chemistry I, Alex and Annie, indicated that there was less of the undissociated form or less reactants. Six of these students (Sam, Bill, Chester, Kent, Mitch, and Sylvia) used descriptors about more of the dissociated form, more protons, more products, or more protons and conjugate base. Four of these students (Sam, Gladys, Chester, and Mitch) verbalized that they were comparing it to a smaller value. However, only two students (Sam and Chester) in general chemistry II used actual descriptors about the smaller value. Sam stated that "compared to a small one where there's more reactants in the solution." Chester contrasted his response by stating, "Then you'd have like a weaker acid if you had like a lower K_a." These students, who described that a larger value of K_a indicated a stronger acid, were the only students not to provide any false justifications of their reasoning.

Four students (Gladys, Kim, Gwen, and Clara) provided incorrect reasoning about a larger K_a. The two students (Gladys and Gwen) appear to have issues rooted in prior knowledge. The other two students (Frances and Clara) have conflated acid strength with rates.

Table 19. Descriptive evaluation of K_a by student and course

Courses	Name	Unable	Larger value											Smaller value			
			Faster	Goes back to reactants	Weak acid	Less undissociated	Less Reactants	More dissociated	More protons	More products	More protons and CB	Stronger acid	Comparison to smaller	Dissociates faster	More acidic, more acid present	More reactants	Weaker Acid
GC II	Sam							X		X		X	X			X	
	Bill							X	X	X		X					
	Gladys			X						X			X				
	Chester									X		X	X				X
	Kim														X	X	
	Marie	X															
OC I	Alex*						X					X					
	Gwen				X						X						
	Kent							X				X					
	Annie					X					X	X					
	Frances		X														
	Louise											X					
OC II	Jack	X															
	Carrie	X															
	Kelly	X															
	Quinn											X					
BC	Clara													X			
	Mitch									X		X	X				
	Sylvia							X	X			X					
	Emily	X															
Summary of Courses	GC II	1	-	1	-	-	-	2	1	4	-	3	3	-	1	2	1
	OC I	-	1	-	1	1	1	1	-	-	2	4	-	-	-	-	-
	OC II	3	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-
	BC	1	-	-	-	-	-	1	1	1	-	2	1	1	-	-	-
		5	1	1	1	1	1	4	2	5	2	10	4	1	1	2	1

Gladys stated,

> *A large value, you're gonna have a whole lot of products, more than you're gonna have the reactants. That might lead it to go a little bit more backwards to make the more reactants so you can kinda balance things.*

At first, Gladys does appropriately describe that there are more products for a larger K_a, but then she indicates that it will shift the reaction toward reactants. Recalling in section 4.3.1, Gladys described equilibrium in terms of equal amounts, in that the reactants and products equaled out to an even number of pieces. She appears to be applying this reasoning to K_a. Gwen indicated that a larger value would mean that there would mean there would be more protons and conjugate base, which is correct. However, this is incongruent with her previous description of a K_a expression, where she provides an inverted expression with reactants on the top and products on the bottom. This knowledge about the mathematical expression of K_a is important in a deeper understanding of the values assigned to K_a rather than mere memorization of facts.

Frances and Clara, in organic chemistry I and biochemistry respectively, conflated their reasoning with rates. It is important to note that this is the first time that either has mentioned rates associated with K_a or acid strength. Furthermore, both attributed their evaluations to faster dissociations to opposite values for their reasoning. Frances guessed more than reasoned when she said, "Well, if it's if K_a does dissociation, right? Maybe that the, if it's a higher Ka, means the acid can dissociate faster." Clara said, "Um…small - I think it dissociates faster than a bigger Ka." When she was asked to explain why she thought it would be faster, she was unable to provide any reasoning.

Kim, in general chemistry II, has a problem associated with the meaning of the word "acidic." Kim states, "So, if I have more reactants… it would be more acidic. Because, because a smaller K, um, because you have more reactants, and there would be more of the acid." While Kim properly reasons that more reactants indicate a smaller K_a, her meaning of the word "more acidic" seems to be conflated with the word "acid."

Overall, eight out of ten students who evaluated a larger value of K_a as a stronger acid were able to successfully provide appropriate justification for their reasoning to back up their decision. Five students, three who were in organic chemistry II, could not descriptively evaluate K_a. Other issues with their prior knowledge impeded three students who had some partial understanding in evaluating K_a. Two students conflated their reasoning with rates and were unable to justify their reasoning beyond that.

4.3.3 Application of K_a in Weak Acid Reaction Task

The participants were asked to complete a strong acid reaction (Figure 11) and explain their reasoning. After the participant completed this portion of the task, the participant was asked to provide a K_a expression.

4. Complete the reaction of ammonium with water:

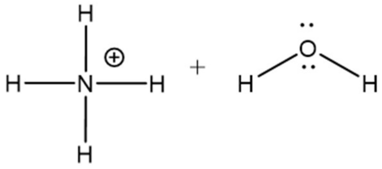


Figure 11. Weak acid reaction task for application of K_a

The two questions were analyzed independently. Students were expected to complete the reaction by inserting a double-headed reaction arrow to indicate that the reaction was at equilibrium. The products were expected to be written or drawn as ammonia and hydronium with appropriate charges. The expected acid equilibrium constant was $K_a = [NH_3][H_3O^+]/[NH_4^+]$.

Table 20. Weak acid reaction task for K_a – initial step and products by student and course

Courses	Name	Initial Step							Products			
		Curved arrows	Identify NH_4^+ as acid	Identify acid strength	Observe charges	Observe # of bonds for stability	Reaction Arrows	Draws products	Incorrect products	Correct products, incorrect formal charges	Correct products, not all lone pairs	Correct products, all lone pairs present
GC II	Sam				X						X	
	Bill			X							X	
	Gladys			X							X	
	Chester						X			X		
	Kim							X			X	
	Marie			X						X		
OC I	Alex				X							X
	Gwen				X							X
	Kent				X							X
	Annie		X									X
	Frances					X				X		
	Louise	X							X			
OC II	Jack				X						X	
	Carrie				X					X		
	Kelly	X									X	
	Quinn		X								X	
BC	Clara				X						X	
	Mitch				X						X	
	Sylvia				X						X	
	Emily						X		X			
Summary of Courses	GC II	-	-	3	1	-	1	1	-	2	4	-
	OC I	1	1	-	3	1	-	-	1	1	-	4
	OC II	1	1	-	2	-	-	-	-	1	3	-
	BC	-	-	-	3	-	1	-	1	-	3	-
		2	2	3	9	1	2	1	2	4	10	4

There was no expectation of lone pair electrons to be drawn in or curved arrow mechanisms, but these were analyzed to provide additional supporting data. The responses were for the completion of the reaction were analyzed based on the initial step performed, the products obtained (Table 20), and the ideas used to reason during the task (Tables 21-22). The reasoning was analyzed according to their verbal reasoning (Table 21) and the reaction arrow(s) they used (Table 22). The K_a expression was analyzed according to the student's response and construction of the expression (Table 23). Examples of K_a expressions are provided (Table 24).

There were a variety of ideas used to initiate the task. However, students in general chemistry II were more likely to observe the acid strength than students in the other courses. The only students to initiate the task by observing the acid strength were three students in general chemistry II (Bill, Gladys, and Marie). The students in organic chemistry I, organic chemistry II, and biochemistry favored beginning the task by observing the positive charge on the ammonium. For example, Clara, in biochemistry, said, "I'm looking at this positive charge." Other students initiated by using a curved arrow mechanism (Kelly and Louise), identifying the ammonium as the acid (Annie and Quinn), identifying the number of bonds needed for stability (Frances), drawing in the reaction arrows (Chester and Emily), or drawing the products without any reasoning (Kim) (Table 20).

Fourteen of the students were able to draw the correct products, NH_3 and H_3O^+. Interestingly, only the organic chemistry I students (Alex, Gwen, Kent, and Annie) drew in the lone pair electrons on the ammonia and the hydronium. Four students (Chester, Marie, Frances, and Carrie) drew the products as NH_3 and H_3O but had incorrect formal charges.

Although this research was not about formal charges when Chester was asked to clarify about his negative formal charge on the NH_3^-, he replied:

> *Well, cause nitrogen is, uh, it's usually plus or minus. But it looks right. It's cause of the hydrogens. Cause you have four. Cause usually hydrogen is plus one. And if, aww, it's something like that. I think it has to do with the hydrogens.*

Chester did not appear to have a clear idea of formal charge, which is a concept taught in general chemistry I. Two students (Louise and Emily) drew the incorrect products. Louise, in organic chemistry I, drew a single complex as a product (Figure 12). Emily, in biochemistry, did not account for atom conservation when she created NH_2 and H_3O^+ as her products.

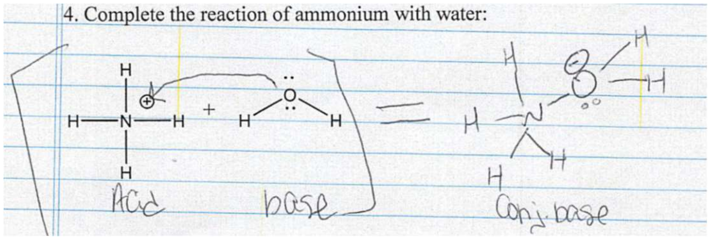


Figure 12. Louise's weak acid reaction task for K_a

Students completed the reactions by describing the acid and base using curved arrow mechanism, acid-base models, acid strength, and observation of the charges on the molecules. A trend was observed that general chemistry I and organic chemistry I students would rewrite the Lewis structures that were presented in the task as formulas; this was not seen in the upper-level courses. Although students were not asked to provide curved arrow mechanisms, a similar trend was observed in the reaction labeling task in section 4.1.2, where organic chemistry II and biochemistry students successfully utilized curved arrow mechanisms in their reasoning. Annie and Louise, in organic chemistry I, attempted to use curved arrow mechanisms on this task but used them improperly.

Table 21. Weak acid reaction task for K_a - reasoning by student and course

Courses	Name	Rewrites reaction as formulas	Curved arrow mechanism	NH_4^+ is acid	H_2O is the base	H_3O^+ conjugate acid	NH_3 conjugate base	Bronsted-Lowry model	Lewis model	Acid strength - weak acid NH_4^+	Acid strength - strong acid NH_4^+	Positive charge on NH_4^+	Number of bonds for stability	Struggled with no OH in products
GC II	Sam			X	X			X		X		X		
	Bill	X		X	X	X	X	X		X				
	Gladys			X						X				
	Chester													
	Kim	X		X	X									X
	Marie	X		X	X						X			
OC I	Alex									X		X		
	Gwen		X	X	X	X	X		X			X		
	Kent			X				X	X	X		X		
	Annie	X		X	X			X		X				
	Frances	X		X	X	X	X						X	
	Louise			X	X									
OC II	Jack		X	X	X				X			X		
	Carrie		X	X	X							X		
	Kelly		X		X			X	X			X		
	Quinn		X	X	X	X		X						
BC	Clara			X				X				X		
	Mitch		X	X	X	X	X		X			X		
	Sylvia	X	X	X	X			X	X			X		
	Emily		X	X	X			X						
Summary of Courses	GC II	3	-	5	4	1	1	2	-	3	1	1	-	1
	OC I	2	1	5	4	2	2	2	2	3	-	3	1	-
	OC II	-	4	3	4	1	-	2	2	-	-	3	-	-
	BC	1	3	4	3	1	1	3	2	-	-	3	-	-
		6	8	17	15	5	4	9	6	6	1	10	1	1

Seventeen out of twenty students stated that ammonium was the acid. Fifteen students stated that water was the base. Five students discussed the hydronium as the conjugate acid. Four discussed ammonia as the conjugate base. Only twelve students (Sam, Bill, Gwen, Kent, Annie, Jack, Kelly, Quinn, Clara, Mitch, Sylvia, and Emily) discussed an acid-base model. Nine students utilized the Bronsted-Lowry model describing the gain or loss of a proton. Six students described the process using the Lewis model. Generally, this reasoning was presented when describing the curved arrow mechanism. Students in organic chemistry I, organic chemistry II, and biochemistry generally identified the acid initially by the positive charge on the ammonium. However, two of the ten students (Alex and Carrie) who identified the acid using the positive charge did not further justify their choice with an acid-base model.

Interestingly, only six students out of twenty (Sam, Bill, Gladys, Alex, Kent, and Annie) indicated that ammonium was a weak acid. Furthermore, these students were all in the lower level courses, general chemistry II and organic chemistry I. Marie, in general chemistry II, incorrectly identify ammonium as a strong acid, because "I know it's a strong something, NH_3 is weak." Marie appears to have activated some idea of the opposite for the conjugate acid of NH_3.

Frances, in organic chemistry I, justified her reasoning by determining the number of bonds that nitrogen would normally have to be stable, a fact she had memorized. Kim, in general chemistry II, struggled with the idea that the products did not have an "OH^-" in them. This struggle with the hydroxide ion was interesting, recalling from section 4.1.1, Kim's acid-base model was a Bronsted-Lowry acid-base model. Something in this task activated Kim to think about the Arrhenius acid-base model.

Table 22. Weak acid reaction task for K_a – Reaction arrow selection by student and course

Courses	Name	Final selection Single arrow			Final selection Double-headed arrow					
		Multiple arrow selection Acid strength	Multiple arrow selection Reversibility	Single arrow Did not state “ at equilibrium”	Multiple arrows - No reason	Multiple arrows - Reversible	Multiple arrows – Acid strength – NH4$^+$ weak acid	Double-headed arrow Ammonium weak acid	Double-headed arrow Assumed "at equilibrium"	Double-headed arrow Reversible
GC II	Sam							X		
	Bill							X		
	Gladys							X		
	Chester									X
	Kim			X						
	Marie	X								
OC I	Alex							X		
	Gwen									X
	Kent						X			
	Annie						X			
	Frances				X					
	Louise		X							
OC II	Jack					X				
	Carrie				X					
	Kelly									X
	Quinn					X				
BC	Clara					X				
	Mitch									X
	Sylvia	X								
	Emily								X	
Summary of Courses	GC II	1	-	1	-	-	-	3	-	1
	OC I	-	1	-	1	-	2	1	-	1
	OC II	-	-	-	1	2	-	-	-	1
	BC	1	-	-	-	1	-	-	1	1
		2	1	1	2	3	2	4	1	4

As part of the task, students provided a symbolic reaction arrow. Reaction arrows are symbols that provide additional information to the reader about the nature of the reaction. Single arrows indicate that the reaction goes in the forward direction to "completion." When two opposite direction arrows are placed, the double-headed arrows, are placed in a reaction between the reactants and products, they indicated that the reaction is at "equilibrium." Equilibrium is when the forward and the reverse reactions are occurring at the same rate. However, most students in this study do not appear to understand what the double-headed arrow indicates. Ten students (Marie, Sylvia, Louise, Kent, Annie, Frances, Carrie, Jack, Quinn, and Clara) changed their arrow selection when they were asked for an explanation of their reaction arrow choice.

Four students (Marie, Sylvia, Louise, and Kim) final arrow selection was a single arrow. Marie and Sylvia were confused about the strength of the acid, whereas Louise was unclear about the concept of reversibility. Kim stated, "if this had stated it was in equilibrium, then I would have used the half arrow on top and the half arrow on bottom." She was unaware of how to choose her own.

Six students (Sam, Bill, Gladys, Alex, Kent, and Annie) selected the double-headed arrows based on the idea that the ammonium was a weak acid. One student, Emily, indicates that she "assumed that's in an equilibrium state." However, recalling section 4.3.1, Emily's idea of equilibrium was equal amounts of reactants and products. Emily did not provide any explanation beyond the words "equilibrium state." On the other hand, Mitch, who also stated it was at equilibrium, explained when he stated, "Well, this should be at equilibrium, or work towards equilibrium, so the reverse reaction can occur." Recalling from section 4.3.1, Mitch indicated that he had no definition for equilibrium. However, his idea activated here is like that of the other participants. He describes equilibrium as a reversible reaction. Six other students described the reaction as reversible using the double-headed arrows.

For the analysis, the K_a expressions were categorized according to the general format of the expression (Table 23). Examples of the responses are illustrated in Table 24. A correct K_a format was considered to be $[NH_3][H_3O^+]/[NH_4^+]$, or any variation that may have omitted the proper formal charges. The discrepancies in formal charges were discussed for this task for the products for the reaction. Additionally, students in this task occasionally omitted a charge when writing a K_a expression. This omission of charges included students who provided charges earlier in section 4.3.2 when providing a generic K_a expression. Furthermore, the reverse occurred for students, like Sam, who previously omitted charges for their generic K_a expression, provided them in this task. These omissions may be an indication of sloppy bookkeeping by the student, rather than any intentional idea being conveyed. Six students, three each in general chemistry II and organic chemistry I, provided a K_a expression consistent with the correct format that did not include water. Sam, Bill, and Gladys, in general chemistry II, responded that water was not included because it was a liquid. They provided no other reasoning beyond that. The students in organic chemistry I were slightly more varied on their explanation for not including water. Alex stated, “for the equilibrium expression, you, uh, you include things that are in solution, and if I remember right, gases, but not solids or liquids.” Annie was slightly off based when she stated, “We just count the solid, but I remember we don’t count the liquid.” Kent, however, continued to conflate his understanding of K_a with rates. He replied:

> *The solution is aqueous because it’s full of water, and including water into the rate law, it would be hectic. Because you can’t really get the concentration of something that all the molecules are supposed to be suspended in. That’s the reason.*

The water is not included in the K_a expression because there is a greater concentration of water, and it would only make the K_a expression smaller. Therefore, all equilibrium expressions omit the water, so they are all relative to water. However, for Kent, something was activated to conflate this concept of the greater concentration of water with the rate law, rather than the K_a expression he is currently discussing. This conflation should not be surprising for Kent. Recalling Section 4.3.2, Kent indicated that the rate order determined the superscripts in the K_a expression.

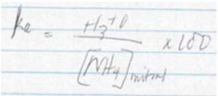
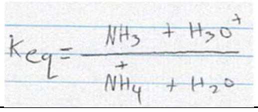
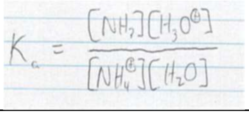
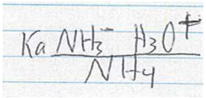
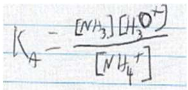
Six students were unable to provide a Ka expression for the weak acid task. The remaining eight students had K_a expressions that were conflated, omitted, or added additional elements to the expression. Two students conflated the K_a expression with percent ionization, Marie and Quinn. Quinn previously provided the K_a expression was the products over reactants (section 4.3.2). In the context of the problem-solving task, she provided it was the "prod $[H^+]$/reactant $[H^+]$." The final expression was $[H_3O^+]/[NH_4^+]$. This final expression has an interesting connection to Marie's expression for K_a, where she wrote out $[H_3O^+]/[NH_4^+]_{initial}$ x 100.

Five students (Kim, Louise, Mitch, Sylvia, and Jack) included water in their K_a expressions. Interestingly, none of these students included water in their K_a expressions previously in section 4.3.2 when they provided their generic K_a expressions. When Mitch was asked about this discrepancy, he replied, "Uh, um, I guess just because it was shown as a reactant here. Whereas I think in the other one, it was just kinda HA, H^+, and A^-." This revelation by Mitch is an important one for instructors.

Table 23. Weak acid reaction task for K_a – K_a expression by students and course

Courses	Name	Unable	K_a conflated with percent ionization	K_a includes addition and water	K_a includes water	K_a omit concentration brackets	K_a format correct
GC II	Sam						X
	Bill						X
	Gladys						X
	Chester					X	
	Kim				X		
	Marie		X				
OC I	Alex						X
	Gwen	X					
	Kent						X
	Annie						X
	Frances	X					
	Louise				X		
OC II	Jack			X			
	Carrie	X					
	Kelly	X					
	Quinn		X				
BC	Clara	X					
	Mitch				X		
	Sylvia				X		
	Emily	X					
Summary of Courses	GC II	-	1	-	1	1	3
	OC I	2	-	-	1	-	3
	OC II	2	1	1	-	-	-
	BC	2	-	-	2	-	-
		6	2	1	4	1	6

Table 24. Examples of student responses for K_a expressions

K_a expression weak acid reaction	Sample	Student Course
K_a conflated with percent ionization	 $ka = \frac{H_3^+O}{[NH_4]_{initial}} x 100$	Marie GC II
K_a includes addition and water	 $K_{eq} = \frac{NH_3 + H_3O^+}{\overset{+}{NH_4} + H_2O}$	Jack OC II
K_a includes water	 $K_a = \frac{[NH_3][H_3O^{\oplus}]}{[NH_4^{\oplus}][H_2O]}$	Mitch BC
K_a omit concentration brackets	 $Ka \frac{NH_3^- \quad H_3O^+}{NH_4}$	Chester GC II
K_a format correct	 $K_A = \frac{[NH_3][H_3O^+]}{[NH_4^+]}$	Alex OC I

Instructors often represent a generic dissociation reaction as HA dissociating to H^+ and A^- without the explicit representation of water. As experts, instructors recognize that the water is there implicitly. However, as novices, students may not be familiar enough with the material to recognize that the water is present in the reaction. Not only did Jack include water, but he also added, rather than multiplied, his reactants together. He also added, rather than multiplied, his products together (Table 24). When Jack provided his expression earlier, he only wrote out an expression for K_{eq}, where he placed the coefficients as subscripts, rather than subscripts (section 4.3.2).

4.3.4 Application of K_a in Strong Acid Reaction Task

The participants were asked to complete a strong acid reaction and explain their reasoning (Figure 13). After the participant completed this portion of the task, the participant was asked to provide a K_a expression. The two questions were analyzed independently. Students were expected to complete the reaction by inserting a single, or double-headed reaction arrow with reasoning to indicate that the reaction was either a completion reaction or at equilibrium. The products were expected to be written or drawn as the chloride ion and hydronium with appropriate charges. The expected acid equilibrium constant was $K_a = [Cl^-][H_3O^+]/[HCl]$. If the student selected not to provide an acid equilibrium constant, a reason would be solicited. There was no expectation of lone pair electrons to be drawn in or curved arrow mechanisms, but these were analyzed to provide additional supporting data. The responses were for the completion of the reaction were analyzed based on the initial step performed, the products obtained (Table 25), and the ideas used to reason during the task (Tables 26-27). The reasoning was analyzed according to verbally reasoning (Table 26), and the reaction arrow used (Table 27). The K_a expression was analyzed according to the student's response and construction of the expression (Table 28).

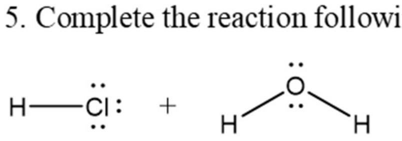

5. Complete the reaction following reaction:

Figure 13. Strong acid reaction task for K_a

Students' initial steps on the strong acid task were similar compared to the weak acid task. However, eight students identified HCl as a strong acid compared to three students who indicated ammonium was a weak acid in section 4.3.3. A curious question is whether this is because students are taught a list of strong acids, or whether this strong acid task did not have any charges to observe, which was the initial observation of choice on the weak acid task in section 4.3.3. Additionally, a similar trend was observed that more general chemistry II and organic chemistry I students relied on acid strength over the upper-level courses. The students in organic chemistry II and biochemistry were not as specific to acid strength. Annie, Louise, and

Carrie simply selected the acid and base. Whereas, Gwen and Sylvia observed which structures would be most stable. Kelly and Quinn, in organic chemistry II, choose to draw their curved arrow mechanism as their first step. Four students (Chester, Kim, Frances, and Clara) drew the products without any verbal reasoning. Emily stated, “I don’t remember.” For Emily, in biochemistry, this is concerning. The reaction of HCl and water is an extremely common reaction presented in the chemistry course as an example of a strong acid dissociation reaction. When Emily was further probed, she was unable to name hydrochloric acid.

The products provided for this task were less varied than for the weak acid task. Interestingly, only one student, Kent, had an incorrect formal charge on this task. However, he provided the products of Cl^- and H_3O. While explanations of formal charges are outside the scope of this research, he was prompted to describe how to calculate the formal charge. He explained the formal charge appropriately, but it did not activate him to correct his H_3O product to add a charge. Eighteen out of twenty students provided H_3O^+ and Cl^- as products. Six of those students (Gladys, Chester, Alex, Gwen, Annie, and Emily) also added all the lone pair electrons on their products. Louise continued to draw incorrect products, H_2Cl^- and OH^+. For this task, Louise activated her idea of an acid and a base. Recalling in section 4.1 on acid-base models, where she defined an acid as a proton acceptor and a base as a proton donor.

When students reasoned about the strong acid reaction task, only two students rewrote the reaction as formulas. Recalling from the weak acid task in section 4.3.3, six students rewrote the reaction. The same curved arrow mechanism trend was observed for the strong acid reaction task. Although these organic chemistry II and biochemistry students were not asked to use the curved arrows, they successfully performed the mechanism in the task.

Table 25. Strong acid reaction task for K_a – initial step and products by student and course

Course	Name	Initial step						Products			
		I do not remember	Curved arrows	Identify acid and base	Identify acid strength	Observe structure for stability	Draws products	Incorrect products	Correct product, incorrect formal charge	Correct product, no lone pairs	Correct, all charges & lone pairs
GC II	Sam				X					X	
	Bill				X					X	
	Gladys				X						X
	Chester						X				X
	Kim						X			X	
	Marie				X					X	
OC I	Alex				X						X
	Gwen					X					X
	Kent				X				X		
	Annie			X							X
	Frances						X			X	
	Louise			X				X			
OC II	Jack				X					X	
	Carrie			X						X	
	Kelly		X							X	
	Quinn		X							X	
BC	Clara						X			X	
	Mitch				X					X	
	Sylvia					X				X	
	Emily	X									X
Summary of Courses	GC II	-	-	-	4	-	2	-	-	4	2
	OC I	-	-	2	2	1	1	1	1	1	3
	OC II	-	2	1	1	-	-	-	-	4	-
	BC	1	-	-	1	1	1	-	-	3	1
		1	2	3	8	2	4	1	1	12	6

Table 26. Strong acid reaction task for K_a – reasoning by student and course

Courses	Name	Rewrites reaction	Complete curved arrow mechanism	Do the same thing as #4	HCl, acid	H_2O, base	H_3O^+, conjugate acid	Cl^-, conjugate base	Bronsted-Lowry Model	Lewis model	Acid strength HCl - strong acid
GC II	Sam				X						X
	Bill	X			X		X	X			X
	Gladys				X				X		X
	Chester										
	Kim				X						X
	Marie				X		X	X			X
OC I	Alex				X						X
	Gwen				X	X					
	Kent		X		X						X
	Annie	X				X			X	X	
	Frances										
	Louise										
OC II	Jack		X		X	X					X
	Carrie		X			X				X	
	Kelly		X			X				X	
	Quinn		X	X							
BC	Clara										
	Mitch		X		X						X
	Sylvia		X						X		
	Emily		X		X	X			X		
Summary of Courses	GC II	1	-	-	5	-	2	2	1	-	5
	OC I	1	1	-	3	2	-	-	1	1	2
	OC II	-	4	1	1	3	-	-	-	2	1
	BC	-	3	-	2	1	-	-	2	-	1
		2	8	1	11	6	2	2	4	3	9

The difference in reasoning in the strong acid task compared to the weak acid task was that students used the acid strength for their reasoning rather than describing the reaction using the acid-base models. Only six students used acid-base models when describing the strong acid task compared to twelve students in the weak acid reaction task. In the strong acid task, nine students (Sam, Bill, Gladys, Kim, Marie, Alex, Kent, Jack, and Mitch) used acid strength compared to six students who used it for the weak acid reaction task. Another interesting comparison between the reasoning for the strong acid and weak acid reaction tasks was that for the strong acid task, approximately fifty percent of the students who identified the acid did not discuss the base identity. However, in section 4.3.3, for the weak acid task, about 80% of the students identified the acid and the base.

Quinn indicated that for this problem, you would just do the same thing as you did in the previous problem, as described for the weak acid task in section 4.3.3. This reliance on the same process as the previous task is interesting because it is a possible indication that she is unaware of the distinction in the reactions of a weak acid and a strong acid. However, combining this with the following provides evidence for a compelling argument that Quinn does not distinguish between weak and strong acids. Recalling in Section 4.2.4, Quinn's ideas about strong and weak acids at the molecular were presented, where she drew ratios of roughly the same amount HA, $H^{+,}$ and A^- in both drawings. Furthermore, in section 4.2.4, she used the double-headed arrows in both reactions for the strong acid and weak acid, and she verbally acknowledges the nature of the reversibility. This trend continued here for this strong acid reaction task and the weak acid reaction in section 4.3.3. Quinn used double-headed arrows for both and indicated that they were both reversible. Quinn was not the only student to misinterpret the symbolism of the reaction arrows for the strong acid reaction.

Table 27. Strong acid reaction task for K_a – reaction arrows by student and course

Course	Name	Double-headed arrows					Single arrow					
		No reason	Rate conflation	Favors reactants, more stable	Reversible	Strong acid, reversible, Goes more to right	No reason	Can't remember what to use	Don't know if reversible	More reactive	No reactants left	Strong acid
GC II	Sam											X
	Bill											X
	Gladys											X
	Chester	X										
	Kim										X	
	Marie											X
OC I	Alex											X
	Gwen				X							
	Kent											X
	Annie											X
	Frances			X								
	Louise						X					
OC II	Jack		X									
	Carrie									X		
	Kelly							X				
	Quinn				X							
BC	Clara	X										
	Mitch					X						
	Sylvia				X							
	Emily								X			
Summary of Courses	GC II	1	-	-	-	-	-	-	-	-	1	4
	OC I	-	-	1	1	-	1	-	-	-	-	3
	OC II	-	1	-	1	-	-	1	-	1	-	-
	BC	1	-	-	1	1	-	-	1	-	-	-
		2	1	1	3	1	1	1	1	1	1	7

Eight students used double-headed arrows for the reaction. Two students (Chester and Clara) provided no reason for their reaction arrows. Jack stated, “I'm just going to put the double arrow because this step right here is going to take a long time, because kinda harder to break the hydrogen off the chlorine.” Jack continues to have a conflation of acid dissociation with rates. Frances indicated that the reactants were more stable and would be favored. Four students (Gwen, Quinn, Sylvia, and Mitch) indicated that the reaction was reversible. However, as students’ progress in chemistry, they are taught that the reaction of HCl and water is a reversible reaction that goes almost to completion. However, the reaction is generally considered to be complete since the equilibrium favors the products so much that the reactants are negligible. Most of the students who indicated that it was a reversible reaction did not mention this aspect, except for Mitch. Mitch stated:

> *Just because it’s a, it’s still an acid-based reaction, so I would assume that it would, it could go back and forth … this is a strong acid, you would expect to have, um, the reaction moving more so, towards the right.*

Twelve students used the single arrow, which would indicate that the reaction goes to completion. Seven students, four from general chemistry II (Sam, Bill, Gladys, and Marie) and three from organic chemistry I (Alex, Kent, and Annie), indicated that they chose the single arrow since it was a strong acid. Kim, in general chemistry II, indicated there would not be any reactants left. Carrie activated her idea of “more reactive” for her choice of a single arrow. Emily, Kelly, and Louise used the single arrow but were not sure why they were using it.

Table 28. Strong acid reaction task for K_a – K_a expression by student and course

Courses	Name	Unable	K_a format same as weak acid	$K_a = [H^+]$, no reactants left	Strong acid has no K_a
GC II	Sam		X		
	Bill				X
	Gladys				X
	Chester		X		
	Kim			X	
	Marie		X		
OC I	Alex		X		
	Gwen	X			
	Kent				X
	Annie				X
	Frances	X			
	Louise		X		
OC II	Jack				X
	Carrie	X			
	Kelly	X			
	Quinn		X		
BC	Clara	X			
	Mitch		X		
	Sylvia		X		
	Emily	X			
Summary of Courses	GC II	-	3	1	2
	OC I	2	2	-	2
	OC II	2	1	-	1
	BC	2	2	-	-
		6	8	1	5

The students' responses for the K_a expression of a strong acid are categorized in comparison to their weak acid K_a expression and whether any new ideas surfaced concerning the difference in acid strength. Students who were unable to produce a K_a expression for a weak acid were not able to produce a K_a expression for the strong acid task. Eight students (Sam, Chester, Marie, Alex, Louise, Quinn, Mitch, and Emily) utilized the same format for the K_a expression for the strong acid and the weak acid. When the discrepancy between the single reaction arrow and the K_a expression was brought to Sam's attention, he exclaimed, "Isn't that fascinating!" He was truly perplexed by the disconnection between the two concepts. In general chemistry II, Kim's thinking was activated to account for the lack of reactants at the completion of the reaction, when she described that the K_a would be equal to just the concentration of the H^+ since there would not be any reactants left. However, there is some flaw in the mathematics of her thinking. She stated, "Cause there wouldn't be any reactants on the bottom. Um, and, basically, if you have a zero on the bottom, then it doesn't exist. You know." Five students - two in general chemistry II (Bill and Gladys), two in organic chemistry I (Kent and Annie), and Jack in organic chemistry II – indicated that there would not be a K_a expression for the strong acid reaction. For example, Bill said, "Um, well, it doesn't have one. Because it's a strong acid."

Overall, when comparing the tasks on weak and strong acid reactions, the general chemistry II and organic chemistry I students tend to activate ideas about acid strength when compared to organic chemistry II and biochemistry. When engaged in these reaction tasks, most of these students are not attributing appropriate symbolic meaning to the reaction arrows. Students attribute mere reversibility to double-headed arrows but should also consider the underlying concept of equilibrium. The single arrow is indicative of a strong acid. Recalling from section 4.2, that students' conceptions of strong and weak acids are different verbally and at the molecular level, within and between students. This translation of the symbolic arrow, yet another level of Johnstone's triangle, adds another level of complexity for the students.

4.3.5 pK_a

Participants were asked, "What is pK_a?" to elicit their ideas about pK_a. The responses were analyzed based on general descriptions of pK_a, mathematical expressions, and descriptive evaluations of the size of pK_a (Table 29). If students struggled, they were further prompted with:

"Do you know any mathematical expression for pK_a?"

"Is pK_a related to K_a?"

Eighteen students were able to describe pK_a by at least one verbal description, mathematical expression, or evaluate and interpret the size of pK_a. Two students (Chester and Louise) were unable to produce any appropriate ideas related to pK_a. Chester, in general chemistry II, tried to utilize part of the Henderson-Hasselbalch equation, "I know the formula of it. It'll be like -log … I think it's base over [divided by] acid. I don't know what pK_a is." Louise, in organic chemistry I, indicated that "I don't remember what that [pK_a] stands for."

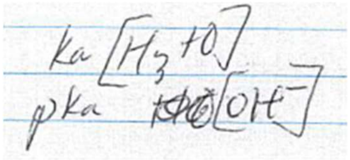
Many students lacked a verbal description of pK_a. Only eleven out of twenty students attempted to provide a verbal description of pK_a. The three students (Sam, Bill, and Kim) in general chemistry II all conflated pK_a with pH. Sam and Bill described it as the acidity in solution. In contrast, Kim thought that pK_a "maybe the pH, the constant for pH?" This conflation for pH was also seen in one biochemistry student, Emily, who also described "how acidic or basic your level of concentration is." The general chemistry students also learned about pK_a within the confines of the Henderson-Hasselbalch equation, where pH = pK_a + log (conjugate base/acid). Therefore, this finding may not be surprising that most of the students who attempted to describe pK_a related it to pH.

Table 29. Ideas used to describe pK_a by student and course

Courses	Name	Unable	Conflated with pH	Conflated with pOH	Use it with pH	How acidic "something" is	How acidic or basic "something" is	Easier way to express K_a/compare acids	Strength of an acid	Inversely related to K_a	-log K_a	Lower more acidic, higher more basic	Smaller pK_a, stronger acid	Larger pK_a, weaker acid
GC II	Sam*		X								X	X		
	Bill*		X											
	Gladys									X	X			
	Chester*	X												
	Kim*		X											
	Marie			X										
OC I	Alex									X	X			X
	Gwen									X	X		X	X
	Kent							X					X	
	Annie								X		X		X	X
	Frances*												X	
	Louise*	X												
OC II	Jack*				X		X					X		
	Carrie*					X							X	
	Kelly											X		
	Quinn									X		X		
BC	Clara*				X									
	Mitch							X	X		X		X	X
	Sylvia								X		X			
	Emily*		X		X		X		X					
Summary of Courses	GC II	1	3	1	-	-	-	-	-	1	2	1	-	-
	OC I	1	-	-	-	-	-	1	1	2	3	-	4	3
	OC II	-	-	-	1	1	1	-	-	1	-	3	1	-
	BC	-	1	-	2	-	1	1	3	-	2	-	1	1
		2	4	1	3	1	2	2	4	4	7	4	6	4

* Required additional prompting

Marie, in general chemistry II, related pK_a to the concentration of OH^-. She verbally responded and drew it out. Marie states, “The K_a, I guess to say, is looking into the H_3O, and then pK_a is asking for HO.”



ka $[H_3{+}O]$
pka ~~HO~~ $[OH^-]$

In organic chemistry II and biochemistry, three students (Jack, Clara, and Emily) mentioned that pH is used with pK_a. Clara was only able to describe how she currently uses pK_a in biochemistry in conjunction with pH. As illustrated by her excerpt:

> *Well, um, well, I know right what we’ve been learning. We’ve been dealing with pH and* pK_a*. Um, and I remember if pH is higher than* pK_a *- proton goes away, and if it’s the other way around then, then proton stays and stuff like that. But like I said, like the basic definition, I can’t really recall it per se.*

Jack and Emily, on the other hand, described pK_a as to how acidic or basic “something” is. Jack does not mention the idea that it has to be in solution, whereas Emily does mention that it is in solution. Emily conflates pK_a with pH by adding in the idea that the acidic or basic something is in solution, which is more consistent with the concept of pH. Another student, Jack, also linked the concept of pH to that of pK_a: “I know it has to do with acidity and how acidic or basic something is… I feel like pK_a is used with pH.” Jack appears to have tightly linked ideas of pK_a and pH, but it is difficult to say if they are conflated with each other. Also, Carrie, in organic chemistry II, indicated that pK_a is “how acidic something is.” She did not mention any aspect of basicity. It might be of concern to instructors that students, who are discussing “how acidic or basic something is” may conflate pK_a with pH due to the initial presentation in general chemistry II by the Henderson-Hasselbalch equation. It is also of concern that none of these students attributed pK_a to the molecule; they omitted the subject of what they were discussing or called it "something." What is this "something"? A solution could be something. A molecule could be something.

Four students (Annie, Mitch, Sylvia, and Emily) indicated that pK_a was a way to measure the strength of the acid. Sylvia described it more specifically as "the strength of the dissociation." Interestingly, only two students described it as an "easier way" to use K_a. Mitch, in biochemistry, indicated that it "would end up being a more round value," and Kent, in organic chemistry I, describe that pK_a was "an easy way to compare it to other acids."

When students described pK_a, only seven out of twenty students provided a mathematical expression. Two students (Sam and Gladys) were in general chemistry II. Three students (Alex, Gwen, and Annie) in organic chemistry I. Two students (Mitch and Sylvia) were in biochemistry. None of the students were in organic chemistry II. These students indicated that pK_a equals the -log (K_a). Furthermore, when discussing and evaluating K_a, four students (Gladys, Alex, Gwen, and Quinn) indicated that this was an inverse relation with K_a.

Eleven out of twenty students described pK_a by interpreting its value. Four students (Sam, Jack, Kelly, and Quinn) described that the lower the $pK_{a,}$ the more acidic it was, and the higher the $pK_{a,}$ the more basic it was. An interesting note here is the incomplete comparison the students are making. During the interviews, the students would say "it" when referring to acidic or basic but prompting could not get the students to expand on the idea of "it." This comparison of the acidic and basic values to pK_a suggests a possible conflation with pH since they are describing basicity. Another possibility is that they are confounding conjugate base strength. However, the following section 4.3.6, which is on the relationship of the acid and its conjugate base, would suggest that it is not the case for these students. Interestingly, Kelly not only described that a lower pK_a meant it was more acidic but also described what her idea of more acidic. Kelly stated:

> *I don't know specifically [what pK_a is], but I know that the higher the pK_a, the more basic… [The lower the pK_a], the more acidic. So, I guess if you had a lower pK_a, that would determine the amount of acidity, so the amount of, um, protons you would have within the compound.*

Recalling that in section 4.2.3 for the strong acid molecular level drawing, Kelly's drawing had a concept of "more H^+" in contrast with her weak acid molecular level drawing, in section 4.2.4, she drew a concept of "more A^-." Kelly appears to be applying a similar idea to pK_a that more acidic means "more hydrogens," but this time, she is applying it to the molecule rather than the solution. Noting, she has not applied this idea in the scientifically appropriate way, but she has a useful idea that the pK_a belongs to the molecule, rather than the solution.

Overwhelmingly, the students who described pK_a in terms of value to strength were in organic chemistry I. Five out of the six organic chemistry I students (Alex, Gwen, Kent, Annie, and Frances) evaluated pK_a by describing it in terms of values. These students described that a smaller value indicated a stronger acid, or a larger value indicated a weaker acid. One student, Carrie, in organic chemistry II and one student, Mitch, in biochemistry, also described pK_a in terms of values for weaker and stronger acids. For example, Gwen stated, "a small K_a is a strong acid, so that means a large pK_a is a weak acid."

Overall, most students lacked an appropriate verbal description for pK_a. All the general chemistry II students who attempted to describe pKa conflated it with pH or pOH. Only seven students mathematically expressed pK_a, of which none were in organic chemistry II. Furthermore, most organic chemistry II students interpreted pK_a as the lower the value, the more acidic, and the higher the value, the more basic. This interpretation for organic chemistry II contrasted with organic chemistry I, who described pK_a in terms of weaker and stronger acids. However, most biochemistry students were successful in describing pK_a.

4.3.6 Strength of an Acid Related to its Conjugate Base

During the open-ended questions, participants were asked to describe the relationship of an acid to its conjugate base. The responses were analyzed for how the participants related the acid and conjugated base (Table 30).

Three students were not able to respond to how the strength of an acid related to its conjugate base. Kim and Marie, in general chemistry II, were unable to respond, as well as Carrie, in organic chemistry II. Twelve students replied that a stronger acid has a weaker conjugate base, including four students in general chemistry II, five in organic chemistry I, one in organic chemistry II, and two in biochemistry. For example, Sam, in general chemistry II, "It's usually the inverse. So, like the stronger your acid, usually the weaker your conjugate base."

Five students indicated that a stronger acid had a stronger conjugate base, including Frances from organic chemistry I, Jack and Quinn from organic chemistry II, and Clara and Emily from biochemistry. Quinn only discussed the strength of the conjugate after she discussed its stability. Quinn stated, "I think that maybe it [a more stable base] would be a stronger conjugate base." Jack discussed it in terms of how nucleophilic the base would be. He stated:

> *Because the charge would be on the more electronegative atom. And when you do resonance, that also increases the strength of the base, because it would increase the strength of the base, because the stronger base, um, can do resonance. The strength of a base is usually determined by where how nucleophilic … molecule is. So, the nucleophilic*

> *properties would include like having lone pairs, or havin' like electric char- a negative charge on an electronegative atom or partial negative, um, charge on the atom.*

This excerpt suggests that Jack may be confounding stability with strength similarly to Quinn, although he does not come right out to state it.

Interestingly out of all twenty students, only one, Gladys in general chemistry II, made connections between the strength of the acid and its conjugate base and its stability. To note, none of the students were prompted to respond about the relationship between the strength and the stability of the base. Gladys stated:

> *Like the conjugate base will be way weaker than the strength of the acid, because it gave up that one proton. And, with a strong base, it'll have a weaker conjugate acid… To be a weaker base means you're less likely to accept another proton because you're already at a happy place being stable.*

Gladys uses an anthropomorphic description of the molecule being "happy" to help with her description.

Recalling section 4.3.5, when the students were describing pK_a in terms of how acidic or basic something was. One suggestion was that students might be confounding ideas about acid and conjugate base strength when interpreting the values to describe them as "more basic." However, it can be seen with Jack, Quinn, and Emily do not possess the idea that an acid and its conjugate base have strengths that vary inversely.

Table 30. Ideas about the strength of an acid related to a conjugate base by student and course

Courses	Name	Unable	Stronger acid, Stronger conjugate base	Stronger Acid, Weaker conjugate base	Stronger acid, more stable base
GC II	Sam			X	
	Bill			X	
	Gladys			X	X
	Chester			X	
	Kim	X			
	Marie	X			
OC I	Alex			X	
	Gwen			X	
	Kent			X	
	Annie			X	
	Frances		X		
	Louise			X	
OC II	Jack		X		
	Carrie	X			
	Kelly			X	
	Quinn		X		X
BC	Clara		X		
	Mitch			X	
	Sylvia			X	
	Emily		X		
Summary of Courses	GC II	2	-	4	1
	OC I	-	1	5	-
	OC II	1	2	1	1
	BC	-	2	2	-
		3	5	12	2

4.3.7 Application of pK$_a$ in the Comparison of Two Weak Acids

6. Which is more acidic, trichloroethanoic acid, or ethanoic acid?

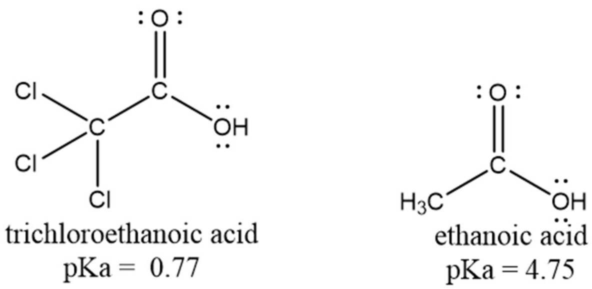


Figure 14. The task to apply pK$_a$ in comparison of weak acids

The participants were asked to select the more acidic molecule and provide their reasoning (Figure 14). After the participant completed this portion of the task, the participant was asked to explain which molecule had a more stable conjugate base. The students were expected to be able to select that the trichloroethanoic acid was the more acidic molecule based on, the lower pK$_a$ value. Students could predict the more stable base by one of two ways. First, students could use the idea that the stronger acid has a weaker conjugate base, which in turn is a more stable conjugate base. Second, students who have taken organic chemistry I, or higher, could reason using the inductive effect to conclude that the trichloroethanoic acid would be more stable. The two questions were analyzed independently. The responses were for the more acidic molecule were analyzed based on the participant's response, the initial step performed, and the reasoning to select the more acidic molecule (Table 31). The responses for the more stable conjugate base were analyzed for the response and reasoning to select the more stable conjugate base.

Thirteen out of twenty students were able to successfully select the trichloroethanoic acid as the more acidic molecule (Table 31). The students used various ways to begin their task.

However, ten students (Sam, Gladys, Gwen, Kent, Annie, Frances, Jack, Kelly, Mitch, and Sylvia) out of thirteen who successfully responded to this task began by observing and analyzing the pK_a values. Frances had an epiphany during this task. As illustrated when she said the following, “This one [trichloroethanoic acid] is more acidic, for sure, because the pK_a value is lower. Oh, yeah! I just figured it out, but then that would mean that everything that I’ve done is wrong. It has, uh, less hydrogens.” This revelation is surprising for Frances. She struggled through many portions of the interview, but she was very confident that she was reasoning about the evaluation of pK_a correct and that she had been wrong about the rest. Frances was actively monitoring her knowledge throughout the interview.

Three students (Kim, Alex, and Emily) initially observed the pK_a values, but it did lead to a successful response. Kim was unable to use the pK_a values and opted to select ethanoic acid based on the idea that it had more hydrogens than the trichloroethanoic acid. Recalling from section 4.3.6, Kim conflated pH with pK_a. Emily interpreted that “the pK_a that is higher pK_a is more acidic.” Previously, on the open-ended question on pK_a, Emily did not attempt to provide any interpretation of the values of pK_a.

Interestingly, of the students that used pK_a values to interpret this task, two students, Gladys and Alex, used K_a to help them during their reasoning. Gladys stated that,

> *Ok, this guy, it [trichloroethanoic acid] has a stronger pK_a. This guy [ethanoic acid] had a much lower K_a, so it probably led it to having a big, fat pK_a. So that might mean it [trichloroethanoic acid] was a to dissociate a little bit more and be a bit stronger of an acid.*

Table 31. The response, initial step, and reasoning for the more acidic weak acid task by student and course

Courses	Name	Response			Initial step				Reasoning							
		I do not know	Ethanoic acid	Trichloroethanoic acid	Writes formulas	pH	Observe structures	pKa values	Unable to use pKa	More hydrogens (protons)	Conflates pH and pKa	Higher pKa, more acidic	Interprets Ka from pKa	Lower pKa, more acidic	Electronegativity of chlorine	Inductive effect of chlorine
GC II	Sam			X				X						X		X
	Bill*	X			X				X							
	Gladys			X				X					X	X		
	Chester		X				X		X	X						
	Kim		X					X		X						
	Marie*		X			X				X	X					
OC I	Alex		X					X				X	X			
	Gwen			X				X						X	X	
	Kent			X				X						X	X	
	Annie			X				X						X	X	
	Frances			X				X						X		
	Louise			X		X					X				X	
OC II	Jack			X				X						X		X
	Carrie			X			X							X	X	
	Kelly			X				X						X		X
	Quinn			X			X							X		X
BC	Clara		X				X			X						
	Mitch			X				X						X		X
	Sylvia			X				X						X		X
	Emily		X					X				X				
Summary of Courses	GC II	1	3	2	1	1	1	3	2	3	1	-	1	2	-	1
	OC I	-	1	5	-	1	-	5	-	-	1	1	1	4	4	-
	OC II	-	-	4	-	-	2	2	-	-	-	-	-	4	1	3
	BC	-	2	2	-	-	1	3	-	1	-	1	-	2	-	2
		1	6	13	1	2	4	13	2	4	2	2	2	12	5	6

This idea of equilibrium is interesting because, previously in the interview, Gladys struggled with her idea of equilibrium, wanting to equal out the reactants and products. When Gladys thinks of the K_a in terms of pK_a, she is thinking of the dissociation component of K_a, but not of activating the equilibrium idea like she did when she discussed K_a in section 4.3.2. When she discussed a larger K_a in section 4.3.2, she stated, "…That might lead it to go a little bit more backwards to make the more reactants so you can kinda balance things." Alex, on the other hand, utilized K_a to interpret pK_a during the task by keying it into a calculator. Unfortunately, Alex incorrectly interpreted the smaller K_a value as more acidic. This interpretation was interesting because early during the interview for the open-ended questions, Alex indicated that a larger value of K_a indicated a stronger acid. Furthermore, Alex indicated that a larger pK_a was a weaker acid, and K_a was inversely proportional to pK_a. This new interpretation of pK_a continues to affect Alex during the next problem-solving task in section 4.3.8. Alex also did not attempt to interpret the representations with any other strategies, such as observing the structural differences.

Four students initially observed the structures of the molecules. Two students, Chester and Clara, began by observing that ethanoic acid had more hydrogens than the trichloroethanoic acid. They were both ultimately unsuccessful. Chester stated, "I was thinking I could use the hydrogen rule, the more hydrogen you have, the more acidic it would be." When Chester was prompted, he stated that "they give you the pK_a, but they don't give you the concentration." In general chemistry II, Chester's experience with pK_a is within the confines of the Henderson-Hasselbalch, and he seems to be unaware of it use outside of that application. Two students in organic chemistry II, Carrie and Quinn, indicated that trichloroethanoic acid has more electron withdrawing groups on it. Both responded that trichloroethanoic acid was more acidic than ethanoic acid. Carrie was more focused on the atoms, where Quinn discussed it from the perspective of the inductive effect throughout the whole molecule.

Two students (Marie and Louise) initially began their problem-solving by discussing pH. Marie, in general chemistry II, wrote $pH > 7$ and $pH < 7$. She stated, "I'm trying to remember exactly what I did with this problem 'cause we had a problem similar to this." Marie eventually used the idea that ethanoic acid had more hydrogens to select it as the more acidic. Louise initially tried to interpret the pK_a values as pH. She stated, "I gonna say cause the pH is lower, but it's the pK_a's listed." Then Louise stated, "Well, this one [trichloroethanoic acid] would be more acidic, because it has chlorines, instead of hydrogens. And that chlorine is more acidic than hydrogen." She goes on to explain that chlorine is more electronegative than hydrogen. This mental model of acid strength has been described before in the literature by McClary and Talanquer, where students use intrinsic properties of the substance like atoms or functional groups to describe acid strength (McClary & Talanquer, 2011a).

Once the students made their initial assessment of the "more acidic" task based on pK_a values, or the structure, the students were asked if there was an alternative way to determine the answer other than the strategy that they had initially used. Of the thirteen students who successfully performed the task, ten students used another alternative but a successful strategy. The students who previously used the structure (Carrie and Quinn) described that the lower the pK_a value, the stronger the acid. Eight students who previously described that a lower pK_a is a stronger acid used either the intrinsic property of the molecule or the inductive effect as an alternative strategy. There was an interesting trend that students in organic chemistry I (Gwen, Kent, and Annie) used the "intrinsic property" idea of chlorine being more electronegative than hydrogen. In contrast, the organic chemistry II and biochemistry students (Jack, Kelly, Quinn, Mitch, and Sylvia) were more developed in their reasoning and described the inductive effect throughout the molecule. Additionally, Sam, in general chemistry II, who is an A+ student, discussed the inductive effect of chlorine to pull the electrons throughout the molecule. Three students (Gladys, Frances, and Louise) provided no alternative strategies to find the more acidic molecule.

Eleven students successfully selected the trichloroethanoic acid as the more stable conjugate base (Table 32). Three students in general chemistry II (Sam, Gladys, and Kim) used varied ways to reason for this response. Sam stated, “it’s gonna be the one the lower K_b.” Kim utilized the higher pK_b to select a more stable base. However, when she was asked to clarify her understanding of a “more stable base,” she stated, “more of a strong base because it’s not gonna, um - well - because it’s not gonna break apart as easily.” Kim is possibly thinking about the word “strong” in terms of everyday language. Alternatively, it may be difficult for her to translate the acid to the conjugate base in her mind. Kim did not draw out the conjugate base, nor did any of the other students. This lack of drawing the conjugate base to perform tasks has been seen in previous research (McClary & Bretz, 2012). Gladys reasoned that the “more stable conjugate base - this guy [trichloroethanoic acid] because if it’s stronger, it’ll create a weaker conjugate base, which means it’s less likely to accept anything.” Recalling from section 4.3.6 on the relationship of the strength of an acid to its conjugate base, Gladys was the only student out of twenty who provided the appropriate reasoning about the relationship of the conjugate base strength and its stability without any additional prompting.

Four students in organic chemistry I (Gwen, Kent, Annie, and Frances) successfully selected trichloroethanoic acid. However, Alex applied appropriate reasoning but selected the incorrect strong acid, which led to an incorrect, more stable base selection of ethanoic acid. Alex, Kent, Annie, and Frances used the idea that the stronger acid had a more stable conjugate base. Alex, Kent, and Annie indicated that their idea of the more stable base is that it would stay in the conjugate base form. Frances used the same reasoning. However, Frances stated, "If its stronger acid, it's gonna be a stronger base." Recalling in section 4.3.7, Frances used this same reasoning when she described the relationship of the strength of an acid to its conjugate base. Gwen selected the correct response of trichloroethanoic acid with incorrect reasoning when she stated, "Mmm. I'm thinking that, well I'm thinking that… it would be hard to remove anything from this, because its [chlorine] electronegativity is so strong." This idea that it will be harder to remove anything is interesting because Gwen has just indicated that trichloroethanoic acid is the stronger acid. To an expert, this indicates that it will lose the hydrogen easier. Gwen was able to describe an acid and a base from both the Bronsted-Lowry and Lewis models in section 4.1.1. Recalling from section 4.3.2, Gwen does not have any name or description of $K_{a,}$ nor does she have a description of pK_a (section 4.3.5) other than a mathematical expression - log K_a. Furthermore, recalling Gwen's conception of a weak acid at the molecular level (section 4.2.4), where she drew no dissociation for a weak acid. Gwen may not be able to reconcile her discrepancy in her reasoning.

Three students in organic chemistry II (Jack, Carrie, and Quinn) successfully responded to the more stable conjugate base. Jack and Quinn described that trichloroethanoic acid would have resonance with a negative charge that would be better stabilized by the chlorines, rather than the hydrogens on the ethanoic acid. Carrie stated, "More stable conjugate base, I would also say this one [trichloroethanoic acid]. Because it's like the strongest acid, the conjugate base will also be a strong conjugate base." This comparison was interesting because something in the task activated Carrie's reasoning about the strength of an acid to a conjugate base as she was

Table 32. Response and reasoning for more stable conjugate base by student and course

Courses	Name	Response			Reasoning										
		Unable	Ethanoic acid	Trichloroethanoic acid	Hard to remove chlorines	Can accept "more hydrogens"	Weaker acid, stronger base	Resonance	Better able to stabilize charge	Lower K_b	Lower pK_a, higher pK_b, more stable	Stronger acid, weaker conjugate base	Stronger acid, more stable base	More stable is stronger base	More stable, harder to break apart
GC II	Sam			X						X					
	Bill	X													
	Gladys			X								X	X		
	Chester		X			X									
	Kim			X							X			X	X
	Marie	X													
OC I	Alex		X										X		
	Gwen			X	X										
	Kent			X									X		
	Annie			X									X		
	Frances			X									X	X	
	Louise		X				X					X		X	X
OC II	Jack			X				X	X						
	Carrie			X									X	X	
	Kelly		X												
	Quinn			X				X	X						
BC	Clara		X					X							
	Mitch			X					X						
	Sylvia	X										X		X	
	Emily	X													
Summary of Courses	GC II	2	1	3	-	1	-	-	-	1	1	1	1	1	1
	OC I	-	2	4	1	-	1	-	-	-	-	1	4	2	1
	OC II	-	1	3	-	-	-	2	2	-	-	-	1	1	-
	BC	2	1	1	-	-	-	1	1	-	-	1	-	1	-
		4	5	11	1	1	1	3	3	1	1	3	6	5	2

previously unable to respond to the open-ended question in section 4.3.6. However, Carrie's reasoning is somewhat flawed. She correctly reasons that the stronger acid has a more stable conjugate base, although she misinterprets the word "more stable" to mean stronger.

Only one student in biochemistry, Mitch, successfully answered that the more stable conjugate base was trichloroethanoic acid. Mitch described the stabilization of the conjugate base by the delocalization of the charge. As illustrated by the following:

> *It would be this one [trichloroethanoic acid], because, um, if you were to look at the conjugate base, it would have a negative charge here [by hydroxyl group], but since …you have three electron withdrawing groups, they're gonna pull electron density, um, throughout the molecule. So, this negative charge on this one would end up, um, it would not, I guess in reality, be as negative as this one [ethanoic acid] because there's more, uh, like, there's more of a negative charge being pulled through the molecule.*

Four students (Bill, Marie, Sylvia, and Emily) were unable to select the more stable conjugate base. Bill was unable to select the more acidic molecule in the first part of the task. Marie continued to struggle with the relationship of acid to the conjugate base, as she did in section 4.3.6. Emily had difficulty interpreting the Lewis structures. She stated, "Ethanoic acid only has a methyl group attached to it. Then while trichloroethanoic acid has three, um, chlorines, and a carbon attached to the carbonyl group." While Sylvia had a problem that pervades several students' ability to appropriately reason: she could not make the appropriate connection with the meaning of "more stable." Sylvia was able to reason that the stronger acid had the weaker conjugate base. When Sylvia was prompted about the words "more stable," she replied, "Oh, so you want a stronger base?" A total of six students (Kim, Frances, Louise, Carrie, and Sylvia) had incorrect reasoning interpreting the words "more stable" as a stronger base.

Five students (Chester, Alex, Louise, Kelly, and Clara) selected the ethanoic acid as the more stable conjugate base. Alex's response was discussed previously in this section, where the appropriate reasoning applied was to an incorrect response in the more acidic portion of this task. However, this finding suggests that Alex is only using memorized facts to arrive at the answer and not using any structural observations to arrive at the answer. Chester, in general chemistry II, indicated that the ethanoic acid could accept more hydrogens, so it was the more stable conjugate base. He stated, "I think it accepts more hydrogens *(points to the methyl group on ethanoic acid)* kinda, so it would have the more stable conjugate base." Recalling section 4.1.1, he used a Bronsted-Lowry model of acid and bases. He appears to continue applying his idea of "more hydrogens" to his idea of a base. Louise, organic chemistry I, selected ethanoic acid for the more stable conjugate base when she misinterpreted the words "more stable." She reasoned that the stronger conjugate base is the more stable base. However, embedded in this incorrect reasoning was the appropriate reasoning for the relationship for the strength of an acid to its conjugate base. She stated, "Because the stronger acid has a weaker base. So, the weaker acid would have a stronger base." Kelly, organic chemistry II, was confused about which would be the "more stable" conjugate base and guessed that it would be the ethanoic acid. Clara, in biochemistry, indicated that due to resonance, the ethanoic acid would have a more stable conjugate base. However, both structures had the same resonance number of resonance structures. The difference was in the substituents on the alpha carbon, and Clara did not notice this discrepancy.

Overall, an interesting trend was observed in the data that organic chemistry I students were better able to use reasoning consistent with relating the strength of the acid to the stability of the conjugate base compared to the other courses. Recall that in section 4.3.6, when these same organic chemistry I students described the relation of an acid to its conjugate base in the verbal task, none of them activated resources related to the stability of the conjugate base. Another interesting aspect of this task was that five students related the words “more stable” to stronger base. Neither Jack nor Quinn used the relationship of the strength of an acid to its conjugate base to reason about the more stable conjugate base. However, reviewing Table 33 in section 4.3.6, there was a trend in organic chemistry II and biochemistry for students to describe the relationship of an acid to its conjugate base as that a stronger acid has a stronger conjugate base. This trend is not conclusive evidence that they harbor the idea that a more stable conjugate base of a stronger base, but it is a possible explanation for the reasoning used by these students.

4.3.8 Application of pK_a in Weak Acid Reaction Task

7. Which side of the following reaction is favored?

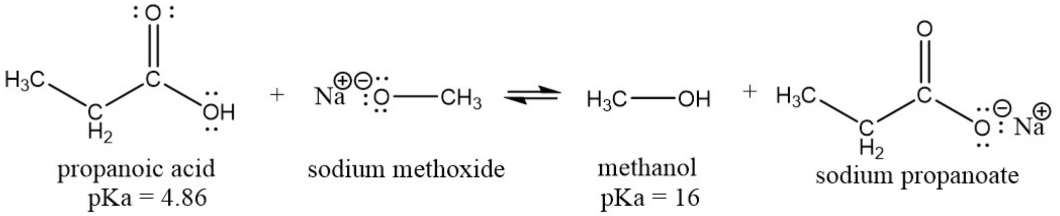


Figure 15. Weak acid reaction task using pK_a to enable determination of which side is favored

The participants in organic chemistry I, organic chemistry II, and biochemistry were asked to predict which side of the reaction would be favored and to provide their reasoning (Figure 15). The reaction provided the pK_a values. It was expected that the students would be able to determine that the lower pK_a was the stronger acid and that the reaction would proceed in the direction of the weaker acid. The responses were analyzed for their answer selection and the reasoning to select their response (Table 33).

Eight students (Gwen, Kent, Annie, Frances, Jack, Quinn, Mitch, and Sylvia) out of fourteen students selected the correct response that the products were favored. Seven out of the eight students used appropriate reasoning to arrive at their response. Frances, however, used a "gut feeling" that it would be the products. An interesting trend continued for the organic chemistry II students (Jack and Quinn) to utilize resonance stability for their reasoning over the use of pK_a values. When Jack was specifically asked about the pK_a values, he stated, "Um, the pK_a values usually just determine the acidity of the, um, product." He did not appear to attribute any value to the pK_a in solving this task. The organic chemistry I and biochemistry students reasoned that the lower the pKa indicated the stronger, more dissociated acid. Although Kent, also indicated that the rate would be higher going towards the products. Recalling, Kent had displayed a conflation with rate and K_a (section 4.3.2), when he described his K_a expression coefficient came from the rate order.

Five students (Alex, Louise, Carrie, Clara, and Emily) selected that the reactants were more favored. Alex selected that the reactants were more favored by continuing to use their line of reasoning that the higher pK_a, the stronger the acid, which was explained in section 4.3.7 when they converted pK_a to K_a to reason. Louise correctly reasoned based on the idea that the lower the pK_a, the stronger the acid. However, part of the reasoning process revealed that Louise was confused by the term "favored." She stated:

> *So, if it's, if the reactants it would be, it would mean that it, it stays more as reactants in the solution, and if the, um, products are favored, then it would be more of the products in the solution and less of the reactants… And, this [propanoic acid] would be a stronger acid. This [methanol] would be weaker. So, then, this side [reactants] would be favored.*

This misinterpretation is an interesting finding. Recalling in section 4.2.3, Louise drew a molecular level drawing of a strong acid with the idea of the "more H^+" concept. Furthermore, in section 4.2, she defined strong and weak acids from the perspective of higher and lower pK_a

values. From the context of this task, she does not appear to properly interpret what a lower pK_a and a stronger acid indicates at the molecular level.

Carrie selected the reactants as more favored based on the reasoning that the idea of the sodium propanoate in the products would have a difficult time doing resonance with the positive and negative charges present. She seems not to understand the nature of the ionic bond, which was outside the scope of this research. However, this finding reveals how many incidental pieces of prior knowledge can impact a single task when evaluating problem-solving.

Two students in biochemistry, Clara and Emily, selected the reactants as more favored. Clara did not believe that the pK_a values were able to help her and used her gut feeling to select the reactants. Emily reasoned that "it's more favored if you have a lower pK_a. It's more favored it is to react because it's more." Emily is misinterpreting the word "favored." She is activating some other definition of the word "favored" from her experiences.

One student, Kelly in organic chemistry II, could not select whether the products or reactants were favored. Kelly stated:

> *It might wanna go on this side, or on this side, depending on, I can't remember which way it would go. But either way, it would want to, kind of, neutralize which one is the most different between the two.*

Overall, approximately half of the students were able to predict that the products would be favored in the reaction. A trend was observed that organic chemistry I and biochemistry students reasoned using the idea that a lower pKa would indicate a stronger acid that would be more dissociated. In contrast, organic chemistry II students used the idea of the stability of the conjugate base. This trend was not surprising as some students in organic chemistry II revealed during their interviews that the instructors preferred that the students did not use pK_a. A second important finding was revealed in the misinterpretation of the word “favored.” Students used different meanings to define the word favored, which impeded their ability to solve the task.

Table 33. Responses and reasoning for pK_a *in weak acid reaction task by student and course*

Courses	Name	Response			Reasoning									
								Reactant				Products		
		Neither	Reactants	Products	Gut feeling	pK_a values don't help	Average out pK_a values	Lower pK_a, more favored to react	Higher pK_a, stronger acid	Lower pK_a, stronger acid	Can’ t do resonance with charges in product	Rate higher	Lower pK_a, stronger, more dissociate acid	Resonance stability of conjugate acid
OC I	Alex		X						X					
	Gwen*			X									X	
	Kent			X								X	X	
	Annie			X									X	
	Frances*			X	X									
	Louise*		X							X				
OC II	Jack*			X		X								X
	Carrie		X								X			
	Kelly*	X					X							
	Quinn			X										X
BC	Clara*		X		X	X								
	Mitch			X									X	
	Sylvia*			X									X	
	Emily*		X					X						
Summary of courses	OC I	-	2	4	1	-	-	-	1	1	-	1	3	-
	OC II	1	1	2	-	1	1	-	-	-	1	-	-	2
	BC	-	2	2	1	1	-	1	-	-	-	-	2	-
		1	5	8	2	2	1	1	1	1	1	1	5	2

* Additional prompting required

4.3.9 Application of pK_a in the Reaction Mechanism Task

8. Complete the following reaction, show the complete reaction mechanism with arrows.

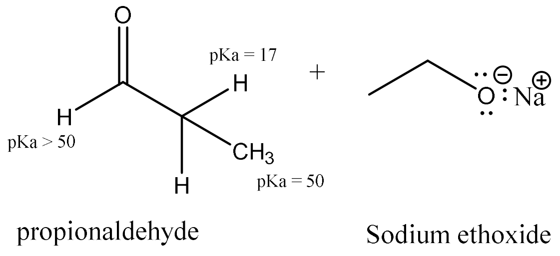


Figure 16. Weak acid reaction mechanism task

The participants in organic chemistry II and biochemistry were asked to complete the reaction mechanism with arrows and provide their reasoning (Figure 16). It was expected that students would use the pK_a values provided to deprotonate the hydrogen with the lowest pK_a value from the propionaldehyde to make an enolate ion. The responses were analyzed for their initial step in problem-solving, products, arrows, and their reasoning (Table 34).

The initial problem-solving steps in this task were split evenly between the eight students. Four students (Jack, Kelly, Mitch, and Annie) chose first to discuss the pK_a values, and four students (Clara, Mitch, Sylvia, and Emily) started to draw the curved arrow mechanisms without any discussion of the pK_a values. An interesting trend was observed in connection with the initial step. The students who selected to begin with the pK_a values were successful in completing the reaction mechanism properly. Students who chose to simply start the reaction mechanism, without paying attention to the pK_a values, did not correctly draw the reaction mechanism.

The students who performed the reaction mechanism correctly obtained the correct products and produced the resonance structure. The students, who reasoned using the pK_a and then performed the mechanism, began by describing the process of the hydrogen with the lowest pK_a being removed by the lone pair of electrons on the oxygen on the sodium ethoxide, followed by the negative charge being left on the alpha carbon. The student proceeded to draw the resonance structure by moving the negative charge from the alpha carbon to the adjacent bond and move the carbonyl bond up to the oxygen as a negative charge. As illustrated by Jack:

> *So, the way I would go about this is - I would take the hydrogen that has the lower* pK_a *because the hydrogen with the lower pKa is more acidic. And because sodium ethoxide is more basic, you wanna to take the acidic hydrogen. So, I would draw an arrow to the hydrogen. And I would break off the bond. And then you're going to have an intermediate [carbanion], but you're also gonna have the OH [ethanol], and you're gonna have* Na^+*.*

Quinn also produced the correct products, but she did not complete the reaction mechanism correctly. She indicated that she was familiar with this type of problem by saying, "We just did like this reaction." She stated, "the alpha hydrogen, it's next to a carbonyl, so this negative charge on the oxygen..." She proceeded to draw the mechanism from the negative charge to the hydrogen. During the task, she did not utilize the pK_a values in her reasoning. She appears to have memorized how to work through the task, rather than understand the underlying concepts.

Three students (Carrie, Clara, and Emily), who were unable to complete the mechanism, were unable to obtain the products. Carrie indicated that the lower the $pK_{a,}$ the more reactive. This idea of "more reactive" has been present for Carrie for during the strong acid definition in section 4.2.1 and the weak acid molecular level drawing, section 4.2.4. She inappropriately described "more reactive" as making more bonds and "less reactive" as making fewer bonds. When she applies that idea here (Figure 17), she displaces the hydrogen on the propionaldehyde and replaces it with the ethoxide. While it is outside the scope of the study, Carrie made the sodium ion negatively charge. She explained that the oxygen gave its electrons to sodium so it could bond to the carbon. Carrie's prior knowledge of acid strength based on reactivity is discussed in section 4.2 was shown to be unstable. This task shows that she is applying this unstable idea, and it is impeding her from being able to reason through the task properly.

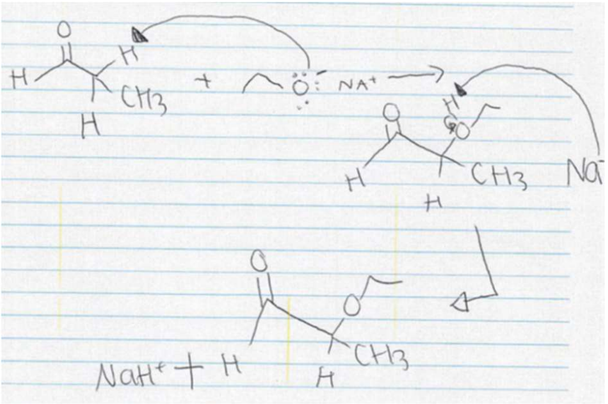


Figure 17. Carrie's reaction mechanism task

Clara did not obtain the products or properly draw the reaction mechanism. Furthermore, when asked about the pK_a values, Clara stated that "Yeah, I don't remember this much."

When the students drew the reaction mechanism, seven out of eight students used a single arrow to represent the reaction arrow. Mitch was the only student to use a double-headed reaction arrow when he drew out his reaction (Figure 18). Students were intentionally not questioned about their reaction arrows on this task. This lack of attention to reaction arrows indicates that the students are not cognizant of what arrows they are using when they are writing out reactions when their attention is not drawn to it. This finding is seen in the literature (Grove et al., 2012).

Table 34. Application of pK$_a$ in reaction mechanism task by student and course

Courses	Name	Initial Step		Products		Reaction			Reasoning			
		Curved arrow mechanism	pK$_a$ values	Did not obtain products	Obtain both products & resonance structures	Double-headed arrow	Single arrow	Mechanism correct	Don't know what to do with pK$_a$ values	Alpha hydrogen next to carbonyl	Lower pK$_a$, more acidic, “ more reactive”	Hydrogen w/ lowest pK$_a$ removed by lone pair of oxygen
OC II	Jack		X		X		X	X				X
	Carrie	X		X			X				X	
	Kelly		X		X		X	X				X
	Quinn	X			X		X			X		
BC	Clara	X		X			X		X			
	Mitch		X		X	X		X				X
	Sylvia		X		X		X	X				X
	Emily	X		X			X					
Summary of Courses	OC II	2	2	1	3	-	4	2	-	1	1	2
	BC	2	2	2	2	1	3	2	1	-	-	2
		4	4	3	5	1	7	4	1	1	1	4

Overall, students used one of two approaches to try to solve this reaction mechanism task. Students either successfully used the pK$_a$ and performed the reaction mechanism successfully or ignored the pK$_a$ and did not perform the task properly. A trend was observed for this task when students were not prompted about their reaction arrows; they did not pay attention to the type of overall reaction, only one student used a double-headed arrow to indicate the reaction was at equilibrium.

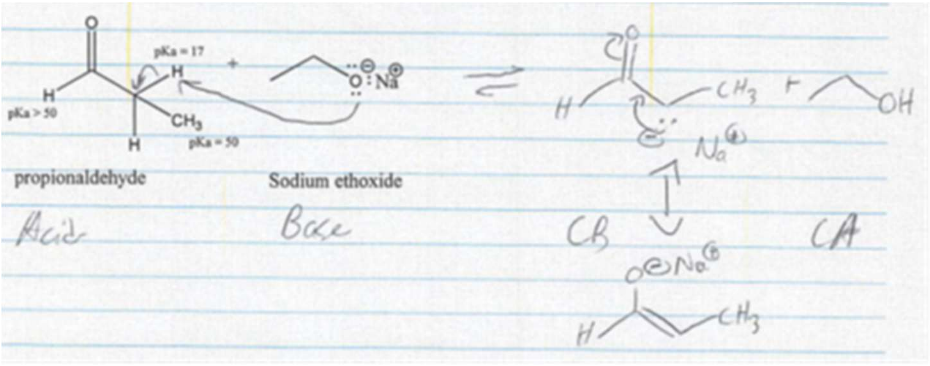


Figure 18. Mitch's reaction mechanism task

5 IMPLICATIONS AND CONCLUSION

This section intends to synthesize the overall findings and limitations of the study and to provide implications for teaching and further research.

This study explored students' understanding of the concepts that are related to acid-base equilibrium as they progress from general chemistry II through biochemistry. The students' understanding was evaluated through think-aloud interviews with open-ended questions and problem-solving tasks to provide multiple contexts. The concepts evaluated were acid-base models, acid strength, equilibrium, K_a, and pK_a.

This study found that only seventy-five percent of the students were able to produce a model with features consistent with one of the three main acid-base models: Arrhenius, Bronsted-Lowry, and Lewis. A trend was observed when students named acid-base models, students were more likely to have a disagreement in the features described and those of the model for the Lewis model, compared to when naming other models. This discrepancy indicated that there was some confusion for students in connection with this model and its features. An interesting finding was that organic chemistry II students comprised half of the students who were unable to describe an acid-base model, but instead preferred to use definitions based on stability and pH. Interestingly, the problem-solving task associated with this concept, in section 4.1.2, revealed that the organic chemistry students, who did not have an acid-base model, relied on the charges of the molecules and the functional groups to decipher the acids and bases. The reliance on features of the molecules in the reactions has been seen in the literature and is associated with superficial understanding (Bhattacharyya & Bodner, 2005; M. M. Cooper et al., 2016; Ferguson & Bodner, 2008; Grove et al., 2012). In contrast, the general chemistry student, who did not provide an acid-base model in the open-ended questions, used features consistent with the Bronsted-Lowry model during the task. As seen in previous literature (Bhattacharyya & Bodner, 2005; Grove et al., 2012), when students constructed curved arrow mechanisms for the reactions, they did so independently of the task. They labeled the reaction and performed the mechanism as if the two had no related meaning. A trend was observed that organic chemistry II students, who perform mechanisms in the course regularly, outperformed the students in organic chemistry I and biochemistry.

Students' understanding of the difference in acid strength was explored by having students evaluate a strong acid and a weak acid in multiple contexts. Only half of the students described acid strength in terms of dissociation. An interesting trend observed was that as students progressed away from general chemistry II, they relied less on ideas of dissociation and more on heuristics or tricks, presence on a list, or pK_a. The idea that students would define acid strength based on pKa is scientifically acceptable. However, most of these students also had other conflated ideas about acids, including the addition of ideas consistent with the concept of pH. This conflation of pH and pKa has been previously observed by other researchers (Orgill & Sutherland, 2008).

In general, students who provided appropriate definitions for acid strength based on dissociation produced molecular level drawings consistent with a strong acid and a weak acid. However, an interesting finding was that twenty-five percent of the students, none of which were in general chemistry II, did not define acid strength based on dissociation. These students produced strong acid molecular-level drawings consistent with the idea of "more H^+" in solution. In contrast, they produced molecular-level drawings for a weak acid with the idea of "more A^-". Furthermore, they drew both drawings as completely or nearly completely dissociated. This combination of findings would indicate that these students do not understand the concept of acid dissociation. Already twenty-five percent of students lack basic knowledge of one of the main concepts that underlie the acid ionization constant. Therefore, they will not be able to comprehend it fully.

When students described a reaction at equilibrium, only twenty percent of them were able to provide a definition consistent with a reaction occurring in both directions at the same rate. An additional five students were able to describe only the reversible nature of the reaction. A trend was observed in this study that students did not attribute meaning to the arrows used to indicate reactions at equilibrium with more than the mere mention of reversibility, which has been seen before in the literature (Gussarsky & Gorodetsky, 1990; Hackling & Garnett, 1985). Over half of the students did not provide an appropriate definition for a reaction at equilibrium. Students in upper-level courses converged on an idea of a reaction at equilibrium meaning "equal amounts." This idea of equal amounts has been seen before in the literature (Hackling & Garnett, 1985; Loertscher et al., 2014). A few students used the idea of "balancing out" the reaction, which has also been observed by other researchers (Johnstone, 2000, 2010).

When students were asked to describe K_a, less than half of the students had a name for it. This finding was interesting as in the lecture courses for the students; it was most often discussed simply by its abbreviation, indicating that they are not making a meaningful connection of K_a to its name, the acid ionization constant. Additionally, there was a trend that general chemistry II and biochemistry were the students that provide a name for K_a, not students in organic chemistry. However, when students were asked to describe K_a, more general chemistry II and organic chemistry I students were able to provide a description based either dissociation or how much acid to the conjugate forms. Less than half of students were able to provide a general expression for K_a, with none of the organic chemistry II students able to provide a correct expression. Less than half of students successfully interpret the meaning of the value of K_a appropriately. The trend of organic chemistry II students struggling continued for this interpretation. It was throughout the study that some students conflated K_a with rates and rate laws. These conflations have been observed in other research studies (Bain et al., 2019; Banerjee, 1991; Becker et al., 2017; Camacho & Good, 1989; Hackling & Garnett, 1985).

When students were engaging in problem-solving tasks related to K_a, they performed the task to construct the expression with little discussion of its meaning. Furthermore, students continued to pay little attention to the meaning of the reaction arrows in the task. Interestingly, general chemistry II and organic chemistry I students were the only ones to reason using acid strength for the weak acid reaction. This trend was similar for the strong acid, although two upper-level students did indicate the acid strength. From the strong acid, students attributed the single reaction arrow to the fact it was a strong acid without discussion of the underlying reason that it goes to completion. Notably, for the K_a expression for the strong acid, students were between the idea that it would be just like the expression for the weak acid, or that it did not have one since it was a strong acid.

Very few students were able to provide a verbal description of pK_a, other than interpreting the meaning of the size of it. Interestingly, when students discussed pKa, they would indicate that it was about how acidic ‘something’ was, as if they did not attribute it to anything particular – for example, an entity such as the molecule. Only thirteen out of twenty students made direct connections between K_a and pK_a. Only one student out of four in organic chemistry II discussed the connection between K_a and pK_a. A trend was observed for students in general chemistry II to conflate pK_a with pH. Researchers have previously observed this conflation (Orgill & Sutherland, 2008).

Students' level of sophistication was evaluated to make connections between the acid equilibrium concepts, which are described in the following section to provide an overall view of the students and the courses.

5.1 Levels of Sophistication

This study was designed to evaluate students in different contexts to probe their understanding. In line with the resources framework used in this study (Hammer et al., 2005), some students are more stable in their ideas related to acid equilibrium concepts than others. The "unstable" student used different ideas for a concept in different contexts. The idea of "stable" is defined as a student is using the same idea for a concept repeatedly. Lastly, a "flexible" student is a special case of the "stable" student who is defined by their ability to use different facets of a scientific concept, demonstrating a more expert-like understanding.

Stability across contexts did not ensure that these students had a coherent understanding of the concepts. The idea of "coherent" understanding is that the idea for the concept is in agreement with the scientific concept. In contrast, "incoherent" understanding indicates that a student has an idea that is incongruent with the scientific concept. Some students had a mixture of both incoherent and coherent understanding and are categorized as both. For example, in section 4.3, Gladys has some useful, coherent ideas about the acid ionization constant. However, her underlying idea about equilibrium impeded her from an overall understanding. Therefore, students were categorized according to their stability of ideas across concepts and their coherency of these ideas (Table 35). These categories led to a combination of five levels of sophistication: unstable/incoherent (U, I), unstable incoherent/coherent (U, I/C), stable incoherent/coherent (S, I/C), stable/coherent (S, C), and flexible/coherent (F, C).

Table 35. Description of levels of sophistication

Category	Description
Unstable, Incoherent	Student does not provide a consistent response about the concept in different contexts. Student has ideas inconsistent with the appropriate scientific concept.
Unstable, Incoherent/ Coherent	Student does not provide a consistent response about the concept in different contexts. Student has some ideas inconsistent and some consistent with the appropriate scientific concept.
Stable, Incoherent/ Coherent	Student provides consistent response about the concept in different contexts. Student has some ideas inconsistent and some consistent with the appropriate scientific concept.
Stable, Coherent	Student provides consistent response about the concept in different contexts. Student has ideas consistent with the appropriate scientific concept.
Flexible, Coherent	Student does not provide a consistent response about the concept in different contexts. Student has ideas consistent with the appropriate scientific concept.

5.1.1 Level of Sophistication for Strong and Weak Acid

In categorizing the levels of sophistication for contrasting concepts of the strong acid and the weak acid, it was seen that all, but four students (Gladys, Chester, Gwen, and Annie), fell into the same level. In section 4.2, the data was analyzed and discussed based on the consistency of the student responses. Seven students (Marie, Frances, Louise, Jack, Carrie, Kelly, and Emily) were in the unstable and incoherent level for the strong acid. These same students were in the unstable and incoherent level for the weak acid, with one additional student, Chester. These students did not provide any ideas consistent with dissociation for a strong acid or a weak acid. For example, Marie used the idea that weak acids were not on the list of strong acids, but she had no explanation of why acids would belong on the list. Her molecular level drawing of a weak acid had all of the acid molecules dissociated because they would be easier to break apart. Lastly, for Marie's selection of a weak acid at the molecular level, she selected the correct represent based on the reaction because it was reversible, so both the reactants and products would be present. Of note here, Marie's responses shifted during the strong acid molecular level picture task in this same portion of the interview when the interviewer challenged her understanding. She used different ideas to address each of the contexts presented and did not discuss dissociation concerning acid strength. An interesting note is that four of these students (Marie, Louise, Jack, and Carrie) had previously not provided any acid-base models.

Four students (Chester, Annie, Quinn, and Clara) were included in the unstable with mixed incoherent and coherent level for strong acids. Three students (Gwen, Quinn, and Clara) were included in the same category for weak acids. These students were inconsistent in their usage of ideas across contexts and had some ideas that were inconsistent with acid strength and dissociation. For example, Annie initially described a strong acid by using pH. In contrast, when she produced her molecular level drawing and selected her molecular level picture, she reasoned using complete dissociation. She was not consistent across contexts and had some incoherent and coherent ideas.

Eight students (Sam, Bill, Gladys, Kim, Alex, Gwen, Kent, and Sylvia) were at the stable and coherent level for the strong acid. All these students, except Gwen, were at this level for the weak acid. These students used the same idea across multiple contexts for acid strength. For example, Sam defined a strong acid as an acid that is complete dissociation, which was reflected in his molecular level drawing he produced and his reasoning for his selection of the molecular level representation.

One student, Mitch, in biochemistry, was at the flexible and coherent level of sophistication. He used multiple ideas to describe acid strength in different contexts. He initially distinguished acid strength by pK_a. He produced a sophisticated drawing of the strong acid at the molecular level with more detail than most students to reflect his idea of nearly completely dissociated. He was then able to select a picture consistent with complete dissociation.

Table 36. Levels of sophistication for acid strength by student and course

Course	Name	Strong Acid					Weak acid				
		U,I	U,I/C	S,I/C	S,C	F,C	U,I	U,I/C	S,I/C	S,C	F,C
GC II	Sam				X					X	
	Bill*				X					X	
	Gladys				X					X	
	Chester		X				X				
	Kim				X					X	
	Marie*	X					X				
OC I	Alex				X					X	
	Gwen				X			X			
	Kent				X					X	
	Annie		X							X	
	Frances	X					X				
	Louise	X					X				
OC II	Jack	X					X				
	Carrie	X					X				
	Kelly	X					X				
	Quinn		X					X			
BC	Clara		X					X			
	Mitch					X					X
	Sylvia				X					X	
	Emily	X					X				
Summary of Courses	GC II	1	1	-	4	-	2	-	-	4	-
	OC I	2	1	-	3	-	2	1	-	3	-
	OC II	3	1	-	0	0	3	1	-	0	0
	BC	1	1	-	1	1	1	1	-	1	1
		7	4	-	8	1	8	3	-	8	1

LEGEND
U = Unstable I = Incoherent
S = Stable C = Coherent
F = Flexible

5.1.2 Levels of Sophistication for Equilibrium

When evaluating these levels of sophistication for the concept of equilibrium in the study, most students maintained the same idea of equilibrium throughout the study, indicating that the students were stable in their reasoning. However, as noted before in section 4.3.1, only four students indicated that a reaction at equilibrium would be a reversible reaction occurring at the same rate in both directions. These students were Sam, Bill, and Kim in general chemistry II, and Annie in organic chemistry I. Therefore, only four students were at the level of stable and coherent for the concept of equilibrium. Four students (Gladys, Alex, Kent, Frances, and Quinn) were considered to be stable and mixed incoherent and coherent as the study revealed, that simply understanding the reversibility of the reaction was not considered to be a comprehension of the concept, but merely part understanding. This lack of understanding was revealed by the lack of meaning to the students of the reaction arrows throughout the study in multiple contexts, where students attributed the idea of simple reversibility to the double-headed arrows. In Gladys's case, she had a particularly problematic idea of equaling out reactants and products that she applies to her concept of K_a. The remaining eleven students (Chester, Marie, Gwen, Louise, Jack, Carrie, Kelly, Clara, Mitch, Sylvia, and Emily) were the unstable and incoherent group. Comparing the unstable and incoherent levels, both here and for acid strength, this level contains six of those seven students. The only student missing is Frances. However, for equilibrium, she has some mixed coherence.

5.1.3 Levels of Sophistication for K_a

Students were evaluated on the level of sophistication for the acid ionization constant, K_a (Table 37). Nine students (Marie, Gwen, Frances, Jack, Carrie, Kelly, Quinn, Clara, and Emily) were categorized at a level of sophistication of unstable and incoherent. Students at this level expressed varying ideas inconsistent with K_a across multiple contexts. For example, Marie was unable to describe K_a and conflated it with percent ionization when she tried to produce a mathematical expression. Notably, six students (Frances, Jack, Carrie, Kelly, Quinn, and Clara), including all of the organic chemistry II students, in this category conflated K_a with rates during various contexts of the interview. Additionally, eight of these nine students have been categorized at this level for one of the other concepts already evaluated.

Table 37. Levels of sophistication for K_a by student and course

Course	Name	U, I	U, I/C	S, I/C	S, C
GC II	Sam				X
	Bill				X
	Gladys			X	
	Chester		X		
	Kim		X		
	Marie	X			
OC I	Alex		X		
	Gwen	X			
	Kent		X		
	Annie				X
	Frances	X			
	Louise			X	
OC II	Jack	X			
	Carrie	X			
	Kelly	X			
	Quinn	X			
BC	Clara	X			
	Mitch			X	
	Sylvia			X	
	Emily	X			
Summary of Courses	GC II	2	2	1	2
	OC I	2	2	1	1
	OC II	4	-	-	-
	BC	2	-	2	-
		10	4	4	3

LEGEND U = Unstable I = Incoherent
S = Stable C = Coherent
F = Flexible

Four students (Chester, Kim, Alex, and Kent) were assigned to the level of unstable with a mixture of incoherent and coherent ideas. Students at this level had some appropriate ideas in one context, yet inappropriate ideas in others. For example, Kim had appropriately described K_a as the products over the reactants. However, her confusion in the word “acidic” and the word “acidic” led her to misinterpret the value of K_a improperly. An interesting case was for Alex, who described K_a appropriately, but when they solved tasks, resorted to using the calculator and incorrectly performed a calculation that changed the course of their answers. Students’ lack of understanding when relying on calculators has been seen in the literature (Watters & Watters, 2006).

Four students were assigned to a level of sophistication of stable with mixed incoherent and coherent ideas. Gladys, Louise, Mitch, and Sylvia were stable across contexts but had mixed incoherent and coherent ideas about K_a. For example, Gladys was consistent as she described K_a in the same manner, but applied a scientifically inappropriate idea of equilibrium, meaning that the reactants and products to be equal amounts. During problem-solving, Louise, Sylvia, and Mitch include water in their K_a expression, but they did not initially include it in their open-ended questions.

For the levels of sophistication for the acid ionization constant, K_a, very few students were classified as stable and coherent. Only three lower-level students were included in this level, including Sam, Bill, and Annie. When discussing K_a, these students provided ideas consistent with the concepts of K_a across multiple contexts. For example, Sam described that K_a was the acid ionization constant, and it described how well an acidic dissociates. He was able to provide an appropriate mathematical expression in the open-ended and problem-solving sections. He was also able to recognize the inconsistency in the consideration that a strong acid should have an equilibrium constant, but the reaction was not written at equilibrium.

A special note, when the students in the two levels that were ‘stable’ were asked about an equilibrium expression for a strong acid, a couple of students indicated that there would be no acid ionization constant. Whereas Sam was able to view the incongruity that a strong acid would have an acid ionization constant, as it has a pK_a value, but was a completion reaction that is represented with a single arrow. In general, the assumption is that a strong reaction is not at equilibrium since it so far to the right. Although the nuance of this idea can elude students when simplified for instruction. However, this concept is taught in a variety of ways in different courses by different instructors. Therefore, it was not considered to be an unacceptable scientific idea.

5.1.4 Levels of Sophistication for pK_a

The concept of pK_a was evaluated for levels of sophistication. However, students need to have a stable and coherent understanding of K_a to comprehend pK_a fully. Therefore, very few students were in the ‘stable’ category. Furthermore, as previously detailed in section 4.3.5, most students lacked any appropriate verbal description of pK_a relying on mathematical expressions and interpretations of values rather than descriptions of pK_a. With those caveats in mind, the students were assigned to levels of sophistication for pK_a.

Five students (Chester, Marie, Louise, Clara, and Emily) were classified as unstable and incoherent. These students were unable to produce any ideas consistent with pK_a across the contexts presented to their various course levels. Chester was unable to make any connections between pK_a to K_a. This finding is not surprising. Throughout the interview, he has indicated his propensity to use tricks and shortcuts to aid him in problem-solving, rather than any focus on conceptually understanding. In contrast, the four students all had problems with other prior knowledge that could contribute to their lack of understanding pK_a.

Table 38. Level of sophistication for pK_a by student and course

Course	Name	U, I	U, I/C	S, I/C	S, C
GC II	Sam		X		
	Bill		X		
	Gladys		X		
	Chester	X			
	Kim		X		
	Marie	X			
OC I	Alex		X		
	Gwen				X
	Kent				X
	Annie				X
	Frances		X		
	Louise	X			
OC II	Jack		X		
	Carrie		X		
	Kelly		X		
	Quinn		X		
BC	Clara	X			
	Mitch				X
	Sylvia				X
	Emily	X			
Summary of Courses	GC II	2	4	-	-
	OC I	1	2	-	3
	OC II	-	4	-	-
	BC	2	-	-	2
		5	10	-	5

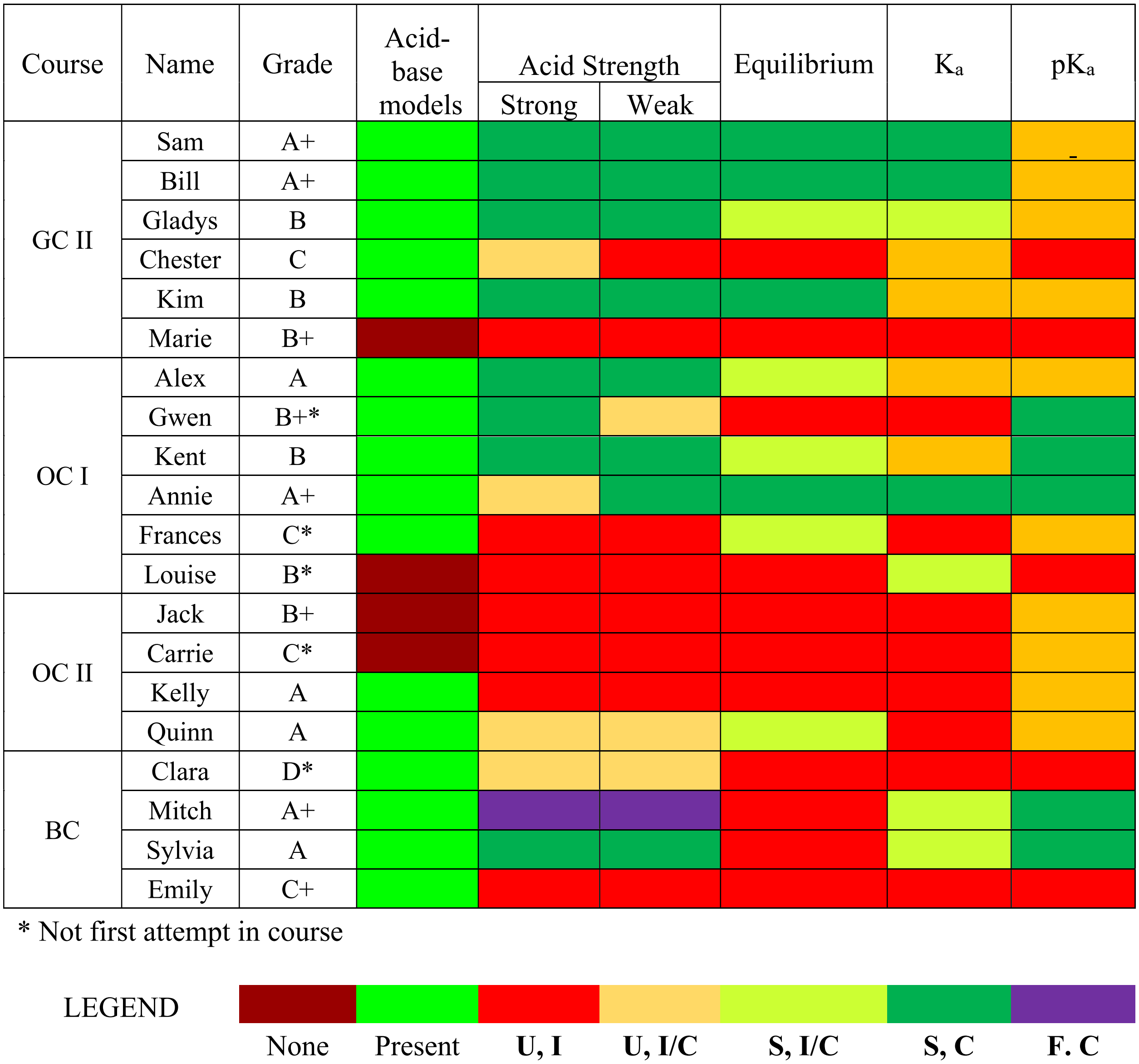
LEGEND
U = Unstable
S = Stable
I = Incoherent
C = Coherent
F = Flexible

The level of sophistication with most students is the level of unstable with mixed incoherent and coherent ideas. Incidentally, this level contains mostly general chemistry II and organic chemistry II students. Ten students (Sam, Bill, Gladys, Kim, Alex, Frances, Jack, Carrie, Kelly, and Quinn) were assigned to this level. Most of the general chemistry II students in this level made connections to K_a but of them conflated pK_a with either pH or pOH. This finding is not surprising since these students in general chemistry II learn about pK_a within the context of the Henderson-Hasselbalch equation, which utilizes pH. This conflation has been seen before in the literature (Orgill & Sutherland, 2008; Villafañe, Loertscher, et al., 2011; Watters & Watters, 2006). All the organic chemistry II students are at the level as well, which is interesting as none of them were able to describe K_a. These students did not see the usefulness of pK_a when it was provided as a tool for problem-solving, preferring to solve the task with alternative means. This finding was confirmed during the interviews when students explained that their course instructor wanted their explanations to be based on structural features rather than relying on pK_a values.

Only five students (Gwen, Kent, Annie, Mitch, and Sylvia) were classified as stable and coherent. These students provided explanations of pK_a that were consistent with ideas of pK_a and made connections to K_a. Furthermore, they were consistent in their application of pK_a across multiple contexts. For example, Mitch described pK_a as and an easier way to express K_a. He provided that it was the -log of K_a. He interpreted the value appropriately and applied these interpretations across multiple contexts for problems for organic chemistry and biochemistry.

However, Gwen's level of sophistication here is questionable because she was considered to be unstable and incoherent for the concept of K_a. Although she invoked the proper language to describe pK_a and applied it appropriately, she may just be going through the motions when working out the problems since the problem tasks were designed to be similar to the courses. Currently, Gwen is being taught this concept in her course as pK_a, so she does not have to translate the idea between K_a to pK_a.

5.1.5 Levels of Sophistication Across for Acid Equilibrium Concepts



Course	Name	Grade	Acid-base models	Acid Strength		Equilibrium	K_a	pK_a
				Strong	Weak			
GC II	Sam	A+	🟩	🟢	🟢	🟢	🟢	🟧
	Bill	A+	🟩	🟢	🟢	🟢	🟢	🟧
	Gladys	B	🟩	🟢	🟢	🟡	🟡	🟧
	Chester	C	🟩	🟨	🟥	🟥	🟧	🟥
	Kim	B	🟩	🟢	🟢	🟢	🟧	🟧
	Marie	B+	🟫	🟥	🟥	🟥	🟥	🟥
OC I	Alex	A	🟩	🟢	🟢	🟡	🟧	🟧
	Gwen	B+*	🟩	🟢	🟨	🟥	🟥	🟢
	Kent	B	🟩	🟢	🟢	🟡	🟧	🟢
	Annie	A+	🟩	🟨	🟢	🟢	🟢	🟢
	Frances	C*	🟩	🟥	🟥	🟡	🟥	🟧
	Louise	B*	🟫	🟥	🟥	🟥	🟡	🟥
OC II	Jack	B+	🟫	🟥	🟥	🟥	🟥	🟧
	Carrie	C*	🟫	🟥	🟥	🟥	🟥	🟧
	Kelly	A	🟩	🟥	🟥	🟥	🟥	🟧
	Quinn	A	🟩	🟨	🟨	🟡	🟥	🟧
BC	Clara	D*	🟩	🟨	🟨	🟥	🟥	🟥
	Mitch	A+	🟩	🟪	🟪	🟥	🟡	🟢
	Sylvia	A	🟩	🟢	🟢	🟥	🟡	🟢
	Emily	C+	🟩	🟥	🟥	🟥	🟥	🟥

* Not first attempt in course

LEGEND	🟫	🟩	🟥	🟨	🟡	🟢	🟪
	None	Present	**U, I**	**U, I/C**	**S, I/C**	**S, C**	**F. C**

Figure 19. Levels of sophistication for acid-base equilibrium concepts for all students by course

When the levels of sophistication for all students across the concepts of acid strength, equilibrium, pK_a, and K_a are compared, it can be seen that there is a cascading effect. In other words, students have more difficulty describing more complex concepts in acid equilibrium, if they lacked prior knowledge of underlying concepts such as acid-base models, acid strength, and equilibrium. (Figure 19). This effect is evident in students like Marie, Jack, and Carrie, who were not even able to provide the most basic component of acid-base models. It was seen that students who were repeating the courses were among those that struggled with prior knowledge. A concerning trend can be observed in Figure 19 that students in the upper-level courses, particularly in organic chemistry II, are missing the concepts that underlie pK_a. However, as reflected in their grades, most of these students generally perform well in chemistry courses.

5.2 Limitations of the Study

This qualitative study represented a small number of participants across four courses from one institution; therefore, the generalizability of the study is limited. Additionally, the small number of participants from the biochemistry course limits claims that we can make about differences between groups. However, we have provided an in-depth analysis of a variety of students in the study to capture the resources that students use regarding the concept of acid dissociation. The findings presented in this dissertation were part of a larger study designed to encompass a longitudinal study. However, due to the large volume of data for this qualitative study and with four courses under observation, the attrition of subjects from the study had a large impact on the ability of the longitudinal study to provide additional information beyond the initial study.

Additionally, five participants in the study had repeated some of the course(s) under investigation. However, this is a frequent occurrence in these courses. Most courses have some students that do not pass the course on the first attempt. One might argue that such students might have an advantage by having seen the material more than once. Alternatively, one might argue that students who have repeated the course do not represent the "average" student and are not representative of the "average" student. After collection of the course grades from the Office of Institutional Research, however, this sample contained twenty-five percent of students that had taken the course under study previously. Two of the students had four attempts at the course under study. However, this provided insight into a group of students who likely need additional support in the classroom. Despite having taken the course more than once, these students were not further along in their conceptual understanding than students who have taken the course once.

The combination of the resources framework and the think-aloud protocol creates a limitation based on the ability of the interviewer to probe the participant. This combination is advantageous in its ability to provide in-depth, real-time information, however the interviewer could have influenced the student's response by the prompting in a task by activating a resource that the student may not have used on his/her own. Furthermore, this study explored prior concepts and different contexts of the same topic. The student may have been primed in one task by interviewer prompting to utilize different resources in a subsequent task. For example, when Marie shifted frames in section 4.2.5 when she used a new set of resources due to prompting by the interviewer. This research does not suggest that any of these contexts is preferential to the other.

Also, we do not claim to have captured all the students' conceptions or problem-solving approaches. A limitation of the think-aloud interview is that only the verbalized ideas of the student can be captured. A student may not have revealed additional ideas or thoughts. However, the think-aloud interview was used in multiple contexts to provide students with the opportunity to provide multiple opportunities to present their ideas.

5.3 Implications for Teaching

One of the recurrent themes in this study was students contrasting concepts, or simply contrasting words, such as 'weak' and 'strong' acids and 'higher' and 'lower' values.

Instructors, as experts, need to be clear on the difference in the degree of the words when discussing topics such as weak and strong acids, especially since everyday terminology may conjure ideas of “opposites” rather than varying degrees. The everyday use of words can be problematic for students. This problem is not new for students (Cassels & Johnstone, 1983; Johnstone & Selepeng, 2001). In acid-base chemistry, the ‘strong’ comes apart, and the ‘weak’ stays together and the opposite is true for strong and weak bonds. Previously literature has noted confusion in both of the words strong and weak (Jasien, 2005, 2011; Smith & Metz, 1996). Additionally, in chemistry, the word ‘equilibrium’ is not used in the same manner as everyday terms such as equal, or balanced, as noted in the previous literature (Gussarsky & Gorodetsky, 1990; Hackling & Garnett, 1985; Johnstone, 2000, 2010; Loertscher et al., 2014). As suggested by other researchers (Stowe & Cooper, 2017), to have a better conceptual understanding, instructors need to provide students with the opportunity to demonstrate conceptual understanding, not just perform mathematical problem-solving, or select a response based on a multiple choice.

Instructors can provide activities that support the development of an understanding of how terminology is used differently in chemistry from everyday terminology, as well as distinguish the same words with different definitions within chemistry. Instructors can include activities utilizing the eight science practices, such as developing models, analyzing and interpreting data, or constructing explanations to provide support to lead students to a better conceptual understanding (National Research Council, 2011; Stowe & Cooper, 2017). Additionally, instructors could use multiple contexts to confirm the stability of a students’ understanding of the words. For example, students could construct explanations about contrasting models of acid strength provided insight into student understanding of the words ‘strong’ and ‘weak.’

When instructors discuss terms such as higher and lower values of acidity, they need to be explicit about the comparisons being made for the higher and lower values. As experts, instructors are clear to the degree in which those values mean something to them. For example, how high is high? How low is low? Furthermore, when making these comparisons, the instructor should be sure to clarify what the values belong to when describing “it.” For example, “when pKa is higher lower, it means it is more acidic.” Students in this study did not appear to consider what the “it” was that was more acidic. Especially with the conflation of pH and pK_a, students need to clearly distinguish that the pH belongs to the entire solution (the environment) and the pK_a belongs to the molecule. A distinction in the meaning of higher and lower values of pH and pK_a early in a student learning is needed as they may be confounded with each other.

Another reason for students to conflate pK_a with acidity and basicity may be the K_a and pK_a charts. Some pK_a charts visually reflect the concept of decreasing acid strength on one side of the chart and increasing base strength for the conjugate base on the other side of the chart. Instructors should take into consideration that students may think about pK_a in terms of the conjugate base, where a stronger acid has a weaker conjugate base. Therefore, a student might interpret a molecule with lower pK_a is more acidic and less basic.

When students are taught about pK_a, in general chemistry II, it is within the Henderson-Hasselbalch equation that relates pH to pK_a. This type of task can be approached by algorithmic problem-solving without making connections to K_a and pK_a (Camacho & Good, 1989). Instructors should design problems that require students to reason and develop models of these buffer systems rather than simply solving a numeric problem to develop better conceptual understanding.

As students' progress in chemistry, concepts that were simplified are often refined to more complex models. Students are taught the Bronsted-Lowry acid-base model in general chemistry II as the model works well for understanding equilibrium. However, when students' progress to organic chemistry, they are presented with the Lewis acid-base model, as it better explains organic reactions. The Lewis model does encompass the Bronsted-Lowry model, but students need to understand that relationship. It was seen that students used mixed acid-base models to explain the curved arrow mechanism. However, students seemed confused when trying to discuss the mechanism in terms of both the electrons and the hydrogens. In this context, students would interchangeably use the word hydrogen for proton when discussing the mechanism because that is what they were moving around. Therefore, instructors need to provide clarity to students who may not appropriately translate the unseen information in a reaction, as has been seen in the literature (Bodner & Domin, 2000).

Another concept that is refined in later courses is the dissociation of a strong acid. In general chemistry II, students are taught that a strong acid dissociation goes to completion by definition, where strong acids completely dissociate. Furthermore, students are often taught that strong acids "do not have" a K_a value. Generally, instructors will provide a qualifying statement that they do not discuss the K_a values because the values of strong acids as they are so large, since the reaction goes to "completion." When students enter organic chemistry, the reaction of HCl and water is presented as a reversible reaction that goes almost to completion. As experts, instructors understand the nuance of this definition, but it appears more difficult for students, as novices, to understand that refinement. Students, in general chemistry II, are not generally presented with K_a values and pK_a values for strong acids, but they do have them. For students to be able to contrast strong acids and weak acids, they need to understand the difference in the reactions is the degree of dissociation, not in the idea that one is "complete" and the other is at equilibrium.

Instructors can use this study to approach student understanding from a fine-grained approach to understand the ideas that students use in different contexts to reveal the stability and coherence about a topic. Then use the information provided to guide the student towards a better understanding by utilizing any helpful ideas that the student may already possess as a starting point (Hammer & Elby, 2003). From well-designed activities that require students to reason, instructors can provide scaffolding to assist students towards a better understanding. For example, when exploring acid strength in section 4.2, students described acid strength in terms of "more H^+" and "more A^-." Most of these students' ideas at the molecular level included all of the ions dissociated. Based on constructivism, instructors can build on what students already do know; these students have an idea of dissociation, but not equilibrium. Based on the resources framework, these students have a useful, productive resource to use as a starting block. However, they need to be scaffolded to build up their understanding of the difference of the dissociation of the two systems, also adding the prior concept of conservation of atoms in the system.

Another way instructors can provide support for their students is to help them build metacognitive strategies, such as reflection. In section 4.1.2, Frances reflects on her response to the task that it did not appear right to her based on the functional groups. Other than Frances, few students in this study reflected on their responses. Another student, who reflected on their understanding was Sam when he was prompted to during his strong acid reaction task for K_a. By challenging his understanding and the discrepancy in the context of equilibrium and completion for a strong acid, it provided him with more insight into his understanding. Instructors could design activities that have challenge students' understanding to reveal nuances such as this to them. This strategy can be useful to students by having the ability to question their understanding; they can, in turn, improve their understanding.

Constraints of assessment in the classroom often bound instructors. This research suggests that instructors should put multiple contexts of the same concept on formative and summative assessment to assess for stability in understanding rather than the ability to simply get the right answer by being able to process one type of question properly or completing a mathematical manipulation. Furthermore, instructors need to make sure that assessment tasks are designed to probe the depth of knowledge intended. The instructor should question whether the student needs to reason about the intended concept, or whether surface-level characteristics and repetition lead the student through the proper procedure to arrive at the correct answer.

Assessments should include at least some questions that prompt students to provide reasoning for their answers rather than picking the appropriate words. For example, knowing the word equilibrium and understanding the meaning of the word equilibrium are not the same. Explanations could be provided when students write out reactions and reaction mechanisms. Students should be able to identify the components of the reaction and explain the meaning of the symbols that they have written to assure understanding.

Curriculum reform in chemistry is needed. There have been several new chemistry curriculums developed in recent years. These curriculums include Chemistry, Life, the Universe, and Everything (CLUE) (M. Cooper & Klymkowsky, 2013; M. M. Cooper & Klymkowsky, 2019), Chemistry Unbound (McGill et al., 2019), and Chemical Thinking (Sevian & Talanquer, 2014). While it is not always practical to change curriculum, these three curricula have similar goals in mind. These curricula emphasize and reiterate the idea of core ideas and crosscutting concepts that are threaded through the courses, which encompass science practices to develop better student understanding. When it is not feasible to change curriculum, instructors can find guidance on core ideas across courses from the anchoring content concept maps (ACCM) (T. Holme et al., 2015; T. Holme & Murphy, 2012; Thomas A. Holme, Reed, Raker, & Murphy, 2018; Marek, Raker, Holme, & Murphy, 2018; Murphy et al., 2012; Raker et al., 2013). It should not be that someone's proficiency in math or the ability to repeat patterns earns them a good grade in chemistry.

5.4 Implications for Research

When researchers are performing studies, they should not only be concerned that participants are saying the appropriate terminology, but it is also important to understand the meaning behind the terminology. Often, words, even very simple words, are taken at face value. This study has revealed that students struggle with terms in acid-base chemistry concepts by conflating them with everyday terms when applying them in different contexts. This work has exposed a lack of understanding of acid equilibrium concepts in upper-level chemistry students, especially organic chemistry II students. Additionally, students not only conflated pH and pKa, but several did not ascribe acidity belong to any particular entity. Further studies need to be performed to assess student understanding of the relationship and differences between pH and pK_a across these courses.

Future work could use this study as a foundation to develop a larger-scale assessment of student understanding of acid dissociation and acid equilibrium concepts. The assessment could contain two sections, the first on acid strength and the second section for the acid equilibrium concepts of K_a and pK_a. The assessment could be designed as a two-tiered multiple-choice instrument. This design would allow students to select a response in the first tier and select their reasoning in a second tier. The assessment could be constructed with two to three items, for each of the concepts, to evaluate them in different contexts. This design would allow for a comparison across different contexts to determine the stability of the understanding.

This work lays the foundation for exploring the stability of student understanding across different contexts related to the same concept to enhance the field of chemistry education research.

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APPENDICES

Appendix A - Student Recruitment Protocols

Appendix A.1 - Student Recruitment Presentation

Recruitment Presentation for Undergraduate Students - Interviews

Good (morning/afternoon/evening). My name is Nancy Kilpatrick. I am a Ph.D. student here at Georgia State. I am conducting a research study on how students understand acid-base concepts in chemistry. I am interested in investigating how students develop from general chemistry and as they progress through both organic chemistry courses and biochemistry. My hope is that this study will give instructors more insight into how to best present this material to help students understanding. If you decided to participate in this study, you will be asked to participate in one interview to discuss your understanding of acid-base concepts in chemistry~~.~~ The interview will be conducted within the next couple of weeks after you have been presented with this material in the course. The interview will require one to one and a half hours of your time. You can only participate in this study if you are at least 18 years of age and are an undergraduate student enrolled in (General Chemistry II/Organic Chemistry I/Organic Chemistry II/Biochemistry I) course at Georgia State. Your participation in the study is completely voluntary. Your decision to participate or not will not affect your grade in the course. Only I will know who participated in the study. Your name will be removed and replaced by a pseudonym when we analyze and present the data. Your participation in the study will not affect your grade in this course. You will receive a $10 gift card as compensation for participation in an interview for this study. If you are willing to assist us in this study and have your collected data used in the study, please provide your name and contact information on the sheet of paper I am passing around. I will contact you and determine if we can schedule a time for the interview. Please keep in mind that there will be opportunities for you to participate in this research study as you progress into the (Organic Chemistry I/Organic Chemistry II/Biochemistry I) courses. If you have further questions about this research study, I will be available at the end of your lecture. You can also contact Dr. Mooring by phone or email at 404-413-5527, or smooring@gsu.edu.

Appendix A.2 - Student Recruitment Presentation Follow up Email

Recently I presented to your (General Chemistry II/Organic Chemistry I/Organic Chemistry II/Biochemistry I) class an invitation to participate in a research study for student understanding in acid-base concepts in chemistry. As stated previously, the study would involve an interview to discuss acid-base concepts and apply these concepts. You provided your email address indicating that you were interested in participating in the study. Attached is the informed consent form. Please review the consent form, you will sign a copy of the consent for at the beginning of the interview if you are willing to participate in the study. If you have any questions about the consent form, please feel free to contact me via this email address or call me at 404-413-5656. Please see the attached scheduling form and pick three of the time slots listed as possible times for your interview. I will email you with a confirmation of your exact interview time. Thank you again for agreeing to participate in this research study.

Appendix B - Informed Consent Forms

Appendix B.1 - Informed Consent for Students 2017 - 2018

Georgia State University
Department of Chemistry
Informed Consent

Title: Student Understanding in Acid-Base Concepts in Chemistry
Principal Investigator: Dr. Suazette Mooring Student
Principal Investigator: Nancy Kilpatrick

I. Purpose:

You are invited to participate in a research study. The purpose of the study is to investigate student understanding in acid-base concepts in chemistry. You are invited to participate because you are currently an undergraduate student enrolled in this chemistry course. You must be at least 18 years or older to participate in the study. This must be the first time you are taking this course. This study has two sections. We are asking you to participate the student section which will enroll 200 student participants from General Chemistry II, Organic Chemistry I, Organic Chemistry II and Biochemistry I courses. Section 2 will enroll 10 faculty participants. Participation will require approximately 1 - 1 ½ hours of your time over the semester for one interview. You may participate in more than one semester over the lifetime of this study for a maximum of 6 hours of time over four semesters, that may be non-consecutive.

II. Procedures:

If you decide to be a part of this study, you will participate in an interview on acid-base concepts in chemistry. You will also complete a demographic survey and answer some interview questions about your previous chemistry experiences, feelings and future plans. The interview will be conducted after you have been presented with acid-base concepts in class, between weeks 7 - 10. The interview will be recorded, including written and spoken responses. Your face will not be shown. The interview will be in a private room away from any classroom. Each interview will take approximately 1-1 ½ hours. We would also like your permission to obtain your grades for specific classes. We would like to obtain your overall grades for relevant chemistry courses which many include: general chemistry I, general chemistry II, organic chemistry I, organic chemistry II, and biochemistry I.

III. Risks:

In this study, you will not have any more risks than you would in a normal day of life. The disclosure of grades, if they are identifiable, represents some risk.

GSU APPROVED
IRB NUMBER: H18262
IRB APPROVAL DATE: 12/11/2017
IRB EXPIRATION DATE: 12/10/2018

IV. Benefits:

Participation in this study may not benefit you personally. Overall, we hope to gain information about how students understand and develop acid-base concepts in chemistry. We hope to help instructors understand their students' needs and promote student learning.

V. Compensation:

You will receive a $10 gift card as compensation for an interview for participating in this study. If you are a study participant in all four courses, you may receive a maximum of $40 in gift cards.

VI. Voluntary Participation and Withdrawal:

Participation in research is voluntary. You do not have to be in this study. If you decide to be in the study and change your mind, you have the right to drop out at any time. You may skip questions or stop participating at any time. Whatever you decide, you will not lose any benefits to which you are otherwise entitled. Your grade in this course will not be affected by your choice to participate, or not participate. Your grade in this course will be provided only after this course has ended.

VII. Confidentiality:

We will keep your records private to the extent allowed by law. Nancy Kilpatrick will know the names of the participants, as well as any other identifying information, and will assign the pseudonyms. Dr. Suazette Mooring will not know the actual identity of the participants. We will use a pseudonym rather than your name on study records. The information you provide will be stored in a locked cabinet at 529 Science Annex and on a password and firewall protected computer. The audio and video recordings will be stored on a password and firewall protected computer. The key (code sheet) used to identify the research participants will be stored separately from the data to protect privacy. The key code will be kept in a locked cabinet and destroyed after the study is complete. Your name and other facts that might point to you will not appear when we present this study or publish its results. The findings will be summarized and reported in group form. You will not be identified personally. Both Dr. Suazette Mooring and Nancy Kilpatrick will have access to all other the information you provide, which may include interview responses, both written and record, grade data after they has been assigned to your pseudonym, and any data analysis performed on the data collected. Information may also be shared with those who make sure the study is done correctly (GSU Institutional Review Board, the Office for Human Research Protection (OHRP)).

VIII. Contact Persons:
Contact Dr. Suazette Mooring, or Nancy Kilpatrick at smooring@gsu.edu, or nkilpatrick1@student.gsu.edu, respectively, or by phone at 404-413-5527 if you have questions, concerns, or complaints about this study. You can also call if you think you have been harmed by the study. Call Susan Vogtner in the Georgia State University Office of Research Integrity at 404-413-3513 or svogtner1@gsu.edu if you want to talk to someone who is not part of the study team. You can talk about questions, concerns, offer input, obtain information, or suggestions about the study. You can also call Susan Vogtner if you have questions or concerns about your rights in this study.

IX. Copy of Consent Form to Participant:
We will give you a copy of this consent form to keep.

If you are willing to volunteer for this research, be recorded by written and spoken responses with audio and video, which will not show your face, and obtain your grades, please sign below.

____ ________________
Participant Date

____ ________________
Principal Investigator or Researcher Obtaining Consent Date

Appendix B.2 - Informed Consent for Students 2018 - 2019

Georgia State University
Department of Chemistry
Informed Consent

Title: Student Understanding in Acid-Base Concepts in Chemistry
Principal Investigator: Dr. Suazette Mooring
Student Principal Investigator: Nancy Kilpatrick

I. Purpose:

You are invited to participate in a research study. The purpose of the study is to investigate student understanding in acid-base concepts in chemistry. You are invited to participate because you are currently an undergraduate student enrolled in this chemistry course. You must be at least 18 years or older to participate in the study. This must be the first time you are taking this course. This study has two sections. We are asking you to participate the student section which will enroll 200 student participants from General Chemistry II, Organic Chemistry I, Organic Chemistry II and Biochemistry I courses. Section 2 will enroll 10 faculty participants. Participation will require approximately 1 - 1 ½ hours of your time over the semester for one interview. You may participate in more than one semester over the lifetime of this study for a maximum of 6 hours of time over four semesters, that may be non-consecutive.

II. Procedures:

If you decide to be a part of this study, you will participate in an interview on acid-base concepts in chemistry. You will also complete a demographic survey and answer some interview questions about your previous chemistry experiences, feelings and future plans. The interview will be conducted after you have been presented with acid-base concepts in class, between weeks 7 - 10. The interview will be recorded, including written and spoken responses. Your face will not be shown. The interview will be in a private room away from any classroom. Each interview will take approximately 1-1 ½ hours. We would also like your permission to obtain your grades for specific classes. We would like to obtain your overall grades for relevant chemistry courses which many include: general chemistry I, general chemistry II, organic chemistry I, organic chemistry II, and biochemistry I.

III. Risks:

In this study, you will not have any more risks than you would in a normal day of life. The disclosure of grades, if they are identifiable, represents some risk.

IV. Benefits:

Participation in this study may not benefit you personally. Overall, we hope to gain information about how students understand and develop acid-base concepts in chemistry. We hope to help instructors understand their students' needs and promote student learning.

GSU APPROVED
IRB NUMBER: H18262
IRB APPROVAL DATE: 12/10/2018
IRB EXPIRATION DATE: 12/09/2019

V. Compensation:

You will receive a $10 gift card as compensation for an interview for participating in this study. If you are a study participant in all four courses, you may receive a maximum of $40 in gift cards.

VI. Voluntary Participation and Withdrawal:

Participation in research is voluntary. You do not have to be in this study. If you decide to be in the study and change your mind, you have the right to drop out at any time. You may skip questions or stop participating at any time. Whatever you decide, you will not lose any benefits to which you are otherwise entitled. Your grade in this course will not be affected by your choice to participate, or not participate. Your grade in this course will be provided only after this course has ended.

VII. Confidentiality:

We will keep your records private to the extent allowed by law. Nancy Kilpatrick will know the names of the participants, as well as any other identifying information, and will assign the pseudonyms. Dr. Suazette Mooring will not know the actual identity of the participants. We will use a pseudonym rather than your name on study records. The information you provide will be stored in a locked cabinet at 529 Science Annex and on a password and firewall protected computer. The audio and video recordings will be stored on a password and firewall protected computer. The key (code sheet) used to identify the research participants will be stored separately from the data to protect privacy. The key code will be kept in a locked cabinet and destroyed after the study is complete. Your name and other facts that might point to you will not appear when we present this study or publish its results. The findings will be summarized and reported in group form. You will not be identified personally. Both Dr. Suazette Mooring and Nancy Kilpatrick will have access to all other the information you provide, which may include interview responses, both written and record, grade data after they has been assigned to your pseudonym, and any data analysis performed on the data collected. Information may also be shared with those who make sure the study is done correctly (GSU Institutional Review Board, the Office for Human Research Protection (OHRP)).

VIII. Contact Persons:

Contact Dr. Suazette Mooring, or Nancy Kilpatrick at smooring@gsu.edu, or nkilpatrick1@student.gsu.edu, respectively, or by phone at 404-413-5527 if you have questions, concerns, or complaints about this study. You can also call if you think you have been harmed by the study. Call Susan Vogtner in the Georgia State University Office of Research Integrity at 404-413-3513 or svogtner1@gsu.edu if you want to talk to someone who is not part of the study team. You can talk about questions, concerns, offer input, obtain information, or suggestions about the study. You can also call Susan Vogtner if you have questions or concerns about your rights in this study.

GSU APPROVED
IRB NUMBER: H18262
IRB APPROVAL DATE: 12/10/2018
IRB EXPIRATION DATE: 12/09/2019

IX. Copy of Consent Form to Participant:
We will give you a copy of this consent form to keep.

If you are willing to volunteer for this research, be recorded by written and spoken responses with audio and video, which will not show your face, and obtain your grades, please sign below.

____ __________________
Participant Date

____ __________________
Principal Investigator or Researcher Obtaining Consent Date

Appendix B.3 - Informed Consent for Students 2019-2020

Georgia State University
Department of Chemistry
Informed Consent

Title: Student Understanding in Acid-Base Concepts in Chemistry
Principal Investigator: Dr. Suazette Mooring
Student Principal Investigator: Nancy Kilpatrick

X. Purpose:

You are invited to participate in a research study. The purpose of the study is to investigate student understanding in acid-base concepts in chemistry. You are invited to participate because you are currently an undergraduate student enrolled in this chemistry course. You must be at least 18 years or older to participate in the study. This must be the first time you are taking this course. This study has two sections. We are asking you to participate the student section which will enroll 200 student participants from General Chemistry II, Organic Chemistry I, Organic Chemistry II and Biochemistry I courses. Section 2 will enroll 10 faculty participants. Participation will require approximately 1 - 1 ½ hours of your time over the semester for one interview. You may participate in more than one semester over the lifetime of this study for a maximum of 6 hours of time over four semesters, that may be non-consecutive.

XI. Procedures:

If you decide to be a part of this study, you will participate in an interview on acid-base concepts in chemistry. You will also complete a demographic survey and answer some interview questions about your previous chemistry experiences, feelings and future plans. The interview will be conducted after you have been presented with acid-base concepts in class, between weeks 7 - 10. The interview will be recorded, including written and spoken responses. Your face will not be shown. The interview will be in a private room away from any classroom. Each interview will take approximately 1-1 ½ hours. We would also like your permission to obtain your grades for specific classes. We would like to obtain your overall grades for relevant chemistry courses which many include: general chemistry I, general chemistry II, organic chemistry I, organic chemistry II, and biochemistry I.

XII. Risks:

In this study, you will not have any more risks than you would in a normal day of life. The disclosure of grades, if they are identifiable, represents some risk.

XIII. Benefits:

Participation in this study may not benefit you personally. Overall, we hope to gain information about how students understand and develop acid-base concepts in chemistry. We hope to help instructors understand their students' needs and promote student learning.

XIV. Compensation:

You will receive a $10 gift card as compensation for an interview for participating in this study. If you are a study participant in all four courses, you may receive a maximum of $40 in gift cards.

XV. Voluntary Participation and Withdrawal:

Participation in research is voluntary. You do not have to be in this study. If you decide to be in the study and change your mind, you have the right to drop out at any time. You may skip questions or stop participating at any time. Whatever you decide, you will not lose any benefits to which you are otherwise entitled. Your grade in this course will not be affected by your choice to participate, or not participate. Your grade in this course will be provided only after this course has ended.

XVI. Confidentiality:

We will keep your records private to the extent allowed by law. Nancy Kilpatrick will know the names of the participants, as well as any other identifying information, and will assign the pseudonyms. Dr. Suazette Mooring will not know the actual identity of the participants. We will use a pseudonym rather than your name on study records. The information you provide will be stored in a locked cabinet at 529 Science Annex and on a password and firewall protected computer. The audio and video recordings will be stored on a password and firewall protected computer. The key (code sheet) used to identify the research participants will be stored separately from the data to protect privacy. The key code will be kept in a locked cabinet and destroyed after the study is complete. Your name and other facts that might point to you will not appear when we present this study or publish its results. The findings will be summarized and reported in group form. You will not be identified personally. Both Dr. Suazette Mooring and Nancy Kilpatrick will have access to all other the information you provide, which may include interview responses, both written and record, grade data after they has been assigned to your pseudonym, and any data analysis performed on the data collected. Information may also be shared with those who make sure the study is done correctly (GSU Institutional Review Board, the Office for Human Research Protection (OHRP)).

XVII. Contact Persons:

Contact Dr. Suazette Mooring, or Nancy Kilpatrick at smooring@gsu.edu, or nkilpatrick1@student.gsu.edu, respectively, or by phone at 404-413-5527 if you have questions, concerns, or complaints about this study. You can also call if you think you have been harmed by the study. Call Susan Vogtner in the Georgia State University Office of Research Integrity at 404-413-3513 or svogtner1@gsu.edu if you want to talk to someone who is not part of the study team. You can talk about questions, concerns, offer input, obtain information, or suggestions about the study. You can also call Susan Vogtner if you have questions or concerns about your rights in this study.

XVIII. Copy of Consent Form to Participant:
We will give you a copy of this consent form to keep.

If you are willing to volunteer for this research, be recorded by written and spoken responses with audio and video, which will not show your face, and obtain your grades, please sign below.

____ ________________
Participant Date

____ ________________

Principal Investigator or Researcher Obtaining Consent Date

Appendix C – Student Interviews

Appendix C.1 – Student Interview Protocol

Thank you for agreeing to participate in this study. The purpose of this interview is to gain insight into your understanding of acid-base concepts in chemistry. From this study, we hope to help instructors better understand their students' needs and promote student learning.

Can you please fill out this demographic form for me?

<u>Introductory questions</u>

- Why are you taking this chemistry course?
- Is this your first time taking this course?
- When did you take…
    a. General Chemistry I – Do you recall the Professor?
    b. General Chemistry II – Do you recall the Professor?
    c. Organic Chemistry I – Do you recall the Professor?
    d. Organic Chemistry II – Do you recall the Professor?
- When do you anticipate that you will graduate?
- What are your career plans after graduation?
- Explain to me the steps you take to prepare for this chemistry course for lecture.
- Explain to me the steps you take to prepare for an exam.
- Is homework required? Do you do the homework problems?
- Do you attend SI sessions or tutoring outside of class? Teacher provided or through SI office?
- Do you attend lectures of any other instructor of this same course as additional support?

Questions to get students thinking about the acid-base concepts

As you consider each question, I would like you to verbally describe what you are doing and what you are thinking.

- From a chemistry perspective, how you define an acid?
- From a chemistry perspective, how you define a base?
- From your chemistry courses, are there any other definitions for acids, or bases you can think of?
- In chemistry, how you define a strong acid?
    - Can you draw a picture of what it looks like?
    - Probe for dilute vs concentrated
- In chemistry, how you define a weak acid?
    - Can you draw a picture of what it looks like?
- What is pH?
- What does it mean for a reaction to be in equilibrium?

Acid-Base Equilibrium Concepts

- What is K_a?
- What does K_a describe?
- What does K_a describe at a molecular level?
- How does the strength of the acid relate to its conjugate base?
- Can you describe the general form of a K_a expression?
- What does a large value of K_a indicate compared to a smaller value of Ka?
    - What does a large (small) Ka value describe at a molecular level?
- What is pKa?

- What kind of relationship does pKa have with K_a?
- What does a large value of pK_a indicate compared to a smaller value of pKa?
- Can you explain the relationship between the pH and pKa?
  - If they can't get there, try to get them to derive Henderson-Hasselbalch equation from Ka.
- What happens when pH = pKa?
- Can you described anytime you have used the Henderson-Hasselbalch equation?

The purpose of this part of the interview is to determine your understanding of acid-base concepts in chemistry. I am going to present you with problems. As you solve each problem, I would like you to verbally describe what you are doing and what you are thinking. After taking the time to solve each problem, I will ask you a series of reflection questions.

- Contextual Problems are presented here on individual sheets of paper (following will show problems consecutively on same page for space considerations only)

During the interview, the student may be asked additional probing questions such as:

What do you mean by…?

Can you further explain?

Can you clarify what you mean by...?

Can you talk a little more about that…?

Why did you select that …?

Are you confused…?

Would you like to move on…?

Can you please fill out this evaluation form for the Institutional Review Board?

(Once the interview is complete, the student will be asked to fill out the Student Research Evaluation Form.)

Here is your $10 gift card. Can you please sign this form acknowledging receipt of the gift card?

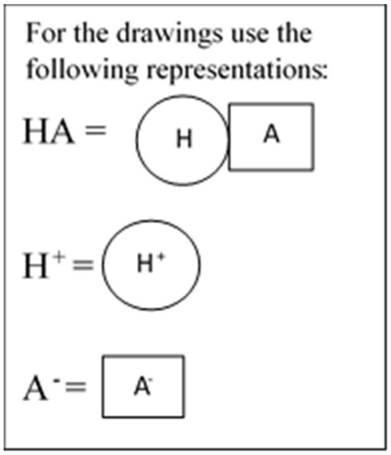
(Students will receive the gift card upon completion of the interview, no matter the length of time of the interview)

Thank you for your time today. I appreciate your help with this research study on acid-base concepts in chemistry.

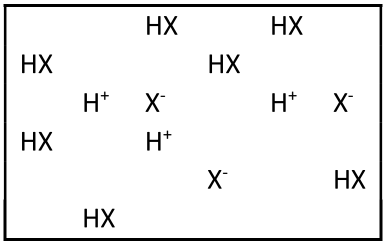
Appendix C.2 – Contextual Problems

1. If you could see what is going on a molecular level in an aqueous solution draw a picture of:
    a. Strong acid in aqueous solution

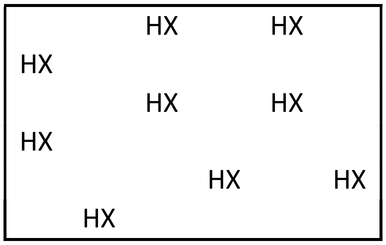
    b. Weak acid in aqueous solution



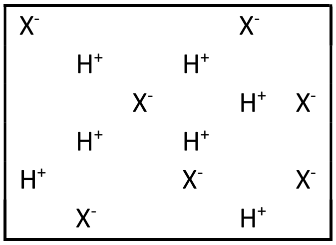
2. If a solid acid HX is mixed with water, which representation is for a strong acid? Weak acid?



I.

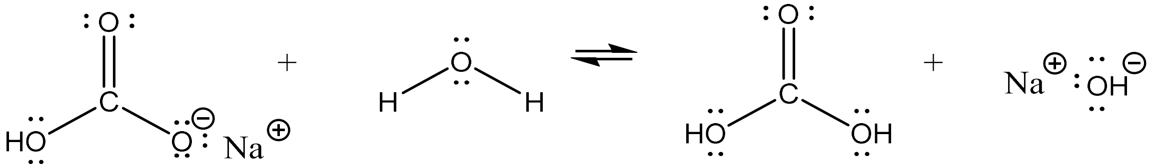


II.

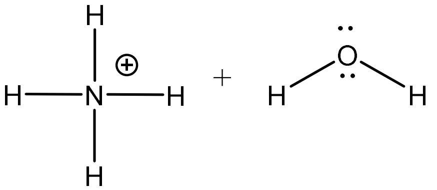


III.

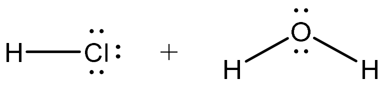
3. In the reaction below label the acid, base, conjugate acid, and conjugate base. Please use curved arrows to show how this reaction occurs.



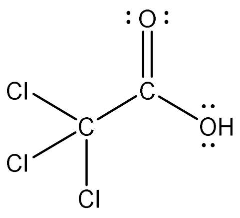
4. Complete the reaction of ammonium with water and if applicable, determine the acid dissociation constant.



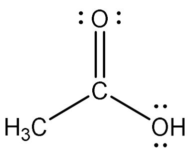
5. Complete the reaction following reaction and if applicable, determine the acid dissociation constant.



6. Which is more acidic, trichloroethanoic acid, or ethanoic acid? Which has the more stable conjugate base?

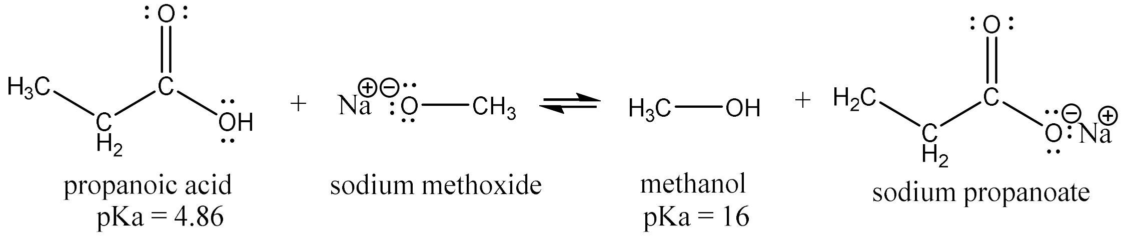


trichloroethanoic acid
pKa = 0.77

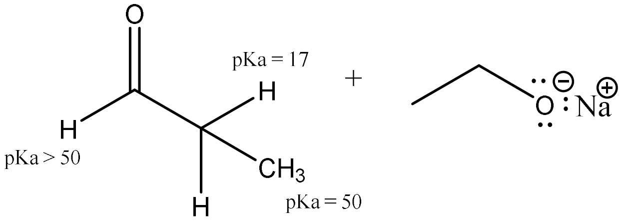


ethanoic acid
pKa = 4.75

7. Which side of the following reaction is favored? Why?



8. Complete the following reaction, show the complete reaction mechanism with arrows.

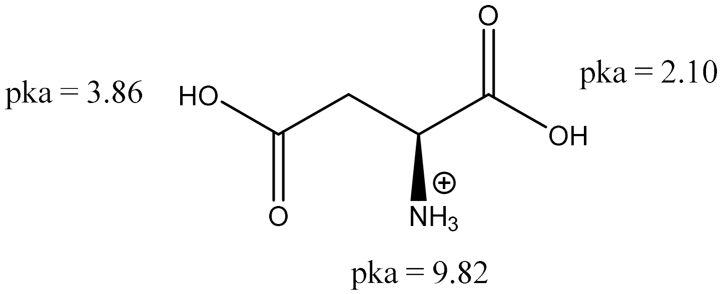


propionaldehyde

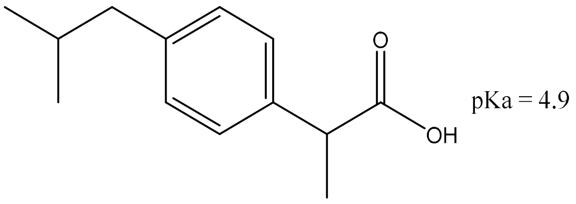
Sodium ethoxide

9. Draw the structure of the predominant form of aspartic acid in solution with a pH of 5.

aspartic acid



10. Charged molecules are more soluble in the stomach. The pH of gastric juice is 2 in a fasted stomach, but after you eat the pH increases to 5. Is ibuprofen more soluble in a fasted stomach or a stomach with food?



ibuprofen

Appendix D – Student Demographic Survey

1. Name ____
2. Interview Tracking Number: ________________________________
3. What is your gender?
   a. Female
   b. Male
4. What is your age?
   a. 18 – 24
   b. 24 or older
5. What is your major? ____
6. What is your Ethnicity? Please circle one:
   a. African-American/Black (Non-Hispanic)
   b. Asian
   c. Caucasian /White (Non-Hispanic)
   d. Hispanic
   e. Native-American
   f. Pacific Islander
   g. Other ____
7. What calendar year did/will you complete the second semester of General Chemistry?
8. At what institution did you take the first semester of General Chemistry?
9. At what institution did you take the second semester of General Chemistry?

Appendix E – Student Research Evaluation Form

Georgia State University Institutional Review Board

STUDENT RESEARCH EVALUATION

Georgia State University recognizes that its' student body is an integral part of research being conducted on our campus. It is the purpose of the GSU Institutional Review Board to insure that students are treated fairly and without coercion when asked to participate in research projects in their classroom.

This evaluation is intended to protect students in research. This evaluation will not be seen by your instructor. Results of the evaluation can be requested by the instructor after the semester is completed, and all final grades submitted. The results will be presented in a summarized group format.

After you complete this evaluation please **submit to:**

Institutional Review Board (IRB)
Office of Research Integrity
Georgia State University
P.O. Box 3999
30 Courtland Street
Atlanta, Georgia 30302-3999

Please complete the following:

Name of Instructor: ________________________
Title of the study: __________________________

Confidential Questions/Answers

1. Did you feel any pressure from your instructor to participate in this study?
   Yes___ No___
   If yes, please explain.

2. Was the participation in the study completely voluntary? **Yes ___ No__**
   If no, please explain.

3. Did you receive any extra credit for this project? **Yes___ No ___**
   If yes, was there an alternative assignment offered in place of the research project? **Yes_ No_**

4. Did you receive informed consent explaining the research and your rights as a subject?
   Yes ___ No ___

Additional Comments:

Have any questions about participating in research:

- Visit our web site: http://www.gsu.edu/irb
- Contact Susan Vogtner with the Institutional Review Board (IRB) at Georgia State University at 404-413-3513

Appendix F – Participant Record of Payment or Gift Card

Georgia State University

Participant Record of Payment of Cash or Gift Card

For participating in this project, I have received a payment of $________ on the date signed below.

*Participant's Printed Name *Participant's Signature Date

Witness (Must be Georgia State University Employee)
By signing below, you certify that you witnessed the above-described payment transaction and receipt signature.

Witnesses Printed Name Witness's Signature Date

Signature can be an x **if Project is approved for anonymous participant payments. In this event, Participant's Subject ID number must be supplied in lieu of Printed Name. A copy of the signed anonymity memo should be attached to the replenishment/closure Form.*

Updated 10/18/13