AN EXAMINATION OF THE TEACHING AND LEARNING OF RESONANCE IN GENERAL CHEMISTRY I AND ORGANIC CHEMISTRY I USING VARIATION THEORY

By

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ABSTRACT

Resonance is a fundamental chemistry concept first introduced to students in General Chemistry I, reintroduced in Organic Chemistry I, and then utilized throughout other higher-level chemistry courses. A molecule or ion can be said to exhibit resonance when it can be represented by two or more chemical structures (i.e., Lewis structures) that differ only in their arrangement of electrons. In other words, resonance represents the electronic structure of a molecule or ion when a single Lewis structure does not adequately depict the true distribution of electrons. The molecule or ion is best represented as a combination of all of the structures and is called the resonance hybrid. Resonance is a tool that practicing organic chemists use to better understand the electronic structure of molecules or ions and to make predictions about molecular behavior (e.g., stability, reactivity, etc.). Therefore, because resonance is a useful tool that helps scientists understand and predict chemical phenomena, it is important for chemistry students to understand and practice using it.

The current educational research shows that General Chemistry I and Organic Chemistry I students have difficulties understanding resonance. Unfortunately, little is specifically known about the possible origins of these challenges and how instruction might influence students' understandings of resonance. These challenges can potentially impact students' success in their chemistry courses, as developing a foundational understanding of resonance is essential to students' understanding of other higher-level chemistry concepts. Thus, the overarching goal of this study, which was guided by variation theory, is to investigate the teaching and learning of resonance from three different perspectives (instructor, classroom, and student perspectives) in the courses it is first introduced, General Chemistry I and Organic Chemistry I. The following three research questions (RQ) were addressed: (RQ1) What do General Chemistry I and Organic

Chemistry I instructors intend for their students to understand about resonance? (RQ2) What is possible for General Chemistry I and Organic Chemistry I students to understand about resonance in General Chemistry I and Organic Chemistry I classrooms based on the information presented to them in their classes? (RQ3) What do General Chemistry I and Organic Chemistry I students understand about resonance in General Chemistry I and Organic Chemistry I classrooms after learning about it in their General Chemistry I and Organic Chemistry I classrooms?

By answering these three research questions, (1) I identified eleven features of resonance that instructors believe to be critical for their students to understand about resonance (via instructor interviews), (2) I identified how/if these eleven features of resonance are made available for students to learn about in their classrooms (via classroom observations), and (3) I identified what students understand about each of the eleven features of resonance (via student interviews). These findings were then compared to draw overarching results. For example, by comparing the results from RQ1 and RQ3, I identified differences in what instructors intended for students to understand about resonance versus what students actually came to understand about resonance. Each of these comparisons is discussed in the chapters of this dissertation.

Overall, I found that while instructors in this study believed a conceptual understanding of resonance was important, they tended to teach and assess students in a way that prioritized their operational understanding of resonance. For example, instead of focusing on the underlying concepts of resonance, such as the resonance hybrid, while teaching students about resonance, the instructors tended to focus on the rules and processes associated with drawing resonance structures. Consequently, many of the students in this study also tended to emphasize an operational understanding of resonance and often lacked a conceptual understanding of resonance, expressing misconceptions while discussing it. Based on the findings presented herein, recommendations are discussed to improve the teaching practices and instructional materials related to resonance, potentially resulting in more students coming to a meaningful understanding of resonance.

ACKNOWLEDGEMENTS

I have no words to express the gratitude I feel for all the individuals who have helped me through this process. Dr. MaryKay Orgill was there from the start of my academic journey and inspired me to pursue this degree. MaryKay, you truly do not know how gifted you are at making people realize their potential. The time, effort, and energy you put into stretching, growing, and developing not only my skills as a researcher but me as a person never went unnoticed or unappreciated. You are absolutely brilliant at everything you do, and I could not have completed this degree without you. I am so blessed to have had you as my teacher, mentor, advisor, and friend. Thank you for believing in me and helping me believe in myself.

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Finally, this project would not have been possible without the students and instructors volunteering their time and energy to participate in my study—thank you!

DEDICATION

This dissertation is dedicated to my parents, Osama and Eileen Barakat. They have always made me feel capable and worthy of my dreams. It is because of their sacrifices, support, and encouragement that my brothers and I have always been able to pursue and achieve our goals. Thank you both from the bottom of my heart. I love you.

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CHAPTER 1 INTRODUCTION

Project Rationale

The purpose of chemistry education research is to systematically investigate the teaching and learning of chemistry. To identify my research interest within this field, I met with faculty members in my department to discuss specific topics that they see students struggle to understand. A conversation with an organic chemistry faculty member sparked my interest. This faculty member explained that year after year, his organic chemistry students struggled with a concept called *resonance*. Despite employing different approaches to teaching it, he did not know what else to do to mitigate students' difficulties with the topic.

Based on this conversation, I began to search the literature for what was known about the teaching and learning of resonance in undergraduate chemistry courses. During my initial search in 2018, I found that numerous other practitioners had reported similar student difficulties with resonance as those shared by the faculty member in my department (e.g., Delvigne, 1989; Gero, 1954; Lin, 2007; Richardson, 1986; Silverstein, 1999). Aside from these practitioner pieces, at the time of this initial search in 2018, there were only two research articles detailing students' difficulties with resonance (Betancourt-Perez, Olivera, & Olivera, 2010; Taber, 2002). It was surprising to see how little evidence-based research had been directed toward a topic that practitioners have reported students' difficulties with for nearly 70 years. I knew I had found my research interest.

What is Resonance?

Resonance is used to describe the approximate structure of a molecule (Wheland, 1955). There is a common saying in chemistry and biology that "structure begets function." In other words, the way the atoms in a molecule are arranged (the molecule's "structure") determines how molecules interact with each other, which then determines the properties and reactivities of a bulk sample of those molecules. Thus, before one can understand how a group of molecules behaves, one must first understand and be able to describe the structure of individual molecules. Historically, Lewis structures were used to describe the structure of molecules; however, there are instances in which a single Lewis structure cannot describe the chemical reality of a molecule. For example, the single Lewis structure of the nitrate ion does not adequately describe its observed properties in nature. To address this limitation, multiple Lewis structures, called resonance structures, are drawn. The actual, most correct molecular structure can be thought of as a mental melding of the different resonance structures and is called the resonance hybrid (Klein, 2012).

Why Is It Important for Students to Learn About Resonance?

Resonance is a fundamental chemistry concept that students will need to understand to build higher-level conceptual understandings in both chemistry and other higher-level chemistry courses (Duis, 2011). Resonance is typically introduced to students in General Chemistry I, is later revisited in Organic Chemistry I, and then, while not formally taught again, is utilized throughout other higher-level science courses. Unfortunately, even with repeated exposure to the concept, educational research has shown that students have many challenges understanding and using resonance (e.g., Brandfonbrener, Watts, & Schultz, 202; Kim, Wright, & Miller, 2019; Taber, 2002; Xue & Stains, 2020).

To address the difficulties students have with resonance, we need to know something about where those difficulties come from. There are many potential sources of student difficulties, but one is from instruction. What instructors choose to expose students to and how they choose to expose students to concepts related to resonance is influenced by many factors, including the instructors' intentions for learning of resonance (i.e., what they think is important for students to know about a particular concept) (Marton & Booth, 1997). These perceptions determine what instructors choose to expose students to in their classes via curricula and instructional design—ultimately determining what students in the classroom have the possibility to learn about resonance. We examined these perspectives and how they relate to each other in the study presented here.

Research Questions

The overarching aim of this study was to examine students' understandings of resonance in the courses it is first introduced, General Chemistry I and Organic Chemistry I. To do so, this study was guided by the theoretical framework variation theory (Bussey, Orgill, & Crippen, 2013; Marton & Booth, 1997), which examines the teaching and learning of a concept—resonance in the current study—from three different perspectives: (1) what General Chemistry I and Organic Chemistry I instructors want their students to understand about resonance (instructor perspective), (2) what the teaching of resonance in General Chemistry I and Organic Chemistry I classrooms looks like (classroom perspective), and (3) General Chemistry I and Organic Chemistry I students' understandings of resonance (student perspective). The following research questions guided this study:

1. What do General Chemistry I and Organic Chemistry I instructors intend for their students to understand about resonance?
2. What is possible for General Chemistry I and Organic Chemistry I students to understand about resonance in General Chemistry I and Organic Chemistry I classrooms based on the information presented to them in their classes?

3. What do General Chemistry I and Organic Chemistry I students understand about resonance after learning about it in their General Chemistry I and Organic Chemistry I classrooms?

CHAPTER 2 REVIEW OF LITERATURE

Overview of Review of Literature

In this review of the literature, I will first focus on the historical development of resonance in the discipline of chemistry, followed by discussions of (1) the modern terminology and nomenclature of resonance and (2) the role of resonance in the General Chemistry I and Organic Chemistry I curricula. Next, I will provide a review of the literature about the teaching and learning of resonance in chemistry education. Within this section, I will first discuss the common challenges and misconceptions students encounter when learning about resonance structures; potential sources of these challenges and misconceptions will be identified. Second, I will discuss the teaching strategies proposed by practitioners for mitigating these challenges and misconceptions. Third, I will discuss the primary foci of research related to the teaching and learning of resonance in chemistry education. Finally, I will present future directions and justifications for the study presented herein. For ease, Figure 1 provides an overview of the organization of this review of the literature.

Figure 1

Outline Depicting Organization of Chapter 2

Historical Development of Resonance in Chemistry

- The Limitations of the Lewis Electron-Pair Bonding Model
- Addressing the Limitations of the Lewis Electron-Pair Bonding Model
    - *Development of Resonance Concepts in Chemistry*

Resonance in Chemistry

- Terminology and Nomenclature of Resonance
    - *Resonance Structures and the Resonance Hybrid*
    - *Major and Minor Resonance Structures*
    - *Resonance Stabilization*
    - *Double Headed Arrow, Brackets, and Curved Arrow Notation*

Resonance in General Chemistry I and Organic Chemistry I Curricula

- Resonance in General Chemistry I
- Resonance in Organic Chemistry I

Review of Literature: Resonance in Chemistry Education

- Methodology
    - *Identifying the Literature*
    - *Synthesizing the Literature*
- Students' Challenges with and Misconceptions about Resonance
    - *Challenge 1: Describing Resonance in Conceptually Correct Ways*
    - *Challenge 2: Identifying or Describing the Resonance Hybrid*
    - *Challenge 3: Identifying or Drawing Resonance Structures*
    - *Challenge 4: Identifying the Correct Use of Curved Arrows*
    - *Challenge 5: Applying Resonance in a Context*
- Practitioner Teaching Strategies for Mitigating Students' Challenges with Resonance
    - *Practitioner Analogies for Teaching Resonance*
    - *Other Techniques for Teaching Resonance*
- Primary Research Foci Related to the Teaching and Learning of Resonance
    - *Establishment and Analysis of a Set of Shared Learning Outcomes Related to Resonance*
    - *Connection between Instructional Strategies and Students' Conceptual Understandings of Resonance*
    - *Students' Application of Resonance in a Context*

Justifications for the Current Study

- What General Chemistry I and Organic Chemistry I Instructors Want Their Students to Understand about Resonance
- What the Teaching of Resonance in General Chemistry I and Organic Chemistry I Classrooms Looks Like
- General Chemistry I and Organic Chemistry I Students' Understandings of Resonance

Historical Development of Resonance in Chemistry

The aim of the section that follows is to provide a brief overview of how the scientific community has come to understand and use the concept of resonance within the field of chemistry.

The Limitations of the Lewis Electron-Pair Bonding Model

The development of resonance in the field of chemistry is often attributed to the limitations of the Lewis electron-pair bonding model (Klein, 2012). The Lewis electron-pair bonding model was developed by Gilbert Lewis based on classical approaches and vast chemical experience in the early to mid 1900s (Lewis, 1916, 1923, 1933). The model describes the molecular bond as a sharing of a pair of electrons and uses Lewis structures to visually represent how atoms are bonded together. These chemical representations convey structural information that can be used to predict and explain a molecule's physical and chemical properties.

The modern Lewis structure for the water molecule shown in Figure 2 denotes each atom using its chemical symbol, the bonds of shared valence electrons by a line, and lone pair electrons by dots (Brown et al., 2018). While this simple depiction of molecular bonding was and continues to be an extremely useful tool for understanding how atoms are bonded together and predicting molecular shape and function, it does have limitations. The bonding in some molecules cannot be easily or adequately represented by a single Lewis structure. For example, carbon monoxide (Figure 3) can be reasonably drawn with either a double bond or a triple bond between carbon and oxygen because one set of lone pair electrons on the oxygen atom is delocalized, meaning the electron density is spread out amongst the entire molecule (Klein, 2012). Data calculating the distance between the two atoms and bond energy do not indicate if carbon monoxide has a double or a triple bond. In other words, Lewis' model falls short as there is not a single Lewis structure that can adequately represent the physical reality of where the electrons are in the structure of carbon monoxide, thus making it difficult to predict and explain its physical and chemical properties.

Figure 2

Lewis Structure of Water

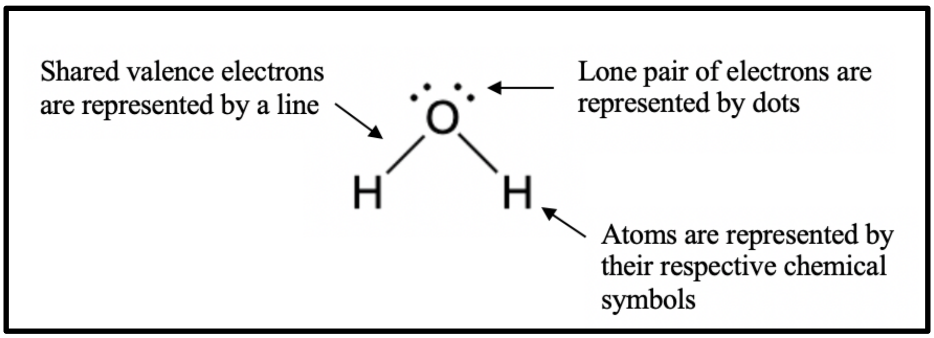
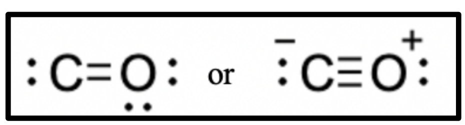


Figure 3

Lewis Structures of Carbon Monoxide



Addressing the Limitations of the Lewis Electron-Pair Bonding Model

The mid-1920s saw the development of a new scientific discipline, quantum mechanics. Scientists began applying information and experimental results from this discipline to address the limitations of Lewis' model (Zhao, Schwartz, & Frenking, 2019). Both valence bond (VB) theory (Heitler & London, 1927) and molecular orbital (MO) theory (Lennard-Jones, 1929) were developed under the framework of quantum mechanics. Specifically, the theories attempted to explain the physical mechanism of chemical bonding that could not always be adequately described or represented through Lewis' model (Zhao et al., 2019). It is not my intention to describe these two theories in detail, but to briefly discuss the components of the theories that are relevant to the current discussion. Briefly, both theories assume that electrons occupy regions of space called orbitals and that a covalent bond is formed by the overlap of atomic orbitals (Klein, 2012). However, the theories diverge in how they explain the nature of the atomic orbital overlap. VB theory encapsulates more of Lewis' model and takes a simpler approach than the highly mathematical MO theory (please note that advances in technology have made calculations associated with MO theory much easier than they once were) (Zhao et al., 2019). That is, VB theory describes the atomic orbital overlap (the chemical bonds) as the sharing of electron density between two atoms (Heitler & London, 1927), while MO theory describes the atomic orbital overlap using a more mathematical approach that assumes that atomic orbitals combine to create new orbitals, referred to as molecular orbitals (i.e., orbitals that are associated with the entire molecule) (Lennard-Jones, 1929).

Development of Resonance Concepts in Chemistry

Linus Pauling was an American chemist with a vast scientific background and who was an early advocate of the Lewis electron-pair bonding model. He aimed to use VB theory to address the limitations of the Lewis model (Zhao et al., 2019). Like Lewis's model, VB theory assumes that the molecular bond is the sharing of electron density between two atoms. Thus, perhaps not surprisingly, because of their similarities, there are cases in which neither can adequately describe the structure of certain compounds, such as conjugated π systems. Again, this was problematic because without an adequate representation of molecular structure it is difficult to predict and explain the physical and chemical properties of a molecule.

Pauling extended valence bond theory by applying a concept called "resonance" as a tool to approach the limitations of Lewis' model (Zhao et al., 2019). While resonance has its foundations in mathematics, Pauling is most known for his qualitative application of resonance in chemistry (1931, 1932a, 1932b). He continued to refine his application of resonance, most notably, with the help of his graduate student Thomas Wheland (Pauling & Wheland, 1933) but also with his colleague Jack Sherman (Pauling & Sherman, 1933) in a series of publications. According to Wheland (1955), resonance can be described as a man-made concept that, under certain conditions, can be used to approximate the actual state of a molecule. In general, it provides a way to explain problematic cases in which just one Lewis structure cannot be used to adequately represent molecular structure.

Take again the example of carbon monoxide, a molecule Pauling commonly used to explain his ideas about resonance (Pauling, 1932c). According to Lewis' model, carbon monoxide can reasonably be drawn with a double bond or a triple bond between carbon and oxygen (see Figure 3). Recall that data calculating the bond length between carbon and oxygen indicated that it is neither a double (interatomic distance of 1.28 Å) nor triple bond (interatomic distance of 1.13 Å) like Lewis' theory suggests, but rather is a bond of intermediate length (interatomic distance of 1.15 Å). VB theory alone, which assumes that electrons are confined between only two atoms, cannot adequately describe why this situation occurs (Klein, 2012). After examining energy curves and applying the concept of resonance, however, Pauling argued that the real structure of carbon monoxide is an intermediate of the different Lewis structures drawn to represent the real structure, with the triple bond structure being slightly closer to the real structure than the double bond structure is (Pauling, 1932c). This application foreshadows how resonance is described in chemistry textbooks today: a way of describing the bonding in certain molecules as being a combination of multiple similar structures.

The qualitative application of resonance was found to be extremely useful for organic chemists, as it allowed them to explain and make predictions about reaction mechanisms in new ways. Although both Pauling's and Wheland's descriptions of resonance evolved as they gained new information and feedback from the scientific community, the pair continued to emphasize resonance as a practical tool for chemists to use out of convenience and that the use of resonance becomes intuitive to the chemist over time (Wheland, 1955). The significance of resonance to the scientific community and structural theory is expressed by Wheland (1955), who stated:

> One can, in fact, hardly question that [structural theory], more than any other single factor, must be given credit for the remarkable advances that have occurred in the sciences during the last hundred years. However, in spite of its outstanding success in correlating and systematizing the vast body of facts with which it deals, its history has been marked from the very beginning by a series of attempts to revise and to amplify it in such a way that its field of usefulness might be extended still further. A number of these attempts have met with complete acceptance. […]. To these must now apparently be added the theory of resonance (Wheland, 1955, p.1).

Resonance in Chemistry

This section first provides an overview of the modern terminology and nomenclature associated with resonance that will be helpful for this study. Second, the teaching of resonance is situated within the General Chemistry I and Organic Chemistry I curricula.

Terminology and Nomenclature of Resonance

The modern terminology and nomenclature of resonance in chemistry can be illustrated using the example of the nitrate ion. In this paragraph, I will describe the nitrate ion. In the sections that follow, I will define terms related to *resonance* with reference to the nitrate ion.

According to the Lewis structure of the nitrate ion shown in Figure 4, the molecule has two different types of nitrogen-oxygen bonds: one double bond (=) and two single bonds (-). Therefore, this single Lewis structure of the nitrate ion suggests that one of the three nitrogen-oxygen bonds (the double bond) is shorter than the others. Furthermore, the formal charges depicted in this single Lewis structure of the nitrate ion also suggest that one of the oxygen atoms is neutral while the other two have -1 charges. As with carbon monoxide, previously discussed, this is not a true representation of the observed properties of the nitrate ion in nature. That is, experimental and theoretical data indicate that (1) all three bonds in the molecule have equivalent bond length and energy and (2) each of the oxygen atoms are equivalent in charge. A plot of the valence electron density of the nitrate ion (Figure 5) can help further illustrate this idea. The red regions shown in Figure 5 represent regions in which there is a high relative amount of negative charge (i.e., electron density). Notice that these regions are evenly spread out amongst the oxygen atoms and not concentrated on only two of the oxygen atoms, as Lewis' theory would suggest.

Figure 4

Lewis Structure of Nitrate

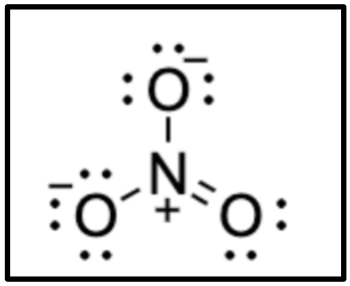
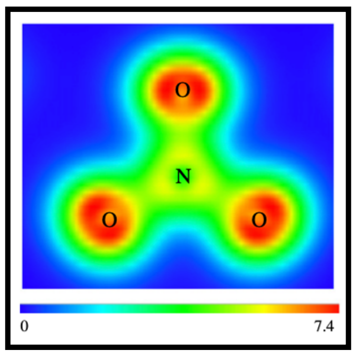


Figure 5

Electron Density Map of Nitrate



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Resonance Structures and the Resonance Hybrid

The limitation described above is addressed by drawing multiple Lewis structures for the nitrate ion to show that the electrons participating in the π bond are delocalized or, in other words, that the electron density is spread out evenly over the three different N – O bonds (Klein, 2012). As shown in Figure 6, these different Lewis structures are referred to as *resonance* *structures* (Klein, 2012). Resonance structures are not real entities and do not exist in nature (Wheland, 1955). They are only used to make predictions of the actual structure that does exist in nature. The actual and most correct structure can be thought of as a mental melding of the different Lewis structures and is referred to as the *resonance hybrid* (Klein, 2012). The resonance hybrid, which is rarely illustrated in chemistry textbooks, is depicted using dashed lines to represent the delocalized electrons (Figure 7).

Figure 6

Resonance Structures of Nitrate

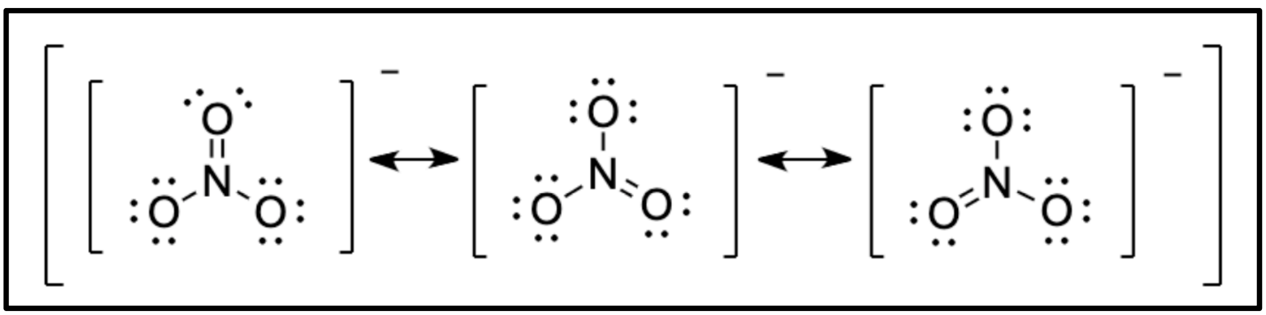
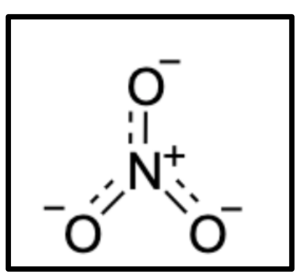


Figure 7

Resonance Hybrid of Nitrate



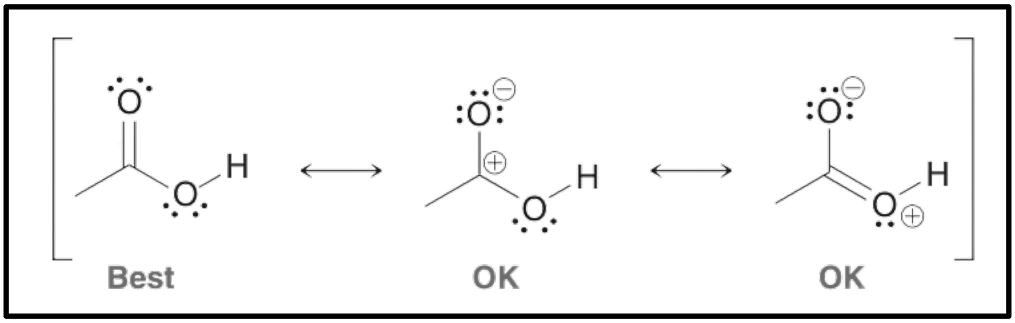
Major and Minor Resonance Structures

It is important to note that sometimes, not all resonance structures will equally contribute to the resonance hybrid (Klein, 2012). For example, three possible resonance structures can be drawn for acetic acid (Figure 8) but one of the resonance structures provides a better depiction of the resonance hybrid than the other two (labeled "Best" in Figure 8). The resonance structure(s) that provides the best depiction of the resonance hybrid is referred to as the *major contributor(s)* and the other less significant resonance structure(s) as the *minor contributor(s)*. The "best" resonance structure is not only the one that contributes the most to the resonance hybrid, but the most stable structure.

There are three general rules to follow when determining the relative significance of resonance structures (Klein, 2012). First, as outlined in the Klein (2012) organic chemistry textbook, the "best" resonance structure is the one with the least amount of charge; structures with one or two charges are acceptable but structures with more than two charges are not (although there are exceptions to this rule). Second, the "best" resonance structure is generally the one in which all atoms have a valence shell octet. Third, a resonance structure in which two carbon atoms have both a positive and negative charge is generally less significant than the other resonance structures. Applying these rules to the example of acetic acid, the first resonance structure is the major contributor to the resonance hybrid because it is the structure with the least amount of charge. Because the other two resonance structures have no more than two charges, they are also significant resonance structures. However, because the structures have charges, they contribute less to the resonance hybrid (i.e., they are minor resonance structures).

Figure 8

Major and Minor Resonance Structures of Acetic Acid



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Resonance Stabilization

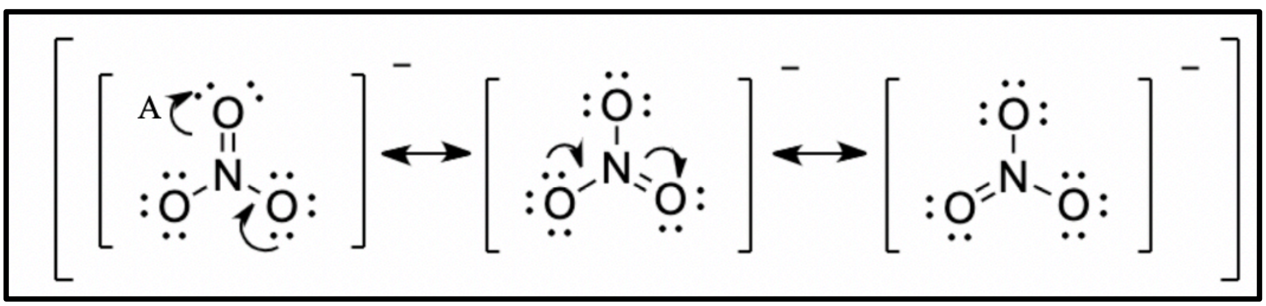
The delocalization of charge in the nitrate ion is referred to as resonance stabilization (Klein, 2012). Recall in the example of the electron density map of the nitrate ion that the negative charge was not localized around one oxygen atom but was distributed or delocalized throughout each of the three oxygen atoms (Figure 5). This distribution of charge or delocalization stabilizes the molecule and is referred to as *resonance stabilization* (Klein, 2012). Resonance stabilization plays a key role in many different chemical contexts, such as when deciphering relative acidity while ranking acids and bases and chemical reactivity (Klein, 2012).

Double Headed Arrow, Brackets, and Curved Arrow Notation

Resonance structures are separated by one double-headed arrow (↔) that should not be confused with equilibrium arrows (⇌) (see Figure 9). Square brackets are commonly placed around the resonance structures (please note that in the example provided, square brackets are also placed around each structure because nitrate is an ion) (Klein, 2012). The arrow and square brackets are used to denote that the collection of resonance structures represent one entity (i.e., the resonance hybrid) (Klein, 2012). While not always shown, resonance structures can be drawn using curved arrow notation. For example, curved arrows can be used to draw the resonance structures of the nitrate ion. As shown in Figure 9, the head of the curved arrow labeled A depicts where the electrons are "moving" to, and the tail depicts where the electrons are "moving" from. It is important to note that the curved arrows must only be thought of as tools to draw resonance structures and not as depicting actual electron movement, as in reaction mechanisms (Klein, 2012).

Figure 9

Example of Curved Arrow Notation using Nitrate



Resonance in General Chemistry I and Organic Chemistry I Curricula

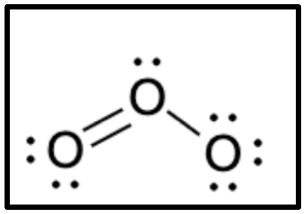
Resonance is typically introduced to students in the first semester of the general chemistry series and is later revisited in the first semester of the organic chemistry series and then utilized throughout organic chemistry and other higher-level science courses, such as biochemistry (Duis, 2011). Because resonance is typically only formally taught in the first semester of general chemistry and the first semester of organic chemistry, this section aims to describe how resonance is taught and what students are supposed to understand and do with resonance in those specific courses. Because textbooks often determine what is taught in the classroom, I will describe how resonance is presented to students from the perspectives of a general chemistry textbook (Brown et al., 2018) and an organic chemistry textbook (Klein, 2012). Please note that these specific textbooks were selected because, when the current study was designed, they were being used in the majority of the classrooms from which data for this study was collected.

Resonance in General Chemistry I

Students in General Chemistry I typically learn about resonance towards the middle of the course: after they learn about constructing and using Lewis structures to predict molecular shape but before they learn about molecular bonding and geometry theories (Brown et al., 2018). Students are expected to "recognize molecules where structures are needed to describe the bonding and draw the dominant [i.e., major] resonance structures" (Brown et al., 2018, p. 329). Typically, resonance is presented in General Chemistry I courses as an approach for dealing with the limitations of Lewis structures, and resonance structures are described as structures that only differ in the placement of electrons but not atoms (Brown et al., 2018). The Brown et al. (2018) textbook uses the ozone molecule as an example. The ozone molecule has a total of 18 valence electrons, which according to Lewis' model, would mean the structure must have one single O-O bond and one double O=O bond in order for each atom in the molecule to achieve an octet (see Figure 10).

Figure 10

Lewis Structure of Ozone



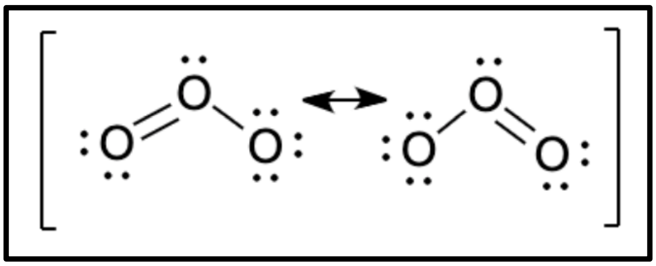
This, however, is contrary to what is known about the structure of the ozone molecule through theoretical and experimental data (Brown et al., 2018). That is, bond length data indicates both of the bonds are identical. The authors argued that to address this issue, two Lewis structures must be drawn to indicate that the bonds are not different from each other (see Figure 11). This example was further illustrated with the use of an analogy:

> Blue and yellow are both primary colors of paint pigment. An equal blend of blue and yellow pigments produces green pigment. We cannot describe green paint in terms of a single primary color, yet it still has its own identity. Green paint does not oscillate between its two primary colors: It is not blue part of the time and yellow the rest of the time. Similarly, molecules such as ozone cannot be described as oscillating between the two individual Lewis structures […] There are two equivalent dominant Lewis structures that contribute equally to the actual structure of the molecule. The actual arrangement of the electrons in molecules such as [ozone] must be considered as a blend of two (or more) Lewis structures. By analogy to the green paint, the molecule has its own identity separate from the individual resonance structures. For example, the ozone molecule always has two equivalent O-O bonds whose lengths are intermediate between the

lengths of an oxygen-oxygen single bond and an oxygen-oxygen double bond. (Brown et al., 2018, p. 320)

Figure 11

Resonance Structures of Ozone



The analogy was followed by other examples of resonance, such as in aromatic compounds (e.g., benzene). The textbook also included a brief section related to the idea that not all resonance structures will always equally contribute to the resonance hybrid and described how to determine which are major and minor contributing structures. The Brown et al. (2018) textbook does not teach students how to draw resonance structures using curved arrow notation. The practice questions found at the end of the chapter align with the learning expectation defined above and focus on students identifying when resonance is necessary, how to construct the different resonance structures, and how to identify the major and minor resonance structures for a compound. For example, one practice question found at the end of the chapter states: "Draw the dominant [i.e., major] Lewis [i.e., resonance] structures for these chlorine-oxygen molecules/ions: ClO, ClO^-, ClO_2^-, ClO_3^-, ClO_4^-" (Brown et al., 2018, p. 332).

Resonance is not typically used or formally discussed throughout the rest of the general chemistry series. It is not until the first semester of organic chemistry that students will be formally reintroduced to resonance.

Resonance in Organic Chemistry I

Students in organic chemistry I courses typically learn about resonance after they are re-introduced to Lewis structures (Klein, 2012). At the beginning of the course, unlike in General Chemistry I, students are now expected to identify and draw resonance structures using curved arrow notation. Later, they are expected to apply resonance concepts in different chemical contexts, such as relative acidity/ basicity determinations and reaction mechanisms (Klein, 2012).

As in General Chemistry I courses, resonance is typically presented in Organic Chemistry I courses as an approach for dealing with the limitations of Lewis structures, and resonance structures are described as structures that only differ in the placement of electrons but not atoms (Klein, 2012). Like the Brown et al. (2018) general chemistry textbook, the Klein textbook uses an analogy to explain resonance:

> A person who has never before seen a nectarine asks a farmer to describe a nectarine. The farmer answers: Picture a peach in your mind, and now picture a plum in your mind. Well, a nectarine has features of both fruits: the inside tastes like a peach, the outside is smooth like a plum, and the color is somewhere in between the color of a peach and the color of a plum. So take your image of a peach together with your image of a plum and meld them together in your mind into one image. That's a nectarine. (Klein, 2012, p. 70)

The authors emphasize the idea that the nectarine represents the resonance hybrid and that it is a combination of both the peach and plum which represent resonance structures. The analogy is followed by a discussion of resonance stabilization, curved arrows, and formal charges before the introduction of a series of patterns in which resonance can be drawn using curved arrow notation.

There are five patterns described for drawing resonance structures using curved arrows. These patterns are described below, and examples are shown in Figure 12:

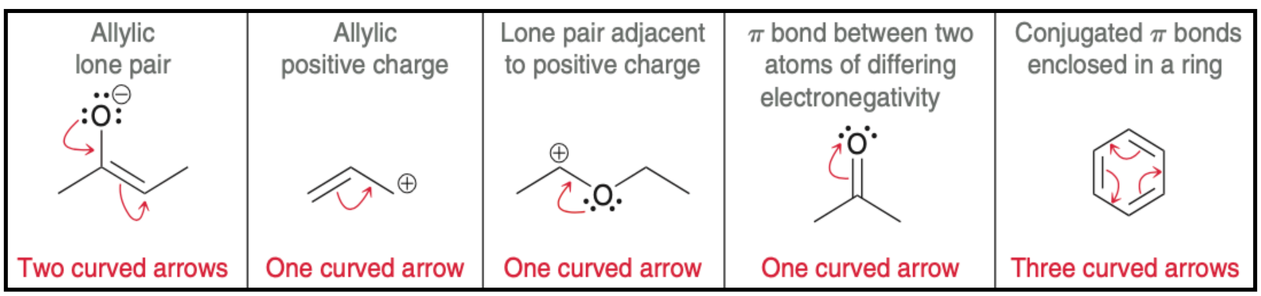
1. *An allylic lone pair*: this pattern focuses on identifying a lone pair in an allylic position (i.e., the position next to a carbon-carbon double bond). In this case, there are two curved arrows. The first curved arrow goes from the lone pair to form the π bond and the second curved arrow goes from the π bond to form a lone pair. If the atom with the lone pair has a negative charge, then the negative charge will be transferred to the atom that received the lone pair. (Klein, 2012, p. 75-76)
2. *An allylic positive charge*: this pattern focuses on identifying a positive charge in an allylic position. In this case, there is one curved arrow. This curved arrow goes from the π bond to form a new π bond. The positive charge moves to the other side of the molecule. (Klein, 2012, p. 77)
3. *A lone pair adjacent to a positive charge*: this pattern focuses on identifying a lone pair adjacent to a positive charge. In this case, there is one curved arrow. The curved arrow goes from the lone pair to form a new π bond. If there was a negative charge on the atom with the lone pair then the new structure will have no charges because they will cancel out. If there was no negative charge on the atom with the lone pair then that atom will now bear a positive charge. (Klein, 2012, p. 78)
4. *A π bond between two atoms of differing electronegativity*: this pattern focuses on identifying bonds between two atoms that have different electronegativity. In this

case, there is one curved arrow. The curved arrow goes from the π bond up to the more electronegative atom to make a lone pair. (Klein, 2012, p. 79)

5. *Conjugated π bonds in a ring*: this pattern focuses on conjugated π bonds in a ring. In this case, there are three curved arrows. The curved arrows either push all of the π bonds clockwise or counterclockwise. (Klein, 2012, p. 80)

Figure 12

Patterns Used to Draw Resonance Structures and Examples



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Following the introduction of these five patterns, students are presented with a series of general rules to assess the major and minor resonance contributors. Next, practice questions in which they can apply their new knowledge related to drawing resonance structures and identifying the most stable resonance structure are provided. For example, one practice question asks students to draw all significant [i.e., major] resonance structures for estradiol and testosterone. For the most part, students are not expected to apply resonance in a context until several chapters later. However, the chapter that immediately follows the initial introduction of resonance (Chapter 3) does expect students to use resonance to compare relative acidity of conjugate bases.

Review of Literature: Resonance in Chemistry Education

Methodology

This section examines the literature on the teaching and learning of resonance in chemistry education. Specifically, any research literature that addressed the teaching and learning of resonance in the general chemistry and organic chemistry classrooms or laboratories was examined. However, once it became apparent that there is limited educational research literature in this area, it was also necessary to include practitioner pieces that addressed different ways to teach resonance in general chemistry and organic chemistry classrooms. Specifically, any practitioner piece that addressed the teaching and learning of resonance in the general chemistry and organic chemistry classrooms was examined. A clear distinction will be made between the research-based articles and the practitioner pieces in this review of the literature.

Identifying the Literature

Initially, a screening was conducted using the *Education Resources Information Center* (ERIC) database with the search terms "resonance" and "chemistry education." Because I was aware of the limited research from prior searches, I did not apply search parameters. The search term yielded eight articles. I scanned the titles of the articles for relevance. If the article seemed relevant, I further searched it for the word resonance to assess its relevance to the teaching and learning of resonance in general chemistry and organic chemistry. If the article was relevant, it was added to an Excel spreadsheet to keep track of it.

From this initial search, four articles met the above criteria (Carle & Flynn, 2020; Kim et al., 2019; Petterson et al., 2020; Shah et al., 2018). I then mined the most recently published of those articles (Carle & Flynn, 2022; Petterson et al., 2020) for additional references that met my above criteria. Carle and Flynn's article yielded one additional research article (Betancourt-Perez et al., 2010) and three practitioner pieces that met my initial criteria (Gero, 1954; Lin, 2007; Silverstein, 1999). Petterson et al.'s article yielded four additional research articles (Ferguson & Bodner, 2008; McClary & Talanquer, 2011a, 2011b; Taber, 2002).

An additional two screens were conducted using the *Journal of Chemical Education* (JChemEd) and *Chemistry Education Research and Practice* (CERP) with the search terms "resonance" and "chemistry education" and "students' understandings of resonance," with no search parameters. In total, the search terms from both journals yielded 4,979 articles. Again, I scanned the titles of the articles for relevance. If the article seemed relevant, I searched the article for the word resonance to further assess its relevancy to the teaching and learning of resonance. From these searches, an additional two research articles (Brandfonbrener et al., 2021; Finkenstaedt et al., 2020) and four practitioner pieces (Abel & Hemmerlin, 1991; Noller, 1950; Richardson, 1986; Starkey, 1995) were identified. Again, I mined the most recently published articles (Brandfonbrener et al., 2021) for additional references. This search yielded one additional research article (Xue & Stains, 2020). Finally, I used Google Scholar with the search terms "resonance" and "chemistry education," with no search parameters. This search yielded an additional three articles (Atieh et al., 2022; Braun, Langer & Graulich, 2022; Tetschner & Nedungadi, 2023).

In summary, the searches described, specific to the teaching and learning of resonance in the general chemistry and organic chemistry classrooms, yielded a limited number of articles to include in this literature review. Specifically, there were 7 practitioner articles and 15 research articles that met the criteria described above. All but one (Starkey, 1995) of the practitioner articles focused on proposing new ways to teach resonance in general chemistry courses. While most of the research articles (12/15) focused on the teaching and learning of resonance in organic chemistry courses, some (3/15) focused on the teaching and learning of resonance in general chemistry courses.

Synthesizing the Literature

To synthesize the literature, I first summarized each article in a Word document. Next, I began to categorize the articles using two different Excel spreadsheets: one for research articles and another for practitioner articles. The research article Excel spreadsheet was labeled with seven different headings: reference, course (general chemistry or organic chemistry), research question(s), research methodology (quantitative, qualitative, or mixed methods), instrument(s) used to collect data, major findings, and student challenges. The practitioner article Excel spreadsheet was labeled with four different headings: publication reference, course (general chemistry or organic chemistry), main goal, and overview of the proposed teaching strategy. Next, I entered the associated information into each of the Excel spreadsheets. This allowed me to further synthesize both the research literature and practitioner pieces systematically.

After synthesizing the practitioner pieces, I decided it was best for this discussion to exclude any practitioner piece that was published prior to Wheland's (1955) textbook. This parameter excluded two practitioner pieces (Gero 1954; Noller, 1950). Through this synthesis of the literature, I identified students' challenges and misconceptions with different resonance concepts, different teaching strategies that practitioners have used to address and mitigate these challenges, the primary research foci related to the teaching and learning of resonance in chemistry education, and justifications for future research.

Students' Challenges with and Misconceptions about Resonance

Educational researchers have identified various challenges and misconceptions students might have about resonance (see Table 1). There are five main challenges associated with students' understandings and application of resonance, as identified by the research literature. Because misconceptions are often tied to specific challenges, they will be discussed specific to each challenge. First, students' challenges describing resonance in conceptually correct ways will be discussed, as resonance is typically first introduced as a conceptual topic. Second, students' challenges identifying or describing the resonance hybrid will be discussed, as students' ability to describe the resonance hybrid is typically tied to students' conceptual understanding of resonance. Third, students' challenges in identifying or drawing resonance structures will be discussed. Fourth, students' challenges associated with employing curved arrows will be discussed, as this topic is typically introduced to students following the initial introduction of identifying and drawing resonance in organic chemistry. Fifth and last, students' challenges applying resonance in a context will be discussed, as this is typically the ultimate goal of learning about and using resonance. These challenges are listed in Table 1 in the order in which they will be discussed alongside the associated publications identifying the challenges. For convenience, the discussion of each challenge will be divided into two sections: one that focuses on findings relevant to general chemistry students and one that focuses on findings relevant to organic chemistry students.

Challenge 1: Describing Resonance in Conceptually Correct Ways

The first challenge—describing resonance in conceptually correct ways—was identified by Taber (2002), Kim et al. (2019), Finkenstaedt-Quinn et al. (2020), Petterson et al. (2020), Xue & Stains (2020), Brandfonbrener et al. (2021), and Tetschner & Nedungadi (2023). Two of these studies identified general chemistry students' difficulties describing resonance in conceptually correct ways: Taber (2002) and Kim et al., (2019). The remaining studies identified organic chemistry students' difficulties describing resonance in conceptually correct ways: Finkenstaedt-Quinn et al. (2020), Petterson et al. (2020), Xue & Stains, (2020), Brandfonbrener et al., (2021), and Tetschner and Nedungadi (2023). In the sections that follow, I will briefly describe the design of each of these studies, followed by the findings that are relevant to the challenge of describing resonance in conceptually correct ways.

Table 1

General Chemistry and Organic Chemistry Students' Challenges with Resonance

Challenge	General Chemistry Publications	Organic Chemistry Publications
Challenge 1: Describing Resonance in Conceptually Correct Ways	• Kim et al. (2019); Taber (2002)	• Brandfonbrener et al. (2021); Finkenstaedt-Quinn et al. (2020); Petterson et al. (2020); Tetschner and Nedungadi (2023); Xue and Stains (2020)
Challenge 2: Identifying or Describing the Resonance Hybrid		• Atieh et al. (2022); Betanancourt-Perez et al. (2010); Xue and Stains (2020); Tetschner and Nedungadi (2023)
Challenge 3: Identifying or Drawing Resonance Structures		• Betancourt-Perez et al. (2010); Braun et al. (2022); Petterson et al. (2020); Tetschner and Nedungadi (2023)
Challenge 4: Identifying the Correct Use of Curved Arrows		• Betancourt-Perez et al. (2010); Tetschner and Nedungadi (2023)
Challenge 5: Applying Resonance in a Context	• Shah et al. (2018)	• McClary & Talanquer (2011a, 2011b); Petterson et al., (2020); Tetschner and Nedungadi (2023)

General Chemistry Studies. Both Taber (2002) and Kim et al. (2019) were interested in general chemistry students' conceptualizations of resonance using the benzene molecule as an example. In semi-structured interviews Taber (2002) showed general chemistry students (N=15) resonance structures of benzene and asked them to interpret the molecular bonding (see Figure

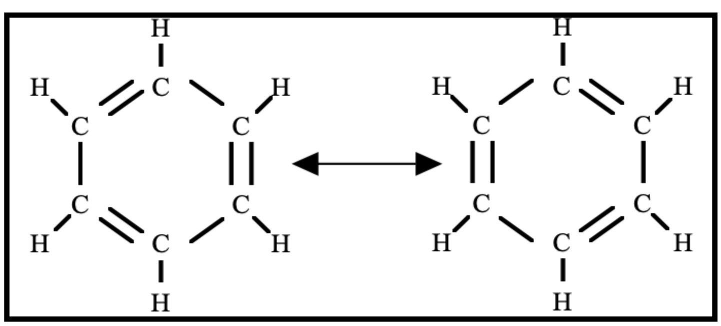
13). Students had the tendency to describe the two resonance structures as real entities that exist in nature. For example, one student described the bonding in benzene as such:

> It will be a double bond, single bond, double bond, single bond, double bond, single...and, to make the resonance, you draw a little two-way arrow, and where there was a double bond in one diagram there would be a single bond in the other one...[the circle] shows that you can either have a double bond, or a single bond, and it happens so quickly that you might as well just have a single bond...[the bond was] sometimes single, sometimes double. (Taber, 2002, p. 168)

Taber (2002) argued that this misconception might have resulted from students incorrectly interpreting the chemical representation of the resonance structures themselves but did not provide further elaboration.

Figure 13

Resonance Structures of Benzene



Note. Used with permission of Royal Society of Chemistry, from Compounding quanta: Probing the frontiers of student understanding of molecular orbitals, K. Taber, volume 3, 2nd ed., 2002; permission conveyed through Copyright Clearance Center, Inc.

Kim et al.'s (2019) study suggested similar findings. The researchers found that many students expressed a conceptually incorrect understanding of resonance after traditional instruction on resonance (Kim et al., 2019). Seventy-eight percent of students in the study described the resonance structures of benzene as separate entities that exist in nature that alternate back and forth. Like Taber (2002), the researchers suggested that these misconceptions might result from students incorrectly interpreting the resonance structures. More specifically, they argued that this misconception can be attributed to the fact that students are visually seeing two distinct structures rather than complementary structures that must be melded together to represent the real structure of benzene (Kim et al., 2019).

Organic Chemistry Studies. Petterson et al. (2020) and Finkenstaedt-Quinn et al. (2020) conducted two companion studies in which they examined first-semester organic chemistry students' mechanistic thinking while proposing reaction mechanisms for different types of reactions (i.e., addition and acid-base reactions). Both studies employed a think-aloud protocol and follow-up questions. Petterson et al. (2020) asked students (N=13) to propose two acid-base reaction mechanisms. Most of the students adequately described the steps associated with the reaction mechanisms; however, two students expressed the misconception that resonance structures are real entities that exist in nature while doing so. For example, when asked about the potential resonance structures during follow-up questions, a student responded, "Oh, you would have a mixture, because you would always have a mixture…like all three of these could still exist in solution" (Petterson et al., 2020, p. 884). While the researchers did not offer an argument as to a possible origin of this misconception, they did argue that the student's responses indicated that they lacked a conceptually correct understanding of resonance.

In their companion study, Finkenstaedt-Quinn et al. (2020) asked students (N=13) to propose mechanisms for two addition reactions. They also found that students struggled to describe resonance in conceptually correct ways. For example, when describing the role of resonance stabilization in one of the addition reactions, one student described resonance structures as such:

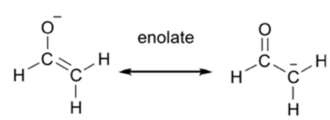
> [If] we think about putting it on this carbon instead, then the lone pairs from this oxygen can make a bond between this oxygen and carbon, which would stabilize it because then this carbon wouldn't really be a carbocation all the time. (Finkenstaedt et al., 2020, p. 1858)

As in their previous study (Petterson et al., 2020), the researchers argued that this description ("Wouldn't really be a carbocation all the time") indicated that the student believed resonance structures to exist in nature and that the molecule alternates between resonance structures in equilibrium. Again, the researchers did not provide an argument on the possible origin of this misconception.

Xue and Stains (2020), Brandfonbrener et al. (2021), and Tetschner and Nedungadi (2023) were interested in describing organic chemistry students' conceptualizations of resonance. In the first stage of a two-stage study, Xue and Stains (2020) interviewed first-semester organic chemistry students (N=6) and asked them about their understandings of resonance. For example, the researchers asked students, "Why do you think that there are resonance structures for certain molecules but not for others?" (Xue & Stains, 2020, p. 896) (see the first column of Table 2 for a complete list of the questions). The researchers then compared students' responses to a list of underlying concepts of resonance (see Table 3). The underlying concepts list was compiled by examining general chemistry and organic chemistry textbooks for concepts related to resonance. Specifically, the researchers were interested in examining students' understandings of "(1) The relationship between the resonance structures and the resonance hybrid, (2) the role of resonance structures, and (3) the origin of resonance structures" (Xue & Stains, 2020, p. 896).

Table 2

Interview and Survey Protocols

<table>
<tr><th>Protocol Pieces</th><th>Stage 1: Interview Protocol</th><th>Stage 2. Survey Protocol</th></tr>
<tr><td>Questions</td><td>1. What do you think is the relationship between these two structures?
2. If you were to explain the concept of resonance structure to your peer, what would you say?
3. Why do you think that there are resonance structures for certain molecules, but not for others?
4. Based on your understanding of the concept of resonance, predict the carbon-oxygen bond length in enolate.
5. What does enolate look like in nature?</td><td>1. What is the relationship between the two structures drawn below?
2. Explain the concept of resonance structure in one or two sentences.
3. Why do you think certain compounds have resonance structures, while others like water don’t?
4. Using the information from the table provided below and the structures for enolate provided earlier, predict the carbon-oxygen bond length in enolate.
5. Describe the structure of enolate that exists in nature.
6. Draw out the enolate structure that you believe would exist in nature on a piece of paper and upload the picture file</td></tr>
<tr><td>Prompts used in both protocols</td><td>
</td><td><table><tr><th>Bond</th><th>Bond length (Å)</th></tr><tr><td>C-O</td><td>1.43</td></tr><tr><td>C=O</td><td>1.21</td></tr></table></td></tr>
</table>

Note. Reprinted with permission from Xue, S., & Stains, M. (2020). Exploring students’ understanding of resonance and its relationship to instruction. *Journal of Chemical Education*, *97*, 894-902. https://doi.org/10.1021/acs.jchemed.0c00066. Copyright (2019) American Chemical Society.

Table 3

Underlying Concepts Related to Resonance

Type of Concept	Underlying Concepts
Differentiation between resonance structures and the resonance hybrid	• The hybrid resonance is a combination of all resonance structures. • The more stable resonance structure is a better representation of but is not the resonance hybrid. • Resonance structures are not real and are not in equilibrium. • Only the resonance hybrid exists in nature.
The role of resonance structures	• Resonance structures help predict the physical characteristics of a resonance hybrid. • Resonance structures help us understand the extent of electron delocalization, which is an important factor in characterizing the stability of a compound
Resonance structures emerge due to the limitations of the Lewis model.	

Note. Reprinted with permission from Xue, S., & Stains, M. (2020). Exploring students' understanding of resonance and its relationship to instruction. *Journal of Chemical Education*, *97*, 894-902. https://doi.org/10.1021/acs.jchemed.0c00066. Copyright (2019) American Chemical Society.

Xue and Stains (2020) found that students lacked a conceptual understanding of resonance and tended to focus on the processes and features (i.e., operational aspects) associated with identifying resonance and drawing resonance structures. Only two of the six students interviewed referred to any of the underlying resonance concepts shown in Table 3. The four other students focused on the processes and features associated with identifying and drawing resonance structures. For example, when asked to explain resonance, one student stated:

> So basically, it's moving the sigma bonds or sigma/pi bonds. Oh gosh, I'm sorry. Um, it's just basically pushing electrons [and] trying to get like more stable form or whatever. And it will have like a filled octet, you know, more electrons are around the electronegative atom. (Xue & Stains, 2020, p. 897)

As previously reported, the researchers also found that two students in their study held the misconception that resonance structures exist in nature and that they alternate back and forth. One student stated in response to a question about what the enolate molecule would like in nature, "Enolate would exist with both resonance structures switching back and forth" (Xue & Stains, 2020, p. 898).

The findings from the first stage of the study prompted the researchers to conduct a second quantitative stage of the study. They developed a six-question survey protocol that was also intended to probe first-semester organic chemistry students' (N= 180) understandings of resonance (see the second column of Table 2 for the survey protocol). The researchers coded students' responses and compared them to the same list of underlying concepts of resonance presented in Table 3. Like the findings in stage one, the researchers found that students tended to focus on the operational aspects associated with identifying resonance and drawing resonance structures. For example, when responding to question two— "If you were to explain the concept of resonance structure[s] to a peer, what would you say?" (Xue & Stain, 2020, p. 896)—of the survey protocol a student stated:

> A resonance structure is when you are given a compound and you are able to transform it into the same compound, with a different physical structure, without breaking any rules, such as not breaking a single bond, exceeding an octet, or changing the total charge. (Xue & Stains, 2020, p. 897)

The use of the phrase “Without breaking any rules” emphasized the notion that students are more focused on the rules and processes associated with resonance rather than a conceptual understanding. Consistent with the findings of the first stage of the study (and the general chemistry studies I described previously), the researchers found that some students held the misconception that resonance structures are real entities that exist in nature in equilibrium (Xue & Stains, 2020). In this stage of the study, the researchers did not provide an argument related to the possible origins of these misconceptions.

Like Xue and Stains (2020), Brandfonbrener et al. (2021) found that students tend to focus on the operational versus conceptual aspects of resonance (2020). The researchers used a writing assignment to probe second-semester organic chemistry students’ (N=105) conceptual understandings of resonance. A condensed version of the writing assignment is shown in Figure 14. Students were asked to explain resonance to the general public in 350-500 words. The writing assignment provided students with the following summarized guidelines: emphasize the limitations of Lewis structures and why resonance structures are needed/ important and provide an example of how resonance and chemical reactivity are related. While not required, students were encouraged to include an analogy in their writing response (Brandfonbrener et al., 2021).

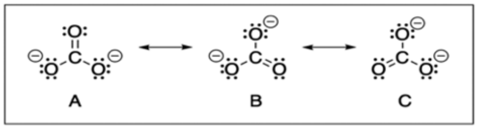
The researchers found that students tended to focus on the rules and processes (i.e., operational aspects) associated with drawing resonance structures rather than on a conceptual description of resonance in their explanations (Brandfonbrener et al., 2021). For example, when asked to describe resonance to the general public, many students provided the rules associated with drawing resonance structures instead of focusing on when resonance can and cannot occur and what specific structural features must be present for a molecule to have resonance. Students’ analogies also lacked conceptual descriptions of resonance. That is, none of the students’ analogies emphasized the idea that resonance structures are not real entities. The researchers argued that one possible origin of this challenge might be that students are typically assessed on their ability to draw resonance structures, not their conceptual understanding of resonance (Brandfonbrener et al., 2021).

Figure 14

Condensed Version of Student Writing Assignment on Resonance

Translating Resonance: An Explainer

Consider structures A, B, and C shown below that represent resonance contributors for the carbonate ion. The three structures are not detectable by any experimental method used to examine the structure of carbonate, which indicates that they do not sufficiently describe the carbonate ion.[1] This example demonstrates the limitation of using Lewis structures to depict resonance because none of the structures represent the actual molecule, which is a hybrid of A, B, and C.



In his book, *Thing Explainer: Complicated Stuff in Simple Words*, Randall Munroe, who created the popular web comic series xkcd, challenges his readers to use the most common 1000 words in the English language to explain highly technical concepts. Neil Degrasse Tyson, Carl Sagan, and Bill Nye are well known for these types of translation skills – their ability to conduct rigorous scientific research and talk about why it matters helped make STEM accessible across generations of public audiences. Your objective for this assignment is to write an "explainer" piece that helps a general public understand *resonance*. An "explainer" is a brief radio spot or short journalistic piece, that aims to help a general public access, understand, and potentially apply a complicated or highly technical concept. The explainer often uses an entertaining, simple analogy to make an abstract, complicated idea simpler to understand and visualize. Explainers also give the reader a sense of why a concept is important for them to understand – what can or should we, the general public, do with the information that's been presented to us?

Note. Used with permission from Brandfonbrener, P. B., Watts, F.M., & Shultz, G. V. (2021). Organic chemistry students' written descriptions and explanations of resonance and its influence on reactivity. *Journal of Chemical Education, 98*, 3431-3441. https://doi.org/10.1021/acs.jchemed.1c00660. Copyright (2021) American Chemical Society.

Tetschner and Nedungadi's (2023) study discussed their design and development of a Resonance Concept Inventory (RCI). The researchers developed 15 items (in multiple-choice format) for the RCI that addressed one of five broad categories of resonance: "resonance theory, resonance structures and the resonance hybrid, using curved arrows to draw resonance structures, identifying the best resonance structure, and resonance and stability" (Tetschner & Nedungadi, 2023, p. 3797). The RCI was then administered to first-semester organic chemistry students (N=97) after they learned about resonance and were tested on the concept. After students took the RCI, they were interviewed about their responses. The researchers used this data to identify common student misconceptions about resonance. They found that students struggled to describe resonance in conceptually correct ways. Overall, students struggled to understand electron delocalization and believed instead that atoms are rearranged in resonance structures. While they did not provide specific student examples, the researchers suggested that this resulted in students being unable to identify correct resonance structures or predict the bond length of structures that exhibited resonance.

Challenge 1 Summary. These studies suggest that both general chemistry and organic chemistry students struggle to describe resonance in conceptually correct ways. It was found that many general chemistry and organic chemistry students held misconceptions that resonance structures are (1) real entities that exist in nature and (2) that they switch back and forth in equilibrium. Furthermore, general chemistry students found it challenging to interpret meaning from the resonance structures of the benzene molecule due to a lack of representational competence (Kim et al., 2019; Taber, 2002). The organic chemistry students found it challenging to describe resonance in conceptually correct ways when working through reaction mechanisms (Finkenstaedt-Quinn et al., 2020; Petterson et al., 2020) and answering concept inventory items related to resonance theory (Tetschner & Nedungadi, 2023). Organic chemistry students also struggled to provide written conceptual descriptions of resonance. Instead, they emphasized the operational aspects associated with identifying and drawing resonance structures rather than the underlying concepts associated with resonance (Brandfonbrener et al., 2021; Xue & Stains, 2020).

Challenge 2: Identifying or Describing the Resonance Hybrid

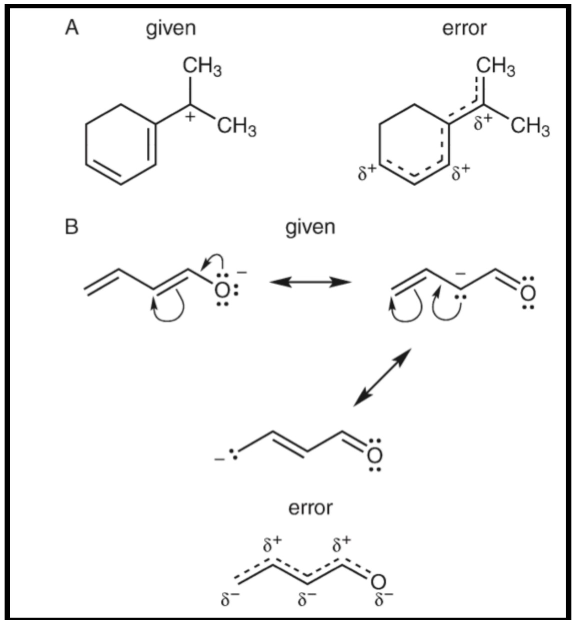
The second challenge—identifying or describing the resonance hybrid—was identified by Betanancourt-Perez, Olivera, and Rodríguez (2010), Xue and Stains (2020), Atieh et al. (2022), and Tetschner and Nedungadi (2023). These researchers found that organic chemistry students struggled to either identify or describe the resonance hybrid of a particular molecule. Currently, no studies have investigated general chemistry students' ability to identify or describe the resonance hybrid. Because Xue and Stains's (2020) and Tetschner and Nedungadi's (2023) research methodologies have already been discussed, only Betanancourt-Perez et al.'s (2010) and Atieh et al.'s (2022) methodologies will be explained in the sections that follows.

Organic Chemistry Studies. Betanancourt-Perez et al. (2010) were interested in how first and second semester organic chemistry students' learning about one type of resonance structure influenced the learning of another, how their understanding of resonance influenced their performance in organic chemistry, and how their understanding of resonance changed over time. The researchers developed seven different multiple-choice tests that assessed students' (N=375) ability to (1) employ curved arrow notation correctly, (2) identify resonance structures, (3) identify the most stable resonance structure, and (4) identify the resonance hybrid.

The researchers found that students struggled to identify the resonance hybrid. For example, when asked to identify the resonance hybrid, from a series of choices, students made two common mistakes. First, students were not able to identify the choice that included features from the most stable resonance structures (i.e., major resonance structures) (Figure 15A) and second students were not able to identify structures with correct charges on atoms (Figure 15B). Furthermore, the findings indicated that identifying the resonance hybrid was more difficult for second semester organic chemistry students than for first semester students. That is, first semester organic chemistry students (N=213) were over 50% more likely to identify the correct resonance hybrid than were second semester organic chemistry students (N=162). The authors argued that this has to do with the fact that the resonance hybrid is mostly discussed in the first semester of the organic chemistry series and is rarely if ever assessed in either the first or second semester of organic chemistry, as has been pointed out by other authors (Carle & Flynn, 2020).

Figure 15

Example of Student Errors Identifying the Resonance Hybrid



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Xue and Stains (2020) were interested in characterizing first semester organic chemistry students' conceptual difficulties with resonance. Similar to Betanancourt-Perez et al.'s (2010) results, Xue and Stains (2020) found that students struggled to describe (versus identify) the resonance hybrid for enolate. For example, only one of six students mentioned that the resonance hybrid would be a mental melding of the contributing resonance structures: "It's the actual structure that is somewhere in between both of these so it's kinda like the average of these two structures" (Xue & Stains, 2020, p. 898). However, this student missed that some resonance structures can be major or minor contributors to the resonance hybrid (i.e., the resonance hybrid is not Is the absolute average of the resonance structures). The student should have mentioned that one resonance structure was the major contributor to the resonance hybrid. Similar results were found in the researchers' survey data, in which 18% of students could not describe the resonance hybrid of enolate.

Xue and Stains further explored these findings in a later study with Atieh et al. (2022). This study focused on first-semester organic chemistry instructors' perceptions of the resonance hybrid and how those perceptions affect students' understandings of the resonance hybrid. After collecting information regarding instructors' perceptions of the resonance hybrid, the researchers surveyed students (N=361) in their classes about their understanding of the topic.

This survey included many of the same questions as Xue and Stains' (2020) survey. As shown in Table 2, students were provided with the resonance structures and bond length data of enolate. Based on this information, the students were asked the following three questions verbatim:

> (1) Using bond lengths and structures for enolate provided, predict the carbon-oxygen bond length in enolate.
>
> (2) Describe the structure of enolate that exists in nature.
>
> (3) Draw out the structure of enolate that exists in nature on a piece of paper and upload the picture file. (Atieh et al., 2022, p. 202)

The first question requires students to understand that the bond length of enolate is a weighted average of the two resonance structures shown, with the actual structure (i.e., the resonance hybrid) being closer to that of the major resonance contributor of enolate. While many students recognized that the bond length of enolate is an average of the bond lengths of the two structures, relatively few students considered the major resonance contributor when predicting bond lengths.

Overall, students performed poorly on survey questions two and three. Interestingly, students who could correctly describe the resonance hybrid of enolate were not necessarily able to correctly draw the resonance hybrid. Later, I will discuss the relationship between instructors' perceptions of the resonance hybrid and students' understandings of it.

Tetschner and Nedungadi (2023) found that students did not fully understand Lewis structures or valence bond theory, leading to misconceptions about the resonance hybrid. For example, while taking the RCI and deciding which resonance structure contributes more to the resonance hybrid, some students believed that placing formal charges on the most electronegative atom was more important than satisfying the octet rule. Students also struggled to correctly apply the octet rule. The researchers did not provide specific student examples.

Challenge 2 Summary. These studies suggest that first- and second-semester organic chemistry students struggle to identify or describe the resonance hybrid. Betanancourt-Perez et al. (2010) suggested that this difficulty might have to do with the fact that the resonance hybrid is not a focus of instruction and that students are rarely assessed on their ability to describe/draw the resonance hybrid in organic chemistry courses. Tetschner and Nedungadi (2023) suggest it could result from students' incomplete understanding of Lewis structures and valence bond theory.

Challenge 3: Identifying or Drawing Resonance Structures

The third challenge—identifying or drawing resonance structures—was identified by Betancourt-Perez et al. (2010), Petterson et al. (2020), Braun et al. (2022), and Tetschner and Nedungadi's (2023). These researchers found that organic chemistry students struggled to draw correct resonance structures for a series of different molecules. Currently, there are no studies that have investigated general chemistry students' abilities to draw resonance structures. After reviewing the research literature, it became apparent that this challenge is tied to students' ability to draw Lewis structures. Therefore, before discussing the results from these studies, it will be helpful to understand students' challenges drawing and using Lewis structures. My aim is not to be exhaustive but to provide enough context on how students' difficulties with Lewis structures might affect their ability to draw resonance structures.

Students' Challenges with Lewis Structures. Educational researchers (Betancourt-Perez et al., 2010; Cooper et al., 2010) have identified the ability to draw and use Lewis structures as a prerequisite to drawing resonance structures. Similar to resonance, Lewis structures are first introduced to students in the first semester of general chemistry and then briefly reviewed in the first semester of organic chemistry (Brown et al., 2018; Klein, 2012). Research indicates that both general chemistry and organic chemistry students have difficulties understanding and using Lewis structures (Betancourt-Perez et al., 2010; Bodner & Shane, 2006; Brady et al.,1990; Cooper et al., 2010; Kaufmann et al., 2017; Taber, 1997, 1998; Underwood et al., 2015). Students' challenges with Lewis structures fit into two main categories: challenges learning how to construct valid Lewis structures and challenges understanding how Lewis structures can be used to gain insights into structure-property relationships.

The first category has four main challenges: (1) understanding/ employing the systematic steps often associated with drawing Lewis structures, (2) constructing Lewis structures when a chemical formula lacks structural cues, (3) constructing Lewis structures for complex molecules, and (4) applying the octet rule appropriately. The second category includes one main challenge: (5) understanding the multiple purposes and uses of Lewis structures. Each of these challenges is briefly discussed in the following paragraphs.

Lewis Structure Challenge 1: Understanding/ Employing the Systematic Steps Often Associated with Lewis Structures. The first challenge—understanding/ employing the systematic steps often associated with drawing Lewis structures—was identified by both Cooper et al. (2010) and Kaufmann et al. (2017). Cooper et al. (2010) found that students had difficulty interpreting what the steps associated with drawing Lewis structures meant. For example, general chemistry students often do not learn about electronegativity until after learning about Lewis structures, so when the procedure states that the central atom should be the least electronegative, students do not understand what the rule means. Kaufmann et al. (2017) found that while working in pairs to construct Lewis structures with a set of explicit rules, general chemistry students struggled to systematically (e.g., in order) apply the rules to construct the Lewis structures of a given molecule.

Lewis Structure Challenge 2: Constructing Lewis Structures When the Chemical Formula Lacks Structural Cues. The second challenge—constructing Lewis structures when the chemical formula lacks structural cues—was identified by Cooper et al. (2010). The researchers found that students struggled to construct valid Lewis structures when the central atom was not abundantly clear. For example, Cooper et al. found that changing the arrangement of the chemical formula for methanol from CH_3OH (where >90% of students were able to construct the correct Lewis structure) to CH_4O resulted in a significantly lower number (60%) of students being able to construct a valid Lewis structure. Cooper's group also showed this same result qualitatively, as students expressed frustration at not knowing how to connect the atoms during interviews in which students were asked to construct Lewis structures (2010).

Lewis Structure Challenge 3: Constructing Lewis Structures for Complex Molecules. The third challenge—constructing Lewis structures for complex molecules—was identified by

Cooper et al. (2010) and Kaufmann et al. (2017). Cooper et al. (2010) found that the transition from one-to two-carbon species caused student accuracy to drop from 80% with one-carbon species to around 30% with two or more carbon atoms. They also found that students struggled to construct valid Lewis structures when double bonds were required, mainly when dealing with N and O, often leaving the structure with either an expanded or deficient octet (Cooper et al., 2010). Kaufmann et al. (2017) found similar results. They reported that while working in groups to construct Lewis structures, students often had considerable discussions about how to construct Lewis structures for molecules or ions that require the formation of multiple bonds (e.g., CO_3^{2-}, NO_3^-, HSO_3^-). Species with formal charges were also difficult for students. Kaufmann et al. (2017) reported that students tended to ignore the charges on molecules and to construct the Lewis structure as if the charges were not there.

Lewis Structure Challenge 4: Applying the Octet Rule Appropriately. The fourth challenge—applying the octet rule appropriately—was identified by Brady et al. (1990), Cooper et al. (2010), and Taber (1997, 1998). Brady et al. (1990) found that students were not able to construct a valid Lewis structure for nitrogen dioxide, NO_2, because N (the central atom) lacked a full octet. Taber (1997; 1998) found similar results; they indicated that students clung to the idea that atoms need eight valence electrons. Cooper et al. (2010) reported students applying anthropomorphic properties to atoms. For example, students described atoms as "wanting" or "needing" a certain number of electrons to be "happy" or "stable." This reasoning likely comes from too much emphasis on the octet rule. Students tended to believe atoms bond to satisfy an octet; leading students to add electrons until "the octet is full" even if there were not enough electrons to do so (Cooper et al., 2010).

Lewis Structure Challenge 5: Understanding the Multiple Purposes and Uses of Lewis Structures. The fifth challenge—understanding the multiple purposes and uses of Lewis structures—was identified by Bodner and Shane (2006), Cooper et al. (2010), and Underwood et al. (2015). Bodner and Shane (2006) found that students had difficulties seeing Lewis structures as symbolic representations. For example, after analyzing a series of student interviews about Lewis structures, the researchers reported that "in many cases, the students perceived dot [Lewis] structures as nothing more than "letters and dots and lines" (Bodner & Shane, 2006, p. 7). Similarly, Cooper et al. (2010) found that only 30-40% of students recognized that Lewis structures could be used to predict molecular shape. Some students even indicated that it was not possible to use Lewis structures in this way. Cooper et al. (2010) also found that only a small number of students indicated that Lewis structures could be used to infer chemical information (e.g., boiling point). Most surprisingly, general chemistry students were more likely to infer this relationship than organic chemistry students.

Underwood et al. (2015) aimed to expand on Cooper et al.'s (2010) findings. That is, Underwood et al. (2015) investigated whether and when students understand that they can predict structure-property relationships from Lewis structures. Their findings indicated that most students were able to recognize that chemical properties can be predicted from Lewis structures after the first semester of general chemistry. It was rare, though, for those students to connect structure with chemical properties, meaning students only required to take one semester of general chemistry might leave chemistry without ever making this connection (Underwood et al., 2015).

It is likely that the challenges associated with constructing and using Lewis structures contribute to students' challenges with drawing resonance structures. That is, if students cannot construct a valid Lewis structure for a molecule, they will not be able to draw resonance structures for that molecule. Furthermore, while not yet directly investigated, if students do not understand the multiple purposes and uses of Lewis structures (e.g., predicting molecular shape and properties) they will likely have difficulties applying and understanding resonance in meaningful ways. The remainder of this section will focus on students' challenges either identifying or drawing resonance structures.

Organic Chemistry Studies. Four studies have identified students' challenges with either identifying or drawing resonance structures they are Betanancourt-Perez et al. (2010), Petterson et al. (2020), Braun et al. (2022) and Tetschner and Nedungadi's (2023). Because Betanancourt-Perez et al. (2010), Petterson et al. (2020), and Tetschner and Nedungadi's (2023) research methodologies have been discussed, only their findings specific to this challenge will be presented here. Braun et al.'s (2022) methodology will be discussed, followed by their relevant findings.

Both Betancourt-Perez et al. (2010) and Tetschner and Nedungadi's (2023) studies shared similar results. Betancourt-Perez et al. (2010) found that some first and second-semester organic chemistry students struggled to identify correct representations of resonance structures on a multiple-choice exam. For example, when asked to select the correct resonance structure for a series of given molecules, students selected structures with the following errors: "Structure(s) violated the octet rule, structure(s) had different delocalized pi system and net formal charges, and structure(s) had incorrect formal charges on atoms" (Betancourt-Perez et al., 2010, p. 548). The researchers suggested that these errors result from students' lack of attention to detail when drawing resonance structures (Betancourt-Perez et al., 2010). Similarly, Tetschner and Nedungadi (2023) also found that students made many of the same mistakes while taking the

RCI, which consisted of 15 multiple-choice items. As previously mentioned, this group of researchers suggested that students lack an adequate understanding of Lewis structures and valence bond theory.

Petterson et al. (2020) and Braun et al. (2022) observed students' difficulties drawing resonance structures while students were solving reaction mechanisms. Petterson et al. (2020) found that some first-semester organic chemistry students struggled to propose correct reaction mechanisms because they could not draw resonance structures. For example, while working through an acid-base reaction mechanism, one student struggled to draw the relevant resonance structures for the reaction, as they did not know where to start drawing curved arrows (Petterson et al., 2020). The researchers did not state how this challenge ultimately affected the student's ability to propose a correct reaction mechanism; however, it would not be unreasonable to assume that it negatively impacted their ability to do so.

Braun et al. (2022) were interested in exploring first-semester organic chemistry students' (N=20) reasoning and drawing processes of resonance structures using eye-tracking technology. Eye-tracking technology within the context of science education has been used to evaluate students' construction processes, as it affords insight into students' drawing processes and possible obstacles students might encounter while constructing chemical representations (e.g., resonance structures).

During semi-structured interviews, this study used a mobile eye-tracking machine to track the students' eye movements while completing tasks that involved drawing resonance structures (i.e., solving reaction mechanisms). To ensure students' natural eye movements were captured, the students were not required to think aloud while solving the tasks. After students completed the tasks using the eye-tracking technology, a retrospective interview was conducted where students explained their rationale for their drawings.

The researchers classified each student's resonance structures as productive or unproductive. Productive resonance structures were valid resonance structures that helped the student complete the task. Unproductive resonance structures were either valid or invalid resonance structures that did not help the student complete the task. Overall, the students constructed a total of 60 resonance structures. Of those resonance structures, 41 were classified as productive and 19 unproductive (the remaining five were classified as auxiliary, meaning they did not relate to drawing resonance structures). The researchers then used the eye-tracking data and student explanations (gathered from the retrospective interviews) to compare the productive and unproductive resonance structures.

Braun et al. (2022) found similar gaze behavior (i.e., where students were looking while constructing resonance structures) between students who constructed productive and unproductive resonance structures. In other words, the students used the same amount of information while drawing productive and unproductive resonance structures. However, what students fixated on during the drawing process differed between unproductive and productive drawings. Students who drew unproductive drawings were often attracted to unrelated information while constructing resonance structures, such as an unrelated double bond. Meanwhile, students who drew productive drawings noticed interrelated and relevant structural features that indicated resonance, such as a positive charge and a double bond. Moreover, students who productively drew resonance structures also applied their conceptual understanding of resonance to describe why the specific structural features they attended to indicated resonance.

Thus, the researchers emphasized the importance of not only teaching students to recognize the structural features that indicate resonance but also why such features indicate resonance.

Challenge 3 Summary. The studies above show that first and second-semester organic chemistry students struggle to identify or draw resonance structures (Betancourt-Perez et al., 2010; Braun et al., 2022; Petterson et al. (2020); Tetschner & Nedungadi (2023). The researchers suggested different reasons students might do so, including a lack of attention to detail, an incomplete understanding of Lewis structures and valence bond theory, or an overall lack of a conceptual understanding of resonance. While there have been no studies that have investigated general chemistry students' challenges drawing resonance structures, the research literature indicates that both general and organic chemistry students struggle to draw Lewis structures. This skill is required for drawing resonance structures. Therefore, it could be expected that general chemistry students who have difficulties with Lewis structures would also have difficulty drawing resonance structures.

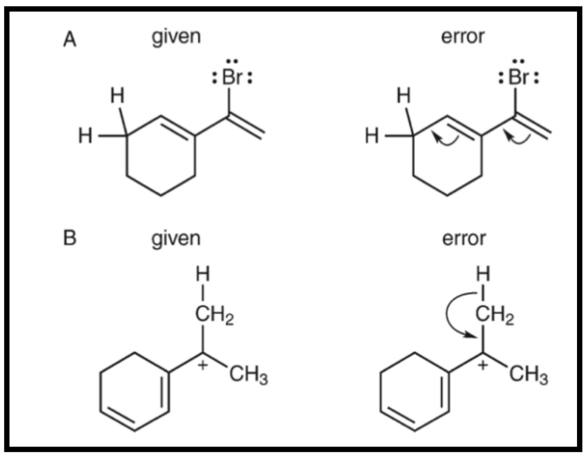
Challenge 4: Identifying the Correct Use of Curved Arrows

The fourth challenge—employing curved arrows—was identified by Betancourt-Perez et al. (2010) and Tetschner and Nedungadi (2023). The researchers found that students struggled to identify the correct use of curved arrows to draw resonance structures, which, while not directly examined, likely implies that students cannot use curved arrows correctly. To my current knowledge, there are no studies that have investigated general chemistry students' understanding of curved arrows, likely because this topic is not typically introduced until the first semester of organic chemistry.

Organic Chemistry Studies. Betancourt-Perez et al. found that first and second-semester organic chemistry students struggled to identify the correct use of curved arrows to depict resonance structures. For example, students were asked to identify, from a series of choices, the curved arrow notation that generated the correct resonance structure for a compound. Students incorrectly selected choices that (1) moved π bonds towards the least electronegative atom (Figure 16A) or (2) broke single bonds between carbon and hydrogen atoms (Figure 16B).

Figure 16

Example of Student Errors using Arrow Pushing Formalism



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Overall, Tetschner and Nedungadi (2023) reported that students who took the RCI had relatively little difficulty using curved arrows. However, what they did have difficulties with was explaining what curved arrows represent. For example, students believed that curved arrows "dictate the direction of positive charge" when, instead, curved arrows depict the delocalization of electrons (Tetschner & Nedungadi, 2023, p. 3798). These results conflict with Betancourt-

Perez et al.'s (2010) findings described above. Interestingly, both studies used multiple choice questions with relatively similar sample sizes; thus, the differing results are surprising and should be the focus of future research.

Challenge 5: Applying Resonance in a Context

The fifth challenge—applying resonance in a context—was identified by Shah et al. (2018), McClary and Talanquer (2011a, 2011b), Petterson et al. (2020), and Tetschner and Nedungadi (2023). One study examined general chemistry students' difficulties applying resonance in a context (Shah et al., 2018), and the other studies described organic chemistry students' difficulties applying resonance in a context: McClary & Talanquer (2011a,2011b), Petterson et al. (2020), and Tetschner and Nedungadi (2023). In the sections that follow, I will briefly describe the design of each of the studies not yet discussed, followed by the findings that are relevant to the challenge of applying resonance in a context.

General Chemistry Study. Shah et al. (2018) were interested in advanced first-semester general chemistry students' (i.e., had taken two years of chemistry in high school) conceptions of relative acid strength and how both discussion-based instruction and active learning environments affected those conceptions. The study had two different sources of data. The first data source was audio recordings of student groups (six student groups with three to four members) actively working together to solve problems about relative acid strength. The second source of data was student interviews (N=12), in which students were asked to elaborate on their group's responses as well as their overall takeaways from the course.

Shah et al. (2018) found that while working in active learning groups, students struggled to rank relative acid strength when all the compounds exhibited resonance. Follow-up interviews indicated that students often rationalized their incorrect answers by explaining they chose the compounds with the most resonance structures to be more acidic rather than considering which resonance structures offered more stability. This idea is expressed in the following two interview excerpts:

> So in terms of looking at [pentane-2,4-dione] and [phenol], cause that's what you have to compare, [phenol] has a benzene ring as opposed to [pentane-2,4-dione] so it would be able to stabilize its own charge more and have more resonance structures, as opposed to what I tried drawing for [pentane-2,4-dione]. So I felt like [phenol] had more resonance structures and it was more stable and more likely to act like an acid Instead of [pentane-2,4-dione]. (Ralph)
>
> So if you were to take off the hydrogen of the alcohol group, the negative charge of [phenol] is better distributed throughout the benzene ring than it could be throughout whatever those are- carbonyl groups. So there's more resonance structures, yeah. I was like [expletive] certain on that one. (Libby) (Shah et al., 2018, p. 550)

These students' justifications suggest that they lack a conceptual understanding of how resonance affects relative acidity. The researchers argued that these difficulties might be attributed to the fact that general chemistry students are not yet skilled in drawing alternative resonance structures, which could have affected their choices (Shah et al., 2018). It is also possible that the students are relying on short-cut reasoning, as Ralph and Libby's descriptions incorporate the commonly taught heuristic "more resonance structures equal more stability." The studies discussed below support this idea.

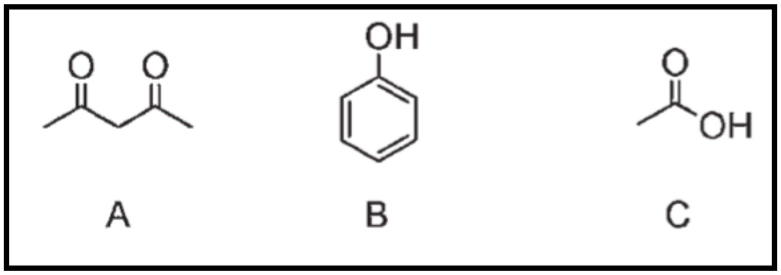
Organic Chemistry Studies. McClary and Talanquer (2011a) were interested in characterizing organic chemistry students' mental models of acids and acid strength. The researchers interviewed first-semester organic chemistry students (N=19) and asked them to predict, observe, and explain various problems. The researchers found that students struggled to conceptually understand how resonance can affect the stability of an acid. For example, students were asked to rank the relative stability of a set of compounds shown in Figure 17. One student's ranking explanation illustrates that the student is aware that resonance can affect acid strength but that they struggled to explain why:

> S19: OK, I said B was the most acidic because it's aromatic, um because it provides more resonance structures.
>
> Int: How does more resonance structures affect acidity?
>
> S19: More resonance structures stabilize the negative charge that would result.
>
> Int: How does it stabilize it?
>
> S19: That's a good question (laughs). It's probably been explained, but I don't know.
>
> (McClary & Talanquer, 2011a, p. 406)

The student should have explained that the resonance stabilizing effect results from the negative charge on the conjugate base being delocalized away from the acidic site instead of focusing only on the number of resonance structures.

Figure 17

Set of Compounds Students Ranked Relative Acidity



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McClary and Talanquer (2011b) were interested in characterizing organic chemistry students' heuristic thinking (i.e., short-cut, rule-based reasoning) while ranking acid strength. The researchers interviewed first-semester organic chemistry students (N=20) and asked them to solve a series of ranking tasks using a think-aloud technique. The findings of this study were similar to those in the McClary and Talanquer (2011a) and Shah et al. (2018) studies. That is, the researchers found that students could identify resonance as contributing to relative acid stability but could not describe why this was the case. For example, as was found by Shah et al. (2018) and McClary and Talanquer (2011a), general chemistry and organic chemistry students relied on the heuristic "More resonance forms mean more acid strength," as is Illustrated in the following interview excerpt:

> So (compound A) automatically jumps out at me as gonna provide a lot of resonance, so I think (compound A) is gonna be most acidic. (S13, final ranking C < B < A)
>
> And between C and (B), I'm trying to remember more about resonance structures here. But um, I think having a group here (in the para-position) in one way or another affects

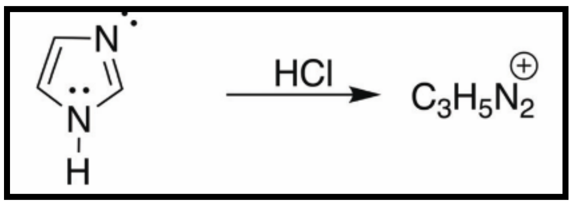
> how the resonance structures work. My instinct would be to say that would make it harder to have a resonance structure. More resonance structures than—my sense is that (B) would have fewer resonance structures than C. Yea, I'm gonna have to say C is intermediate, and (B) is the least acidic. (S19, final ranking B < C < A) (McClary & Talanquer, 2011b, p. 1448).

The researchers suggested that this reasoning can be largely attributed to traditional organic chemistry teaching practices (McClary & Talanquer, 2011b). That is, instructors often emphasize the idea that the number of resonance structures is a criterion for determining stability in conjugated systems instead of an underlying understanding of the resonance stabilizing effect (i.e., electron delocalization). In other words, McClary and Talanquer (2011b) are suggesting that students rely on heuristics (rather than an underlying conceptual understanding) because that is what instructors tend to emphasize in the classroom.

Petterson et al. (2020) were interested in first-semester organic chemistry students' reasoning while working through acid-base reaction mechanisms. For example, students were asked to describe their thinking while proposing the reaction mechanism for the protonation of imidazole by hydrochloric acid (a strong acid) (Figure 18) (Petterson et al., 2020). The students needed to be able to recognize that after protonation, the positive charge on only one of the nitrogen atoms would be resonance stabilized, thus indicating the preferred product for the reaction. The researchers found that while working through this reaction mechanism, organic chemistry students struggled to correctly apply the concept of resonance stabilization. That is, four students (N=13) incorrectly focused on the resonance stabilization of the reactant rather than the resonance stabilization of the possible products, which led many students to protonate the wrong nitrogen atom (Petterson et al., 2020). The researchers argued that this mistake indicated a gap in students' understanding of resonance concepts and how to apply them while proposing acid-base reaction mechanisms (Petterson et al., 2020).

Figure 18

Reaction Students Were Presented with During the Interview



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Tetschner and Nedungadi (2023) briefly discussed students' difficulties in using resonance to determine relative molecular stability. Prior research has shown that students tend to focus on the operational rather than conceptual aspects of resonance (Brandfonbrener et al., 2021). Similar to the studies discussed above, the researchers suggested students' difficulties using resonance to determine relative molecular stability were related to students' poor conceptual understanding of resonance, specifically how the delocalization of electrons affects molecular stability. For example, students were unaware that Lewis structures that have formal charges on atoms are more stable when the charge can be delocalized via resonance. The researchers did not provide specific student examples.

Challenge 5 Summary. These studies suggest that advanced general chemistry and organic chemistry students struggle to understand how resonance affects relative molecular stability in acid-base chemistry, which is likely in part a result of students focus on the operational rather than conceptual aspects of resonance. McClary and Talanquer (2011a; 2011b) and Shah et al.'s (2018) studies showed that students struggle to adequately describe how resonance affects relative acid strength. Instead of chemical thinking, general chemistry, and organic chemistry, students in their studies often relied on the heuristic "More resonance forms mean more acid strength" to rationalize and explain their reasoning (McClary & Talanquer, 2011a; 2011b; Shah et al., 2018). Tetschner and Nedungadi (2023) suggest this difficulty to be a result of students' poor understanding of electron delocalization. Not surprisingly, Petterson et al. (2020) found that this challenge persisted when students were asked to propose acid-base reaction mechanisms, thus suggesting a gap in students' understanding of resonance concepts related to acid-base chemistry.

Practitioner Teaching Strategies for Mitigating Students' Challenges with Resonance

In response to some of the challenges just described, practitioners have shared some of the different ways that they teach resonance concepts in their classrooms. It is important to note that these teaching methods are not necessarily research-based. Overall, the practitioners aimed to help students better conceptualize resonance through the use of analogy (Abel & Hemmerlin, 1991; Silverstein, 1999; Starkey, 1995; Lin, 2007) as well as through other teaching techniques (Abel & Hemmerlin, 1991; Richardson 1986).

Practitioner Analogies for Teaching Resonance

Analogies can be a useful tool for helping students understand abstract and complex concepts by connecting new information to something students are already familiar with (Orgill

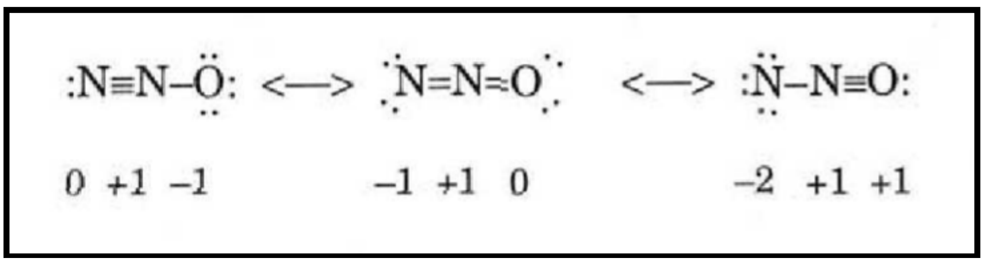
& Bodner, 2004). Analogies have been used in both general chemistry and organic chemistry textbooks to teach resonance (e.g., Brown et al., 2018; Klein, 2012). Practitioners have used analogies to help students understand the underlying concepts associated with resonance as well as to address the common misconception that resonance structures are real structures that exist in equilibrium (Abel & Hemmerlin, 1991; Silverstein, 1999; Starkey, 1995; Lin, 2007). There have been a variety of different analogies that practitioners have used to help their students better understand resonance structures and how they relate to the resonance hybrid.

Simple Analogies for Resonance. Some practitioners have proposed relatively simple analogies that instructors might explain to students when first introducing resonance in either general chemistry or organic chemistry classrooms. Both Abel and Hemmerlin's (1991) and Starkey's (1995) analogies are relatively simple and similar to those found in general chemistry and organic chemistry textbooks (e.g., Brown et al., 2018; Klein, 2012). In these analogies, resonance is compared to concepts that many students are already familiar with—colors (Abel & Hemmerlin, 1991) and the cartoon characters Charlie Brown and Dennis the Menace (Starkey, 1995).

Color Analogy. Abel and Hemmerlin (1991) drew an analogy between colors and the resonance structures for N_2O (Figure 18). The practitioners begin by explaining to their students that green is a combination of both primary colors yellow and blue. They then posed the problem that if the only way to describe green is in terms of primary colors (i.e., yellow and blue) and we are trying to describe a green wall, we would not say that the green wall is sometimes yellow and sometimes blue—we would describe it as a mixture of yellow and blue that looks green all the time. The authors extended their analogy to include the concept of major and minor resonance contributors. That is, if there is more blue than yellow, the wall could be described as blueish green, but not as a blue and green wall. As shown in Figure 19, the practitioners then connected this idea to the N_2O (which has major and minor resonance contributors) by drawing its resonance structures with formal charges. The formal charges show that the first two structures would be more stable than the third. While there was no visual provided linking the colors and resonance structures, the practitioners verbally told students that the primary colors yellow and blue represent the resonance structures, while green represents the resonance hybrid.

Figure 19

Resonance Structures of Nitrous Oxide (N_2O)



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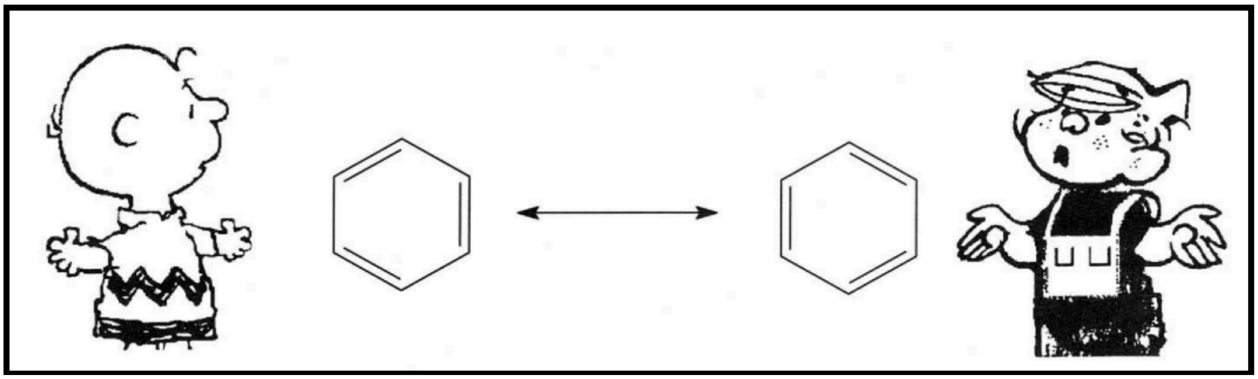
Cartoon Analogy. To begin his analogy, Starkey (1995) posed the problem to students that he would like to show them what his Uncle Bob looks like, but he does not have a photo to do so (Starkey, 1995). As shown in Figure 20, he drew two cartoon characters—Charlie Brown and Dennis the Menace—and explained that Uncle Bob looks a little like Charlie Brown and a little like Dennis (Starkey, 1995). Starkey stressed that while both cartoon characters can be drawn, they are not real people. Conversely, while Uncle Bob cannot be drawn it does not mean that he is not a real person. Starkey then connected this analogy to an example of resonance using benzene (Starkey, 1995). That is, the cartoon characters represent the resonance structures of benzene and Uncle Bob represents the resonance hybrid of benzene (Starkey, 1995).

Figure 20

Analogy that Describes Resonance Using Cartoon Characters



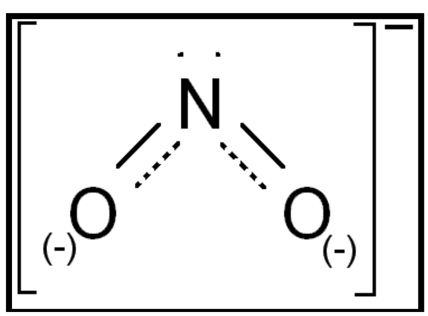
Note. Reprinted with permission from Starkey, R. (1995). Resonance analogy using cartoon characters. *Journal of Chemical Education, 76*(6), 542. https://doi.org/10.1021/ed072p542. Copyright 1995 American Chemical Society.

More Complex Analogies for Resonance. Other practitioners have proposed more complex analogies: analogies that require that students have more advanced background in chemistry or that require students' active participation (Lin, 2007; Silverstein, 1999). For example, in order to understand Silverstein's (1999) analogy, students need a somewhat advanced background in chemistry. Lin's (2007) analogy, on the other hand, requires a classroom environment that can accommodate active student participation (Lin, 2007).

Dog Analogy. Silverstein (1999) used a rather intricate dog analogy to help his general chemistry students understand the resonance hybrid of the nitrite ion (Figure 21). In his analogy (shown in Figure 22), the nitrogen and oxygen atoms (represented by their chemical symbols) represent fixed points on an imaginary dog run connected by two wires (there are two O-N dog runs total). The two puppy dogs can only move between one of the dog runs and represent localized or σ bonding electrons in the nitrite ion. The big dog can move between both dog runs and represents the delocalized or π bonding electrons in the nitrite ion. Finally, the bunny rabbit can "tunnel" from one oxygen atom to another to escape the big dog and represents the electron that gives nitrite its negative charge, which will always be opposite of the π bonding electrons (i.e., the big dog). While Silverstein wrote this analogy for his general chemistry students, it is possible that many students at this level will not have been exposed to the language used in the analogy (e.g., σ or π bonding electrons) and, like any teaching strategy, it should be used only when appropriate.

Figure 21

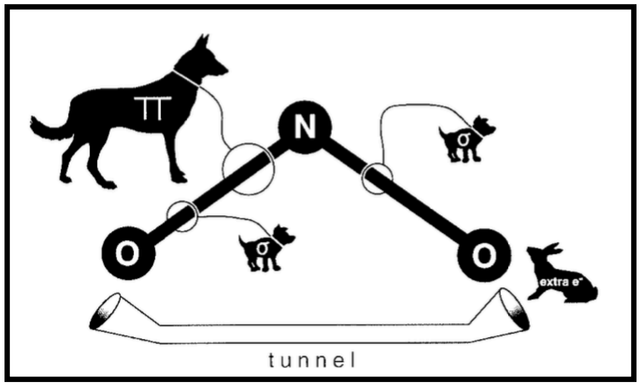
Resonance Hybrid of Nitrite



Note. Adapted with permission from Silverstein T. P. (1999), The ''big dog-puppy dog'' analogy for resonance. *Journal of Chemical Education, 76*(2), 206. https://doi.org/10.1021/ed076p206. Copyright 1999 American Chemical Society.

Figure 22

Big-Dog Puppy-Dog Analogy

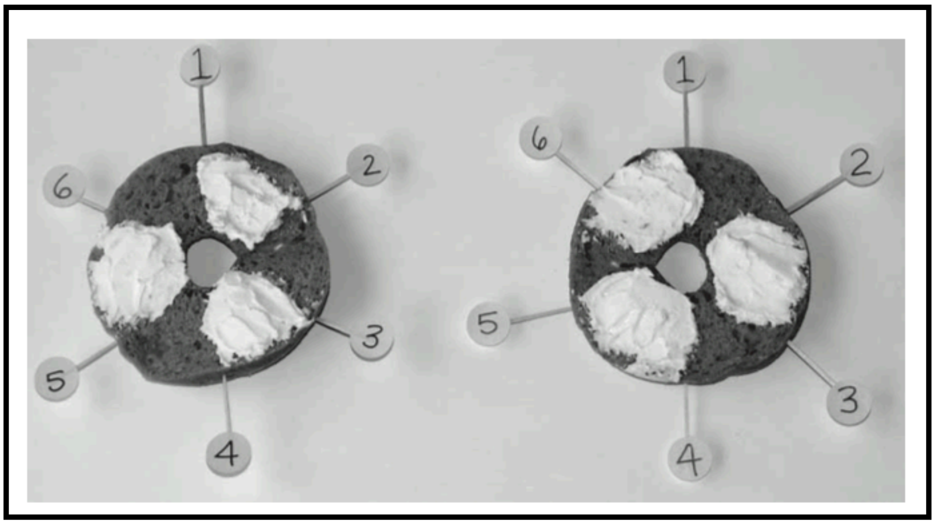


Note. Reprinted with permission from Silverstein T. P. (1999), The ‘‘big dog-puppy dog’’ analogy for resonance. *Journal of Chemical Education, 76*(2), 206. https://doi.org/10.1021/ed076p206. Copyright 1999 American Chemical Society.

Bagel Analogy. Lin’s (2007) analogy is unique in that it is the only resonance analogy I found that required explicit active student participation. She used a bagel analogy to help her general chemistry students understand resonance. Like Starkey (1955) she analogized the benzene molecule. Students worked in pairs in which each student had half of a bagel and six toothpicks that they labeled with numbers 1-6. The numbered toothpicks, which each represented a carbon atom of benzene, were inserted into the bagel with the numbers increasing in the clockwise direction (Lin, 2007). Next, one student in the pair smeared cream cheese between the toothpicks 1-2, 3-4, and 5-6. While the other student smeared cream cheese between the toothpicks 2-3, 4-5, and 6-1 (Figure 23). The two bagel halves represented the two resonance structures of benzene (Figure 24). Lin (2007) emphasized the importance of having students take note that the two bagel halves are not identical to each other; it is impossible to rotate the halves in a way that the regions of cream cheese would align. Next, the students were instructed to smear the cream cheese across the entire half of the bagel. The smeared cream cheese is meant to depict the spreading of electron density over all six of the carbon atoms in benzene (i.e., the resonance hybrid of benzene).

Figure 23

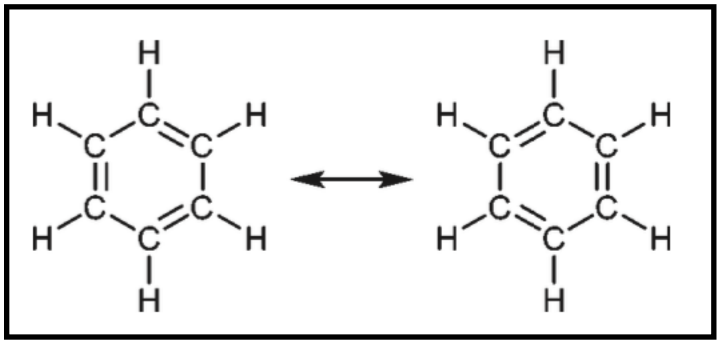
Bagel Halves Representing the Resonance Structures of Benzene



Note. Reprinted with permission from Lin S., (2007). Aromatic bagels: An edible resonance analogy. *Journal of Chemical Education, 84*(5), 779. https://doi.org/10.1021/ed084p779. Copyright 2007 American Chemical Society.

Figure 24

Resonance Structures of Benzene



Note. Reprinted with permission from Lin S., (2007). Aromatic bagels: An edible resonance analogy. *Journal of Chemical Education, 84*(5), 779. https://doi.org/10.1021/ed084p779. Copyright 2007 American Chemical Society.

Other Techniques for Teaching Resonance Concepts

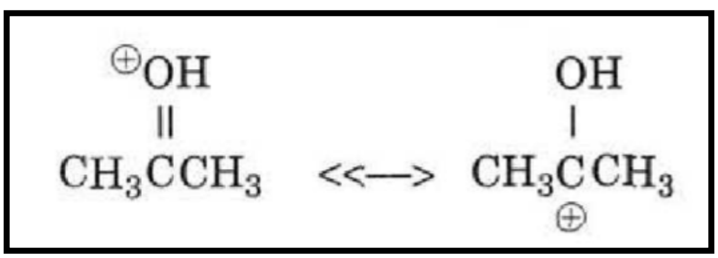
Practitioners have also used other simple and creative ways to re-frame the teaching of resonance in their classrooms (Abel & Hemmerlin, 1991; Richardson 1986).

Transparent Overlays. Richardson's (1986) technique aimed to address students' misconception that resonance structures are real entities that exist in nature. He suggested using transparent overlays in which one resonance structure is projected on top of the other, indicating that the resonance hybrid is a combination of the two Lewis structures. Richardson (1986) believed that the double headed arrow contributed to students' misconception that the resonance structures are in equilibrium, he suggested not depicting it until after students have had time to understand resonance. It is important to note that this teaching strategy is a great starting point for introductory students, but it does not account for the fact that some resonance structures are not equal contributors to the resonance hybrid, which was of great concern for Abel and Hemmerlin (1991).

Modifying Resonance Arrows. After Abel and Hemmerlin (1991) described their color analogy for resonance, they provided instructors with one last suggestion to improve the teaching of resonance: the modification of the resonance arrow. That is, the practitioners suggested that when one resonance structure contributes more than another that an “extra” arrow tip be added in the direction of that structure, as in the example shown in Figure 25. The practitioners believed this was easier than labeling the resonance structure as the major contributor. They also stated that they had successfully used this modification for over five years and believed it helped their students understand that resonance structures are not real and do not flip back and forth, although they did not present any data to confirm their assumption.

Figure 25

Example Showing Modification of Resonance Arrows



Note. Reprinted from Abel, K. B., & Hemmerlin, W. M. (1991). Explaining resonance—A colorful approach. *Journal of Chemical Education, 68*(10), 834. https://doi.org/10.1021/ed068p834. Copyright 1991 American Chemical Society.

Primary Research Foci Related to the Teaching and Learning of Resonance

The research findings discussed thus far have focused on general chemistry and organic chemistry students’ challenges with resonance, followed by a discussion of different analogies and other teaching strategies that practitioners have proposed to address some of those challenges. In the next section, I will examine the overarching themes of the existing literature. That is, instead of describing specific findings (e.g., student challenges) within each of the studies, I will present the research foci of the studies. In other words, when researchers study the teaching and learning of resonance, what do they focus on? This perspective of the literature is important as it helps to position this study within the broader academic landscape.

In the literature I reviewed, I found three themes of research foci: (1) establishment and analysis of a set of shared learning outcomes related to resonance, (2) connection between instructional strategies and students' conceptual understandings of resonance, and (3) students' application of resonance in a context. Here, I will present those themes, along with any corresponding findings that have not been discussed previously in this dissertation. Please note that the only articles considered for this section of the literature review were those where resonance was the primary focus of the reported study, as opposed to a secondary focus. These themes and their associated publications are listed in Table 4 in the order in which they will be discussed.

Table 4

Primary Research Foci Related to the Teaching and Learning of Resonance

Primary Research Foci	General Chemistry Publications	Organic Chemistry Publications
• Establishment and Analysis of a Set of Shared Learning Outcomes Related to Resonance		• Carle and Flynn (2020)
• Connection between Instructional Strategies and Students' Conceptual Understandings of Resonance		• Atieh et al. (2022); Brandfonbrener et al., (2021); Kim et al. (2019); Xue and Stains (2020)
• Students' Application of Resonance in a Context	• Shah et al. (2018)	• Ferguson and Bodner (2008); McClary and Talanquer (2011a, 2011b); Petterson et al. (2020)

Establishment and Analysis of a Set of Shared Learning Outcomes Related to Resonance

Previous studies have identified aspects of resonance that educational researchers believed general chemistry and organic chemistry students should know about resonance (e.g., Betancourt-Perez et al., 2010; Xue & Stains, 2020), but Carle and Flynn (2020) were the first to identify evidence-based learning outcomes related to resonance (which they refer to as "delocalization") concepts. They identified ten essential learning outcomes that students should achieve by the end of the organic chemistry series. They also investigated how the essential learning outcomes are taught, practiced, and assessed in organic chemistry. First, an overview of their research methodology will be presented. Next, a discussion of each of the ten essential learning outcomes will be presented, followed by a discussion of the associated implications.

Carle and Flynn's (2020) Methodology. The ten essential learning outcomes were identified by conducting a content analysis of seven of the main textbooks used to teach organic chemistry (Carle & Flynn, 2020). In general, the content analysis was a multi-step process that required the first author to identify or flag each section of the textbooks in which resonance was either mentioned or required. After this process, the authors began coding each of the sections based on similarity. For example, the flagged sections that addressed drawing resonance structures were all grouped. This stage of the process resulted in thirty-three learning outcomes related to resonance.

Next, the authors were interested in further refining these learning outcomes by consulting with two researchers and five organic chemistry instructors, each with their doctorate in organic chemistry. To do so, the researchers sent the experts the thirty learning outcomes and asked them to rank each of them as either "essential, useful but not essential, not essential, or to be left for later courses" (Carle & Flynn, 2020, p. 625). The researchers also gave the experts the chance to add any learning outcomes that they believed were missing, but none did. These results were statistically analyzed to determine the importance of each learning outcome using a content validity ratio (Carle & Flynn, 2020). Content validity is a "trigger mechanism to link abstract concepts [e.g., learning outcomes] to visible and measurable indices" (Zamanzadeh et al., 2015, p. 166). It is calculated using the following formula: $\left(\mathrm{N_e} - \frac{\mathrm{N}}{2}\right)\left(\frac{\mathrm{N}}{2}\right)$, where N_e is equal to the number of experts that deemed the information "essential" and N is equal to the total number of experts (Zamanzadeh et al., 2015). The numeric value of the content validity ratio is referenced using the Lawshe Table (Zamanzadeh et al., 2015). The ratio can very between 1 and -1

(Zamanzadeh et al., 2015). A score closer to 1 indicates more agreement from the experts interviewed about the necessity of an item in an instrument. In Carle and Flynn's (2020) study, if the content ratio was over 0.8, the content was considered essential by a majority of the experts. This analysis resulted in ten of an original thirty-three learning outcomes being deemed as essential learning outcomes related to resonance.

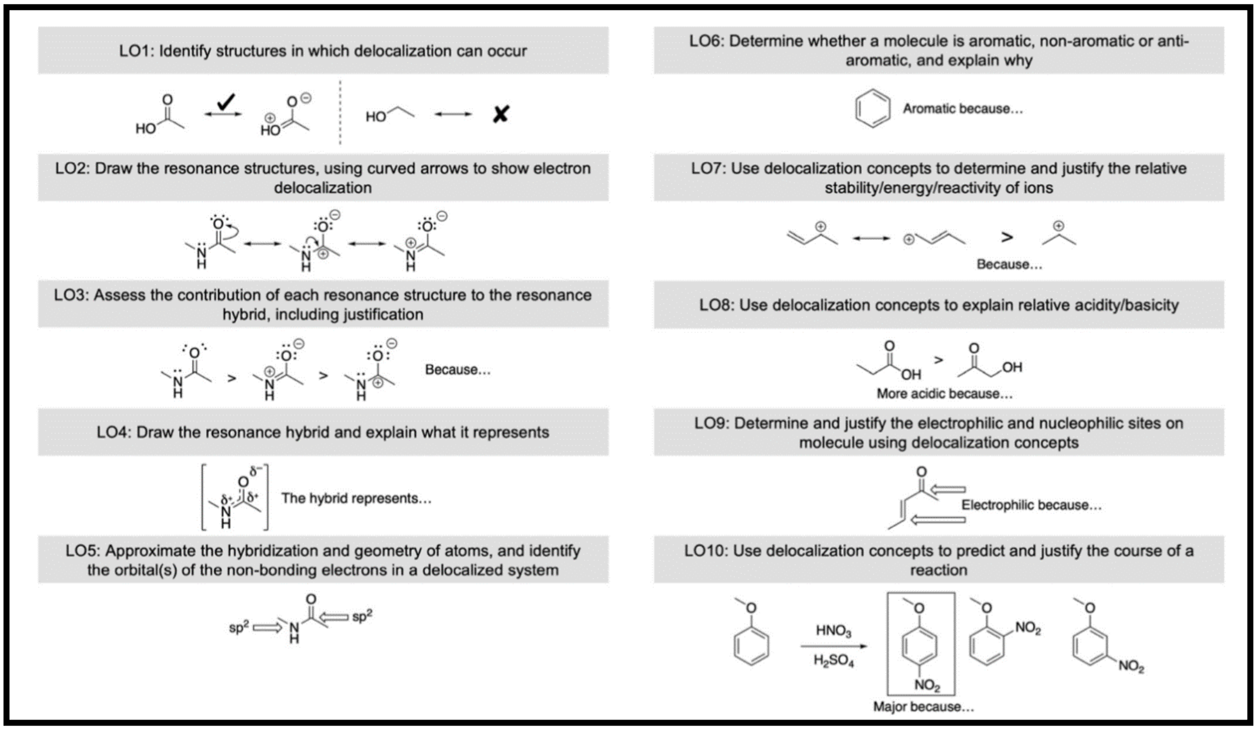
The researchers were also interested in how the learning outcomes were taught, practiced, and assessed in organic chemistry (Carle & Flynn, 2020). To examine how the learning outcomes were *taught*, the researchers revisited each of the flagged sections in the seven textbooks and identified the common themes in how resonance was addressed and made sure to note any inconsistencies between textbooks. To examine how the learning outcomes were *practiced*, the researchers labeled all of the end of chapter questions as either requiring or not requiring an understanding of resonance. The questions that required an understanding of resonance were linked to their associated learning outcomes. To examine how the learning outcomes were *assessed*, the researchers examined (1) fifty-one different organic chemistry summative exams from research intensive universities and (2) the Organic Chemistry Practice Exam from the American Chemical Society Exams Institute. Within each exam, the researchers flagged any question that either explicitly (states resonance is needed to solve the problem) or implicitly (does not state that resonance is needed to solve the problem) required an understanding of resonance concepts and linked these to their associated learning outcomes. In the discussions that follow, I use the phrase "practice questions" to refer to the resonance-related end-of-chapter problems and the phrase "assessment questions" to refer to the resonance-related questions that came from the analyzed exams.

Ten Essential Learning Outcomes. There are ten learning outcomes related to resonance concepts that Carle and Flynn (2020) identified as essential to students' success in organic chemistry. These essential learning outcomes, along with examples, are shown in Figure 26. The researchers provided a one-word identifier for each learning outcome that will be used verbatim for consistency purposes (Carle & Flynn, 2020). The essential learning outcomes build on each other and are listed in the order of increasing complexity. Each of these ten essential learning outcomes will be discussed based on Carle and Flynn's (2020) analysis of how they were taught, practiced, and assessed.

Identify. The first essential learning outcome was termed *Identify* by Carle and Flynn (2020). According to this essential learning outcome, students should be able to identify if resonance can occur in a structure or not (Carle & Flynn, 2020). This essential learning outcome was directly taught in three of the textbooks analyzed and was addressed within the first five chapters of all three textbooks (Klein, 2012; Smith, 2014; Ogilvie et al., 2018). For example, Klein (2012) provided students with a list of five patterns to help them identify (and draw) resonance (Figure 9). Around 6% of the resonance-related practice questions were directly related to this learning outcome (Carle & Flynn, 2020). For example, after students were introduced to the five patterns used to identify resonance, Klein provided a series of compounds and directly asked students to identify the pattern(s) used to do so (Klein, 2012). Around 7% of the resonance-related assessment questions were directly related to this essential learning outcome (Carle & Flynn, 2020). It was assessed in both the first and second semester of organic chemistry in explicit ways. *Identify* is a prerequisite skill for the other essential learning outcomes.

Figure 26

Ten Essential Learning Outcomes Related to Resonance Concepts



Note. Used with permission of Royal Society of Chemistry, from Essential learning outcomes for delocalization (resonance) concepts: How are they taught, practiced, and assessed in organic chemistry?, M.S. Carle and A.B. Flynn, volume 21, 2019; permission conveyed through Copyright Clearance Center, Inc.

Draw. The second essential learning outcome was termed *Draw* by Carle & Flynn (2020). According to this essential learning outcome, students should be able to use curved arrow notation to draw resonance structures (Carle & Flynn, 2020). This outcome was addressed within the first two chapters of all seven textbooks. For the most part, this essential learning outcome was taught using a set of rules or patterns. For example, as described above, Klein (2012) provided students with a list of five patterns to help them identify and draw resonance structures (Figure 11). *Draw* was the most practiced of any of the essential learning outcomes; around 18%

of the practice questions related to resonance were directly related to this essential learning outcome. Similarly, *Draw* was also the most assessed of any of the essential learning outcomes; around 30% of the assessment questions related to resonance were directly related to *Draw*. This essential learning outcome was mostly assessed in the first semester of organic chemistry in explicit ways. Being able to draw resonance structures is a prerequisite skill for all of the remaining essential learning outcomes.

Contribution. The third essential learning outcome was termed *Contribution* by Carle and Flynn (2020). According to this essential learning outcome, students should be able to assess and justify which resonance structure(s) will be the major contributor(s) or best representation of the resonance hybrid (Carle & Flynn, 2020). This outcome was addressed within the first two chapters of all seven textbooks. For the most part, this essential learning outcome was taught using a set of rules. However, four of the textbooks also used chemical stability as a way to situate the importance of being able to identify the major contributor of the resonance hybrid (Solomons & Fryhle, 2000, 2011; Wade, 2010; Vollhardt & Schore, 2018). For example, Klein (2012) provided students with causal reasoning behind why one resonance structure can contribute more to the resonance hybrid than another, as well as a series of rules to help students identify the major contributor. Around 4% of the resonance-related practice questions were directly related to this learning outcome. Like *Identify* and *Draw,* the *Contribution* practice questions were asked in explicit ways. For example, a practice question might ask a student to draw the significant structures for a compound (Wade, 2010). Around 14% of the assessment questions identified were directly related to this outcome. This essential learning outcome was only assessed in the first semester of organic chemistry in explicit ways (Carle & Flynn, 2020). This essential learning outcome also represents a prerequisite skill that students will need later in the course. For example, upon mastering this essential learning outcome, students should be able to quickly identify the reactive sites of a compound (Carle & Flynn, 2020).

Hybrid. The fourth essential learning outcome was termed *Hybrid* by Carle and Flynn (2020). According to this essential learning outcome, students should be able to draw the resonance hybrid after identifying the major contributors and be able to explain what the hybrid represents (Carle & Flynn, 2020). While the resonance hybrid was discussed in all seven textbooks, only four of the textbooks addressed how to draw the resonance hybrid and what the symbolism represents (e.g., dashed lines represent electron density delocalization) (Ogilvie et al., 2018; Smith, 2014; Solomons & Fryhle, 2000, 2011). The three other textbooks took a variety of approaches to teach about the resonance hybrid. For example, Wade (2010) and Vollhardt and Schore (2018) showed an image of the resonance hybrid and described it as a combination of the resonance structures, while Klein (2012) used an analogy to describe the resonance hybrid as the actual representation of the resonance structures but did not show an image of it. Only around 0.7% of the practice questions identified were directly related to *Hybrid*, making it the least practiced essential learning outcome. Only three of the textbooks had practice questions related to this learning outcome (Solomon & Fryhle, 2011; Smith, 2014; Vollhardt & Schore, 2018). Around 1% of the assessment questions identified were directly related to this essential learning outcome (Carle & Flynn, 2020). Furthermore, this essential learning outcome was only assessed in the first semester of organic chemistry in explicit ways (Carle & Flynn, 2020). It was not directly evident that students would need this skill later in the course.

Hybridization. The fifth essential learning outcome was termed *Hybridization* by Carle and Flynn (2020). According to this essential learning outcome, students should be able to use resonance structures to identify the expected hybridization states and approximate the geometry of atoms in a molecule that exhibits resonance (Carle & Flynn, 2020). This essential learning outcome was addressed in different places in the seven textbooks; its location in the textbooks was the most varied of any of the essential learning outcomes. Concepts related to this essential learning outcome are taught before resonance in four of the textbooks (Solomons & Fryhle, 2000, 2011; Wade, 2010; Volhardt & Schore, 2018), while the remaining textbooks introduced these concepts after resonance. This outcome requires that students have mastered the first four essential learning outcomes. Students must first be able to identify if resonance is possible, draw the resonance structures, and identify the major contributors to assess which contributors will affect the hybridization of a particular atom more. Only three of the textbooks directly taught how to identify the hybridization states and approximate the geometry of atoms in a molecule that exhibit resonance (Klein, 2012; Smith, 2014; Wade, 2010). Around 2% of the resonance-related practice questions were related to this learning outcome, while around 11% of the assessment questions identified were directly related to this essential learning outcome. This essential learning outcome was assessed most often in the first semester of organic chemistry in explicit ways.

Aromatic. The sixth essential learning outcome was termed *Aromatic* by Carle & Flynn (2020). According to this essential learning outcome, students should be able to conceptualize what makes a molecule aromatic and how aromaticity might be used to predict molecular reactivity (Carle & Flynn, 2020). This essential learning outcome was most often taught in the middle of all seven textbooks, when conjugation and aromaticity were first introduced. The textbooks taught this essential learning outcome using a series of rules—such as the compound must be a ring structure with delocalized π electrons and follow Huckel's rule to be aromatic (Carle & Flynn, 2020). Carle and Flynn (2020) argue that this approach lacks causal reasoning and does not explain why these guidelines can be used to identify aromatic compounds. Around 4% of the resonance-related practice questions were related to this essential learning outcome, while around 10% of the assessment questions were directly related to this outcome. Furthermore, this essential learning outcome was assessed most often in the second semester of organic chemistry in explicit ways.

Stability/ Reactivity. The seventh essential learning outcome was termed *Stability/ Reactivity* by Carle and Flynn (2020). According to this essential learning outcome, students should be able to apply resonance concepts to identify an ion's relative stability, energy, and reactivity (Carle & Flynn, 2020). This essential learning outcome was most often taught at the beginning of all seven textbooks. The textbooks only briefly explained the concept and most did not make direct connections with resonance. Around 3% of the practice questions were related to this essential learning outcome. Interestingly, this learning outcome was assessed significantly more often than it was practiced. Around 17% of the assessment questions were directly related to this essential learning outcome. It was assessed in both the first and second semester of organic chemistry, most often in implicit ways, indicating the first shift (from explicit to implicit) in how questions related to resonance are asked.

Acid/Base. The eighth essential learning outcome was termed *Acid/Base* by Carle and Flynn (2020). According to this essential learning outcome, students should be able to apply resonance concepts to explain relative acidity and/or basicity (Carle & Flynn, 2020). This essential learning outcome was taught at the beginning of all seven textbooks. The textbooks only briefly explained the connection between resonance and acidity/basicity (Carle & Flynn, 2020). For example, Klein makes a broad statement that Carle and Flynn argued promotes rule-based reasoning, ''In this case, the charge is delocalized over both oxygen atoms. Such a negative charge will be more stable than a negative charge localized on one oxygen'' (Klein, 2012 p. 110). Around 11% of the practice questions were directly related to this essential learning outcome (Carle & Flynn, 2020). The most common type of practice question related to this essential learning outcome asked students to compare different conjugate bases in different environments: in these problems, one of the conjugate bases was resonance-stabilized and the other was not (Carle & Flynn, 2020). Around 38% of the assessment questions were directly related to this outcome (Carle & Flynn, 2020). *Acid/Base* was assessed in both the first and second semester of organic chemistry, most often in implicit ways (Carle & Flynn, 2020).

Electrophilic/ Nucleophilic. The ninth essential learning outcome was termed *Electrophilic/Nucleophilic* by Carle and Flynn (2020). According to this essential learning outcome, students should be able to apply resonance concepts to determine and justify the reactive sites of molecules (Carle & Flynn, 2020). This essential learning outcome was only addressed by one of the textbooks, two chapters after resonance was first introduced (Ogilvie et al., 2018). Thus, students are left to make the connection between resonance and areas of high and low electron density of a molecule on their own (Carle & Flynn, 2020). Around 2% of the practice questions were directly related to this essential learning outcome (Carle & Flynn, 2020). This essential learning outcome was not assessed (Carle & Flynn, 2020).

Reaction. The tenth essential learning outcome was termed *Reaction* by Carle and Flynn (2020). According to this essential learning outcome, students should be able to apply resonance when appropriate to predict and justify reaction mechanisms. This essential learning outcome was taught towards the middle/end of all seven textbooks. Around 6% of the practice questions were directly related to this essential learning outcome (Carle & Flynn, 2020). Similarly, around 10% of the assessment questions were directly related to this essential learning outcome. This outcome was assessed almost exclusively in the second semester of organic chemistry and in explicit ways (Carle & Flynn, 2020).

Implications. Carle and Flynn's list of ten essential learning outcomes could be used as a tool for both educational researchers and practitioners to investigate the teaching and learning of resonance (Carle & Flynn, 2020). That is, practitioners can evaluate their own teaching practices based on these ten essential learning outcomes, as well as provide students with the outcomes to help guide their studying (Carle & Flynn, 2020). Researchers can use these ten essential learning outcomes to investigate the teaching and learning of resonance (Carle & Flynn, 2020). For example, Brandfonbrener et al.'s (2021) study used the ten essential outcomes to build a coding framework to analyze their data on students' written descriptions/explanations of resonance, as will be discussed in a section that follows.

The essential learning outcomes can also be used to identify potential shortcomings in the teaching of resonance. For example, the researchers argued, based on their analysis of the ten essential learning outcomes, that there are three shortcomings related to the current teaching of resonance: (1) textbooks do not do a complete job teaching resonance, (2) textbooks use rule-based reasoning to teach resonance (i.e., textbooks focus on the operational aspects versus the conceptual aspects of resonance) and (3) textbooks do not directly help students understand how resonance is used in a context (Carle & Flynn, 2020).

The authors argued the first shortcoming primarily based on the notion that the textbooks did not emphasize dispelling common misconceptions that the research literature has identified students having. For example, when first introducing how to *Identify* resonance, the textbooks mention that resonance structures are not real entities and do not exist in equilibrium; however, this is never mentioned again throughout any of the textbooks (Carle & Flynn, 2020).

The authors argued the second 82imensionalg primarily based on the notion that the textbooks did not encourage conceptual understandings of resonance. For example, when introducing how to decipher the relative *Contribution* of different resonance structures to the resonance hybrid, the textbooks used a set of rules. Providing students with a series of rules is not inherently bad teaching; however, with one exception (Klein, 2012), the textbooks did not help students connect the rules with concepts explaining why a particular structure was the major contributor (Carle & Flynn, 2020). In other words, the textbooks use rules to emphasize students' development of operational understandings of resonance over conceptual understandings of resonance. This could, in part, explain students' focus on *using* resonance instead of *understanding* it, as has been reported in the research literature (Atieh et al., 2022; Brandfonbrener et al., 2021; Braun et al., 2022). Unfortunately, this lack of conceptual understanding could be a problem, as Braun et al. (2022) showed that without conceptual understandings, students' operational understandings of resonance can suffer.

The authors argued the third shortcoming primarily based on the notion that the textbooks do not situate resonance within the contexts in which it is needed. For example, the textbooks did not provide direct and meaningful connections between resonance and the essential learning outcomes of *Stability/Reactivity, Hybridization, Acid/Base,* and *Electrophilic/Nucleophilic*, leaving students to make the connections themselves.

Connection between Instructional Strategies and Students' Conceptual Understandings of Resonance

Another focus of the educational research has been investigating a connection between specific instructional strategies and students' conceptual understanding of resonance. This involved implementing different instructional interventions that focused on developing students' conceptual understandings of resonance (Brandfonbrener et al., 2021; Kim et al., 2019), as well as exploring instructors' perceptions of their teaching practices related to resonance (Atieh et al., 2022; Xue & Stains, 2020).

Previously, in this dissertation, I discussed that students struggle to describe resonance in conceptually correct ways. Here, I will present a more general discussion of students' conceptual understandings of resonance and how instruction might impact these understandings. I will first discuss studies related to specific instructional strategies used in general chemistry classes, followed by a discussion of studies related to strategies used in organic chemistry classes.

General Chemistry. Kim et al. (2019) used a mixed-methods research methodology to determine if traditional conventions for representing resonance structures were adequate for helping general chemistry students come to a conceptual understanding of resonance. The researchers wanted to know what features of resonance structures students were drawn to and how that affected their conceptualization of resonance (Kim et al., 2019). The study was broken down into two main stages. As previously discussed, results from stage one indicated that some students struggled to provide a conceptually correct description of resonance structures (Kim et al., 2019). Therefore, in stage two of the study, the researchers were interested in how an instructional intervention might mitigate this challenge. The instructional intervention and results will be discussed below.

Instructional Intervention. The researchers developed an instructional intervention to help students to develop metarepresentational competence of resonance structures (Kim et al., 2019). Metarepresentational competence focuses on having students move beyond the simple usage of representations to a deeper understanding of the strengths and limitations of representations by requiring students to create or develop their own representation (Kim et al., 2019). This stage of the study included two new cohorts of general chemistry students (Cohort B, N=29; Cohort C, N=38). Both cohorts of students were presented with the concept of resonance using the same teaching approach as in stage one, except instead of showing students the resonance structures, the researchers had students work in groups (three to four members per group) to create their own representation of benzene. To do this, students were provided with the bonding data of benzene (see Table 5) and asked to create a representation that incorporated the contradictions that were apparent from the bonding data (i.e., the fact the carbon-carbon bond lengths for benzene are all identical and somewhere in between that of single and double bond). After the groups constructed their own representations of benzene, each group presented their representation to the class. The class discussed each representation's strengths and limitations. The remaining instruction and materials were the same as in stage one. The effect of this instructional intervention was measured using the same open-response question that students took before instruction (i.e., students were provided with the resonance structures of the benzene molecule and asked to describe in written form what the image means to them) on the next mid-term exam item that covered resonance (there were several days lag time between the activity and the exam).

Table 5

Bonding Data of Benzene

Molecule	C-C Bond Order, calculated	C-C Bond length, pm
Ethane, CH_3-CH_3	1.01	150
Ethene, CH_2=CH_2	2.00	133
Ethyne, CH≡CH	2.96	120
Benzene, C_6H_6	1.42	139

Note. Used with permission of Royal Society of Chemistry, from An examination of students' perceptions of the Kekule resonance representation using a perceptual learning theory lens, T. Kim, L.K. Wright, & K. Miller, volume 20, issue 4, 2019; permission conveyed through Copyright Clearance Center.

Results. The data from the open response question were analyzed using perceptual learning theory. Perceptual learning theory aims to explain how people makes sense of their experiences through a series of four perceptual mechanisms: dimensionalization, segmentation, unitization, and idealization (Goldstone, 2000). Table 6 describes each of these perceptual mechanisms, as well as examples from student transcripts (Kim et al., 2019). The researchers used the perceptual mechanisms as a coding scheme for their data. For example, when students described the resonance structures of benzene as being "rotated or viewed from a different perspective" (Kim et al., 2019, p. 661) *dimensionalization* was coded. If a student described benzene in nature as "an average of both represented structures or in both forms simultaneously" (Kim et al., 2019, p. 661) *unitization* was coded. The pre-instruction and post-instruction responses, based on this coding scheme, were compared, as shown in Figure 27 (Kim et al., 2019). This comparison indicated that there was a decrease in students' misperceptions of the resonance structures after the instructional intervention (Kim et al., 2019). That is, significantly more responses were coded as *unitization* after the intervention compared to before (see Figure 25), thus suggesting that the instructional intervention helped students develop metarepresentational competence and form a more correct conceptual understanding of resonance (Kim et al., 2019).

Table 6

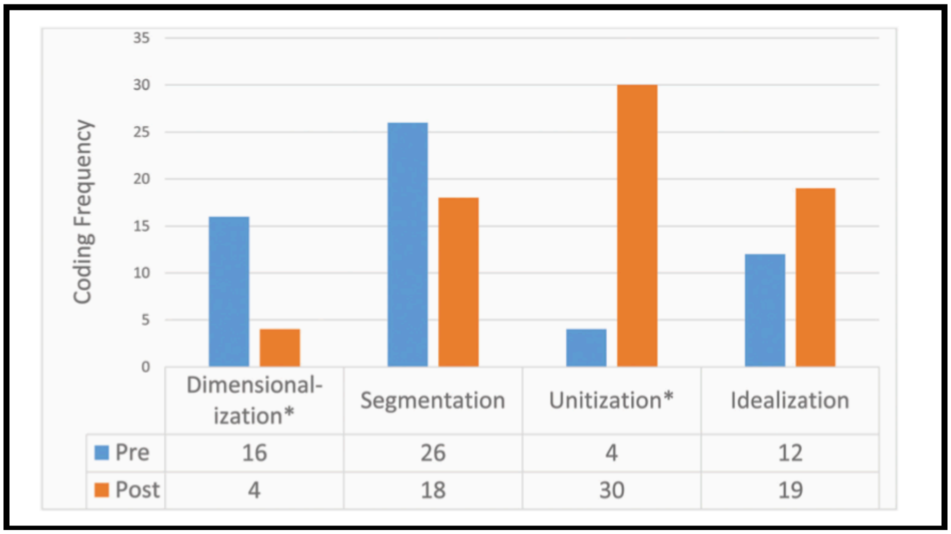
Description and Examples of the Perceptual Mechanisms

Perceptual mechanism	Description	Example quote
Dimensionalization	Witnessing variation along a perceptual dimension, *e.g.,* rotation, reflection	"The same molecule just flipped. Two different ways of drawing the same molecule."
Segmentation	Breaking objects into parts that are relevant or important, *e.g.,* bonds, bond order, isomers	"They are the same, the double bonds are just in different places—resonance structures"
Unitization	Creation of a single unit from multiple parts that occur together, *e.g.,* averaging, mixing, multiple representations	"These two molecules are resonance structures with the real structure being a blending of the two."
Idealization	Simplification of objects to capture the basic essence of the underlying concept	Re-drawing of figure as a hexagon with circle embedded inside

Note. Used with permission of Royal Society of Chemistry, from An examination of students' perceptions of the Kekule resonance representation using a perceptual learning theory lens, T. Kim, L.K. Wright, & K. Miller, volume 20, issue 4, 2019; permission conveyed through Copyright Clearance Center.

Figure 27

Comparison of Perceptual Learning Coding Responses Pre and Post Instruction



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Organic Chemistry. Xue and Stains (2020) used a mixed-methods research methodology to investigate how instruction might influence organic chemistry students' conceptual understanding of resonance. It is helpful to note that this aim was born out of the observation that students' responses about resonance (while investigating their first research question) seemed to differ depending on the section of organic chemistry in which they were enrolled.

Instructional Approaches of Professors 1 and 2. To address their research question, the researchers interviewed two organic chemistry professors, Professor 1 and Professor 2. In separate interviews, the instructors were asked to walk the researchers through their lecture notes on resonance (Xue & Stains, 2020). The analysis of these interviews revealed that while the researchers took many similar approaches to teaching resonance concepts, there were differences in what they did and did not emphasize during instruction (Xue & Stains, 2020).

The professors devoted around fifty minutes of lecture time to teaching resonance. They both began instruction by providing students with features and steps associated (i.e., operational aspects) with drawing resonance structures, as well as describing how to identify the major contributor to the resonance hybrid (Xue & Stains, 2020). Professor 1, however, emphasized the operational aspects of resonance throughout their lecture:

> Resonance is difficult for students. Even getting started. They don't know how to start to write resonance structures because they don't understand where electrons are pushed, where to start pushing, where to start pulling electrons from. So there are these basic patterns that you will see in any resonance structure that you are drawing and there might be a combination of more than one of these going on throughout the structure; but they just start to look for these; so I just show them a very simple model for each one and then I go through more complex problems in the notes. You know that looks bigger but they're still following these concepts. For example, phenolate has an oxygen with the lone pair next to a double bond; well that's the same pattern you see here so you should be able to follow the same arrow- pushing. (Xue & Stains, 2020, p. 899)

Professor 2 emphasized resonance in more conceptual ways by reiterating to students the limitations of chemical representations in chemistry: "So when I draw these two resonance contributors, I'm using curved arrows to show the movement of electrons, but when I think about the resonance hybrid, I'm thinking that electrons are everywhere... We can't represent [what molecule actually looks like] on a two-dimensional page" (Xue & Stains, 2020, p. 899). Furthermore, unlike Professor 1, Professor 2 directly addressed the resonance hybrid through an analogy (Xue & Stains, 2020). The professors assessed students' ability to draw resonance structures and identify the major contributor, but neither assessed students' ability to draw the resonance hybrid.

Results. To determine if there were differences in instructional approach and student learning, Xue and Stains (2020) used the data they collected via student surveys (previously discussed in Challenge 1). The researchers did not collect any student data before instruction. They did not provide examples of student responses from the survey data to better illustrate their statistical results, which could have provided more meaningful explanations (Xue & Stains, 2020). Nevertheless, the researchers found that students in Professor 1's section (N=95) (who, while teaching, emphasized the operational aspects of resonance) were significantly less likely to mention underlying concepts of resonance compared with students in Professor 2's section (N=85). That is, students enrolled in Professor 2's section (who, while teaching, emphasized the conceptual aspects of resonance) mentioned at least one underlying concept more frequently than students enrolled in Professor 2's (36% versus 9%).

Furthermore, students enrolled in Professor 2's section were also less likely to hold the misconception that resonance structures exist in nature and that they alternate back and forth (47% versus 72%). Finally, students enrolled in Professor 2's section could better describe the resonance hybrid than those in Professor 1's (7% versus 2%). The researchers acknowledge that while useful and interesting, these results are limited and do not demonstrate a causal relationship between instruction and students' understanding of resonance (Xue & Stains, 2020).

Instructors' Perceptions. In a later study, Xue and Stains collaborated with Atieh et al. (2022) to further explore the relationship between instruction and students' understandings of resonance. Specifically, this article focused on first-semester organic chemistry instructors' enacted Pedagogical Content Knowledge (ePCK) and how instructors' ePCK affects students' understandings of the resonance hybrid.

Pedagogical Content Knowledge (PCK) is the knowledge an instructor uses while teaching a specific topic to a specific group of students in a specific context (Atieh et al., 2022). PCK has four *main* components used by the authors in this study: (1) Knowledge of Curriculum (KoC), (2) Knowledge of Students (KoS), (3) Knowledge of Instructional Strategies (KoIS), and (4) Knowledge of Assessment (KoA) (Magnusson, Krajcik, & Borko, 1999). Effective instruction relies on the ability to integrate these components. There are three layers of PCK: collective PCK, personal PCK, and enacted PCK. This study addresses instructors' enacted PCK (ePCK), which can be defined as the professional content knowledge instructors use during (1) lesson planning, (2) teaching in the classroom, and (3) reflecting on their teaching.

Results. The researchers interviewed 15 first-semester organic chemistry instructors from 6 institutions across the United States. The instructors were asked open-ended questions regarding how they teach the resonance hybrid in their classrooms, including describing their lesson plans and reflecting on past experiences teaching about it. The transcripts were transcribed verbatim and coded using the four PCK components (KoC, KoS, KoIS, and KoA). The researchers also coded the transcripts for integrations between two or more PCK components. For example, one instructor explained during an interview that their students have difficulties understanding the resonance hybrid (the textual evidence was coded as KoS). This same instructor explained specific teaching strategies that they used to mitigate these difficulties (the textual evidence coded as KoIS). This instructor clearly integrated their knowledge of what their students find challenging about the resonance hybrid with their knowledge of specific instructional strategies to mitigate these difficulties.

After the initial round of analysis, the instructors were grouped based on commonalities. Overall, the researchers found that the instructors disagreed on the importance of teaching about the resonance hybrid and whether or not to assess students' understanding of it. There were three main groups of instructors. The first group of instructors believed it was important for students to have a conceptual understanding of the resonance hybrid and made sure to include a discussion of it while first introducing resonance to their students. They taught students about the resonance hybrid and addressed common student misconceptions but chose not to assess students on the resonance hybrid. They also did not discuss connecting the resonance hybrid to other topics. The instructors were more concerned with students' ability to draw resonance structures than their conceptual understanding of the resonance hybrid. For example, one instructor stated:

> I'm not assessing you on whether you can draw the hybrid structure, [I'm] assessing you on whether you can draw the contributors and tell me which one is the major one because, from a practical standpoint, that's the skill that you're going to need. Not that I don't want you to know the concept, but when, when we have to use resonance in the course of a reaction mechanism, that's probably going to be how you do it. (Atieh et al., 2022, p. 205)

The second group of instructors did not believe it was important to discuss the resonance hybrid while first introducing resonance to their students; they planned to do so later in the course (e.g., while discussing NMR data). This group of instructors chose to not assess students' understanding of the resonance hybrid. The third group represented a single instructor. This instructor taught students about the resonance hybrid while first introducing resonance. They also discussed how the resonance hybrid connects to other concepts later in the course. This instructor was the only one who chose to assess students' understanding of the resonance hybrid.

The researchers were also interested in the relationship between instructors' ePCK and first-semester organic chemistry students' understanding of the resonance hybrid. They administered surveys (see Challenge 2) to 361 students of the seven instructors who participated in the study. As previously mentioned (see Challenge 2), their analysis indicated no obvious alignment between the two. Overall, the students who participated in their study, regardless of which instructor they had, did not understand and/or held misconceptions about the resonance hybrid. The researchers reported that across all instructors, only 21.6% of students could correctly describe the resonance hybrid. Furthermore, only 20.1% of students could correctly draw the resonance hybrid. Instead, the students incorrectly described (39.1%) or incorrectly drew (54.1%) one of the resonance structures while describing or drawing the resonance hybrid.

Writing Assignment. Brandfonbrener et al. (2021) were interested in describing second-semester organic chemistry laboratory students' conceptual understandings of resonance and how resonance and chemical reactivity are related.

As previously discussed (see Challenge 1), the researchers used a writing assignment (Figure 14) to probe students' (N=105) conceptual understandings of resonance (Brandfonbrener et al., 2021). The students received no formal instruction on resonance before the writing assignment, as they were expected to have already been introduced to the concept in the first semester of organic chemistry (Brandfonbrener et al., 2021). The writing assignment was designed as an instructional strategy to support students' learning of resonance and allow researchers to investigate students' conceptions of resonance. This writing assignment required that students explain resonance to the general public, as well as the most salient aspects of resonance. They were also meant to include an example and a direct connection to how resonance influences chemical reactivity. The writing assignment encouraged but did not require students to provide an analogy in their responses. The students were given one week to independently work on the writing assignments before engaging in a double-blind peer review process (Brandfonbrener et al., 2021). The students were given another week to make revisions after peer review. Throughout this process, the students had access to undergraduate students who had already successfully completed the course and were trained in providing feedback on the writing assignments (Brandfonbrener et al., 2021).

Results. To examine students' conceptual understandings of resonance, the researchers developed a coding scheme incorporating Carle and Flynn's (2020) 10 essential learning outcomes (Brandfonbrener et al., 2021). The researchers argued that Carle and Flynn's (2020) 10 essential learning outcomes represent what is necessary for students to have mastered by the end of the second semester of organic chemistry to be successful in the course (Brandfonbrener et al., 2021). The coding scheme was used to "match" the learning outcomes to students' responses from the writing assignment. For example, while addressing how resonance influences chemical reactivity, one student stated, "Well, when a structure is stable, it's happy as it is. It does not want to react with other molecules because reacting with another molecule could make it unstable" (Brandfonbrener et al., 2021, p. 3438). This statement was coded as "Resonance leads to more stability" and was matched to the essential learning outcome *stability/reactivity.*

Brandfonbrener et al.'s (2021) findings provided insight into students' conceptual understandings of resonance and which aspects of resonance instructors might need to draw students' attention towards during instruction. As discussed previously, the researchers found that students' analogies of resonance were often incomplete and did not address all conceptual aspects of resonance (Brandfonbrener et al., 2021). Students tended to focus their explanations on the rules and processes (i.e., operational aspects) associated with drawing resonance structures and not the conceptual aspects of the concept (Brandfonbrener et al., 2021).

The researchers also found that students often used molecular examples of resonance to describe the concept (Brandfonbrener et al., 2021). The researchers found this interesting because students were only required to use an example to explain how resonance influences chemical reactivity, not resonance in general (Brandfonbrener et al., 2021). Therefore, the researchers argued that because 86.7% of students used an example to explain resonance that students find molecular examples of resonance useful. In these examples, students were more likely to use carbonyl-containing compounds than to use benzene to explain resonance to the general public (Brandfonbrener et al., 2021). For example, 34.1% of students used either a carboxylic acid or a derivative of a carboxylic acid that had resonance to explain the concept, while only 15.4% of students used benzene to explain resonance (Brandfonbrener et al., 2021). This aligned with the current research in that students find the resonance structure of benzene confusing (Kim et al., 2019); therefore, it is perhaps not surprising that many students did not use benzene as an example.

Furthermore, when asked to explain how resonance influences chemical reactivity, most students discussed the context of relative acidity (Brandfonbrener et al., 2021). For example, one student wrote,

> To tie this all together and mention one last important point about resonance and reactivity, lets [sic] consider two acidic molecules: one with resonance, and one without. Acids give up their hydrogens. When the H’s leave, two electrons are left behind. However, the molecule without resonance cannot do anything to move these electrons around and the negative charge is “stuck” in one place. In the resonating acid, the

> electrons can move around to different, more favorable positions. Thus, this negative charge is "shared" throughout the molecule. Thus, this molecule is more stable than an acid where the negative charge is stuck on one, unfortunate atom. (Brandfonbrener et al., 2021, p. 3437)

This finding suggests that students have mastered Carle and Flynn's (2020) essential learning outcome 8, termed *Acid/Base,* but not essential learning outcomes 6 and 9, termed *Aromatic* and *Electrophilic/Nucleophilic*. That is, while explaining how resonance influences chemical reactivity students tended to use examples related to *Acid/Base* (as illustrated in the student responses above) and not *Aromatic* and *Electrophilic/Nucleophilic*. The researchers argued that this suggests that students did not find these essential learning outcomes (i.e., *Aromatic* and *Electrophilic/Nucleophilic*) as important (Brandfonbrener et al., 2021). It is possible, however, that because these essential learning outcomes are more complex and the writing assignment directed students to explain resonance to the general public, the students might have left out examples of chemical reactivity related to these essential learning outcomes on purpose (Brandfonbrener et al., 2021).

Students' Application of Resonance in a Context

The last major focus of the educational research to be discussed is students' application of resonance in a context. McClary and Talanquer (2011a, 2011b), Shah et al. (2018), Ferguson and Bodner (2008), Finkenstaedt-Quenn et al. (2020), and Petterson et al. (2020) were all interested in how students apply resonance in a specific context. Previously, it was established that students struggle to apply resonance in a context. Now, a more general discussion of how students apply resonance in particular contexts will be discussed. Specifically, the researchers were interested in how students use resonance while solving (1) acid/base chemistry problems and (2) reaction mechanisms.

Students' Application of Resonance while Deciphering Relative Acidity

Some researchers have found that students apply resonance concepts while deciphering relative acidity (McClary & Talanquer, 2011a, 2011b; Shah et al., 2018). McClary and Talanquer (2011a, 2011b) and Shah et al. (2018) found that while students struggle to conceptually describe why resonance affects relative acidity, they often attempted to apply the concept while trying to decipher relative acidity for a set of substances.

McClary and Talanquer (2011a, 2011b) and Shah et al. (2018) found that students tended to focus on both the structural features of molecules that suggested resonance and the number of possible resonance structures a molecule might have when attempting to determine which of a set of molecules is more acidic. For example, McClary & Talanquer (2011a) found that if there was a benzene ring present, organic chemistry students had the tendency to use resonance in their predictions and explanation of relative acidity, as one student stated while ranking the relative acidity of the substances shown in Figure 28:

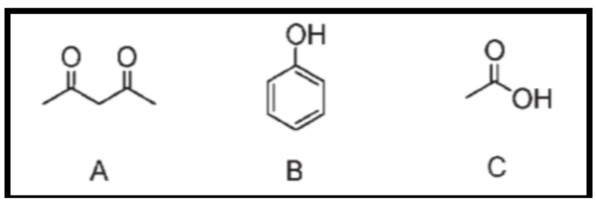
> This is a different thing altogether, but I'm pretty sure B is gonna be the most acidic. Well, for one reason, it's really, really stable. It has all these multiple resonance forms . . . you've got this benzene ring which basically is these two resonance forms that when you put them together are ridiculously stable. So, on that one, the stability makes it more acidic. Because it means that once the hydrogen comes off, what's remaining is also really stable. (McClary & Talanquer, 2011a, p. 408)

Similarly, a chemistry student enrolled in an advanced general chemistry course in Shah et al.'s (2018) study described the relative acidity of phenol and 2,4-pentadione:

So in terms of looking at [pentane-2,4-dione] and [phenol], cause that's what you have to compare, [phenol] has a benzene ring as opposed to [pentane-2,4-dione] so it would be able to stabilize its own charge more and have more resonance structures, as opposed to what I tried drawing for [pentane-2,4-dione]. So I felt like [phenol] had more resonance structures and it was more stable and more likely to act like an acid Instead of [pentane-2,4-dione]. (Shah et al., 2018, p. 550)

Figure 28

Series of Substances Students Ranked Based on Relative Acidity



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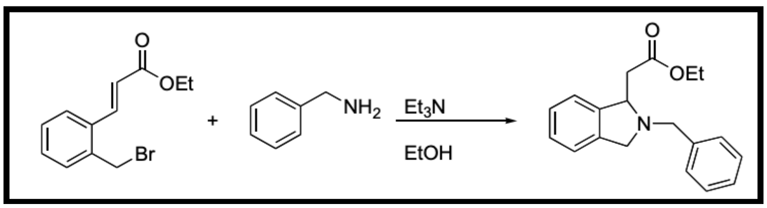
Students Apply Resonance while Solving Reaction Mechanisms.

Other researchers found that students apply resonance concepts while solving reaction mechanisms (Ferguson & Bodner, 2008; Finkenstaedt-Quenn et al., 2020; Petterson et al., 2020). In Ferguson and Bodner's (2008) qualitative study, organic chemistry students (N=16) solved a series of reaction mechanisms while explaining their thought processes. The researchers found that resonance was fundamental in students' thought processes towards understanding and solving the reaction mechanism (Ferguson & Bodner, 2008). For example, while solving the reaction mechanism shown in Figure 29, a student drew resonance structures (see Figure 30) to determine the course of the reaction, "the electrons here [nitrogen] were to attack at this carbon [the β-carbon] because you can draw the carbon as a negative charge on one end and a positive charge on the other end" (Ferguson & Bodner, 2008, p. 109).

Figure 29

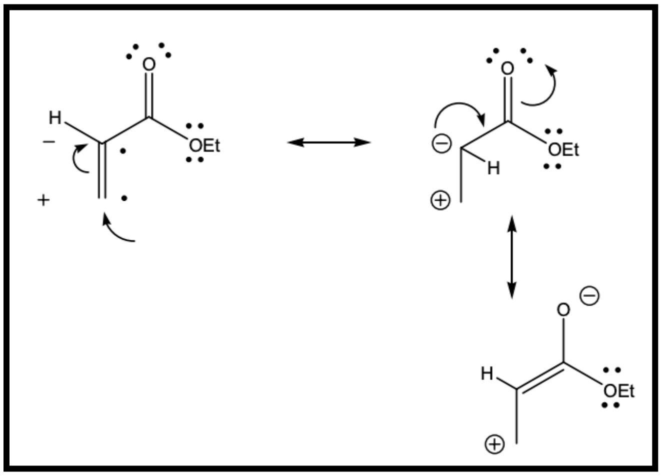
Reaction Mechanism Students Were Asked to Solve



Note. Used with permission of Royal Society of Chemistry, from Making sense of the arrow-pushing formalism among chemistry majors enrolled in organic chemistry, R. Ferguson and G.M. Bodner, volume 9, issue 2, 2008; permission conveyed through Copyright Clearance Center, Inc.

Figure 30

Student's Drawing of Resonance Structures to Solve Reaction Mechanism



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Petterson et al. (2020) shared similar results. They found that while some organic chemistry students struggled to appropriately apply resonance, there were other students that correctly employed the rules and syntax associated with resonance while solving a reaction mechanism. Finkenstaedt-Quinn et al. (2020) also shared similar results. Again, while they found that some organic chemistry students struggled to describe resonance stabilization in conceptually correct ways, there were also students who were able to correctly apply resonance while solving reaction mechanisms (Finkenstaedt-Quinn et al., 2020).

Justifications for the Current Study

It is evident from this review of the literature that information related to the teaching and learning of resonance is vastly underdeveloped in the research literature. This study addresses the following gaps in the research literature: (1) what do General Chemistry I and Organic

Chemistry I instructors want their students to understand about resonance, (2) what does the teaching of resonance in General Chemistry I and Organic Chemistry I classrooms look like and (3) what are General and Organic Chemistry I students' understandings of resonance?

What General Chemistry I and Organic Chemistry I Instructors Want Their Students to Understand about Resonance

There is very little information about what organic chemistry instructors believe students should understand about resonance and no information about what general chemistry instructors believe students should understand. These beliefs have important implications for the teaching and learning of resonance, as instructors' perceptions determine what they choose to expose students to in their classes via curricula and instructional design, ultimately determining what students in the classroom have the possibility to learn about resonance.

What the Teaching of Resonance in General Chemistry I and Organic Chemistry I Classrooms Looks Like

No studies have observed the actual teaching practices of resonance when it is first introduced in General Chemistry I or Organic Chemistry I classrooms. This is important because what instructors intend to teach is not always what happens in the classroom for numerous reasons, such as expert blind spots. It is not instructors' intentions that directly affect what students have the possibility to learn about, but rather what the students are exposed to in their classrooms.

General Chemistry I and Organic Chemistry I Students' Understandings of Resonance

There is very little information about General Chemistry I and Organic Chemistry I students' understandings of resonance. Thus, it will be important to determine what General

Chemistry I and Organic Chemistry I students understand about resonance and how those understandings align with what instructors intend for students to know about resonance.

CHAPTER 3 THEORETICAL FRAMEWORK

Qualitative Research

This study follows a qualitative research design. The nature of qualitative research is different than that of the typically more familiar quantitative research. Generally, the focus of quantitative research is numerical data that is interpreted using different statistical techniques to draw generalizable results (e.g., predictions, cause-effect relationships) across a population (Braun & Clarke, 2006). In contrast, qualitative research is not focused on broadly generalizable results across a population but rather in uncovering an individual's or group's meaning of a particular experience or phenomenon in their own words (Patton, 2002). Hypothetically, for example, an educational researcher might be interested in students' understandings of the electron transport chain. Instead of numerically evaluating students' understanding using a multiple-choice exam (i.e., quantitative research), instructors could interview students using a series of open-ended questions that probe their understandings of the process (i.e., qualitative research). Similar to quantitative research, there are many different types and approaches to qualitative research. However, despite the type of qualitative research being conducted, any qualitative research study should be guided by a theoretical framework (Bodner, 2007).

Theoretical Frameworks in Qualitative Research

A theoretical framework provides the researcher with the lens through which they will approach their study. In other words, it provides the theoretical assumptions and methodologies that the researcher will use, as well as the types of research questions that can be asked (Patton, 1990; 2002). Each theoretical framework has its own unique goals/purposes, focus, methods, results, and research questions. That is, two different research groups might be interested in students' understandings of Lewis structures, but depending on the theoretical frameworks selected, their studies could look completely different. For example, if the first research group selected the theoretical framework phenomenography to guide their study, their goals/purpose might be to identify the different ways in which individual students understand Lewis structures by collecting data through semi-structured interviews (Marton, 1981). On the other hand, if the second research group selected the theoretical framework communities of practice to guide their study, their goals/purpose might be to investigate how a group of students' shared knowledge of Lewis structures evolves over the course of a semester in the learning laboratory using a variety of data sources, such as semi-structured interviews, observational data, and field notes (Wenger, 2000).

Neither of the hypothetical studies described above is more important than the other; they simply are answering different research questions and looking at the topic of interest—students' understandings of Lewis structures—from different perspectives. Thus, it is important for the researcher to carefully select their theoretical framework, keeping in mind what is and is not possible to ask within the framework selected. Because I was interested in why/how there is variation in individuals' understanding of resonance, I selected variation theory to guide my research study, which aims to answer the following research questions:

1. What do General Chemistry I and Organic Chemistry I instructors intend for their students to understand about resonance?
2. What is possible for General Chemistry I and Organic Chemistry I students to understand about resonance in General Chemistry I and Organic Chemistry I classrooms based on the information presented to them in their classes?

3. What do General Chemistry I and Organic Chemistry I students understand about resonance after learning about it in their General Chemistry I and Organic Chemistry I classrooms?

Variation Theory

Variation theory is a theory of learning that is an independent, theoretical extension of traditional phenomenographic research (Bussey et al., 2013). Variation theory, though not yet referred to as such, was first described in Marton and Booth's 1997 publication entitled *Learning and Awareness*. It was this publication that marked the turning point from traditional phenomenographic research. While the two frameworks share theoretical assumptions, they differ in both the focus of the study and the types of questions that can be asked (Akerlind, 2015). For example, phenomenography is concerned with identifying the qualitatively different ways that people experience and understand a particular phenomenon (Marton, 1981). Variation theory, on the other hand, goes beyond the descriptive as it aims to investigate how and why people can experience the same phenomenon differently and how that information can inform classroom teaching and learning (Tan, 2009). Variation theory was applied to the field of chemistry education most notably through the work of Bussey et al., (2013). As such, their application of the framework (Bussey et al., 2013) had a key role in the development of this study. This chapter will discuss the aims, key concepts, assumptions, methodology (data collection and analysis), and limitations associated with variation theory research. Finally, a justification for using variation theory as the theoretical framework for this study will be presented.

Aims of Variation Theory

The overarching aim of variation theory is to describe the differences and/or similarities in students' understandings of a concept based on the variation in awareness of the aspects experienced when exposed to the same concept—and to use those findings to inform classroom teaching and learning (Marton & Booth, 1997). Students' understanding of a concept (later defined as the object of learning) can be described in terms of the specific aspects of the concept to which they pay attention (Marton & Booth, 1997). In other words, according to variation theory, a student creates meaning about the concept based on the aspects they notice during the learning event. Certain aspects (later defined as critical features) are critical in distinguishing the intended understanding of the concept (Marton, Runesson, & Tsui, 2004). To notice or pay attention to a particular feature (either critical or not) of the concept, students must experience variation within and between those features (Marton & Booth, 1997). It is this variation that characterizes students' different understandings of the concept and explains why two students sitting in the same classroom and hearing the same lecture about a concept can come to different understandings about the concept (Orgill, 2012). If educators want their students to come to understand a particular concept in a specific way, then they must direct students' focus to the "critical" features of the concept (Marton & Booth, 1997). Variation theory describes this process as being composed of three main components—awareness, discernment, and simultaneity (Marton & Booth, 1997).

Key Concepts of Variation Theory

The following section aims to discuss and provide examples of the key concepts and terminology associated with variation theory research. First, the concepts of awareness, discernment, and simultaneity will be discussed. This will be followed by a discussion of the object(s) of learning, critical features, and patterns of variation.

Awareness

The way students experience a new concept depends on which aspects of the concept students hold in their focal awareness (Marton & Booth, 1997), as no person can process or even be aware of all the aspects of a concept at any given time (Miller, 1956). That is, as the Nobel Prize winners Chabris and Simmons (2010) demonstrated in their famous "gorilla experiment," when people are focused on a certain aspect of a phenomenon, they can overlook many other things happening at the same time. For example, while learning how to identify an acid, a student might be aware that acids are substances that ionize in solution to give hydrogen ions while overlooking the aspects that strong acids will completely ionize and weak acids will only partially ionize. This raises the question, to which aspects do students direct their attention? According to variation theory, students are most likely to be drawn to the feature of the concept that is being varied (Marton & Booth, 1997).

Discernment

The way students assign meaning to the information brought into their focal awareness is through discernment (Marton & Booth, 1997). Discernment is students' ability to contrast what is brought into awareness (the concept) from its environment (everything else). This can be facilitated by variation (different types of the same concept) of that concept (Marton et al., 2004). For example, while learning how to identify an acid, students might be asked to notice different features of acids within the context of Arrhenius acids. One important feature of an Arrhenius acid is that the substance dissociates to give hydrogen ions in water. Therefore, being able to discern if a substance can or cannot dissociate to give a hydrogen ion in water becomes one important feature in being able to distinguish Arrhenius acids from other types of substances (e.g., other types of acids). To distinguish this critical feature, students must experience many different types of substances that can and cannot dissociate to give a hydrogen ion in water and then connect the "dissociation to give a hydrogen ion" as an important characteristic of an Arrhenius acid.

Simultaneity

It is rare, if ever, that a student would only need to be aware of a single feature of a given concept. Simultaneity is the students' ability to discern the variation between multiple features of the concept at the same time to make meaningful connections (Marton & Booth, 1997). For example, while learning to decipher a strong acid (e.g., HCl) from a weak acid (e.g., CH_3COOH) a student must first discern what an acid is (i.e., substances that ionize in solution to give hydrogen ions) as well as discern a strong acid (i.e., will completely ionize) from a weak acid (i.e., will partially ionize).

Object of Learning

The object of learning can be described as the something that is to be learned (Marton & Booth, 1997) and may be referred to synonymously with the terms concept, idea, or phenomenon (Bussey et al., 2013). For example, an elementary teacher might want to teach their students the concept of subtraction. The object of learning in this case would be subtraction. There are three different perspectives from which the object of learning can be examined: the intended object of learning, the enacted object of learning, and the lived object of learning. I will use the example of subtraction to discuss each of these three different objects of learning.

Intended Object of Learning

The intended object of learning refers to what the instructor intends for students to learn based on their selection, organization, and preparation of instructional materials (Marton et al., 2004). The intended object of learning is bound by the knowledge and experience of the teacher (Bussey et al., 2013). Take again subtraction as the object of learning. There is little chance that an elementary teacher expects their students to learn everything about subtraction. Instead, they might first only intend for their students to understand that subtraction is when you take numbers away and what the minus and equals signs represent.

Enacted Object of Learning

The enacted object of learning is what actually happens in the classroom or learning environment, regardless of what the instructor plans for their students to learn about a concept (Marton & Tsui, 2004). In other words, instructors create a space in which learning certain things about a concept can take place but cannot cause learning to occur (Marton et al., 2004). The possibility of what students can learn is confined by what actually happens in the classroom. Building on the example above, an instructor might intend for their students to understand that the equals sign represents two or more mathematical statements that are balanced to produce a Product that is the same. However, if the instructor does not explain this feature of subtraction during the lesson, the students can’t come to understand it. On the other hand, if the instructor does explain the concept, then it becomes possible for the student to form an understanding of what the equals sign means. It is important to note that, although the instructor has made it possible for students to learn the meaning of the equals sign, a *possibility* for learning does not guarantee that the learning will occur.

Lived Object of Learning

The lived object of learning refers to how students perceive and make sense of the enacted object of learning (Marton et al., 2004). In other words, the lived object of learning represents what is actually learned by the student and is impacted by the student's prior knowledge (Bussey et al., 2013). It is the "way students see, understand, and make sense of the object of learning when the lesson ends and beyond" (Marton et al., 2004, p. 22). Again, building on the example above, the students' understanding of the equals sign is co-constructed by their perception of what took place during the learning event (i.e., enacted object of learning) and their prior knowledge of the concept.

Critical and Non-Critical Features

Critical features can be described as the aspects that are critical for distinguishing the object of learning and are those to which instructors should direct their students' attention (Marton et al., 2004). According to variation theory, critical features of a concept are those that are essential for developing a correct understanding of a concept (Marton et al., 2004) and are dependent on the disciplinary level (e.g., kindergarten, 1st grade, etc.) as well as students' prior knowledge (Marton et al., 2004). A commonplace example might be useful to illustrate this idea. When teaching a child how to identify rotten milk (without tasting it), a critical feature is its sour smell. However, for the child to understand how a sour smell relates to rotten milk, they must experience variation within smell. That is, they must also experience what non-rotten milk smells like. It is this experience in the variation of smell that the child can use to understand how a sour smell relates to rotten milk. Smell is not the only feature that characterizes rotten milk. For example, the consistency of the milk (e.g., curdled milk) can also help signify rotten milk. Therefore, the curdled consistency is another critical feature of rotten milk. On the other hand, milk comes in many different types of containers (e.g., carton of milk). This feature is not critical in distinguishing if the milk has soured or not. Thus, the type of container is a non-critical feature (i.e., will not help the child understand how to identify rotten milk).

Patterns of Variation

According to variation theory, when students are first learning about a concept, it is difficult for them to discern all of the critical features of a concept at once (Marton & Pang, 2006; Marton et al., 2004). Instead, students must first discern the critical features individually before doing so simultaneously (Marton et al., 2004). To discern the features individually, students' attention must be drawn to those features. Variation theory suggests that this can be accomplished by varying certain critical features while keeping others the same (Pang & Marton, 2005). There are four main patterns of variation: contrast, separation, generalization, and fusion (Marton & Pang, 2006; Marton et al., 2004).

Contrast

The pattern of variation termed *contrast* allows students to compare a specific feature of a concept with what it is not (Bussey et al., 2013). For example, to experience what a mirror is, students must also experience different non-reflective items. That is, once the student has experienced many different items that are not reflective, they can better discern what a mirror is.

Separation

The pattern of variation termed *separation* allows students to focus on a single feature of a concept. This occurs when the feature of interest is varied while keeping all other features invariant (Bussey et al., 2013). For example, you could expose students to many different sized mirrors while keeping all other aspects of the mirror the same (e.g., the color of the reflective coating, the curvature of the glass). This might help students understand that reflection/ curvature of the glass are important features (i.e., critical features) of a mirror but size is not.

Generalization

The pattern of variation termed *generalization* allows students to apply their understandings of the concept to different contexts (Bussey et al., 2013). For example, to fully understand what a mirror is, students must experience it in many different contexts, such as in a dressing room or a scientific instrument, thus allowing students to generalize their understanding of the concept.

Fusion

The pattern of variation termed *fusion* allows students to discern multiple features of a concept that differ simultaneously (Bussey et al., 2013). For example, to fully understand what a mirror is, students should experience variation in all the critical aspects of a mirror (e.g., the shape of the surface, reflective covering, etc.) at once. Students' ability to recognize that not just one thing makes up the whole but rather that many different aspects make up the whole (Marton et al., 2004) is an important part of students creating a meaningful understanding of the concept.

Assumptions of Variation Theory

Regardless of the theoretical framework chosen for a study, there are underlying assumptions on which the framework is built. As variation theory was developed from phenomenography, the frameworks share similar epistemological assumptions. Contrary to positivist/objectivist theoretical perspectives of knowledge, variation theory assumes knowledge to be non-dualistic and relational (Akerlind, 2015). That is, any student's understandings of a specific concept are a result of their past and present experiences with their external world. Another assumption of variation theory, like that of phenomenography, is that researchers can access the student's constructed meaning of an object of learning through language. In other words, it is assumed that a student's re-telling of their experience is synonymous with what actually took place and provides the researcher with access to the student's experiences, perceptions, or conceptions (Svensson, 1997).

Methodology: Data Collection

Three different research questions can be asked when designing a research study informed by variation theory: (1) what do instructors intend for students to learn about a concept? (intended object of learning), (2) what is actually possible for students to learn about the concept (based on what they have been exposed to in the classroom)? (enacted object of learning), and (3) what did students actually learn about the concept? (lived object of learning) (Bussey et al., 2013). To investigate these research questions, two main sources of data must be collected: (1) interview data and (2) observational data.

Data analysis in variation theory is dependent on the object of learning and the research question that was asked. As such, data collection will be described for each of the three different objects of learning and their respective research questions.

Intended Object of Learning: What Do Instructors Intend for Students to Learn About a Concept?

The purpose of data collection for the intended object of learning is to answer the question "what do instructors intend for students to learn or understand about a concept?" (Bussey et al., 2013). The data collected to answer this question usually involves one-on-one semi-structured interviews between the researcher and instructor but could also involve written artifacts or group discussions (Marton & Booth, 1997). For example, in an interview, the researcher might ask instructors how they go about introducing the concept (i.e., object of learning) in their classroom or how they typically assess students' understanding of the concept. This data represents a second-order perspective, which means that the information is expressed by someone other than the researcher, in this case, the instructors (Marton & Booth, 1997).

Enacted Object of Learning: What is Actually Possible for Students to Learn about the Concept?

The purpose of data collection for the enacted object of learning is to answer the question "what is actually possible for students to learn about the concept (based on what they have been exposed to in the classroom)?" The data is usually collected through direct, unobtrusive classroom observations (Marton & Booth, 1997). For example, the researcher might record and/or take detailed notes during the entire class period in which the object of learning is being taught. This data represents a first-order perspective, which means that it is the researcher that decides what was possible to learn during the learning event (Marton & Booth, 1997; Runesson, 2005).

Lived Object of Learning: What Did Students Actually Learn About the Concept?

The purpose of data collection for the lived object of learning is to answer the question "what did students learn about the concept?" (Bussey et al., 2013). Like the intended object of learning, the data collected to answer this question usually involves one-on-one semi-structured interviews between the researcher and students but could also involve written artifacts or group discussions (Marton & Booth, 1997). For example, in an interview, the researcher might ask the student to describe what they understand about a concept (i.e., the object of learning), to solve a problem about the concept while thinking aloud, or to imagine they are the teacher and to describe the challenges they foresee their students having with the concept. Like the intended object of learning, this data represents a second-order perspective (Marton & Booth, 1997).

Lived Object of Learning and Students' Prior Knowledge

It is important to note that Bussey et al. (2013) proposed an extension of variation theory for the lived object of learning. They argued that to truly discover the lived object of learning, students' prior knowledge must be investigated before the learning event takes place. Bussey et al. (2013) argued the importance of this extension of variation theory because research has shown that prior knowledge plays a fundamental role in forming conceptual knowledge (Novak, 1990). There is currently no uniform way in which a study informed by variation theory assesses students' prior knowledge; and, indeed, it may not be practical to attempt to measure a student's prior knowledge before a learning event occurs. Bussey et al. (2013) suggested implementing an interview, survey, or questionnaire before the learning event to assess students' prior knowledge of the concept; however, the examination of prior knowledge is not currently a part of most studies informed by variation theory.

Methodology: Data Analysis

Data analysis in variation theory also varies by the object of learning and its associated research question. As such, data analysis will be described for each of the three objects of learning separately. It might be useful to note that it is not unusual in qualitative research designs, such one informed by variation theory, for data analysis to begin during data collection because data analysis of initial data could inform subsequent data collection. It is also typical to continue to gather data until no new themes emerge from the data (i.e., data saturation) during data analysis. Thus, it is essential to analyze data early in the data collection process in order to determine when it is appropriate to end data collection (Creswell & Poth, 2017).

Intended Object of Learning: What do Instructors Intend for Students to Learn about a Concept?

As mentioned, the data used to identify the intended object of learning are typically gathered through one-on-one semi-structured interviews between the researcher and instructor (Marton & Booth, 1997). Generally, the analysis process involves the verbatim transcription of the interviews followed by thematic analysis, which is a common and widely used qualitative analysis method across a range of research questions with different underlying epistemological assumptions (Creswell & Poth, 2017). The thematic analysis begins with the researcher familiarizing themselves with the data. This can include the initial transcription process as well as jotting down any ideas about repeated ideas and themes that are present in the transcripts (Creswell & Poth, 2017). Next, the researcher begins to generate initial codes, descriptions of the themes in the transcripts. These codes are guided by the research questions and require the researcher to organize the data based on similarity (Creswell & Poth, 2017). The researcher will then search for larger themes amongst the initial coding schemes before reviewing and refining the specifics of each theme to draw their conclusions (Creswell & Poth, 2017).

Specific to a study informed by variation theory, the researcher should develop a coding system that helps them identify the major themes in what the instructors believe their students should learn about the object of learning under investigation. This information would include the identification of the critical features of the object of learning.

Enacted Object of Learning: What is Actually Possible for Students to Learn about the Concept?

The data used to identify the enacted object of learning are typically observational in nature and can be analyzed using a variety of different methods. Observational data typically consist of detailed field notes (e.g., audio and video recording, handwritten notes, etc.) taken by the researcher during the entire time in which the object of learning is being taught (Creswell & Poth, 2017). These detailed field notes are then analyzed by the researcher with the focus of "identifying the variation of features of the object of learning presented to students" (Bussey et al., 2013, p. 15). In other words, the researcher is interested in elucidating what was made available for students to understand about a specific object of learning. (e.g., both critical and non-critical features), if and how the critical features of a concept were presented during the learning event, and any noticeable patterns of variation used while teaching about the concept.

Lived Object of Learning: What did Students Actually Learn about the Concept?

The data used to identify the lived object of learning are typically gathered through one-on-one semi-structured interviews (Marton & Booth, 1997) and analyzed using the thematic analysis process previously described for the intended object of learning (Creswell & Poth, 2017).

Specific to a study informed by variation theory, the researcher should be focused on developing a coding system to identify the major themes in what students learned or understand about the object of learning under investigation. According to variation theory, the differences in what students pay attention to are what make up an individuals' unique understanding of a concept (Marton & Booth, 1997). Therefore, researchers should be focused on which features of the concept students paid attention to during the learning event and which ones they did not. The differences in what certain students paid attention to compared to other students are important as this information can help account for differences in student understandings.

Lived Object of Learning and Students' Prior Knowledge

It is again important to note here the extension of variation theory proposed by Bussey et al. (2013). They suggested that researchers analyze students' prior knowledge of the object of learning. This is to provide the context to examine what was actually learned by students during the learning event separated from what they already knew before the learning event took place. As previously, discussed this data can take many different forms, such as interview or survey data (Bussey et al., 2013). For example, if the researcher decides to conduct student interviews to examine students' prior knowledge of a concept these interviews would need to be conducted prior to the class period in which students are first introduced to the object of learning. These transcripts could then be analyzed using thematic analysis (Creswell & Poth, 2017). Specifically, the researchers would be interested in elucidating students' understandings of the object of learning prior to any instruction.

Comparing the Objects of Learning

Ultimately, the purpose of examining the object of learning from three different perspectives (intended, enacted, and lived) is to be able to compare the findings from each perspective in order to draw overarching results. These results have the potential to inform classroom teaching and learning (Marton & Booth, 1997). That is, a comparison of the intended object of learning to the enacted object of learning can be used to identify potential differences in what an instructor intended to teach about resonance versus what they actually taught about resonance. A comparison of the intended object of learning and lived object of learning can be used to identify potential differences in what instructors want their students to understand about resonance versus what students actually came to understand about resonance (Marton & Booth, 1997). Finally, a comparison of enacted object of learning and the lived object of learning can be used to provide information about what students typically pay attention to during instruction and ultimately integrate into their understanding of a particular concept (Marton & Booth, 1997).

Limitations of Variation Theory

There are limitations associated with any theoretical framework. This section will discuss three of the main limitations associated with a research study guided by variation theory. The first limitation to be discussed is one that variation theory shares with phenomenography: that a participant's re-telling of their experience might not be the same as the experience itself (Richardson, 1999), although both phenomenography and variation assume the equivalency of an experience with the re-telling of that experience. The remaining two limitations that will be discussed were raised by Bussey et al. (2013): (1) the original developers of variation theory did not address the role of prior knowledge on the lived object of learning and (2) the original developers of variation theory did not address how the instructional materials (e.g., textbook, YouTube video, etc.) used during a learning event might influence the enacted and lived objects of learning.

As in phenomenographic research, a primary assumption of variation theory research is that participants' ideas or conceptions are the result of how they interact (e.g., what is observed or focused on) with the outside world (Svensson, 1997). It is this relationship with the outside world that ultimately forms participants' conceptions. Like phenomenography, it is also assumed in studies informed by variation theory that these conceptions are accessible through language (Svensson, 1997). Therefore, variation theory assumes that a participant's re-telling of their experiences represents the experience itself (Richardson, 1999) even though this may not be objectively true. While this limitation is one that should be acknowledged, there is currently no other way to gain insight into participants' experiences without asking them about those experiences (Orgill, 2007). Because a participant's re-telling of an experience may not be equivalent to the experience itself, it is common for researchers using phenomenography or variation theory to refer to their results as being "useful" instead of referring to them as "truth" (Orgill, 2007).

Bussey et al. (2013) raised a concern about variation theory not explicitly addressing why or how students' prior knowledge affects the lived object of learning. Students' prior knowledge or past experiences with a phenomenon shape what and how they integrate and learn new information (Novak, 1977). Thus, it can be argued that to truly evaluate the lived object of learning that students' prior knowledge of the concept should be taken into consideration by the researcher (Bussey et al., 2013), as has been suggested and described in previous sections.

Another concern raised by Bussey et al. (2013) was about variation theory not taking into account the fact that many instructors do not exclusively use their own teaching materials and how that might influence both the intended and enacted objects of learning. It is possible that the instructor's intentions and teaching materials selected do not have the same intentions for what students should learn about a concept, indirectly influencing the lived object of learning (Bussey et al., 2013). Thus, it can be argued that to truly understand the impact of the enacted object of learning on the lived object of learning, researchers must be aware of this limitation and consider the potential impact of the teaching materials selected on the lived object of learning (Bussey et al., 2013).

Justification for using Variation Theory for the Current Study

Through an evaluation of the literature (see Chapter 2: Literature Review) it became apparent that (1) there is a deficit of research-based information on what students should know about resonance in general and organic chemistry I to be successful and (2) both general and organic chemistry students have challenges understanding and using resonance. Lack of information, both about what students should know about resonance and why students continue to struggle with resonance, can make it difficult for instructors to teach in a way that creates a space where a meaningful understanding of resonance can occur. To address these gaps in the literature the current study has the following three intentions: (1) investigate what general chemistry I and organic chemistry I instructors want their students to understand about resonance, (2) investigate what the teaching of resonance in general chemistry I and organic chemistry I classrooms looks like, and (3) investigate general chemistry I and organic chemistry I students' understandings of resonance. These aims align well with the variation theory framework and translate to the following three research questions:

1. What do General and Organic Chemistry I instructors intend for their students to understand about resonance?
2. What is possible for General and Organic Chemistry I students to understand about resonance in General and Organic Chemistry I classrooms based on the information presented to them in their classes?
3. What do General and Organic Chemistry I students understand about resonance after learning about it in their General and Organic Chemistry I classrooms?

Please note that my research questions to do not address students' prior knowledge of resonance. While Bussey et al. (2013) raised a valid concern regarding the importance of addressing students' prior knowledge (e.g., through use of interviews, survey or questionnaire prior to instruction on the object of learning) it is not feasible for this study. Attrition is of considerable concern for this particular study. Additionally, a survey or questionnaire before the learning event might influence what students direct their attention to during the learning event

(McMillan & Schumacher, 2009). Therefore, based on these concerns, as well as the facts that (1) the original developers of variation theory did not include evaluating students' prior knowledge as part of the theory and (2) it is not currently a part of most studies informed by variation theory, I have chosen to not evaluate students' prior knowledge in my study.

CHAPTER 4 METHODOLOGY

Research Questions

This study employed a qualitative research design using variation theory as the guiding theoretical framework to examine the teaching and learning of resonance in General Chemistry I and Organic Chemistry I. Specifically, the study addresses the following research questions:

1. What do General Chemistry I and Organic Chemistry I instructors intend for their students to understand about resonance?
2. What is possible for General Chemistry I and Organic Chemistry I students to understand about resonance in General Chemistry I and Organic Chemistry I classrooms based on the information presented to them in their classes?
3. What do General Chemistry I and Organic Chemistry I students understand about resonance after learning about it in their General Chemistry I and Organic Chemistry I?

Research Design

This study was approved by the Institutional Review Board at the University of Nevada, Las Vegas (Appendix A). The sections that follow describe the methodology that was employed for this study. Because data collection and analysis techniques for each research question are qualitative in nature and unique to each object of learning, data collection and analysis will be discussed separately for each research question. At the very end of the current chapter, I will address how I ensured the rigor of the proposed study through a discussion of establishing the credibility, transferability, dependability, and confirmability of results.

Intended Object of Learning: What Should Be Understood?

The first research question—What do General Chemistry I and Organic Chemistry I instructors intend for their students to understand about resonance? —addresses the intended object of learning. In this study, the intended object of learning pertains to what General Chemistry I and Organic Chemistry I instructors believe students *should* learn about resonance and was elucidated from a second-order perspective using semi-structured interviews.

Participants

General Chemistry I and Organic Chemistry I lecture instructors constituted the participants for the intended object of learning, as I was interested in what they intend for their students to understand about resonance in General Chemistry I and Organic Chemistry I. I have identified General Chemistry I and Organic Chemistry I lecture instructors to be any individual that has taught either General Chemistry I and Organic Chemistry I at the tertiary level and who is over 18 years of age. All of the instructors that were interviewed for this study were either currently teaching one of these courses or would be teaching one of these courses the semester following the interview. This allowed me to also observe their classrooms while they taught resonance concepts. I chose to interview instructors of these classes because resonance is typically only formally taught in General Chemistry I and Organic Chemistry I.

Recruitment. The participants were recruited from the following institutions: College of Southern Nevada (CSN), Nevada State College (NSC), and the University of Nevada, Las Vegas (UNLV) via email (see Appendix B for the email instructor recruitment script). I chose to recruit from these institutions based on access and institutional variance. Access is always a notable consideration for any study, while institutional variance can provide insights as to whether the instructors' beliefs are institutionally specific or shared across the participant's respective discipline. Based on a previous study (Bussey & Orgill, 2019), I recruited 5 General Chemistry I instructors and 5 Organic Chemistry I instructors using criterion sampling (Creswell & Poth, 2017) (see Appendices C and D for a copy of the General Chemistry I and Organic Chemistry I instructor informed consent forms). One instructor was interviewed twice because she taught both General Chemistry I and Organic Chemistry I and, therefore, could offer insight about teaching resonance in both courses. Data saturation (i.e., no new themes emerge from the data) was achieved with these participants (Creswell & Poth, 2017). Thus, I did not need to recruit additional participants.

Instructor Interview Guide

The instructor interviews were semi-structured and lasted approximately 60 minutes. The participants had access to paper and pencil throughout the interview process. A complete copy of the interview guide discussed below can be found in Appendix E. There are three main stages of the interview that will be discussed here: (1) participant background, (2) what students should know about resonance, and (3) reflection and final remarks.

Participant Background. The interviews began with a series of questions that helped the participant and interviewer get acquainted and comfortable speaking with each other. For example, I asked the participant about their academic background (e.g., where did you go to college) and research interests (e.g., what projects are you currently working on?). These types of questions not only allowed me to understand more about the participant but also built rapport and lessened any initial discomfort that might have kept the interviewee from speaking freely and openly during the remainder of the interview.

What Students Should Know about Resonance. The interview transitioned to questions that focused on my first research question (what do General Chemistry I and Organic Chemistry I instructors intend for their students to understand about resonance?). This portion of the interview began with me asking instructors to describe resonance in their own words. Next, I asked questions related to what they expect their students to already know about resonance before coming into their class. This question helped me understand instructors' expectations of what their students should know about resonance before entering either General Chemistry I and Organic Chemistry I, as these expectations might influence what instructors teach. It also provided insight into what instructors believe and/or have identified their students' prior knowledge about resonance to be.

I also asked questions related to the teaching of resonance. For example, I asked instructors when they typically teach resonance in the semester and how they typically teach resonance. Additionally, I asked what instructors believe students should understand about resonance in their class and how instructors assess those understandings. I then asked questions related to both the challenges of teaching and learning about resonance. For example, I asked instructors why they believe students have a hard time understanding resonance and about any specific student misunderstandings that they have noticed their students having while learning about resonance. These questions helped provide context regarding why instructors teach resonance the way they do and/or why they emphasize or exclude specific aspects of resonance while teaching.

This portion of the interview ended by asking instructors what they think is most important for students to understand about resonance and what is not as important for students to understand about resonance. This question helped further provide insight into what instructors believe to be the most important aspects of resonance for students to understand.

Reflection and Final Remarks. I thanked the participant and asked them one final reflection question: what would you tell a student coming into the class they would need to know about resonance to be successful? Finally, I asked the participant if they have any final thoughts before ending the interview.

Data Collection

The instructor interviews were audio-recorded using two separate devices: an iPad via the Notability application and a standard audio recorder. Two devices were used to safeguard my data in the event that one of the recorders did not work properly during the interview. The instructor interviews were transcribed using the software Otter.ai (Otter.ai, 2023). To ensure that the interviews were transcribed verbatim, I cleaned up the transcripts produced by Otter.ai by listening to the interview myself and making any necessary corrections to the transcripts. I collected any artifacts the instructors produced during the interview and scanned them into my computer.

Data Analysis

The interview data from General Chemistry I instructors was initially analyzed separately from the interview data from Organic Chemistry I instructors although, ultimately, I did compare the findings from the two groups. That is, Chapter 2 made it clear that the expectations of what students are meant to understand about resonance are different in General Chemistry I and Organic Chemistry I. It would be inappropriate to expect that general and organic chemistry instructors have the same intentions while teaching resonance. The transcripts and artifacts were read, reread, and iteratively coded for what instructors identified as critical features students should understand about resonance using the software MAXQDA (VERBI Software, 2021). Generally, any information that could be used to answer what students should understand about resonance was coded as a critical feature.

This analysis resulted in identifying a total of eleven critical features of resonance. The critical features were categorized based on what type of instructor identified them: (1) both General Chemistry I and Organic Chemistry I instructors, (2) General Chemistry I instructors, or

(3) Organic Chemistry I instructors. These critical features were compared and contrasted based on the type of instructor that identified them to determine the differences and/or similarities in what General Chemistry I and Organic Chemistry I instructors intend for their students to understand about resonance. This analysis provided insight into the expected progression of students' understandings of resonance from General Chemistry I and Organic Chemistry I. It also provided insight into what General Chemistry I students are expected to know about resonance before entering organic chemistry. Furthermore, these critical features were used as parameters for the analysis of the enacted object of learning. I also used this list of critical features during my analysis of the lived object of learning.

Enacted Object of Learning: What is Possible to Understand?

The second research question— What is possible for General Chemistry I and Organic Chemistry I students to understand about resonance in General Chemistry I and Organic Chemistry I classrooms based on the information presented to them in their classes? —addresses the enacted object of learning. This object of learning was elucidated from a first-order perspective using classroom observational data.

Participants and Recruitment

The same group of instructors that were interviewed for the intended object of learning allowed me to either observe their classrooms or provided me with a recording of their lecture when they first introduced resonance (see Appendices F and G for General Chemistry I and Organic Chemistry I classroom observation consent forms). To ensure that this was the case when I recruited participants for the intended object of learning, I asked if they would be willing to give consent for me to observe their instruction on resonance in the upcoming semester or provide me with a recording of the lecture (if an in-person observation did not align with my data collection schedule). All of the instructors that I interviewed agreed. I asked that they give me an estimate of the day/time that they would be first introducing resonance in their classrooms, and I built myself an observation schedule based on this information. Three of the instructors (one General Chemistry I and two Organic Chemistry I instructors) provided me with a pre-recorded lecture, but the remaining observations were observed live. I did not observe any classrooms in which I did not interview the instructor.

Classroom Observations

Classroom observational data has traditionally been used to elucidate the enacted object of learning (Marton et al., 2004) and was used to answer my second research question (What is possible for General Chemistry I and Organic Chemistry I students to understand about resonance in General Chemistry I and Organic Chemistry I classrooms based on the information presented to them in their classes?). I observed (either live or through the recorded lectures) 5 General Chemistry I and 5 Organic Chemistry I classrooms when resonance was introduced for the first time. I chose to limit my observations to only the initial introduction of resonance as I am not specifically interested in students' ability to use resonance in a context, which is often how resonance is used in organic chemistry, but rather in students' understandings of resonance. Furthermore, it is often the initial introduction of a concept that forms students' dominant understanding of that concept, correct or not (Vosniadou, 2013). I did not use a formal observational protocol because I audio-recorded and took detailed notes of each lecture I observed.

I should again note that some instructors had pre-recorded lectures of themselves teaching resonance for the first time in General Chemistry I and/or Organic Chemistry I that they provided me. These were used in the instance that the instructor taught asynchronous remote courses, or their teaching schedule did not align with my data collection schedule (and they happened to have a pre-recorded lecture to provide me). None of the lecture recordings showed students' or instructors' faces. The instructors used voice-over presentation slides. If the lecture was pre-recorded, I acted as though it was a live class while analyzing the data and followed the same data collection process and analysis as with the in-person classes, with the exception of not needing to audio record the class (because I already had the recording). During the observations, I acted solely as an observer and did not participate in the class in any way.

Data Collection

The in-person classroom observations were audio recorded using two separate devices, an iPad via the Notability application and a standard audio recorder. I posted a sign on the door notifying students that audio recording was in progress during the class period (Appendix H). Two devices were used to safeguard my data in the event that one of the audio recorders did not work properly during the observation. Prior to the observation, I asked the instructors if they would be using presentation slides (e.g., PowerPoint presentation) during instruction. If so, I asked if they would be willing to provide me with a copy so that I could follow along easier. Seven of the ten instructors used some type of presentation slides. I also took detailed notes using my iPad via the Notability application. If the instructor used presentation slides, I made sure to import the slides into my Notability app so that I could take notes directly on the slides. I wrote down anything the instructor wrote and/or projected on the board. If the instructor was going too fast for me to handwrite the material, then I quickly took a picture of only the board with my iPad (with the prior permission of the instructor). I took special caution not to get any individuals in these pictures. If an individual did get in the camera frame, I had planned to either crop them out of the image or delete it altogether. This issue did not arise.

Immediately after the classroom observation took place I went home and began the transcription process while my memory of the event was fresh. The recordings were first transcribed using the software Otter.ai. To ensure that the lectures/class periods were transcribed verbatim, I cleaned up the transcripts produced by Otter.ai by listening to the recording myself and making any necessary corrections to the transcripts. I excluded any questions that students might have asked during the class period, as I did not have students' permission to include their questions in my data analysis. In place of their questions, I inserted the phrase "student question" in the transcript.

I inserted any of my notes that corresponded with the transcript, which is why a fresh memory was useful. For example, if the instructor drew a resonance structure on the board at a certain timeframe of the audio recording, I added my drawing and/or image that I took on my iPad of that resonance structure to that part of the transcript. The final transcript included both a verbatim transcript of the instructor's lesson on resonance as well as any of the examples that were either written and/or projected on the board. If the class period covered more than resonance concepts, then I excluded those sections of the class from my final transcript, as they are not the focus of this study.

Data Analysis

Like the interview data, the observational data from General Chemistry I classrooms was initially analyzed separately from the observational data from Organic Chemistry I classrooms although, ultimately, I did compare the findings from the two groups. Again, Chapter 2 made it clear that the expectations of what students are meant to understand about resonance are different in General Chemistry I and Organic Chemistry I. Therefore, because it would be inappropriate to expect that general chemistry and organic chemistry instructors have the same intentions while teaching resonance, it would also be inappropriate to expect that what is possible to learn about resonance is the same in both the General Chemistry I and Organic Chemistry I classrooms. The data analysis for the enacted object of learning did not begin until all of the data for the intended object of learning was analyzed, as data from the intended object of learning informed the analysis of the enacted object of learning.

Both sets (i.e., General Chemistry I and Organic Chemistry I) of the observational data were read, reread, and iteratively coded for the critical features of resonance that were identified from the instructor interviews. I also coded for non-critical features, meaning aspects/features of resonance that were not identified as critical by the instructors but were addressed in the classroom. In other words, during this analysis, I identified both things that the instructors identified as essential for students' developing a correct understanding of resonance, as well as other features of resonance that were discussed during the lessons, but which are not essential (and, as a consequence might be distracting to students). I constructed tables that are like those shown in Table 7 and Table 8 using the software MAXQDA to carry out my analysis.

The first column of Table 7 (Critical Features) is a list of the critical features identified from the analysis of the instructor interviews. The second column of Table 7 (Supporting Evidence from Observational Data) is supporting evidence from the observational data that confirms the identification of a specific critical feature. The first column of Table 8 (Non-critical Feature) is a list of non-critical features identified during this analysis of the enacted object of learning. The second column of Table 8 (Supporting Evidence from Observational Data) is supporting evidence from the observation data that confirms the identification of a specific non-critical feature during the lecture. I coded the critical features and non-critical features for both data sets (i.e., General Chemistry I and Organic Chemistry I observational data) separately.

Analysis using Table 7 and Table 8. There were two copies of Table 7 and Table 8. One copy of Table 7 and 8 was used to analyze data from the General Chemistry I observations. The other was used to analyze the data from the Organic Chemistry I observations. The first column of Table 7 was filled in before I began the analysis of the enacted object of learning (i.e., after analysis of the intended object of learning was complete). The second column of Table 7 was filled in as I evaluated and re-evaluated the classroom data, finding textual evidence that supports the identification of a specific critical feature. The first column of Table 8 was filled in during my analysis of the enacted object of learning, as instructors did not identify these features as critical for students' understanding of resonance. For example, any time I identified a non-critical feature of resonance (i.e., was not found on the list of critical features) it was added to the first column of Table 8.

Table 7

Analysis of Critical Features

Critical Features Identified by Both Organic Chemistry I and General Chemistry I Instructors	
Critical Features	Supporting Evidence from Observational Data
• Critical Feature	• *Supporting text from the transcript (Instructor name, Course, lines x-y)*
• Critical Feature	
Critical Features Identified by General Chemistry I Instructors	
Critical Features	Supporting Evidence from Observational Data
• Critical Feature	
• Critical Feature	
Critical Features Identified by Organic Chemistry I Instructors	
Critical Features	Supporting Evidence from Observational Data
• Critical Feature	
• Critical Feature	

Table 8

Analysis of Non-Critical Features

Non-Critical Features Identified by both General Chemistry I and Organic Chemistry I Instructors	
Non-critical Features	Supporting Evidence from Observational Data
• Non-Critical Feature #1	• *Supporting text from the transcript (lines x-y)*
• Non-Critical Feature #2	
Non-Critical Features Identified by General Chemistry I Instructors	
List of Non-Critical Features Identified during the Intended Object of Learning	Supporting Evidence from Observation Data
• Non-Critical Feature #1	
• Non-Critical Feature #2	
Non-Critical Features Identified by Organic Chemistry I Instructors	
Critical Features	Supporting Evidence from Observational Data
• Critical Feature	
• Critical Feature	

This analysis resulted in two separate data sets (i.e., General Chemistry I and Organic Chemistry I) that identify what is possible (i.e., critical and non-critical features) for students to understand about resonance in General Chemistry I and Organic Chemistry I classrooms. I compared these data sets to the intended object of learning to determine the differences and/or similarities between what instructors intended students to understand about resonance and what was actually possible for students to understand about resonance in either General Chemistry I or Organic Chemistry I classes. Next, I compared the data sets to each other to investigate the differences and/ or similarities in what is possible to learn about resonance in General Chemistry I versus Organic Chemistry I.

Lived Object of Learning: What is Actually Understood?

The third research question—What do General Chemistry I and Organic Chemistry I students understand about resonance after learning about it in their General Chemistry I and Organic Chemistry I classrooms? —addresses the lived object of learning. In this study, the lived object of learning was elucidated using semi-structured interviews.

Participants

General Chemistry I and Organic Chemistry I students constituted the participants for the lived object of learning, as I am interested in what was understood by students in General Chemistry I and Organic Chemistry I classes. I have identified General Chemistry I and Organic Chemistry I students to be any individual that is over 18 years of age and is currently enrolled in either General Chemistry I or Organic Chemistry I for the first time. These criteria were established based on the information discussed in Chapter 2 that resonance is typically only formally taught in General Chemistry I and Organic Chemistry I classes. Furthermore, I chose to limit my participant pool to students who are currently enrolled in their respective courses for the first time (i.e., students who are not repeating the course) because I am interested in students' understandings of resonance while first learning about the concept. I interviewed students after their first exam that included resonance, because students should be able to give more reflective interview responses after they have thought about resonance in preparation for that exam.

Recruitment. The participants were recruited from the following institutions: College of Southern Nevada (CSN), Nevada State College (NSC), and the University of Nevada, Las Vegas (UNLV) via in-class announcements (see Appendix I for the student recruitment script). I chose to recruit from these institutions based on access and institutional variance. Access is always a notable consideration for any study, while institutional variance can provide insights as to whether the students' beliefs are institutionally specific or not. Based on a previous study (Bussey, 2013), I recruited 15 General Chemistry I students and 15 Organic Chemistry I students using criterion sampling (Creswell & Poth, 2017) (see Appendices J and K for a copy of the General Chemistry I and Organic Chemistry I student informed consent forms). Data saturation was reached with this number of participant (Creswell & Poth, 2017).

Student Interview Guide

The student interviews were semi-structured and lasted approximately 60 minutes. The participants had access to paper and pencil throughout the interview process. A complete copy of the interview guide discussed below can be found in Appendix L. There are five main stages of the interview that will be discussed here: (1) participant background, (2) introduction to the interview topic, (3) students' understandings of resonance, (4) reflections, and (5) final remarks.

Participant Background. The interview began with a series of questions that helped the participant and interviewer get acquainted and comfortable speaking with each other. For example, I asked the participant about where they are from and what they are majoring in. These types of questions allowed me to understand more about the participant as well as build rapport and lessen any initial discomfort that might have kept the interviewee from speaking freely and openly during the remainder of the interview.

Introduction to the Interview Topic. The interview then transitioned to the interview topic. I let students know that we will be talking about a chemistry topic called resonance.

Students' Understandings of Resonance. The next portion of the interview centers on students' current understandings of resonance and focuses on my third research question (What do General Chemistry I and Organic Chemistry I students understand about resonance in General Chemistry I and Organic Chemistry I?). First, I asked students to describe resonance in their own words, to elucidate their understanding of resonance prior to showing them resonance structures. Like Xue and Stains (2020) I then showed students a picture of the resonance structures of the enolate ion and asked them to describe the relationship between the two structures (Appendix M). Exercises similar to this were seen throughout the literature (e.g., Brandfonbrener et al., 2021; Xue & Stains, 2021) and provided insightful findings regarding students' conceptual understandings of resonance.

I then asked students questions related to how they were taught the concept of resonance and the specific features of resonance that they remember their teachers emphasizing. This question helped me better understand how specific teaching strategies might have influenced what students came to understand about resonance.

Next, I presented both groups of students with the chemical formulas of four different compounds (See Appendices N and O). The compounds that I showed General Chemistry I students reflected the types of compounds they were likely exposed to in general chemistry (e.g., simple, inorganic compounds), while the compounds that I showed the Organic Chemistry I students reflected the types of compounds they were likely exposed to in organic chemistry (e.g., more complex, organic compounds). I showed students all four chemical formulas at the same time and ask them to select which, if any, of these compounds exhibit resonance and to explain their reasoning. I repeated this exact process but instead showed students the Lewis structures of four different chemical compounds (See Appendices P and Q). The compounds were different to avoid redundancy in student responses and to provide richer data.

My reasoning for first providing students with only the chemical formulas before the Lewis structures was informed by the research literature, which indicates that students often use structural cues to identify resonance (McClary & Talanquer, 2011a, 2011b; Shah et al., 2018). Therefore, it was up to the students to draw out the compound's Lewis structure to help them decipher whether the compound has resonance. Nevertheless, it was possible that participants would not be able to draw the associated Lewis structure, which is why I also included an activity in which the Lewis structures were drawn out for the participants.

Reflections. The remaining questions were more reflective in nature. I asked students about other topics that they believe are useful to understand resonance, specific problems or challenges they could see other students having with resonance, and what they believed would be helpful to tell a student struggling to understand resonance. Additionally, I asked the Organic Chemistry I students to reflect on why they think it was important for them to learn about resonance in general chemistry and how they felt it was different from and/or similar to when they learned about it in organic chemistry.

Final Remarks. I thanked the participant and ask them one final reflection question: what would you tell a friend coming into the class they would need to know about resonance to be successful? Finally, I asked the participant if they have any final thoughts before ending the interview.

Data Collection

The student participants were recruited after the first exam which included resonance, to allow students time to really think about the concept, in either their General Chemistry I or Organic Chemistry I classes. Because resonance in Organic Chemistry I is introduced within the first few weeks of the course, I interviewed Organic Chemistry I students towards the beginning of the semester. I interviewed General Chemistry I students towards the middle of the semester after they had been introduced to resonance in their classes and taken their midterm exam that included resonance topics. The student interviews were audio-recorded using two separate devices, an iPad via the Notability application and a standard audio recorder. Two devices were used in the event that one of the recorders does not work properly during the interview. The student interviews were first transcribed using the software Otter.ai. To assure that the interviews were transcribed verbatim, I cleaned up the transcripts produced by Otter.ai by listening to the interview myself and making any necessary corrections to the transcripts. I collected any artifacts that the students produced during the interview and scanned them into my computer.

Data Analysis

The interview data from General Chemistry I students was initially analyzed separately from the interview data from Organic Chemistry I students although, ultimately, I did compare the findings from the two groups. As previously stated, Chapter 2 made it clear that the expectations of what students are meant to understand about resonance could be different in General Chemistry I and Organic Chemistry I. It would be inappropriate to expect that General Chemistry I and Organic Chemistry I students have the same level of understanding of resonance. The transcripts and artifacts were read, reread, and iteratively coded for what students understand about resonance using the software MAXQDA. Generally, any information that could be used to answer the question of what students understand about resonance was coded.

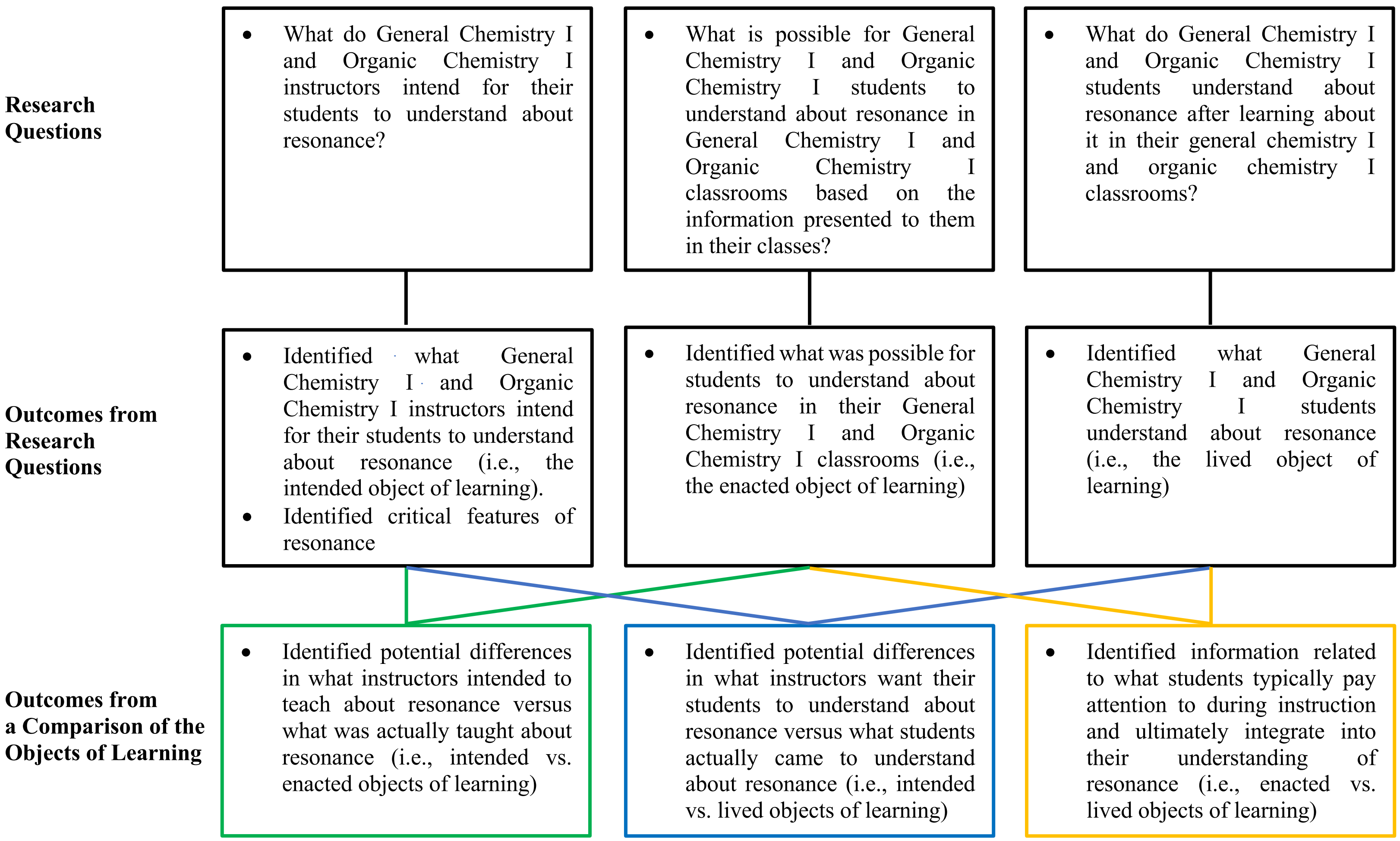
This analysis resulted in two separate lists identifying what students understand about resonance, a list for general chemistry students and a list for organic chemistry students. Both lists were compared to determine the differences and/or similarities in what General Chemistry I and Organic Chemistry I students understand about resonance.

Comparing the Objects of Learning

I have discussed throughout this chapter and previous chapter the need to compare the various objects of learning during analysis as a means to draw results. This section aims to provide a clearer depiction of how and why each of these objects of learning were compared. For ease, Figure 31 provides an overview of my research questions and related outcomes, which includes both the outcomes directly related to answering my research questions as well as the outcomes related to the comparison of my research questions (i.e., the objects of learning). The outcomes related to the comparison of my research questions are color coded to illustrate the outcomes which were compared. For example, the green text box and green lines represents the results that were drawn from a comparison of the results from the intended object of learning and the enacted object of learning.

Figure 31

Research Questions and Related Outcomes



Note. The outcomes resulting from a comparison of the research question outcomes are color coded to illustrate which research questions (i.e., objects of learning) were compared.

Comparing the Intended and Enacted Objects of Learning

First, I compared the intended object of learning to the enacted object of learning. By comparing the intended object of learning to the enacted object of learning, I identified potential differences in what instructors intended to teach about resonance versus what was actually taught about resonance. That is, what was actually made possible for students to learn about resonance versus what the instructor intended to teach about resonance.

Comparing the Intended and Lived Objects of Learning

Next, I compared the intended object of learning to the lived object of learning. By comparing the findings from the intended and lived object of learning, I identified potential differences in what instructors wanted their students to understand about resonance versus what students actually came to understand about resonance. That is, how do students' understandings of resonance compare with what their instructors intended for them to learn about resonance?

Comparing the Enacted and Lived Objects of Learning

I then compared the enacted object of learning to the lived object of learning. By comparing the enacted object of learning to the lived object of learning, I identified information related to what students typically pay attention to during instruction and ultimately integrate into their understanding of resonance (Marton & Booth, 1997). That is, are students focusing on the critical features of resonance identified by their instructors or are they focusing on other, perhaps, less important features that were presented in their classes?

Comparing the Intended, Enacted, and Lived Objects of Learning

I then compared the findings from the intended, enacted, and lived objects of learning to identify potential reasons why students did not come to understand resonance in the way that the instructors intended them to. This comparison allowed me to identify the information that students paid attention to during instruction and what they ultimately integrated into their understanding. Finally, as stated in Chapter 2, it is my goal that by answering and comparing the results from these three different research questions, guided by the aims and assumptions of variation theory, I might provide practical and well-rounded suggestions for the improvement of the teaching and learning of resonance in both General Chemistry I and Organic Chemistry I.

Establishing Credibility, Transferability, Dependability, and Confirmability of Results

This research study, and its respective methodology might be unfamiliar to those who typically do quantitative research. As expressed in Chapter 3, one of the main differences between qualitative and quantitative research is that qualitative researchers are not focused on broadly generalizable results across a population (i.e., through statistical analysis) but rather on uncovering an individual's or group's meaning of a particular experience or phenomenon from their perspective (Patton, 2002). This, however, Is not to say that qualitative researchers should not be interested in designing and carrying out rigorous studies, as it is rather the opposite. Lincoln and Guba (1985) developed four criteria that are used to ensure the rigor of qualitative research. That is, a qualitative researcher must work to establish the credibility, transferability, dependability, and confirmability of their results (Lincoln & Guba, 1985). This is not to say that every good qualitative study will be able to meet all four criteria; however, Creswell explained that good qualitative research study should employ at least two of the criteria (Creswell & Poth, 2017). I will briefly define each of these strategies as well as how I operationalized them to ensure the rigor of the current study.

Credibility

Credibility has to do with the idea that the results should directly mirror the ideas expressed by the participants (Lincoln & Guba, 1985). Of course, while it is the researcher's responsibility to separate their personal assumptions/views from their study, it is impossible for anyone to be truly neutral. However, there are ways in which a researcher can help ensure credibility, such as triangulation of data, member checking, or prolonged interactions (Lincoln & Guba, 1985). For this study, I asked multiple follow up questions and made sure to not ask leading questions during interviews as to allow my data to best reflect the ideas of my participants.

Transferability

While it is not the focus of qualitative researchers to generate generalizable findings, that is not to say that those results should not be transferable. *Transferability* has to do with the idea that results should be described using thick descriptions (Lincoln & Guba, 1985). In other words, there should be enough details described about the study that someone interested in the results might be able to decipher if the results are applicable in a different context or situation. For this study, I made sure to provide thick descriptions of my populations, context, findings, etc., as to allow others the possibility to decide if my results are applicable to their situation (Lincoln & Guba, 1985).

Dependability

It is impossible to measure the same phenomenon twice. Nevertheless, a study should use consistent, logical processes that are well-documented and described over time. This practice is referred to as *dependability* (Lincoln & Guba, 1985). To ensure dependability, Lincoln and Guba (1985) suggested that researchers use an audit trail, where an outside person reviews and critiques the researcher's study. For this study, a fellow chemistry education researcher served in this role. To further establish the dependability of this study, I was careful to describe the steps I took and the rationale for doing so in data collection and data analysis.

Confirmability

Finally, *confirmability* has to do with the degree to which findings can be confirmed by other researchers (Lincoln & Guba, 1989). While no researcher can be truly neutral, findings should not be so clouded by the researcher's biases that they do not reflect the experiences of the participants. There are different ways in which to ensure this does not happen. For example, similar to what was described above, an audit trail can be performed. This time, the outside researcher might serve to examine if the data actually supports the results that are being presented or not. For this study, a fellow chemistry education researcher served in this role.

CHAPTER 5 ANALYSIS, RESULTS, AND DISCUSSION OF THE INTENDED OBJECT OF LEARNING (RESEARCH QUESTION 1)

My first research question asks what General Chemistry I and Organic Chemistry I instructors intend for their students to understand about resonance. Because this study was informed by variation theory, answering this question involved interviewing five General Chemistry I instructors and five Organic Chemistry I instructors about their beliefs on what is essential for students to understand about resonance. Table 9 lists the pseudonyms of the instructors, along with their associated courses, in alphabetical order. I found that the instructors' beliefs were not institutionally specific, meaning their beliefs were not dependent on the type of institution at which they taught. Thus, to protect their identities, I do not identify the instructors' institutions or institution types in the discussion below. I also recreated the instructors' artifacts to further protect their identity. Please note that one instructor (Maryann) was interviewed twice because she taught both General Chemistry I and Organic Chemistry I and, therefore, could offer insight about teaching resonance in both courses.

I found that all of the instructors in this study believed resonance was an important topic for their students to understand. One instructor went as far as to describe not learning resonance as "fatal" to their students' overall success in chemistry. When I analyzed the instructor interviews to identify the critical features of resonance (discussed in the following sections), I also found that many shared similar beliefs on what was important for students to learn about resonance. Interestingly, the instructors tended to prioritize what students should do with each critical feature rather than what they should know about each critical feature.

Any differences in what the instructors perceived as important for students to understand about resonance were attributed mainly to the course they taught (i.e., general chemistry or organic chemistry). As such, I categorized the critical features based on which type of instructor identified them—(1) Organic Chemistry I instructors and General Chemistry I instructors, (2) General Chemistry I instructors, or (3) Organic Chemistry I instructors. In the sections that follow, I will first present instructors' overall perceptions of the importance of resonance for their students' learning of chemistry. Then, I will discuss how I analyzed the instructors' perceptions of the critical features of resonance (in more detail than was discussed in the previous chapter). Lastly, I will discuss each of the critical features identified by the instructors. [Note. The findings presented in this chapter have been published in the article "Identifying the critical features of resonance: Instructors' intentions for the teaching and learning of resonance in General Chemistry I and Organic Chemistry I" (Barakat & Orgill, 2024).]

Table 9

Instructors' Pseudonyms and Their Associated Course

General Chemistry I Instructors	Organic Chemistry I Instructors
Annabelle	Anthony
Destiny	Brad
Kory	Dallas
Maryann	Joe
Ryan	Maryann

Instructors' Perceptions of the Importance of Resonance

Resonance is typically formally taught to students during General Chemistry I and Organic Chemistry I. Thus, it was necessary to establish that the instructors of these courses believe resonance to be a relevant and important topic for their students to learn about. Through their interviews, I found that all of the instructors in this study believed resonance was an important topic for students to learn about. Most General Chemistry I instructors in this study stated that resonance is not an extensive course focus for them. However, they believed resonance was necessary for their students to learn about because they would need the concept for future classes, specifically the organic chemistry series. For example, when I asked Maryann why resonance was important for her students to learn about in General Chemistry I, she shared, "They are going to need it in organic chemistry." The Organic Chemistry I instructors gave more specific examples of why they believed resonance was important for students to learn. For example, these instructors emphasized resonance's importance in predicting reaction mechanisms, determining relative acidities of molecules, and interpreting data from spectroscopy instruments (e.g., NMR). Rather succinctly, one Organic Chemistry I instructor, Joe, shared that he believed resonance was important because he views it as "the end and the beginning of organic chemistry." He described resonance as "the end of organic chemistry" because students must first establish a vast amount of foundational chemical knowledge to understand resonance. He then described it as the "beginning of organic chemistry" because you need resonance to understand different, more advanced chemistry topics, like reaction mechanisms. Despite differences in why General Chemistry I and Organic Chemistry I instructors believe resonance is important in their courses, this shared consensus of the importance of resonance establishes the context for determining what the instructors believe to be the critical features of resonance.

Data Collection and Analysis of Instructors' Perceptions of the Critical Features of Resonance

The purpose of this component of the current study is to identify the intended object of learning or, in other words, to investigate what General Chemistry I and Organic Chemistry I instructors intend for their students to understand about resonance. This involves identifying what the instructors perceive to be the critical features of resonance (i.e., features that the instructors deem critical for developing a correct understanding of resonance). As mentioned, to do so, I conducted a total of ten instructor interviews, five General Chemistry I instructor interviews, and five Organic Chemistry I instructor interviews. I asked the instructors in this study questions about the teaching and learning of resonance in their classrooms. For example, I asked the instructors questions such as, "If I was a student in your class, how would you teach me about resonance? What would you tell me? Show me?" and "What do you think students should be able to understand/do related to the topic of resonance in your class"?

The interviews were transcribed verbatim. I then coded the instructors' responses to these questions for features that were either directly stated or implied as important for students to understand resonance. For example, a number of the instructors that participated in this study said that understanding the resonance hybrid was essential to students' developing a correct understanding of resonance in their classes. Thus, "resonance hybrid" was coded as a critical feature. Assigning codes was a constant comparative process; the codes were reviewed and refined as the data analysis progressed. To establish confirmability, I reached out to a fellow chemistry education researcher with a master's in analytical chemistry and a doctorate in chemistry education. I provided her with six transcripts (three from General Chemistry I instructors and three from Organic Chemistry I instructors), my initial coding system, and a description of each code. I asked her to apply the coding system to the transcripts and to identify (1) any code definitions that were confusing and (2) any critical features that were not described in my coding system. Any code definitions that she found confusing were reviewed and refined. She did not identify any critical features that were not already included in my coding system.

Based on the analysis described above, the instructors in this study identified eleven critical features of resonance (Table 10). In the current study, I have defined a critical feature of resonance as anything an instructor deems important for developing what they perceive to be a correct understanding of resonance. A concept was considered to be a "critical feature" if at least one instructor identified it as opposed to all of the instructors that participated in the study. As previously mentioned, many instructors shared similar beliefs on what was important for students to learn about resonance, and any differences were primarily attributed to the course the instructor was teaching at the time of the interview (i.e., General Chemistry I or Organic Chemistry I). As such, I categorized the critical features based on which type of instructor identified them—(1) Organic Chemistry I and General Chemistry I instructors, (2) General Chemistry I instructors, or (3) Organic Chemistry I instructors. Within those three categories, I discuss the critical features in descending order of the total number of instructors that identified them. If this distinction is not possible, I will justify the order in which they will be discussed. I also distinguish between what instructors want students to know about a particular critical feature and what instructors want students to do with that critical feature.

Table 10

Critical Features of Resonance Identified by Instructors

Identified by General Chemistry I (GCI) and Organic Chemistry I (OCI) Instructors, GCI Instructors, or OCI Instructors	Critical Feature	Description of Critical Feature
GCI and OCI Instructors		
	Lewis structures	Students should understand Lewis's model of chemical bonding (i.e., Lewis structures) and that a single Lewis structure cannot adequately represent the bonding in some molecules. Students should draw and use Lewis structures to identify resonance.
	Resonance structures	Students should understand that resonance structures only differ in the placement of electrons (i.e., electron movement), not atoms. Students should identify and draw correct resonance structures.
	Resonance hybrid	Students should understand that resonance structures are not real entities and do not exist in nature. They should also understand that the actual, most correct structure, the resonance hybrid, is a mental melding of the different resonance structures. Students should use the resonance hybrid to visualize resonance.
	Octet rule	Students should understand that second-row elements should not exceed an octet while drawing resonance structures. Students should use the octet rule to decide if a resonance structure is valid.
	Formal charge	Students should understand that atoms in resonance structures can have different formal charges, but the overall net charge of the molecule

		does not change. They should also understand how formal charge can be used to identify the major resonance contributor. Students should use formal charge to decipher the major and minor resonance contributors to the resonance hybrid.
	Major and minor resonance contributors	Students should understand that there are certain instances in which one (or more) of the resonance structures is a major contributor to the resonance hybrid. Students should identify the major resonance contributor to the resonance hybrid.
GCI Instructors		
	Bond length	Students should understand that there can be differences between the expected and observed bond lengths predicted by Lewis structures of certain molecules and how resonance can explain these discrepancies. Students should calculate bond order.
OCI Instructors		
	Pattern recognition	Students should understand that resonance structures can be identified by recognizing specific patterns in molecular structure. Students should recognize the specific patterns and, if a pattern is present, use the corresponding resonance structure to problem solve.
	Curved arrows	Students should understand that curved arrows are used to draw resonance structures. Students should use curved arrows to draw resonance structures.
	Delocalized and localized lone pairs	Students should understand the difference between electrons that participate in resonance (i.e., delocalized) and those that do not (i.e.,

		localized). Students should identify if a lone pair of electrons participate in resonance.
	Hybridization	Students should understand how hybridization affects whether there is resonance or not. Students should identify the hybridization of each atom in a species to identify resonance.

Finally, it is important to reiterate that I identified a concept as a "critical feature" if at least one instructor verbally mentioned its importance to students' developing what they believe to be a correct understanding of resonance, regardless of how many instructors identified that concept or how much any of the instructors emphasized the concept. For example, one instructor might have discussed a critical feature in detail or multiple times throughout the interview, while another instructor may have only briefly mentioned it once during the interview, and another instructor may not have mentioned it at all. Nevertheless, because I do qualitatively reference how many instructors identified each critical feature throughout the discussion that follows, for ease, Table 11 provides a list of the number and type of instructors that identified each critical feature. Again, I should be clear that a feature is not deemed critical based on how many instructors mentioned it. In other words, this information was not used to determine if a feature was critical or not.

Table 11

Number of Instructors that Identified Each Critical Feature during the Instructor Interviews

Identified by General Chemistry I (GCI) and Organic Chemistry I (OCI) Instructors, GCI Instructors, or OCI Instructors during Instructor Interviews	Critical Feature	Number of GCI Instructors Identifying Critical Feature during Instructor Interviews (N=5)	Number of OCI Instructors Identifying Critical Feature during Instructor Interviews (N=5)
GCI and OCI Instructors			
	Lewis structures	5	5
	Resonance structures	5	5
	Resonance hybrid	5	4
	Octet rule	5	3
	Formal charge	4	2
	Major and minor resonance contributors	2	4
GCI Instructors			
	Bond length	2	0
OCI Instructors			
	Pattern recognition	0	5
	Curved arrows	0	4
	Delocalized and localized lone pairs	0	4
	Hybridization	0	1

In the following sections, I discuss the critical features. When possible, I distinguish between what instructors want students to know about a specific critical feature and what instructors want students to do with one particular critical feature. Please note that instructors' names have been replaced with pseudonyms, and any artifacts (e.g., instructor drawings) were reproduced to protect the instructors' privacy.

Critical Features Identified by Both General Chemistry I and Organic Chemistry I Instructors

The critical features in this category were identified by at least one General Chemistry I instructor *and* one Organic Chemistry I instructor participating in this study. The critical features in this category are *Lewis structures, resonance structures, resonance hybrid, octet rule, formal charge,* and *major and minor resonance contributors.* As mentioned above, these critical features will be discussed in descending order of the total number of instructors that identified them, which is the order in which they are listed in the previous sentence. If this distinction is not possible (i.e., two critical features were identified by the same number of instructors), I will justify the order in which they will be discussed.

Lewis Structures and Resonance Structures

Two critical features were mentioned by all of the General Chemistry I and Organic Chemistry I instructors who participated in the study. These were *Lewis structures* and *resonance structures.* Lewis structures will be discussed first because instructors identified this critical feature as foundational for students to understand before learning about resonance structures.

Lewis structures. As mentioned above, all of the General Chemistry I and Organic Chemistry I instructors in this study indicated the importance of understanding Lewis's model of chemical bonding (i.e., Lewis structures) and that a single Lewis structure cannot adequately represent the bonding in some molecules. The instructors perceived this critical feature as foundational knowledge for students' understanding of resonance. If students cannot draw a valid Lewis structure, they will likely struggle to interpret and understand the limitations of Lewis structures and the need for resonance in the first place.

Collectively, General Chemistry I and Organic Chemistry I instructors believed that students should understand the limitations of Lewis structures and why resonance is needed to address those limitations. For example, when I asked Annabelle, a General Chemistry I instructor, how she typically introduces resonance to her students, she began drawing on paper while providing me with an overview of her teaching approach. She explained that she starts by asking her students to draw the Lewis structure for the carbonate ion before she draws it on the whiteboard herself (Figure 32). She then explained to me that she asks students if they drew the double bond in the same place as her and why/if it was correct if they did or did not. After this discussion with the students, she said that she draws all of the possible Lewis structures of the carbonate ion on the whiteboard with the word *or* between each structure (Figure 33). Annabelle shared that students typically agree that all of the Lewis structures that she drew on the board are valid ways to draw the carbonate ion while keeping the octet rule, but they usually do not know why. Annabelle uses this moment to introduce resonance to her students. Other General Chemistry I instructors in this study took similar approaches to Annabelle.

Figure 32

Annabelle's Drawing of Carbonate

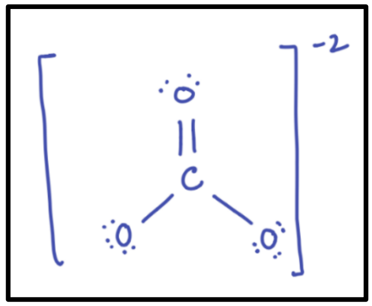
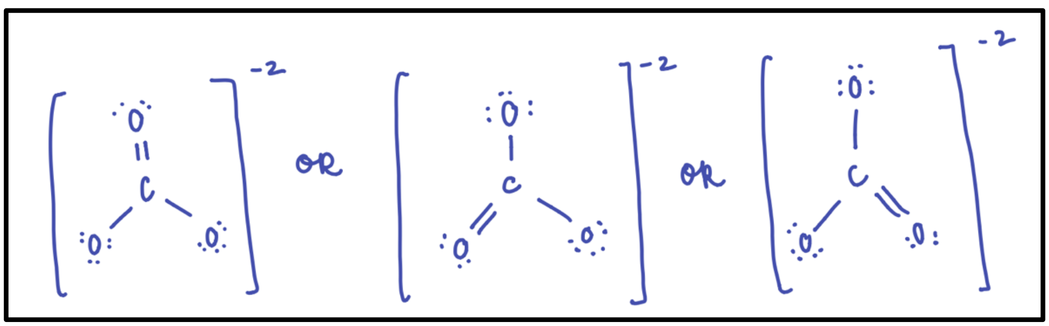


Figure 33

Annabelle's Drawing of the Lewis Structures of Carbonate



The Organic Chemistry I instructors also believed students should understand the limitations of Lewis structures; however, they tended to think that students should come into organic chemistry with this understanding. For example, while Maryann believed that Lewis structures were necessary for students to understand resonance, she shared, "I don't have time to cover Lewis structures […], and I just said [to students], you did this in [your general chemistry I course]". She also shared that she provides students with a review sheet to access online if they need extra help with Lewis structures.

Concerning what the General Chemistry I and Organic Chemistry I instructors believed students should be able to do relative to this critical feature, there was consensus among both groups of instructors that students should be able to draw Lewis structures, including all lone pairs, and determine the formal charges on the individual atoms in the molecule. The instructors believed that students should then be able to use the Lewis structure they have drawn to identify whether the molecule could exhibit resonance. The General Chemistry I instructors limited this task to relatively simpler molecules, like carbonate. The Organic Chemistry I instructors expected students to draw Lewis structures and be able to identify resonance in larger, more complex molecules, such as $CH_2{=}CHOCH_2CH(CH_3)_2$.

Resonance structures. The other critical feature to be mentioned by all the General Chemistry I and Organic Chemistry I instructors participating in this study was *resonance structures*. Every instructor indicated the importance of understanding that resonance structures only differ in the placement of electrons (i.e., electron movement), not atoms.

All of the instructors stated that both General Chemistry I and Organic Chemistry I students should know that resonance structures are two-dimensional representations showing electron "movement" between atoms. Nearly all the instructors emphasized a phrase similar to "electron movement" while describing what students should know about resonance structures. For example, Ryan, a General Chemistry I instructor, explained: "Essentially, you're writing Lewis structures where you're moving electrons around." Initially, I assumed that the instructors were using phrases like "electron movement" to describe the fact that the electrons are "moved" from one atom to another in the drawings of different resonance structures, and this was, indeed, true for some of the instructors I interviewed. However, as I continued my analysis, I found that other instructors expressed the misconception that resonance structures are real entities that exist in nature and that electrons were literally moving as a molecule transitioned from one resonance structure to another. For example, an instructor who teaches General Chemistry I and Organic Chemistry I stated: “I really want to emphasize the electrons that are moving, and that’s how you can get to multiple resonance structures.” Similarly, during her interview, Annabelle stated that “electrons are moving and that there’s not always one stable structure for something.” Her phrasing suggests that she believes molecules that exhibit resonance have multiple stable structures instead of a single resonance hybrid in which the molecule’s electron density is spread out amongst multiple atoms. Resonance structures do not depict the actual movement of electrons, but, rather, “treat electrons as if they [are moving] (Klein, 2012, p. 70) because this is useful for thinking about chemical reactions. In other words, a participant in this study stated, “Resonance is a tool to predict reaction mechanisms; it’s not a real phenomenon. Resonance structures don’t actually exist.” It will be important for future research to examine potential misconceptions that instructors themselves might hold about resonance, as this will impact what students can learn about the concept.

There was consensus amongst the two groups of instructors related to what they expected students to do with resonance structures. All of the instructors in this study agreed that students should be able to identify and draw correct resonance structures for a species, although the specific ways the students should do this differed by course. Unsurprisingly, the General Chemistry I instructors expected students to do less with resonance structures than the Organic Chemistry I instructors. Those teaching general chemistry told students when a molecule or ion exhibited resonance and wanted them to either identify or draw correct resonance structures without curved arrows on homework, quizzes, or exams. Kory explained that he focuses more on his general chemistry students' ability to draw resonance structures than on the underlying conceptual aspects of resonance. On exams, all of the General Chemistry I instructors shared that they would either tell students how many possible resonance structures there are for a species or expect them to figure it out on their own and draw each. For example, Kory said he might ask students to “write one or more Lewis structures for the nitrate ion.” This example seems to be representative of what a General Chemistry I instructor in this study might expect their students to be able to do relative to this critical feature.

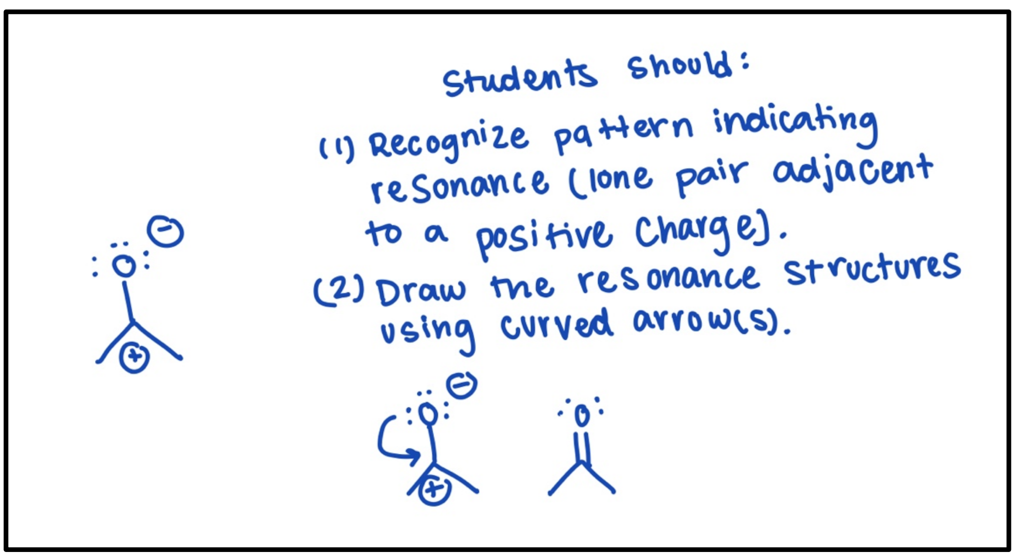
The Organic Chemistry I instructors also expected students to be able to identify and draw resonance structures. They went a step further, though, and wanted students to identify resonance using specific patterns in molecular structure (see Figure 12) that typically indicate a molecule exhibits resonance. The instructors also wanted students to use curved arrows to draw resonance structures. I will discuss both of these concepts further as critical features in their own right in later sections. The fact that Organic Chemistry I instructors expected students to do more with resonance structures was unsurprising as resonance is briefly introduced in General Chemistry I, but it is a big focus in both semesters of organic chemistry. When I asked Anthony what he thought was most important for students to be able to do with resonance at the organic level, he stated:

> So, I guess top priority is being able to spot when there are resonance structures. So, look for multiple bonds, and that has to be adjacent to either another multiple bond or a charge of some sort. So, first step, when is there going to be a resonance structure possible? Sort of identifying that. The next tier above that is, what are those resonance structures? Can you draw them? Can you ideally push the arrows correctly?

These expectations were echoed amongst all of the other Organic Chemistry I instructors. The instructors explained that on the first quiz and exam following the introduction of resonance, they will provide a structure and ask students to draw all possible resonance structures for it. For example, if the instructor provided students with the structure shown on the far left of Figure 34, they would expect students to (1) recognize if resonance is possible by identifying the common patterns of resonance and (2) draw all possible structures using curved arrows. The instructors did not mention using double-headed arrows between the structures or brackets to designate the structures as resonance structures. Based on the instructor interviews, this example seems to be representative of what an Organic Chemistry I instructor in this study might expect their students to be able to do relative to this critical feature.

Figure 34

Example of Organic Chemistry I Exam Question on Resonance



Resonance Hybrid, Octet Rule, Formal Charge, and Major and Minor Resonance Contributors

The remaining critical features identified by both General Chemistry I and Organic Chemistry I instructors are *resonance hybrid*, the *octet rule*, *formal charge*, and *major and minor resonance contributors*. Six or more of the General Chemistry I and Organic Chemistry I instructors who participated in the study identified these critical features, which will be discussed in the order in which they were just listed. The same number of instructors identified *formal charge* and *major and minor resonance contributors* as critical features. I will discuss formal charge before major and minor resonance contributors because some instructors perceived formal charge as necessary to distinguish between major and minor resonance contributors.

Resonance hybrid. Most of the General Chemistry I and Organic Chemistry I instructors in this study indicated the importance of understanding that resonance structures are not real entities and do not exist in nature, as well as the importance of understanding that the actual, most correct structure, the resonance hybrid, is a mental melding of the different resonance structures. There were various responses to what instructors believed students should know and be able to do relative to this critical feature. For the most part, the General Chemistry I instructors reported spending more time discussing the resonance hybrid during classroom instruction than the Organic Chemistry I instructors did. All of the General Chemistry I instructors mentioned that they wanted students to know about the resonance hybrid. Maryann shared that she was concerned that students know:

> …that there are multiple correct ways to draw Lewis structures for a molecule. And to understand that there are multiple correct ways because the true molecule is a hybrid of

all of those correct ways. And there's not one; I don't want them thinking that for every structure, there's just one.

Kory and Ryan, two General Chemistry I instructors, also emphasized the importance of students understanding the resonance hybrid and pointed out student misconceptions about the resonance hybrid that they noticed in their classes. Kory explained, "The hard thing they might not understand [about resonance] immediately is that it's a hybrid, that it's not an equilibrium." Similarly, when describing how he teaches resonance, Ryan stated, "In this case, [the molecule] does not flip back and forth between these different resonance structures. Rather, we say it's like a hybrid of all three resonance structures." This misconception—that the molecule alternates between resonance structures in equilibrium (or that resonance structures are real entities that exist in nature)—has been widely reported in the research literature (e.g., Kim et al., 2019; Petterson et al., 2020; Taber, 2002; Xue & Stains, 2019). It was also a misconception that some of the instructors seemed to express while describing "electron movement" in resonance structures, as previously mentioned.

Although the Organic Chemistry I instructors who participated in this study believed the resonance hybrid is an important concept for understanding resonance overall, they did not believe the resonance hybrid was as directly relevant to their course as the General Chemistry I instructors did. For example, Anthony, who has taught both general and organic chemistry during his career, said, "I guess I don't spend too much time on the resonance hybrid in organic. I talked about that more in gen chem, in organic, the hybrid, I guess, is not much of a concern for me." While the Organic Chemistry I instructors might not view the resonance hybrid as relevant to their course, some still believed it was important to go over quickly in class, as many wanted to dispel the common misconception that a molecule alternates back and forth between different resonance structures. For example, Joe shared that while first introducing resonance to his Organic Chemistry I students, he likes to "explain that the conjugated double bond is not really a double bond, single bond, double bond it is actually a mixture [of the two bonds]."

A few of the instructors who participated in this study identified what they wanted their students to be able to do with the resonance hybrid to (e.g., drawing it), but none of the instructors expected students to do anything with the resonance hybrid on homework, quizzes, or exams. Destiny and Annabelle, two General Chemistry I instructors, and Kory, an organic chemistry instructor, were the only ones who emphasized students' ability to "visualize resonance" via the resonance hybrid. While none of the instructors expected students to draw the resonance hybrid, they shared that they do so themselves in class to illustrate the concept further and to help students "visualize [resonance] better" while teaching the concept (Destiny).

Octet rule. Most of the General Chemistry I and Organic Chemistry I instructors in this study mentioned the importance of students understanding the octet rule and, more specifically, recognizing that second-row elements cannot have expanded octets in Lewis structures. This understanding establishes a context for introducing resonance concepts. For example, Destiny, a General Chemistry I instructor, shared that before she introduces resonance to her students, they naturally question why there can be multiple correct Lewis structures (i.e., they all keep the octet rule) for the same molecule. Their questions give her a reason to introduce resonance to her students.

Both groups of instructors were relatively vague regarding what they wanted students to know about this critical feature. Instead, they emphasized what they wanted students to do with it. Instructors from both groups wanted students to use the octet rule to decipher if a resonance structure was valid. For example, Brad, an Organic Chemistry I instructor, wanted students to draw a resonance structure and then "decide whether that structure is acceptable. Like, does it follow the octet rule?"

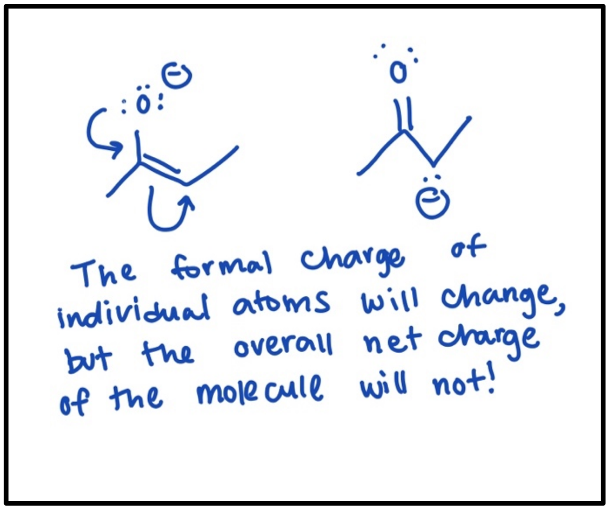
Similarly, after drawing a possible resonance structure for a molecule, Destiny wanted students to count to ensure all the atoms had a complete octet. If not, she expected that they go back and review their structure. Dallas shared that his Organic Chemistry I students struggle to decipher how many bonds certain elements can typically form, often resulting in their drawing too many bonds to a given atom.

Formal charge. Understanding the concept of formal charge is fundamental to understanding the differences between resonance structures for the same species. Most of the instructors in this study wanted students to understand that while a given atom can have different formal charges in different resonance structures, the overall net charge of the molecule does not change from one resonance structure to another. The instructors also said that students should understand how formal charge can be used to identify the major resonance contributor out of a group of resonance structures. The instructors believed that students should understand what a formal charge is and how to calculate formal charges before being introduced to resonance.

As with the critical feature *octet rule*, the instructors were relatively vague concerning what they wanted students to know about this critical feature. Dallas, an Organic Chemistry I instructor, discussed this aspect the most. When I asked Dallas to teach me resonance during the interview, he drew the molecule in Figure 35 as an example. After drawing the resonance structure for the molecule using curved arrows, he stated, "It's really easy to get lost in resonance structures. I always try to remind my students to remember formal charges; no reactions are occurring, so there should be the same sum of formal charges across every resonance structure." He wrote a note under the resonance structures to emphasize his point (Figure 35).

Figure 35

Dallas' Example Showing That the Net Charge of a Molecule Does Not Change Between Resonance Structures



Both General Chemistry I and Organic Chemistry I instructors were concerned with students' ability to use formal charge to identify the major resonance contributor, which is the most stable of the resonance structures (i.e., the resonance structure with the lowest formal charges on individual atoms). The instructors that identified this critical feature did not express what they wanted students to know about it but emphasized what they wanted students to do with it. For example, when I asked Ryan what type of practice problems or homework he typically has students do related to resonance, he shared:

> I might draw a couple of molecules and ask them to determine the number [of resonance structures], the formal charge of each atom present and then tell me which [resonance structure] is more likely, you know, the predominant resonance structure and explain why. So that's kind of about the depth.

When I asked Destiny a similar question, she expressed that she, too, wants students to be able to decipher the more dominant structure based on formal charge.

Major and minor resonance contributors. Most of the instructors in this study wanted students to understand that there are certain instances in which one (or more) of the resonance structures is the major contributor. The instructors used different words to describe the major and minor resonance contributors. For example, Kory and Ryan used “prominent” to describe the major resonance contributor, and Destiny used “dominant.” Despite these differences, it was obvious that the instructors were referring to the same thing; as such, they were given the same code during data analysis (i.e., *major and minor resonance contributors*).

The instructors wanted students to know that not all resonance structures equally contribute to the resonance hybrid. Interestingly, none of the instructors specifically used the term “resonance hybrid” while describing this critical feature. They were not specific in what the resonance structure was the major contributor of (i.e., the major contributor to the resonance hybrid). However, it is likely that at their level of expertise, they assumed this to be implied.

Concerning what instructors expected students to do with this critical feature, there was consensus amongst General Chemistry I and Organic Chemistry I instructors. That is, after first introducing resonance, instructors expected students to be able to identify the major and minor resonance contributors. For example, when I asked Brad, an Organic Chemistry I instructor, what type of practice problems and test questions he asks students to solve after first learning about resonance, he said, “I ask them to draw the resonance [structures] and [figure out] if they are equivalent or not equivalent. Then they need to figure out which is the major form, and which is the minor form.” The General Chemistry I instructors shared similar ideas. Nevertheless, while both General Chemistry I and Organic Chemistry I instructors expected students to decipher the major and minor resonance contributors, as mentioned earlier, the instructors did not expect students to connect this critical feature to the resonance hybrid. There was no discussion of wanting students to understand that the major resonance structure contributes more to the overall structure of the resonance hybrid than do the minor resonance structures.

Critical Features Identified by General Chemistry I Instructors

Only General Chemistry I instructors identified the critical feature of *bond length*. It is discussed below.

Bond Length

Bond length was mentioned by two of the General Chemistry I instructors that participated in this study. A few General Chemistry I instructors in this study believed that students should understand how resonance can explain the differences between the bond lengths that would be predicted by Lewis structures and the observed bond lengths for certain molecules. None of the Organic Chemistry I instructors mentioned this critical feature.

Both Ryan and Annabelle expected students to know that electron density can be shared over multiple atoms, which results in an intermediate bond length compared to that predicted by individual Lewis or resonance structures. Ryan said:

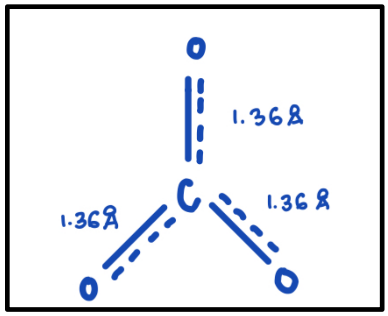
> I guess just my main hope is that they'd have a little better understanding of what molecules really are and how these atoms are connected. And that the bonds [i.e., electrons] can be kind of shared over multiple atoms, as opposed to like having discrete double bonds and single bonds, but there's like, kind of a middle ground. […]. If they get that feeling and appreciation, I've done my job.

Annabelle shared similar ideas. When I asked her how she typically introduced resonance to her students, she drew the carbonate molecules and stated:

> What would you expect to measure if we could take a snapshot of this [see Figure 32] and measure this distance, this distance, and this distance [pointed to each of the bonds on Figure 32]? So expected, we would measure a carbon-oxygen double bond at 1.23 angstroms. And you would expect me to measure two carbon-oxygen single bonds at 1.43 angstroms. If this is how it was if we took a snapshot, maybe the double bond would be here, [if we took another snapshot, it could be] here or here [pointing to the double bond in each resonance structure in Figure 33].
>
> What actually happens? So, actually, if we took a snapshot of this, we would have something that looks like this [see Figure 36], where we have three equal bonds at 1.36 angstroms. So, it’s not really that these electrons are confined here. They are actually in kind of fluid motion all around. And the double bond is actually being shared between all of these atoms. So, we wouldn’t say it’s a single, a single and a double bond. We would say each of these has a bond length of 1 and 1/3 kind of a bond order. They each get their own [bond], and then they're ’ll shari’g that second one.

Figure 36

Annabelle's Example of the Resonance Hybrid of Carbonate



While the two instructors shared similar ideas about what students should know about this critical feature, they disagreed on what they expected students to do with it. Annabelle expected students to calculate and predict bond lengths on homework and exams; she said, "What I generally assess them on is if they draw a Lewis structure, [they should] be able to come up with kind of that bond order." Ryan, on the other hand, does not expect students to calculate or explain bond orders. He perceived this critical feature as an important way to introduce resonance and have students gain an appreciation and underlying understanding of why resonance is needed but was not interested in students applying the concept.

Critical Features Identified by Organic Chemistry I Instructors

The critical features in this category were identified only by Organic Chemistry I instructors. Overall, at least one Organic Chemistry instructor identified the following critical features: *pattern recognition, delocalized and localized lone pairs, curved arrows, and hybridization.* These critical features will be discussed in the order they were just listed, in descending order of the total number of instructors that identified them. If this distinction is not possible, I will justify the order in which they will be discussed.

Pattern Recognition

All of the Organic Chemistry I instructors in this study agreed it was important for students to understand that they can use specific patterns in molecular structures in order to determine if a molecule will exhibit resonance or not. The instructors all broadly referred to these patterns as the "five different patterns of resonance." The patterns are (1) an allylic lone pair, (2) an allylic positive charge, (3) a lone pair adjacent to a positive charge, (4) a π bond between two atoms of differing electronegativity, and (5) conjugated π bonds in a ring (Klein, 2012, p. 81) (see Figure 12).

The instructors expected students to recognize each pattern (e.g., an allylic lone pair) in different molecular structures and, if a pattern was present, use the corresponding resonance structures to problem solve. When I asked Maryann to pretend I was an organic chemistry student and teach me resonance, she gave me a basic introduction to the concept and then went over all of the possible patterns of resonance with me. Other instructors described similar approaches to Maryann's, with some emphasizing that if students had a hard time identifying the patterns, "they're gonna have a hard time [in organic chemistry]."

Delocalized and Localized Lone Pairs, Curved Arrows, Hybridization

The remaining critical features identified by Organic Chemistry I instructors are *curved arrows, delocalized and localized lone pairs,* and *hybridization*. At least one of the Organic Chemistry I instructors mentioned each of these critical features in this study. The same number of instructors identified *delocalized and localized lone pairs* and *curved arrows*. I will discuss *curved arrows* first because it is introduced before *delocalized and localized lone pairs* in many organic chemistry textbooks (e.g., Klein, 2012).

Curved arrows. Nearly all of the Organic Chemistry I instructors in this study believed it was important for students to understand that curved arrows are used to draw resonance structures. The instructors only discussed what they expected students to do with curved arrows and not what they expected students to know about them. That is, none of the instructors discussed what the head or tail of the arrow represents and that curved arrows do not represent the actual movement of electrons (i.e., they are merely a tool used to draw resonance structures). In other words, as Klein (2012) explains, curved arrows "treat the electrons as if they were moving, even though the electrons are actually not moving at all" (p. 70).

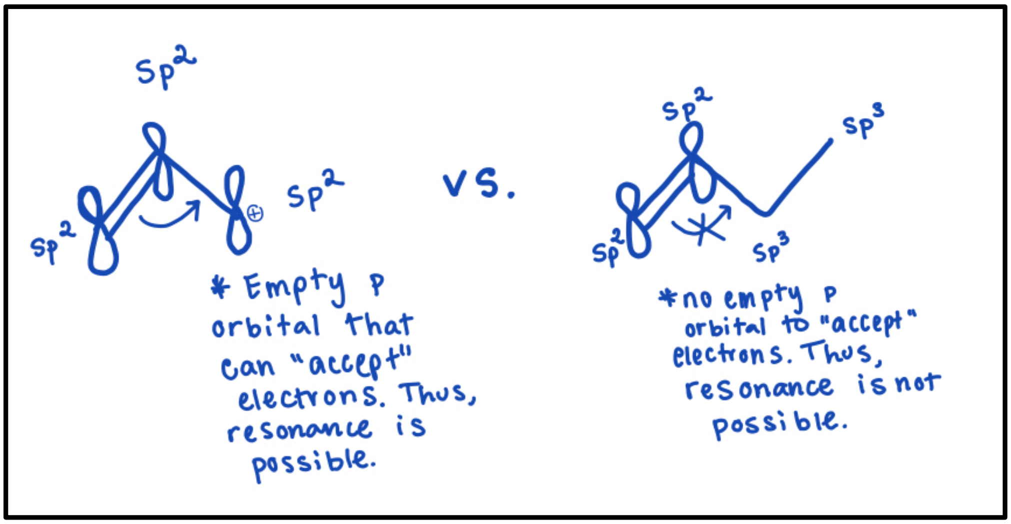
The Organic Chemistry I instructors expected students to use curved arrows while drawing resonance structures on homework, quizzes, and exams. Some instructors specifically examined and graded students' use of curved arrows, ensuring that the resulting structure matched what their curved arrows depicted. The instructors generally agreed that students' success with resonance in organic chemistry largely depends on their ability to use curved arrows.

Delocalized and localized lone pairs. Nearly all of the Organic Chemistry I instructors in this study believed it was important for students to understand the difference between electrons that participate in resonance (i.e., delocalized electrons) and those that do not (i.e., localized electrons). Most of the instructors that identified this critical feature were vague in what they expected students to know and do with it. That is, they only briefly mentioned that it was important for students to identify whether a lone pair would participate in resonance or not. For example, Anthony stated, "Resonance usually comes in when there's either charge moving around or a lone pair that can move around." While most instructors expected students to identify if a lone pair is localized or delocalized, Joe was the only instructor who tied this idea to resonance and hybridization during his interview. This stands out as most of the instructors in this study have relied on using only pattern recognition to describe how they teach resonance. Joe's response was coded as both *delocalized and localized lone pairs* and *hybridization*. It is discussed in the following paragraph.

Hybridization. As stated, Joe was the only instructor who identified this critical feature. In fact, he introduces his students to hybridization before he discusses the five resonance patterns previously mentioned. To do this, he shared that his first goal is to get students to be able to identify the hybridization of each individual atom in a molecule (e.g., sp, sp^2, sp^3). After students can do this, he shared that he would introduce the concept of resonance. Next, he combines the two concepts and shows students how to recognize if a molecule exhibits resonance using hybridization. It might be helpful to point out that for resonance, you need to have sp^2 or sp hybridized orbitals with empty p orbitals for electrons to move to. Atoms that are sp^3 hybridized do not have an empty p orbital and cannot accept electrons. Based on this information, Joe shared that he expects students first to identify the hybridization of each atom and then decide if resonance is possible. Figure 37 provides an example of this approach. He believes that this should be students' first or main approach to resonance.

Figure 37

Joe's Approach for Teaching Resonance using Hybridization



As mentioned earlier, Joe connected hybridization and delocalized and localized lone pairs while discussing resonance. When I asked Joe what his students have difficulty understanding about resonance, he shared that they have difficulty understanding the difference between delocalized and localized lone pairs because "there is a disconnect between resonance and hybridization." To elaborate, he used the example of pyridine (Figure 38). This molecule appears to have resonance at first glance because the lone pair is allylic to a π bond (one of the five resonance patterns), and the atoms are sp^2 hybridized. Joe stated, "Students have a hard time understanding that the lone pair on the nitrogen atom does not participate in resonance because it is in the sp^2 hybridized orbital. It's not in the p orbital because the p orbital is being used for the double bond" (as illustrated in Figure 39). Again, it might be helpful for me to point out that a lone pair only participates in resonance if it occupies a p orbital that can overlap with the p orbitals of adjacent atoms. So as Joe explained, because the p orbital is being used for the double bond in pyridine, the lone pair (which is in a different orbital) cannot participate in resonance. While this is what Joe wanted students to know, he reiterated that students struggle to do so. He suggested that it is because they do not take the time to understand hybridization. Instead, students rely solely on identifying the patterns of resonance, which in the case of pyridine (and other molecules), leads them astray. Interestingly, the example of pyridine that Joe used is discussed in the Klein (2012) textbook two sections after the five patterns of resonance are introduced (see Figure 12), and it is discussed in almost the entirely same way that Joe did. Based on what was discussed during the interview, the main difference between Joe and Klein (2012) seems to be that Joe discusses hybridization before the five patterns of resonance and also spends more time emphasizing hybridization throughout his entire discussion of resonance. How this affects student learning will be discussed in the chapters that follow.

Figure 38

Joe's Example of the Lewis Structure of Pyridine, Showing the sp^2 Hybridization of the Nitrogen Atom

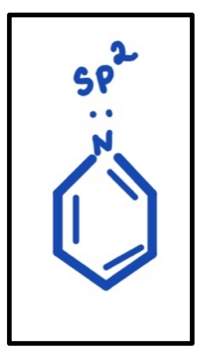
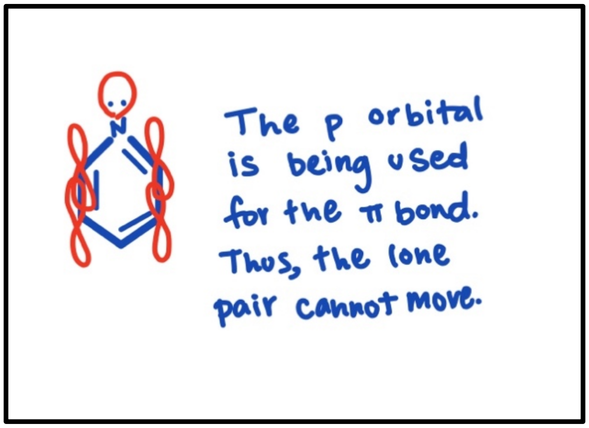


Figure 39

Joe's Example of the Lewis Structure of Pyridine, Showing the Localization of the Lone Pair on the Nitrogen Atom



Conclusions

Through these interviews with General Chemistry I and Organic Chemistry I instructors, I identified what instructors intended their students to understand about resonance (i.e., the intended object of learning). All in all, I identified eleven critical features that the instructors believed were important for their students to understand resonance. I found that both groups of instructors shared many of the same beliefs on what was important for students to learn about resonance. That is, they identified many of the same critical features of resonance (*Lewis structures, resonance structures, resonance hybrid, octet rule, formal charge,* and *major and minor resonance contributors*). Nevertheless, what the instructors expected students to know and do with each critical feature listed in the previous sentence depended on the course they taught.

I also found that there was/were critical feature(s) identified by only General Chemistry I instructors (*bond length*) and critical features identified by only Organic Chemistry I instructors (*pattern recognition, curved arrows, delocalized and localized lone pairs,* and *hybridization*). Again, this was unsurprising as the focus/role of resonance in each classroom differs. That is, resonance is typically only introduced to students in the first semester of the general chemistry series for a brief period but is later revisited in the first semester of the organic chemistry series and then utilized throughout organic chemistry and other higher-level chemistry courses. Therefore, it is reasonable that the Organic Chemistry I instructors identified four additional critical features not mentioned by the General Chemistry I instructors.

Interestingly, the General Chemistry I instructors mentioned a critical feature that the Organic Chemistry I instructors did not mention, *bond length.* This is perhaps because the Organic Chemistry I instructors were less interested than General Chemistry I instructors in discussing the resonance hybrid (Organic Chemistry I instructors reported focusing on the resonance hybrid less during classroom instruction), and bond length is typically discussed to describe the resonance hybrid.

The General Chemistry I and Organic Chemistry I instructors in this study often highlighted what they believed students should do with a critical feature without clearly explaining what students should know about it. For example, while many instructors in this study clearly explained that they wanted students to use formal charge to identify the major and minor resonance contributors, they were relatively vague when describing what they wanted students to know about formal charge. In other words, it seems many of the instructors in this study emphasized an operational rather than a conceptual understanding of resonance. This aligns with the fact the instructors also explained that they do not assess students on the resonance hybrid, as this critical feature addresses students' conceptual understanding of resonance. It also aligns with the findings of other studies (Atieh et al., 2022; Carle & Flynn, 2020; Xue & Stains, 2020)

Finally, it should be mentioned that some instructors seemed to express scientifically inaccurate conceptions of resonance during the instructor interviews. While discussing *resonance structures,* some instructors described resonance as the actual movement of electrons in nature or, in other words, that resonance structures actually exist. Interestingly, while discussing the critical feature *resonance hybrid*, some instructors identified that their students held this same misconception (i.e., that resonance structures are real entities that exist in nature), unaware that they previously suggested that they had the same misunderstanding. To further understand how the instructors conceptualize these two critical features in relation to each other, more specific interview questions would need to be developed for a future study.

In conclusion, these critical features provide an important picture of what instructors intend or expect their students to know about and do with resonance. For this reason, the critical features provided a framework for subsequent analyses in the current study. Specifically, these critical features were used to analyze what is possible for students to learn about resonance in the classroom (i.e., the enacted object of learning) and what students came to understand about resonance (i.e., the lived object of learning). These results will be discussed in the chapters that follow.

CHAPTER 6 ANALYSIS, RESULTS, AND DISCUSSION OF THE ENACTED OBJECT OF LEARNING (RESEARCH QUESTION 2)

My second research question asks what is possible for General Chemistry I and Organic Chemistry I students to understand about resonance in General Chemistry I and Organic Chemistry I classrooms based on the information presented to them in their classes. Because this study was informed by variation theory, answering this question involved observing five General Chemistry I and five Organic Chemistry I classrooms to explore what was made possible for students to learn about resonance in those classes. Table 9 lists the pseudonyms of the instructors that allowed me to observe their classrooms (i.e., the same instructors I interviewed in Chapter 5), along with their associated courses, in alphabetical order. Like instructors' beliefs described in Chapter 5, I found that the instructors' teaching practices were not institutionally specific, meaning their teaching practices were not dependent on the type of institution at which they taught. Thus, to protect their identities, I do not identify the instructors' institutions or institution types in the discussion below. I also recreated any classroom artifacts (e.g., anything the instructors drew during the classroom observations) created by the instructors to protect their identities further. Please note that one instructor (Maryann) was observed twice: once when she taught resonance in her General Chemistry I course and once when she taught resonance in her Organic Chemistry I course.

In the following sections, I will briefly overview how resonance was taught in the General Chemistry I and Organic Chemistry I classrooms I observed. Then, I will discuss how I analyzed the classroom observations for what was possible for students to learn about resonance. Next, I will discuss how each of the eleven critical features identified in Chapter 5 was or was not mentioned during instruction in the classrooms I observed. Finally, I will discuss additional non-critical features (i.e., those features not mentioned as important for students to understand resonance during the instructor interviews) presented in the classrooms I observed.

Overview of Instruction on Resonance in General Chemistry I and Organic Chemistry I

Here, I briefly describe the main approaches used to teach resonance in the General Chemistry I and Organic Chemistry I classrooms I observed. This is meant to provide an overview of the approaches used to teach resonance before I discuss each of the critical and non-critical resonance features mentioned during the classroom observations in detail. It is not meant to represent every instructor's approach to teaching resonance in this study. Rather, it provides a "big picture" of the common flow of instruction used to teach resonance in these courses.

Main Approach to Teaching Resonance in General Chemistry I

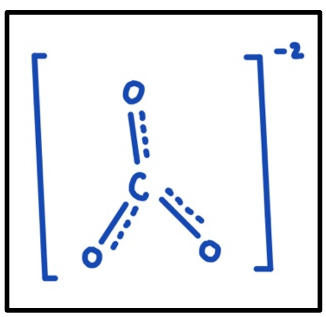
Coincidently, despite institutional variance, all of the General Chemistry I instructors in this study used the same textbook for their course (Brown et al., 2018). Destiny, Maryann, and Kory used the associated textbook publisher's PowerPoint slides while teaching but made modifications to them. Annabelle created her own PowerPoint slides. Ryan did not use PowerPoint but wrote on the whiteboard while teaching. Likely because the instructors were using the same textbook, their approaches to teaching resonance followed a similar pattern, with some instructors going into more or less detail on specific topics (e.g., the resonance hybrid).

Resonance was introduced towards the middle of the semester in all of the General Chemistry I classrooms I observed, after teaching students how to draw Lewis structures, but before teaching them about molecular bonding and geometry theories. The instructors explained that multiple correct Lewis structures, called resonance structures, could be drawn for some molecules. However, the most correct structure was a combination of all the structures, called the resonance hybrid. Many instructors used carbonate (like that shown in Figure 32) as an example to introduce resonance. They showed that multiple correct Lewis structures (i.e., resonance structures) that keep the octet rule can be drawn for this polyatomic ion (like that shown in Figure 33). Many instructors then explained that the actual structure of carbonate is a combination of all the resonance structures, called the resonance hybrid (Figure 40). Some instructors expressed misconceptions while discussing the resonance hybrid, which will be discussed in a later section.

Nevertheless, most instructors mentioned the underlying concept of the resonance hybrid by discussing the differences in expected versus observed bond length data. The instructors spent time reviewing how to draw resonance structures using different examples. The instructors ended their presentation of resonance by discussing how formal charge can be used to determine which resonance structures will contribute more or less to the resonance hybrid.

Figure 40

Resonance Hybrid of Carbonate



Main Approach to Teaching Resonance in Organic Chemistry I

The Organic Chemistry I instructors in this study did not all use the same textbook. There were three different textbooks used (Bruice, 2017; Klein, 2012; Smith, 2019) (three instructors used the same textbook). Because of the limited number of participants in this study, I will not identify which instructors used a particular textbook as that would give away too much information and compromise the instructors' privacy. Anthony and Maryann were the only instructors who used PowerPoint while teaching. They both made modifications to their associated textbook publishers' PowerPoint slides. The rest of the instructors used the whiteboard or their tablet to teach. All but one instructor introduced resonance during the first week of the semester. Anthony did not introduce resonance until the end of the semester (around three weeks were left before the final exam). He shared that this was the order in which the textbook presented it.

The Organic Chemistry I instructors introduced resonance similar to the General Chemistry I instructors. They reminded students of the limitations of Lewis structures and described resonance as an approach to this issue. Like the General Chemistry I instructors, many of the instructors in this group used carbonate as an example (like that shown in Figure 32). The instructors discussed that multiple correct Lewis structures, called resonance structures, could be drawn for carbonate (Figure 33). Then, they explained that the actual structure of carbonate is a mental melding of all the resonance structures and is called the resonance hybrid (Figure 40). After an initial introduction to resonance, the Organic Chemistry I instructors focused on teaching students how to draw resonance structures using curved arrows by focusing on pattern recognition and/or hybridization. The instructors who focused their teaching of resonance on pattern recognition emphasized identifying resonance by looking for specific patterns in molecular structure. While only one instructor identified using hybridization to teach resonance in the instructor interviews, multiple instructors used it while teaching. The instructors who focused their teaching of resonance on hybridization emphasized identifying the individual hybridization of each atom in a structure to determine if resonance is possible (i.e., an empty p orbital). As mentioned, some instructors explained both approaches while teaching about resonance. The Organic Chemistry I instructors also discussed certain instances in which one or more resonance structures contribute more to the resonance hybrid than others and how to identify the major resonance contributor using formal charge.

Overview of Classroom Observations and Analysis

The purpose of this component of the current study is to investigate what was possible for students to understand about resonance in their General Chemistry I and Organic Chemistry I classrooms. This involved identifying what I, the researcher, perceived as possible for students to understand about resonance through classroom observations. Previously, in Chapter 5, I discussed the eleven critical features that five General Chemistry I instructors and five Organic Chemistry I instructors identified as important for students to understand about resonance during one-on-one interviews. For this component of the study, I observed each of these instructors' classrooms while they introduced resonance for the first time to identify how/if these critical features were being taught, as well as to identify any additional non-critical features of resonance presented in the classrooms (i.e., those features that are not critical for students to understand to come to the desired understanding of resonance). I should mention that, while important, I was not interested in the application of resonance in a context or in students' ability to apply resonance, as that information is outside the parameters of this study. Thus, if an instructor discussed an application of resonance during a classroom observation, I did not include that information here. For example, during the classroom observations, multiple instructors mentioned using resonance to determine relative molecular stability. While this is an essential skill for organic chemistry students, I did not analyze these segments of the observations as it was outside of the parameters I set for the study (i.e., the focus is on students' understandings of resonance while first learning about it in General Chemistry I and Organic Chemistry I).

One instructor's (Maryann's) classroom was observed twice because she taught General Chemistry I and Organic Chemistry I during the same semester (as mentioned, this instructor was also interviewed twice). I should note that three instructors gave me a pre-recorded lecture of themselves teaching resonance in General Chemistry I (Destiny) or Organic Chemistry I (Dallas and Brad) that they had recently used to teach resonance. Aside from not needing to record the pre-recorded lectures, data collection and analysis were the same despite this difference. I acted solely as an observer and was not an active participant during the classroom observations.

The classroom observations were recorded and transcribed verbatim. I should be clear that the enacted object of learning concerns what instructors *actually* made possible for students to learn about resonance, regardless of whether it is correct or not. For this study, I only coded information that instructors verbally mentioned (i.e., some instructors had information related to resonance on their slides that they did not discuss). I coded the classroom observations for the critical features of resonance identified from the instructor interviews (i.e., the critical features identified in Chapter 5 were used as my coding scheme). For example, while Ryan was teaching, he stated, "The resonance hybrid is a combination of all the resonance structures." This phrase was coded as the critical feature "resonance hybrid." I also coded for the non-critical features, meaning aspects of resonance not identified as critical features of resonance by the instructors but addressed in the classroom. For example, some of the instructors drew a double-headed arrow between their resonance structures while teaching and described the double-headed arrows as "showing resonance" or "resonance arrow." This was coded as a non-critical feature (i.e., *resonance arrow*) because none of the instructors had identified it as a critical feature during instructor interviews. Data analysis was a constant comparative process; the codes were reviewed and refined as the data analysis progressed.

Based on the analysis described above, I will describe how each of the eleven critical features of resonance was or was not mentioned in the General Chemistry I and Organic Chemistry I classrooms I observed. Similar to how the critical features were presented in Chapter 5, I will first discuss the critical features mentioned by both groups of instructors during the classroom observations. Then, I will discuss the critical features only General Chemistry I instructors mentioned during the classroom observations. Finally, I will discuss the critical features only the Organic Chemistry I instructors mentioned during the classroom observations.

It is important to note that, during their classroom teaching, some of the General Chemistry I instructors referred to critical features that had previously only been identified by the Organic Chemistry I instructors during the instructor interviews (*curved arrows* and *delocalized and localized lone pairs*). Therefore, for the sake of the analysis presented in the current chapter, these critical features were re-categorized to reflect this change, as presented in Table 12. In other words, although the two critical features of *curved arrows* and *delocalized and localized lone pairs* were categorized as "OCI Instructors" in the analysis of the intended object of learning presented in Chapter 5, they are categorized as "GCI and OCI Instructors" in the analysis of the enacted object of learning here in Chapter 6.

I will discuss each critical feature in descending order of the total number of instructors who mentioned them during the classroom observations (within their respective categories). If the same number of instructors mentioned a critical feature within the same category, I will discuss the critical features in the order in which they were discussed in Chapter 5.

For clarity, Table 12 reflects the order in which the critical features will be discussed. It also lists each of the eleven critical features, which type of instructors, and how many instructors mentioned each critical feature during the classroom observations. In a later section, I will discuss additional non-critical features of resonance mentioned by the instructors during my classroom observations. As previously mentioned, the instructors are referred to by pseudonyms in the discussion that follows, and any artifacts (e.g., instructor drawings) were reproduced to protect their privacy.

Table 12

Number of Instructors that Mentioned Each Critical Feature during the Classroom Observations

Mentioned by General Chemistry I (GCI) and Organic Chemistry I (OCI) Instructors, GCI Instructors, or OCI Instructors During Classroom Observations	Critical Feature	Mentioned by "X" Number of General Chemistry I Instructors During Classroom Observations (N=5)	Mentioned by "X" Number of Organic Chemistry I Instructors During Classroom Observations (N=5)
GCI and OCI Instructors			
	Lewis structures	5	5
	Resonance structures	5	5
	Resonance hybrid	5	5
	Formal charge	5	5
	Major and minor resonance contributors	5	5
	Octet rule	4	5
	Delocalized and localized lone pairs	3	5
	Curved arrows	1	4
GCI Instructors			
	Bond length	4	0
OCI Instructors			
	Hybridization	0	4
	Pattern Recognition	0	3

Critical Features of Resonance Mentioned During General Chemistry I and Organic Chemistry I Classroom Observations

Here, I discuss the critical features mentioned by the General Chemistry I and Organic Chemistry I instructors in the classrooms I observed. The critical features in this category are *Lewis structures, resonance structures, resonance hybrid, formal charge, major and minor resonance contributors, octet rule, curved arrows,* and *delocalized and localized lone pairs.* As mentioned above, these critical features will be discussed in descending order of the total number of instructors that identified them during the classroom observations, which is the order in which they are listed in the previous sentence. If this distinction is not possible, I will discuss the critical features in the order they were discussed in Chapter 5. For example, the same number of instructors mentioned *curved arrows* and *delocalized and localized lone pairs* during the classroom observations. In Chapter 5, *curved arrows* was discussed before *delocalized and localized lone pairs;* thus, this chapter will follow that same order.

I should also remind readers that these two critical features (*curved arrows* and *delocalized and localized lone pairs*) were not initially identified as critical features by the General Chemistry I instructors in this study. However, they did mention these critical features during the classroom observations, which is why they are now listed and discussed within this category.

Lewis structures, resonance structures, resonance hybrid, formal charge, and major and minor resonance contributors

Five critical features were mentioned in all the General Chemistry I and Organic Chemistry I classrooms that I observed. These were *Lewis structures, resonance structures,* *resonance hybrid, formal charge,* and *major and minor resonance contributors.* I will discuss these critical features in the same order they were presented in Chapter 5.

Lewis structures. All of the General Chemistry I and Organic Chemistry I instructors in this study mentioned the importance of understanding Lewis's model of chemical bonding (i.e., Lewis structures) and that a single Lewis structure cannot adequately represent the bonding in some molecules during the classroom observations. While at different points in the semester, both groups of instructors began their instruction on resonance by introducing this critical feature. Because Lewis structures are presented to students for the first time in General Chemistry I, instructors teaching this course taught students how to draw Lewis structures (including all lone pairs and formal charges on the individual atoms in the ion or molecule). The Organic Chemistry I instructors assumed students to be proficient at drawing Lewis structures before coming into their class and focused on helping them translate these structures to bond line structure. It is worth noting that even though Organic Chemistry I students learned about Lewis structures previously, Lewis structures are not used to a great extent in General Chemistry II (they might see them, but not be asked to create them from a formula), so it has likely been a while since Organic Chemistry I students have had a lot of interaction with Lewis structures.

Nevertheless, both groups of instructors used the limitations of Lewis structures to present the "need" for resonance. For example, like many other General Chemistry I instructors in this study, Ryan used carbonate to introduce resonance to students. Before presenting students with the example of carbonate, Ryan had only selected molecules or polyatomic ions with a single, valid Lewis structure for students to practice drawing. Ryan began to draw the Lewis structure of carbonate on the board while working through a list of steps associated with drawing

Lewis structures that he had just introduced to students. When he got to the step requiring a double bond to be drawn, he asked students:

> I'm going to have to put a double bond between one of the carbon and oxygen atoms. Which oxygen atom should I choose to put the double bond on? Should I put it here, here, or here [he pointed to each oxygen atom on carbonate]?

After waiting for students to respond, based on classroom consensus, he placed a double bond between the top oxygen and central carbon atom (like that shown in Figure 32). After doing so, he explained that he could have "easily and correctly" put the double bond between any of the other oxygens and the central carbon atom, and he drew the two additional valid Lewis structures (like that shown in Figure 33). He asked students, "What have I drawn? These are all Lewis structures for the carbonate ion. The carbonate ion *actually* exists as a hybrid of all these structures. These are also called resonance structures." He continued explaining Lewis structures' limitations for certain molecules or polyatomic ions and introduced the concept of resonance to his students as a solution. As mentioned, the other General Chemistry I instructors used similar approaches to teach students about the limitations of Lewis structures. It should be noted that most of the examples the General Chemistry I instructors used to teach resonance in their classes were relatively simple and had outer atoms that were all the same, such as PO_4^{3-} or NO_3^-.

The Organic Chemistry I instructors also discussed the limitations of Lewis structures while introducing resonance but spent less time doing so. Interestingly, most of the Organic Chemistry I instructors also used the carbonate ion to introduce this idea. For example, during his pre-recorded lecture, Brad drew the three Lewis structures for the carbonate ion; unlike Ryan, he included the formal charges on the individual atoms in the molecule (Figure 41). He then posed the question, "How did I get each of these three structures?" He explained that some students might assume that the molecule was "rotated" before clarifying that this was incorrect. To show why it was incorrect, he labeled each of the oxygen atoms using a different color to illustrate that the double bond was in a different position (i.e., on different oxygen atoms), that there were three distinct Lewis structures, and that the molecule was not just rotating (Figure 42). Maryann also spent time during instruction in her Organic Chemistry I classroom to point out that resonance structures are "not just rotating molecules." Brad then introduced the concept of resonance to explain why multiple correct Lewis structures can exist. The examples that followed were often larger and more complex molecules than those presented in the General Chemistry I classrooms observed, such as the example of the resonance structures shown in Figure 43. The Organic Chemistry I instructors made it clear to students that they needed to be able to use Lewis structures (and other critical features that will be discussed) to identify resonance throughout the rest of the semester.

Figure 41

Brad's Example of the Resonance Structures of Carbonate with Formal Charges

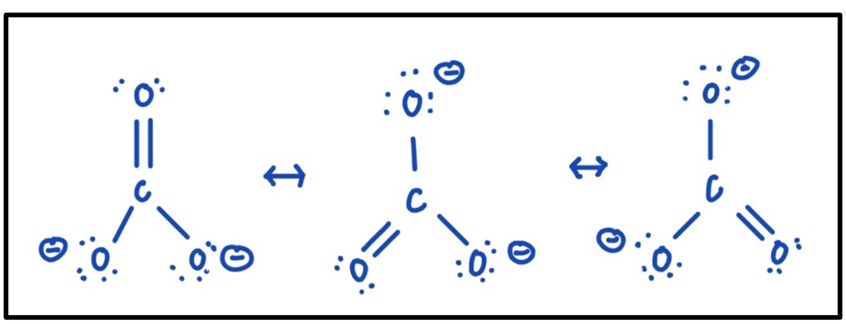


Figure 42

Brad's Example of the Resonance Structures of Carbonate Illustrating "Movement" of Double Bond

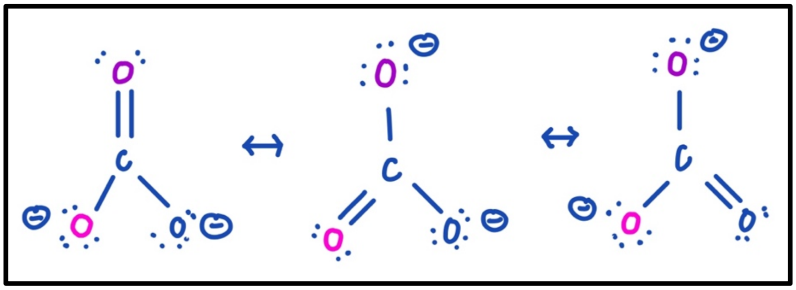
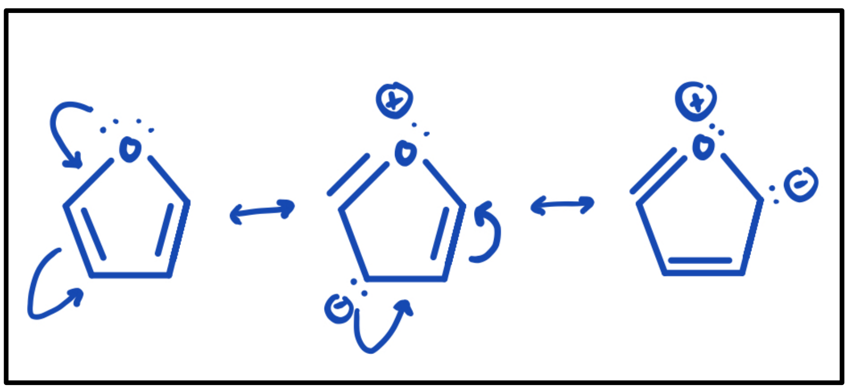


Figure 43

More Complex Example of Resonance Structures in Organic Chemistry I



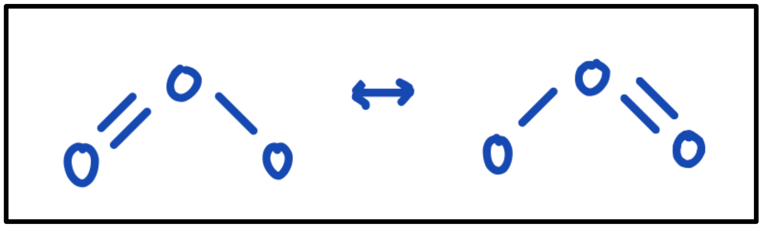
Resonance structures. All of the instructors in this study discussed the importance of understanding that resonance structures only differ in the placement of electrons, not atoms, while I observed their classrooms. Shortly after discussing the limitations of Lewis structures, resonance structures were introduced to General Chemistry I and Organic Chemistry I students.

A few instructors briefly did so with the use of an analogy. The General Chemistry I instructors used the color analogy described in Chapter 2 of this dissertation. Some of the Organic Chemistry I instructors also used this analogy. Overall, if an instructor used an analogy, they spent little class time describing it when the analogy was initially introduced and did not refer back to it throughout the remainder of the class period. Almost all of the instructors presented their students with a list of rules to consider while drawing resonance structures: (1) only electrons move (i.e., atoms do not move), (2) do not break single bonds (i.e., only pi electrons and lone-pair electrons can move), (3) never exceed an octet for 2nd-row elements.

Interestingly, just as during the instructor interviews, many instructors emphasized a phrase similar to “electron movement” while teaching students about resonance structures. For example, after describing the need for resonance structures in his General Chemistry I classroom, Kory stated, “In resonance, atoms do not move; only electrons move within the molecule.” However, after stating this, he did clarify that electrons are not actually moving in nature. Rather, “resonance allows electrons to spread out.” He further illustrated this by using ozone as an example. He presented students with the resonance structures of ozone on a PowerPoint slide (he did not include lone pair electrons in his drawing) (Figure 44). He explained the electrons are not actually moving back and forth between the resonance structures and that we just draw them as if they are.

Figure 44

Kory's Example of the Resonance Structures of Ozone (Without Lone Pair Electrons on Oxygen Atoms)



He then showed the resonance hybrid of ozone to help students understand the actual structure of ozone (Figure 45). Anthony, who teaches Organic Chemistry I, also used language that suggests "electron movement." That is, while first introducing resonance and explaining the resonance structures of benzene (Figure 46), he stated, "Benzene is a mixture of two compounds in rapid equilibrium. The bonds [or electrons] are not stationary." Nevertheless, he shared with students what this language meant to him by using hybridization and an electron density map of benzene to misspell the misconception that resonance structures actually exist in rapid equilibrium. He explained that resonance structures do not depict the actual movement of electrons but electron density being spread out amongst multiple atoms in the molecule. While his initial introduction of resonance was confusing and incorrect, it seems the instructor is at least aware of the underlying concepts of resonance and tried to clarify his initial description to students.

Figure 45

Kory's Example of the Resonance Hybrid of Ozone

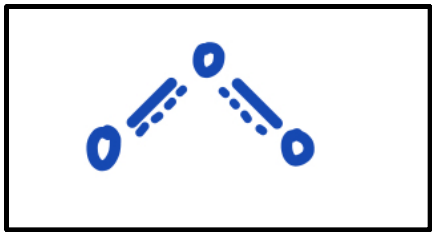
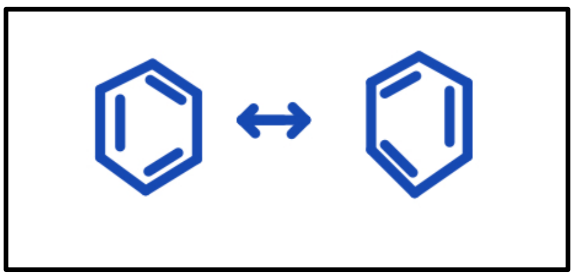


Figure 46

Anthony's Example of the Resonance Structures of Benzene



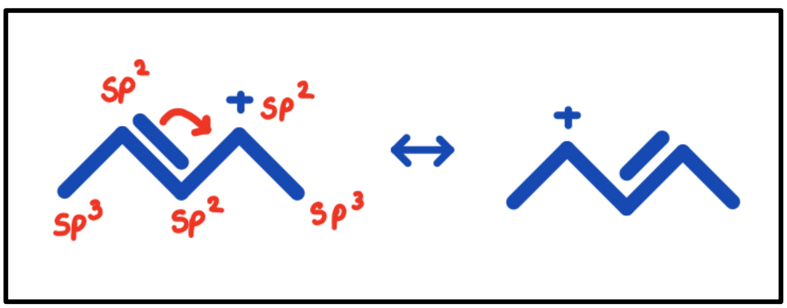
Unfortunately, other instructors who used the phrase "electron movement" did not spend time clarifying their language and instead emphasized the misconception that resonance structures are real entities that exist in nature, flipping back and forth between resonance structures. For example, after discussing the limitations of Lewis structures with her General Chemistry I students while introducing resonance structures and using ozone as an example (like that shown in Kory's example in Figure 44), Destiny stated, "The electrons in ozone cannot stop continuously moving. They are not restricted in one location… due to these continuously moving electrons, ozone spends about 50% of the time with the left resonance structure, about 50% of the time with the right structure." Interestingly, the slides she presented during her pre-recorded lecture displayed scientifically correct information. She is also correct in stating that electrons are not static they are fluid. Nevertheless, it was her elaboration and descriptions of the examples shown on her PowerPoint slides that were incorrect. There was also information on her slides that she did not discuss. For example, like many of the instructors in this study, Destiny presented students with the electron density map of ozone. However, she did not spend time explaining what the figure illustrated, nor did she mention it during instruction. This is likely attributed to the fact that she was using the PowerPoint slides provided by the textbook publisher.

In addition to presenting resonance structures, most instructors clarified their expectations regarding what students would need to do with resonance structures in their classes. The General Chemistry I instructors told students that they would need to be able to draw the resonance structures if given a molecular formula or a Lewis structure for a molecule on homework, quizzes, and exams. They did so by providing students with practice questions during the lectures. For example, Kory asked his General Chemistry I students to "Draw each of the three resonance structures for the nitrate ion (NO_3^-)." He suggested to students that this might be a potential exam question.

The Organic Chemistry I instructors shared similar expectations with their students. However, most of the Organic Chemistry I instructors also expected students to draw or identify resonance structures using *hybridization* or *pattern recognition* using *curved arrows* (critical features discussed in later sections). This group of instructors also gave their students opportunities to practice drawing resonance structures using hybridization and/or pattern recognition and curved arrows in class. For example, Anthony provided students with the structure depicted on the left in Figure 47 and asked students to (1) identify the hybridization of each carbon atom and (2) draw the resonance structures using curved arrows (Figure 47). Interestingly, none of the instructors directly stated to students during the lecture that they needed to draw resonance structures using double-headed arrows between the structures or brackets to designate the structures as resonance structures, despite some of the instructors doing so themselves (this will be further discussed as a non-critical feature).

Figure 47

Anthony's Example of Drawing Resonance Structures using Hybridization and Curved Arrows in Organic Chemistry I



Resonance Hybrid. All of the General Chemistry I and Organic Chemistry I instructors mentioned the resonance hybrid during instruction. However, only some of these instructors explained it in scientifically correct ways, mentioning that resonance structures are not real entities and do not exist in nature, as well as the fact that the actual, most correct structure, the resonance hybrid, is a mental melding of the different resonance structures. Just as there were various responses during the instructor interviews to what instructors believed students should know and do relative to this critical feature, there was a varied emphasis on this critical feature during classroom observations. The General Chemistry I instructors spent more time discussing the resonance hybrid during instruction compared to the Organic Chemistry I instructors. This was unsurprising as more General Chemistry I instructors reported doing so during instructor interviews. In the General Chemistry I classrooms I observed, this critical feature was most often introduced while first introducing resonance. That is, after discussing the limitations of Lewis structures and drawing resonance structures, instructors described the actual structure as a mental melding of all the resonance structures drawn. For example, Annabelle introduced the resonance hybrid after discussing the differences in the expected versus observed bond lengths (i.e., how she described the limitations of Lewis structures) of the carbonate ion at the beginning of her lecture on resonance. After discussing the resonance structures of the carbonate ion (like that shown in Figure 33), she introduced the idea of the resonance hybrid. She stated:

> The electrons aren't confined here. These electrons are moving around. They are not stationary. They are very much able to move around…The reality is something like this [pointed to the structure shown in Figure 40]. [The resonance hybrid] is a sandwich of all the resonance structures…it is sharing those electrons all throughout the molecule…it is something in-between.

While Annabelle made valid points, her discussion of the resonance hybrid could be misconstrued as the molecule being in rapid equilibrium, a misconception, according to the research literature, that many students have about resonance. Instead, like Kory and Ryan did (while discussing *resonance structures*), Annabelle should have explained that the molecule's electron density is being spread out amongst multiple atoms and clarified that it is not that electrons are bouncing back and forth between atoms.

Furthermore, as previously mentioned, while discussing the critical feature *resonance structures*, one General Chemistry I instructor, Destiny, seemed to hold the misconception just mentioned herself as she struggled to describe the resonance hybrid in conceptually correct ways throughout the class period. This instructor used ozone to introduce resonance. Destiny showed the resonance structures of ozone to students (like that shown in Figure 44) and accurately explained the discrepancies in expected versus observed bond lengths. Unfortunately, she incorrectly described why the expected and observed bond lengths differ. As previously mentioned, she stated:

> The electrons in ozone cannot stop continuously moving. They are not restricted in one location… due to these continuously moving electrons ozone spends about 50% of the time with the left resonance structure [in Figure 43], about 50% of the time with the right structure [like that shown in Figure 44].

Later in the lecture, she reiterated the same misconception by stating, "Both resonance structures of ozone exist in equal percentages, so 50% and 50%." Interestingly, after stating this, the instructor drew out the resonance hybrid for ozone correctly, thus suggesting that it is the underlying concept of the resonance hybrid that she does not understand.

All of the Organic Chemistry I instructors mentioned the resonance hybrid during instruction and presented students with an example of the resonance hybrid. However, as the instructors previously reported in instructor interviews, they did not spend much time in class discussing it. Like the General Chemistry I instructors, most of the Organic Chemistry I instructors introduced the idea of the resonance hybrid while first introducing resonance to students. After introducing resonance structures, Maryann told her Organic Chemistry I students that "neither resonance structure is an accurate representation for $(HCONH)^-$. The true structure is a composite of both resonance forms and is called a resonance hybrid. The hybrid shows characteristics of both structures."

Dallas discussed the limitations of Lewis structures and the need for resonance structures before introducing the idea of the resonance hybrid. He drew all three of the resonance structures of the carbonate ion (like that shown in Figure 41) and asked students, "Which one is the real structure [i.e., the resonance hybrid]?" He answered his own question, "All of them are correct…The resonance hybrid is a combination of all the different resonance structures." However, as he continued to explain the concept, his language was confusing. That is, he told students that the resonance structures of carbonate represented "snapshots of [carbonate] at different stages it can go between." This description suggests that the resonance structures actually exist, which they do not. He finished his discussion of the resonance hybrid by drawing the resonance hybrid of carbonate on the board (Figure 40).

Other Organic Chemistry I instructors used similar language to describe the resonance hybrid. For example, as previously mentioned, while first introducing resonance, Anthony showed students the resonance structures of benzene (Figure 46). He explained that when a molecule has resonance, "the bonds [or electrons] are not stationary. They don't sit there all of the time. They are dynamic. They are moving around." Furthermore, he described the resonance structures of benzene as being in "rapid equilibrium." Again, as previously mentioned, he later clarified that the molecules do not actually exist in equilibrium. Nevertheless, it did seem as though Anthony might hold misconceptions about the resonance hybrid.

Joe and Brad spent the least amount of time discussing the resonance hybrid. Unlike the other instructors in this study, Joe did not explain the resonance hybrid until the end of his lecture on resonance. Both Joe and Brad kept their classroom teaching of the resonance hybrid brief but made it clear to students that the resonance hybrid was the structure that existed in nature (not resonance structures) and was a "mental melding" of all the resonance structures. Brad explained that the resonance hybrid is not drawn "all of the time because it is complicated, and you cannot do any reaction mechanisms with it. We need resonance forms [structures] for reaction mechanisms." Most instructors made it clear to students that they would not be tested on the resonance hybrid.

Formal charge. As stated in Chapter 5, understanding the concept of formal charge is fundamental to understanding the differences between resonance structures for the same species. All of the instructors in this study explained to students during the classroom observations that atoms in different resonance structures can have different formal charges, but the overall net charge of the molecule does not change from one resonance structure to another. They also discussed this critical feature while teaching students how to identify the major resonance contributor out of a group of resonance structures during classroom observations. Many instructors shared during the instructor interviews that formal charge should be introduced to students in General Chemistry I while learning about Lewis structures but before resonance. They were not specific if this meant that formal charge should be introduced in a class period prior to the one in which resonance is introduced or if formal charge could be introduced in the same class period in which resonance is introduced, as long as it was before learning about resonance. However, it should be noted that in the General Chemistry I courses I observed, Lewis structures, formal charge, and resonance were discussed within the same class period, with formal charge typically being introduced before resonance was discussed. There was only one General Chemistry I instructor, Ryan, who introduced the concept of formal charge after he introduced resonance.

All of the General Chemistry I instructors in this study spent a good amount of time discussing formal charge and how to calculate the formal charge for individual atoms in a molecule before connecting the concept to resonance during the classroom observations (except Ryan, who did so immediately after introducing resonance). For example, after Destiny taught her General Chemistry I students about Lewis structures and how to draw them, she introduced formal charge. She explained that "formal charge is the charge an atom would have if all of the electrons in a covalent bond were shared equally." Other General Chemistry I instructors gave similar explanations. All of the General Chemistry I instructors provided students with a formula to calculate formal charge (e.g., formal charge equals the number of valence electrons – nonbonding electrons – ½ bonding electrons). The instructors provided students with examples and asked them to calculate formal charges on individual atoms in a molecule.

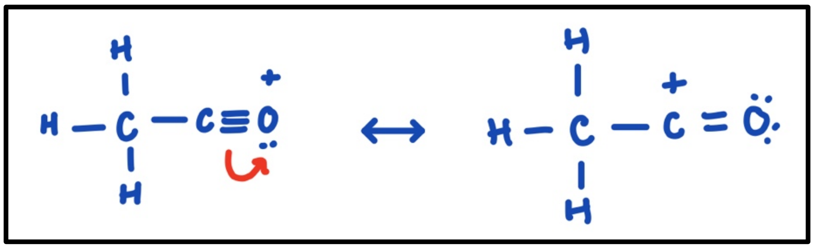
After students were taught about resonance structures, both groups of instructors spent time re-introducing the concept of formal charge to students. As mentioned, they emphasized that atoms in different resonance structures can have different formal charges, but the overall net charge of the molecule does not change from one resonance structure to another. For example, after drawing resonance structures for a molecule, Joe pointed out to his Organic Chemistry I students that the charge on individual atoms can change between different resonance structures for the same molecule, but the overall net charge does not change. He stated, while referencing the structure shown in Figure 48:

> The [structure with a] carbon-oxygen triple bond has a positive charge on oxygen… since the π electrons on the carbon moved to the oxygen [in the other resonance structure], it is now neutral…make sure that when you draw resonance structures, before and after, that you have charge balance.

Other instructors provided similar examples. None of the instructors calculated formal charges on resonance hybrid structures.

Figure 48

Joe's Example of Charge Balance Between Resonance Structures

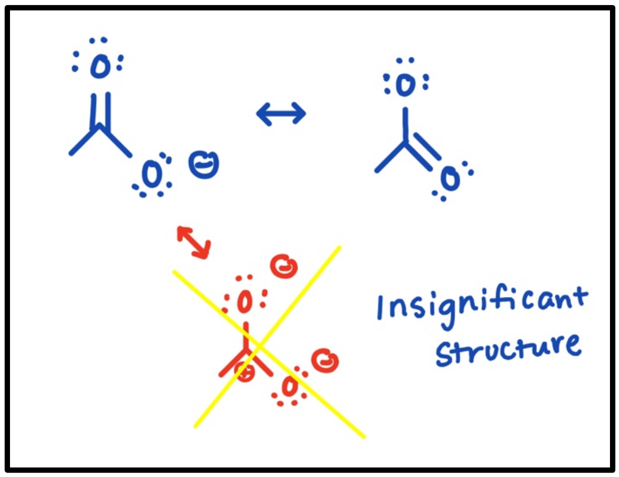


Both groups of instructors also spent time during the classroom observations teaching students how to identify the major resonance contributor using formal charge. The instructors explained that the major resonance contributor (i.e., the most stable structure) was the structure with the lowest formal charges on individual atoms. For example, Maryann explained to her General Chemistry I students that "formal charge is a method used to determine the best structure. The preferred structure [i.e., the major resonance contributor] is the one with the lowest formal charge." I should note that she used the word "preferred structure" to explain the major resonance contributor.

Like other instructors who participated in this study, Brad taught his Organic Chemistry I students how to identify *insignificant* resonance structures using formal charge. He drew the resonance structures shown in Figure 49 and asked if the resonance structure drawn in red was significant. He explained that the structure was not significant because "it has too many charges." That is, resonance structures with more than two charges are typically not significant structures and should not be drawn.

Figure 49

Brad's Example of Identifying "Insignificant" Resonance Structure using Formal Charge



Major and minor resonance contributor. All of the instructors in this study mentioned certain instances in which one (or more) of the resonance structures is the major contributor to the resonance hybrid. As in the instructor interviews, the instructors used different words to describe the major and minor resonance contributors. Interestingly, while they had the same connotation, many used different words than they did during the instructor interviews. For example, Kory and Annabelle used "best structure" to describe the resonance hybrid during classroom observations but used "prominent" during the instructor interviews. Ryan used "prominent" during his interview but "most reasonable structure" during his classroom observation. It was obvious they were all referring to the same thing; as such, just as in the instructor interviews, they were given the same code during data analysis (i.e., *major and minor resonance contributor*).

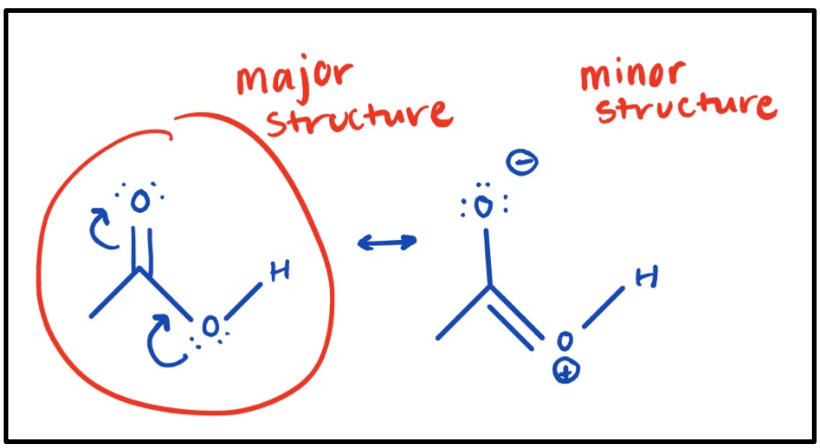
The General Chemistry I instructors in this study spent the least time discussing this critical feature in the classes I observed. During the instructor interviews, none of the instructors specifically used the term "resonance hybrid" to describe what the resonance structure was the major contributor of (i.e., the major contributor to the resonance hybrid). While analyzing the instructor interviews, I assumed this was due to their level of expertise, meaning the term "resonance hybrid" was implied. Unfortunately, during the classroom observations, the General Chemistry I instructors did not elaborate on this while teaching novice students. None of the General Chemistry I instructors in this study mentioned the resonance hybrid while discussing this *specific* critical feature during classroom observations, even though some of them showed it on their PowerPoint slides. While none of the Organic Chemistry I instructors mentioned what the resonance structure was the major contributor of during instructor interviews, unlike the General Chemistry I instructors, they did so during the classroom observations.

Most often, this critical feature was discussed after resonance structures were introduced. Surprisingly, the General Chemistry I instructors did not provide examples of instances where one structure would be the major resonance contributor. However, Kory explained that not all resonance structures are "equal" and that the structure with the least amount of formal charge was the "better structure" because it "is the most stable structure." He also emphasized that sometimes, more than one resonance structure can be the "best structure." Other General Chemistry I instructors shared similar explanations.

Like the General Chemistry I instructors, the Organic Chemistry I instructors introduced this critical feature after teaching students how to draw resonance structures. As previously mentioned, unlike the General Chemistry I instructors, they spent time explaining that a resonance structure could be a “major contributor” to the resonance hybrid and then reviewed examples of this in class. While introducing major and minor resonance contributors, Dallas stated, “The best resonance structure contributes more to the resonance hybrid.” To illustrate this, he drew the two resonance structures shown in Figure 50 and explained that the structure on the left contributes more to the resonance hybrid because “it has the least non-zero formal charges.” He did not physically draw the resonance hybrid for this specific example.

Figure 50

Dallas’ Example of Major and Minor Resonance Contributors to the Resonance Hybrid



Organic Chemistry I instructors also emphasized that the major contributor out of a group of resonance structures is the one that is more stable and gave students rules to determine which of a group of resonance structures is more stable. This was not something that this group of instructors had discussed during the instructor interviews. For example, during Anthony’s classroom observation, he had more than five PowerPoint slides dedicated to *major and minor resonance contributors*. He gave students a list of features that "determine how stable or how preferred a given resonance contributor is." He explained that the features listed in Figure 51 decrease the predicted stability of the molecule, meaning if a resonance structure has one of these features, it will be the "less preferred" resonance structure. He provided students with numerous examples to apply this concept. For example, he showed students the resonance structures in Figure 52 and asked his students to predict the most stable structure. He explained, "[structure] A has greater predicted stability than [structure] B because B has separated charges." All of the other Organic Chemistry I instructors took similar approaches. They were all straightforward with students about their needing to decipher the major and minor resonance contributors on homework, exams, and quizzes.

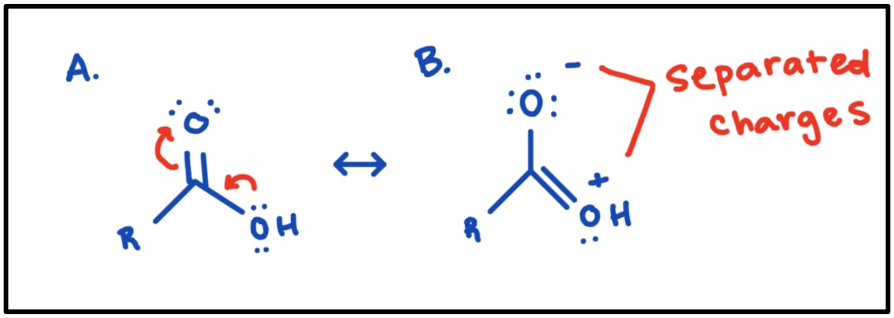
Figure 51

Anthony's List of Features that Decrease the Predicted Stability of a Molecule

1. An atom with an incomplete octet
2. A negative charge that is not on the most electronegative atom
3. A positive charge that is on an electronegative atom
4. Separated charges

Figure 52

Anthony's Example Showing that Structure A has Greater Predicted Stability than Structure B because of Charge Separation in Structure B



Octet rule, delocalized and localized lone pairs, and curved arrows

The remaining critical features identified by both General Chemistry I and Organic Chemistry I instructors during their classroom presentations are *octet rule, delocalized and localized lone pairs, and curved arrows.* Five or more of the General Chemistry I and Organic Chemistry I instructors who participated in this study mentioned these critical features during the classroom observations.

Octet rule. During the classes I observed, nearly all of the General Chemistry I and Organic Chemistry I instructors in this study mentioned the importance of students understanding that second-row elements should not have more than eight electrons associated with them in resonance structures. Neither group of instructors spent much time discussing this critical feature during the classroom observations. Most often, in General Chemistry I, this critical feature was first mentioned while teaching students how to draw Lewis structures, again while introducing resonance, and then throughout the rest of the lecture.

In Organic Chemistry I, the critical feature was reviewed while introducing students to resonance structures. The Organic Chemistry I instructors used phrases such as "if you remember," thus indicating they expected students to understand and remember this critical feature from general chemistry. Both groups of instructors presented it as a tool to decipher if a resonance structure was valid or not. For example, while teaching his Organic Chemistry I students how to draw resonance structures, Dallas stated, "Each [resonance structure] must be a valid structure. You want to avoid breaking the octet rule. You don't have to have a full octet on every atom. You just can't violate it." Similarly, Joe explained to his Organic Chemistry I students that while drawing resonance structures, he wrote on the board that they should "never exceed an octet for second-row elements (less is OK)". Interestingly, Destiny, a General Chemistry I instructor who emphasized the importance of this critical feature during her instructor interview, did not mention this critical feature during her classroom observation.

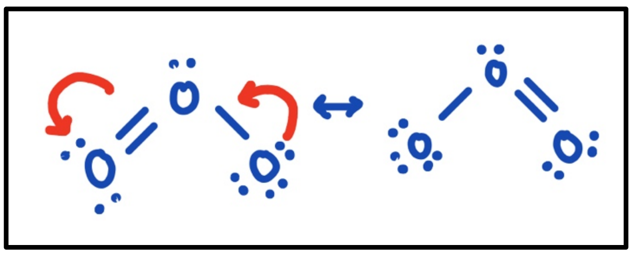
Delocalized and localized lone pairs. General Chemistry I and Organic Chemistry I instructors in this study mentioned the difference between electrons that participate in resonance (i.e., delocalized electrons) and those that do not (i.e., localized electrons) during classroom observations. This critical feature was not identified by the General Chemistry I instructors during interviews. Thus, it was surprising that instructors from this group mentioned it during classroom observations. This critical feature was often discussed during the initial introduction of resonance in both General Chemistry I and Organic Chemistry I. For example, while explaining some of the underlying concepts of resonance using ozone as an example, Kory stated, "Resonance allows electrons to spread out…The electrons in ozone are spread out over multiple atoms. We call it delocalized charge…delocalization can only happen with lone pair electrons and with second bonds." He made sure to direct students' attention to lone pair electrons and “second” or double bonds while explaining this critical feature. Destiny and Maryann, who used textbook publishers’ PowerPoint slides in their General Chemistry I classrooms, presented students with the same PowerPoint slide about delocalized and localized lone pairs. This slide had the resonance structures of benzene (Figure 46) on it and the following text: “Localized electrons are specifically on one atom or shared between two atoms; delocalized electrons are shared by multiple atoms.” While this information is correct, the instructors did not explain which electrons are typically delocalized, which could have been helpful for students.

All of the Organic Chemistry I instructors in this study mentioned *delocalized and localized lone pairs* during classroom observations. Like the General Chemistry I instructors in this study, most instructors in this group described the differences between delocalized and localized lone pairs while first introducing resonance. The instructors suggested that being able to identify which electrons in a molecule can participate in resonance (i.e., delocalized electrons) is key to being able to successfully draw resonance structures. For example, while reviewing how to write resonance structures in his Organic Chemistry I classroom, Dallas stated, “It works out, in general, that your electrons [participating in resonance] are going to be either a lone pair or pi bond.” Other instructors mentioned similar statements while teaching resonance but tied the idea to hybridization. For example, Anthony stated, “In order to have delocalized electrons, you typically need to have sp^2 or sp hybridized atoms.” Joe and Brad made similar statements. It was surprising to see more instructors connect these two critical features (i.e., *delocalized and localized lone pairs* and *hybridization*) during the classroom observations, as only Joe explained using this approach during instructor interviews. As such, these instructors' explanations during classroom observations were coded as *delocalized and localized lone pairs* and *hybridization*.

Curved arrows. Most of the General Chemistry I and Organic Chemistry I instructors in this study *used* curved arrows to draw resonance structures during classroom observations. However, only those who directly explained their use were coded as such. For example, while drawing the resonance structures of ozone, Destiny used curved arrows (shown in red in Figure 53) to show how she got to the resulting resonance structure. However, because she did not explain them, it was not coded as such.

Figure 53

Destiny's Example of Resonance Structures of Ozone Using Curved Arrows



Kory was the only General Chemistry I instructor who directly discussed what the curved arrows represent. While introducing resonance using ozone as an example, he explained, "Curved arrows can show the redistribution of valence electrons." His choice to use "redistribution" and not "movement" (like many of the Organic Chemistry I Instructors) seemed intentional. That is, curved arrows do not represent the actual movement of electrons (i.e., they are merely a tool used to draw resonance structures), which is what it seems Kory's language was trying to emphasize. Finally, while Kory used and explained curved arrows during classroom observations, he did not mention that he expected students to use them while drawing resonance structures themselves.

All Organic Chemistry I instructors in this study *used* curved arrows while introducing resonance in their classrooms. Unlike most of the General Chemistry I instructors, all of the Organic Chemistry I instructors in this study, except Anthony, spent time during classroom observations to explain what the curved arrows represent. As such, Anthony was not included in the instructor count for this critical feature. Maryann spent the most time discussing what curved arrows meant. She had an entire PowerPoint slide dedicated to discussing curved arrows that she presented to students while first teaching them how to draw resonance structures. She explained:

> Curved arrow notation is a convention that shows how electron position differs between two resonance forms…the tail of the arrow always begins at the electron pair, either in a bond or lone pair. The head points to where the electron pair moves.

Brad and Dallas also discussed what curved arrows represent at a similar point in the lecture to Maryann. Interestingly, Joe did not explain what curved arrows represent until the end of his instruction on resonance.

Anthony was the only Organic Chemistry I instructor who used curved arrows to teach resonance but did not spend time explaining what they represented (thus, he was not included in the count for this critical feature). Unlike the other Organic Chemistry I instructors who participated in the study, Anthony did not introduce resonance until the very end of the semester (compared to the beginning). Because of this, his students had already been exposed to curved arrows while drawing reaction mechanisms. Thus, to avoid/address misconceptions, Anthony arguably should have pointed out to his students that curved arrows used to draw reaction mechanisms depict the actual movement of electrons (i.e., bond breaking and formation), while curved arrows used to draw resonance do not (i.e., they are merely a tool used to draw resonance structures). Nevertheless, it is possible that Anthony did not make this distinction to his students because he does not believe there to be one. That is, during the instructor interviews, when I asked Anthony how he typically teaches resonance in his class, he said, “So teaching resonance in organic chemistry is really about the arrow pushing [i.e., curved arrows], I guess, for me to show how the electrons move.” This explanation suggests that he perceives curved arrows as depicting the actual movement of electrons in nature, which is not an accurate conception of resonance.

Critical Features of Resonance Mentioned During General Chemistry I Classroom Observations

Only General Chemistry I instructors mentioned the critical feature of *bond length* during the classroom observations. They were also the only ones to identify this critical feature in the instructor interviews.

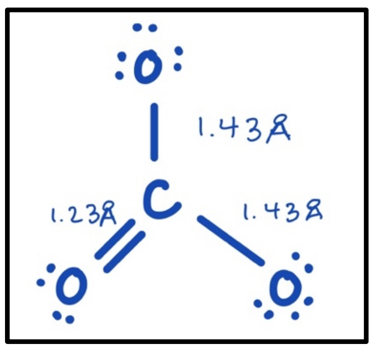
Bond length

Most of the General Chemistry I instructors in this study discussed how resonance can explain the differences between the bond lengths predicted by Lewis structures and the observed bond lengths for certain molecules during the classroom observations. Only General Chemistry I instructors mentioned this critical feature during instructor interviews and classroom observations, and Maryann was the only General Chemistry I instructor who did not mention bond length during her classroom observations.

Annabelle spent the most time discussing this critical feature with her students. Before introducing resonance, she presented students with the average bond lengths for some single, double, and triple bonds. She explained that “as the bond order increases, the bond length gets shorter." Next, she introduced the concept of resonance using carbonate. She explained that there are instances in which more than one correct Lewis structure can be drawn for a molecule or polyatomic ion, like carbonate. She drew all three resonance structures of carbonate (Figure 32) and asked students what they would "expect to measure" using the bond length data previously presented. She wrote down the expected bond lengths next to the respective bonds on one of the resonance structures for carbonate (Figure 54).

Figure 54

Annabelle's Example of Expected Bond Lengths of Carbonate



She then explained that this is not consistent with experimental data. Instead, the experimental bond length comes out to around 1.36 angstroms for each bond, which led her to draw and explain the resonance hybrid for carbonate (Figure 36). This approach was consistent with what Annabelle explained during her instructor interview.

Kory and Ryan also spent time discussing this critical feature during their classroom observations. Unlike Annabelle, they used a more qualitative approach to discuss bond length.

Their main concern was that students understand that electrons can be shared over multiple atoms. For example, while explaining the resonance hybrid of ozone, Kory stated, “The distances [between the oxygen-oxygen bonds] are the same. It’s not that [one bond] is long, and then sometimes the other one is long. It doesn’t go back and forth. It is just one combined hybrid of the two [resonance] structures.”

Unfortunately, while Destiny mentioned bond length, she also expressed misconceptions related to this critical feature. As previously discussed, Destiny used ozone as an example while introducing resonance. While doing so, she explained:

> Single and double bonds have completely different lengths. Single bonds are longer than double bonds. So, according to the resonance structures of ozone [Figure 53], this bond [pointed to the single bond] is longer than this bond [pointed to the double bond]. This isn’t what happens in nature. Both oxygen-oxygen connections are found to be the same…This is because the electrons in ozone cannot stop continuously moving. They are not restricted in one location… due to these continuously moving electrons, ozone spends about 50% of the time with the left resonance structure about 50% of the time with the right structure.

She did not explain why this results in differences in the expected versus observed bond lengths.

Critical Features of Resonance Mentioned During Organic Chemistry I Classroom Observations

The critical features in this category were mentioned in the Organic Chemistry I classrooms I observed for this study. They were also only initially mentioned by Organic Chemistry I instructors during the instructor interviews. Nearly all of the Organic Chemistry I instructors in this study mentioned *hybridization* during classroom observations, while fewer identified *pattern recognition*. As more instructors mentioned *hybridization* during the classroom observations, it will be discussed first.

Hybridization. Most of the Organic Chemistry I instructors in this study discussed how hybridization affects whether a molecule exhibits resonance. Maryann was the only instructor who did not mention this critical feature during her classroom observation. It was surprising to see how many instructors discussed this critical feature during classroom teaching, considering only Joe mentioned it during the instructor interviews. While Dallas mentioned *hybridization* during his classroom observation, Anthony, Brad and Joe discussed it at greater length in their classes.

It seemed as though the instructors who identified this critical feature had all introduced the general topic of hybridization *before* introducing and connecting it to resonance during the classroom observations (which would be typical). I was not present in the class periods prior to those in which resonance was discussed, but I assume hybridization had been discussed in a previous class period because students could readily recall the names and shapes of the different atomic orbitals (e.g., s, p) and hybridized atomic orbitals (e.g., sp, sp^2, sp^3) when asked by their instructors during the class periods I attended.

Before further discussion, it might be helpful for me to point out that in chemistry, orbitals refer to a region of space where there is a high probability of finding electron density. Atomic orbitals are associated with individual atoms and describe the likelihood of finding electrons around the nucleus of a single atom. While not a physical process (but a mathematical explanation), hybrid orbitals are formed when the atomic orbitals of the same atom combine to create a new, more stable hybridized atomic orbital.

When it came to connecting the concept of hybridization to resonance, the instructors did so somewhat similarly but discussed it at varying lengths (Anthony, Brad, and Joe spent the most time doing so). Anthony, Brad, and Joe explained that for resonance to be "possible," there needs to be an empty p orbital that can accept electrons. As a reminder, both sp and sp^2 hybridized atoms have empty p orbitals, making resonance possible, while sp^3 hybridized atoms do not. These instructors gave examples of what they meant. For example, Anthony showed students the resonance structures shown in Figure 55 and identified the hybridization of the carbocation on the resonance structure shown on the left. In reference to the resonance structure on the left in Figure 55, he stated, "We have an alkene, and next door, we have a carbocation. Carbocations are effectively sp^2 hybridized…it is going to participate in electron delocalization [resonance]." He also provided students with the example shown in Figure 56. He stated, "Triple bonds or sp carbons can also participate in delocalization [resonance]. There is no reason they cannot…We have no sp^3 carbons in the way, so there's no reason why we can't delocalize these electrons [pointed to the double bond]." Anthony also provided students with the structure shown in Figure 57 and explained, "Electrons can't move through a sp^3 [carbon atom]. It acts as a roadblock…there is no electron delocalization [resonance]." He reiterated that sp^3 hybridized atoms "act as roadblocks" throughout the rest of the lecture.

Figure 55

Anthony's Example of Moving π Electrons to an sp² Carbon Atom

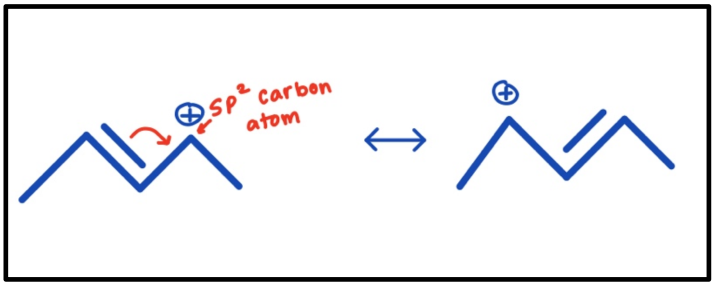


Figure 56

Anthony's Example of Moving π Electrons to an sp Carbon Atom

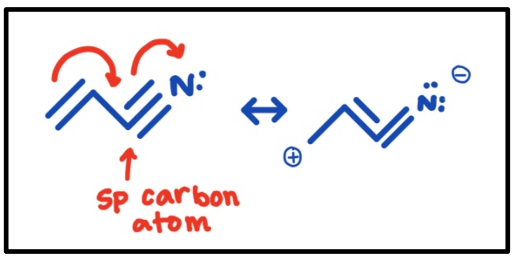
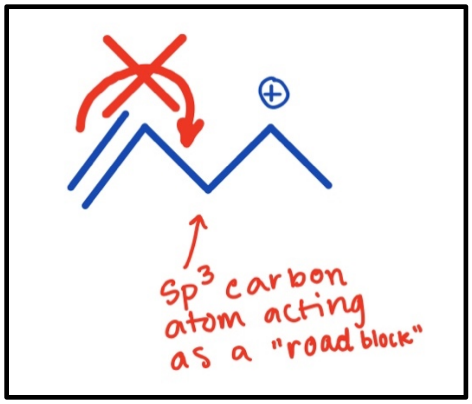


Figure 57

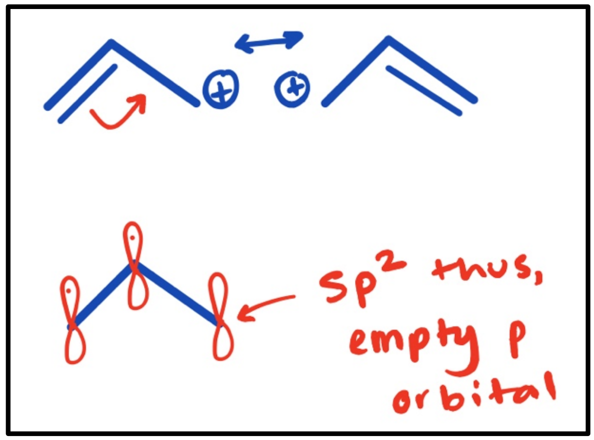
Anthony's Example of a sp^3 Carbon Atom Acting as a "Roadblock"



While discussing how hybridization is connected to resonance in his class, Brad drew the resonance structures shown in Figure 58 (i.e., the top two structures in Figure 58). He stated, "When you draw the orbitals [for the top left structure], the center and leftmost carbon have a p orbital with one electron each. The rightmost carbon, since it is sp^2, the p orbital is empty [Brad then drew the structure and orbitals shown at the bottom in Figure 58]." He explained that because there was an empty p orbital, the resulting resonance structure shown on the top right of Figure 58 was possible.

Figure 58

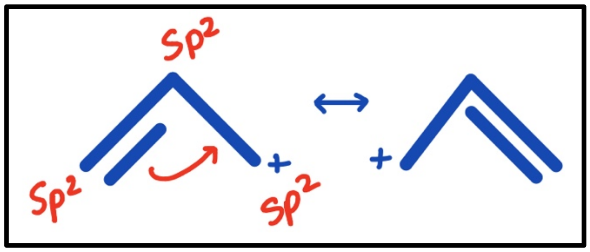
Brad's Example of Hybridization and Resonance by Drawing p Orbitals



Joe provided explanations and examples similar to those mentioned above, including Brad's example that was just described. While Joe discussed *pattern recognition* (a critical feature that will be discussed later) he drew the structure shown on the left in Figure 59. He explained that this structure has a common pattern that typically indicates resonance and continued to explain why using hybridization. That is, after identifying each carbon atom's hybridization (as sp^2), he explained that resonance is possible because there is an empty p orbital that can accept electrons. He then drew the resulting resonance structure shown on the right in Figure 59.

Figure 59

Joe's Example Identifying Resonance using Pattern Recognition and Hybridization



Interestingly, though, Joe only emphasized the need for an sp^2 hybridized orbital for resonance (and not sp). He stated:

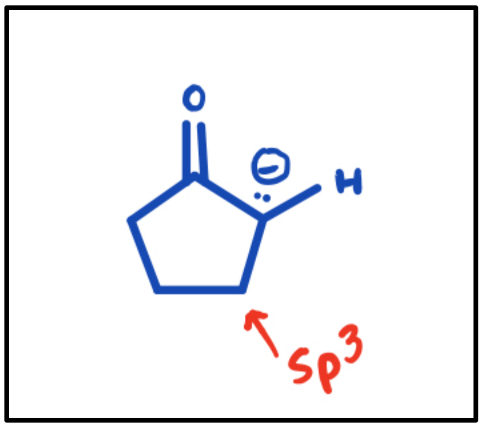
> Resonance structures are based on hybridization. To draw the resonance structure, you must have all sp^2 hybrid orbitals. That's because the electron that occupies the p orbital can only push and pull…Resonance structures are basically pushing the electrons to the neighboring p orbital. That's all. So that is why you must have sp^2 hybrid orbitals. That is the key concept. You don't have to memorize it; you can see the connections.

However, for what I assume to be simplicity purposes, Joe did not discuss resonance being possible with sp hybridized atoms during his classroom observation. Additionally, unlike other instructors, Joe did not give students examples of sp-hybridized carbon atoms participating in resonance.

Of the instructors who identified this critical feature, Dallas spent the least amount of time discussing it during his classroom observation. Unlike Anthony, Brad, and Joe, who thoroughly explained to students that for resonance to be "possible," there needs to be an empty p orbital that can accept electrons, Dallas did not do so. That is, towards the end of his lecture, while discussing the structure shown in Figure 60, he asked students if he could move the lone pair of electrons down to make a double bond between the two carbon atoms. He explained that he could not as the bottom right carbon is sp^3 hybridized, and thus, it will not participate in resonance. He did not elaborate further.

Figure 60

Dallas' Example of sp^3 Carbon Not Participating in Resonance



Overall, it should be noted that while discussing this critical feature, many of the instructors used metaphoric language that suggests resonance as the actual movement of electrons. For example, Anthony stated "Electrons can't move through a sp^3 [carbon atom]. It acts as a roadblock…there is no electron delocalization [resonance]." While Joe said, "Resonance structures are basically pushing the electrons to the neighboring p orbital." This language more closely aligns with how you would talk about reaction mechanisms and not resonance structures; and, thus, it could possibly be contributing to student misconceptions about resonance.

Pattern recognition. Some of the Organic Chemistry I instructors in this study identified the importance of students understanding that resonance structures can be identified by recognizing specific patterns in molecular structures during interviews; however, not all discussed these patterns during the classroom observations (Anthony and Maryann did not). During the instructor interviews, the instructors broadly referred to these patterns as the "five different patterns of resonance" (see Figure 12) but did not always do so during the classroom observations (Brad and Joe referred to some of the patterns by name but not all of the patterns as a group). These patterns were described in detail in Chapter 2 of this dissertation; they are an allylic lone pair, an allylic positive charge, a lone pair adjacent to a positive charge, a π bond between two atoms of differing electronegativity, and conjugated π bonds in a ring (see Figure 12).

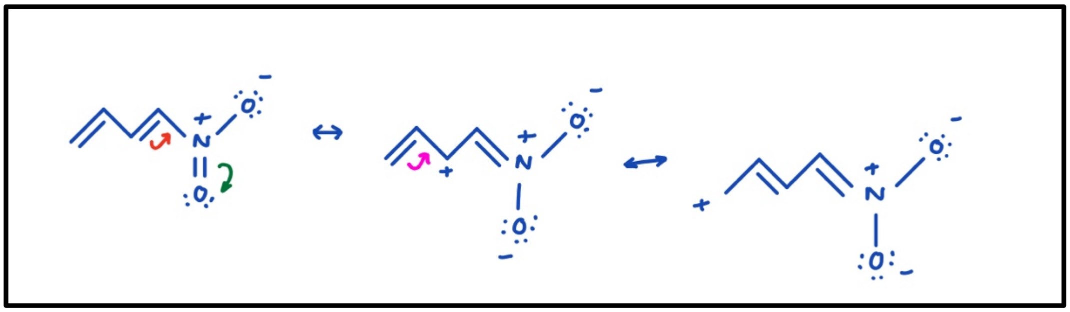
Surprisingly, Joe, who spent the least time emphasizing these patterns during his interview, was one of the few instructors who directly referred to some of these patterns during instruction. In the same example partially described in the previous section (Figure 59), while teaching students how to draw resonance structures, Joe wrote on the board, "Pattern number one: an allylic positive charge," and drew the molecular structure shown on the left in Figure 59. He made sure that students did not just memorize the pattern but understood why this pattern indicated resonance using *hybridization* (a critical feature previously discussed). That is, after identifying each carbon atom's hybridization (as sp^2), he explained that resonance is possible because there is an empty p orbital that can accept electrons. He then drew the resulting resonance structure shown on the right in Figure 59. He ended the discussion of this example by stating, "That is the first pattern that you need to recognize."

Dallas and Brad took similar approaches to each other while discussing this critical feature during classroom observations. After discussing the "hard rules" for resonance (e.g., only electrons move), they introduced two main patterns for identifying resonance that broadly encompass the five main patterns of resonance previously mentioned. Dallas called these two patterns "(1) chasing the positive and (2) pushing the negative" and provided the following example of "chasing the positive" in Figure 61. He explained:

> This is chasing the positive. We have a positively charged nitrogen, so typically, if you have a positive that can accept more electrons, you are going to push towards it. So, we are going to push towards this [he drew the red curved arrow]. We need a second arrow push [drew green curved arrow]. If I were to stop here [without the green curved arrow], nitrogen already has four bonds. I cannot show a fifth bond forming there, so I [had to draw the other curved] …here is our new structure. Now, we need to add formal charges…We will continue to chase the positive [drew the pink curved arrow] …Unfortunately, there is no set rule on how many resonance structures you can get…you can't go anymore.

Figure 61

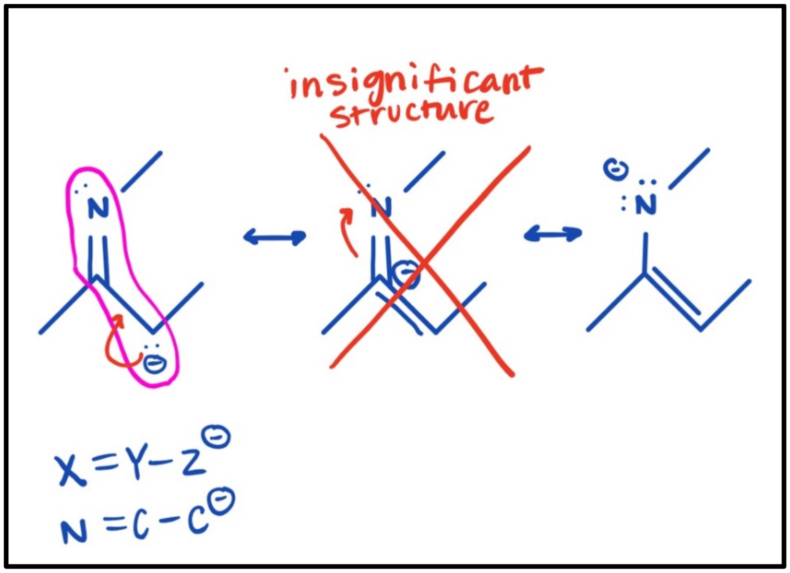
Dallas' Example of Drawing Resonance Structures using the Pattern Chasing the Positive



Similarly, Brad explained to students that "the easiest way to draw resonance structures is to find out the way electrons flow. It's always more to less." He gave students a way to recognize the pattern by providing a generic example. He explained that if you see "a three atom group" connected in the following way, resonance structures can usually be drawn: X=Y-Z* or *X-Y=Z (where X, Y, and Z denote atoms, = denotes a double bond, - denotes a single bond, and * denotes either a radical, a positive charge, or a negative charge). Brad used a "real" molecule as an example to help further explain his generic example (Figure 62). He drew the structure shown on the far left in Figure 62 and asked students, "Can you draw all the resonance forms?" He then circled the "three atom group" (N, C, and C) and the negative charge in the structure (what he circled is shown in pink in Figure 62). He then showed how it connected to one of his original generic examples (as shown in Figure 62). Next, Brad reminded students that "electrons always flow more to less" before drawing the resulting resonance structures (including an insignificant resonance structure that he pointed out to students as such) using curved arrows (Figure 62).

Figure 62

Brad's Example of a Three Atom Group and Resonance



As with the critical feature *hybridization*, while discussing *pattern recognition* the instructors often used language that is typically associated with reaction mechanisms. That is, the instructors often described the electrons as *actually* moving. For example, Dallas used the phrases: "Chasing the positive" and "Pushing the negative." Similarly, Brad stated, "Electrons flow more to less." As previously argued, it is likely that this language promotes student misconceptions.

Non-Critical Features of Resonance Mentioned During Instruction in General Chemistry I and Organic Chemistry I Classrooms

There was one additional feature of resonance directly mentioned in some of the General Chemistry I and Organic Chemistry I classrooms I observed that had not been identified as a critical feature during the instructor interviews. That is, I noticed that some of the instructors, during their classroom observations, drew and verbally discussed the double-headed arrow that they drew between their resonance structures. This information was coded as a non-critical feature called “resonance arrow.” It might be helpful for me to point out that some instructor interviewees included resonance arrows in drawings, as seen in earlier figures in Chapter 5. However, because none of the instructors had directly mentioned these features it was not coded as a critical feature of resonance in Chapter 5.

Overall, non-critical features are important to identify and discuss as these features might be distracting to students, making it more difficult for them to direct their attention to the critical features of resonance (i.e., those features that are essential in developing a correct understanding of resonance). This non-critical feature, its description, and instructor counts are listed in Tables 13 and Table 14.

Table 13

Non-Critical Feature of Resonance Identified by Instructors during the Classroom Observations

Identified by General Chemistry I (GCI) and Organic Chemistry I (OCI) Instructors, GCI Instructors, or OCI Instructors during Classroom Observations	Non-Critical Feature	Description of Non-Critical Feature
GCI and OCI Instructors	Resonance arrow	A resonance arrow is a double-headed arrow that denotes that the actual electron density distribution is a mental melding of the various resonance structures drawn.

Table 14

Number of Instructors that Identified the Non-Critical Feature during the Classroom Observations

Identified by General Chemistry I (GCI) and Organic Chemistry I (OCI) Instructors, GCI Instructors, or OCI Instructors during Classroom Observations	Non-Critical Feature	Number of GCI Instructors Identifying Non-Critical Feature during Classroom Observations (N=5)	Number of OCI Instructors Identifying Non-Critical Feature during Classroom Observations (N=5)
GCI and OCI Instructors			
	Resonance arrow	2	1

Resonance Arrow

A resonance arrow is a double-headed arrow (↔) used between resonance structures to denote that the actual electron density distribution is a mental melding of the various resonance structures drawn. While all of the instructors in this study used a resonance arrow(s) while drawing resonance structures, not all of them explained its meaning to students during the classroom observations. Only those who directly mentioned this non-critical feature were included in the instructor counts (Table 14).

While introducing resonance, Kory, Ryan, and Dallas made sure to point out the distinction between a resonance arrow and an equilibrium arrow. For example, Ryan, a General Chemistry I instructor, drew a double-headed arrow between the resonance structures of benzene (as shown in Figure 46). After drawing the double-headed arrow, he circled it and stated:

> When we represent resonance structures, we use an arrow that has two points [↔]. It is different from the equilibrium arrow [⇌]…which [shows a reaction] is flipping back and forth. When we draw resonance arrows, it does not mean it is flipping back and forth. It means the structures are a hybrid of the two structures.

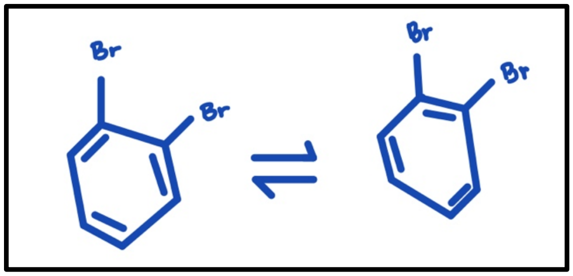
Similarly, while first introducing resonance, Dallas stated:

> Use this arrow [↔] and not this arrow [⇌]. Some people like to use [an equilibrium] arrow instead. What does [an equilibrium arrow] state? That is equilibrium. This one [pointed to resonance arrow] is resonance. Why does that matter? It's because resonance is not a reaction. Electrons are moving around the same molecule. Nothing has actually reacted yet. An [equilibrium arrow] implies a reaction. You cannot use that arrow.

Unfortunately, not all instructors pointed out the distinction between a resonance arrow and an equilibrium arrow. One instructor, who seemed to possibly hold the misconception that resonance structures are in rapid equilibrium, described a resonance arrow as an equilibrium arrow. Anthony showed his Organic Chemistry I students the resonance structures in Figure 63 with an equilibrium arrow between them. Anthony was the only instructor who did so.

Figure 63

Anthony's Example Using Equilibrium Arrow Instead of Resonance Arrow Between Resonance Structures



Conclusions

Through these General Chemistry I and Organic Chemistry I classroom observations, I identified what I perceived was possible for students to understand about resonance in their General Chemistry I and Organic Chemistry I classrooms (i.e., the enacted object of learning). Overall, the General Chemistry I instructors tended to teach resonance in similar ways to each other. There was more variation in how the Organic Chemistry I instructors taught students about resonance. This includes when the Organic Chemistry I instructors chose to introduce resonance during the semester (Anthony taught it at the end of the semester while the other instructors taught it at the beginning) and how/the length at which they chose to discuss the critical features.

I found that while teaching, the instructors often prioritized what they wanted students to do with resonance (operational understandings) over what they wanted students to know about it (conceptual understandings). For example, instructors often spent most of the class period teaching students how to identify or draw resonance structures. When they did mention more conceptual aspects, such as the resonance hybrid, the topic was often quickly breezed over, or the instructors made it clear to students that this was not something they would be assessed on. Similarly, while all of the instructors mentioned *major and minor resonance contributors* during classroom teaching, only the Organic Chemistry I instructors explained its relationship to the resonance hybrid. These findings are consistent with previous research (e.g., Atieh *et al.*, 2022; Carle and Flynn, 2020; Xue and Stains, 2020) and suggest that students in these classes had more opportunities to build their operational understandings of resonance than their conceptual understandings.

The fact that instructors in the current study emphasized operational aspects of resonance while teaching might also explain why some of them expressed misconceptions about the resonance hybrid while teaching, as their lack of focus on the conceptual aspects of resonance limits situations in which they have to confront the validity of their own ideas (Kruse & Roehrig, 2005). It might also explain why some instructors contradicted themselves while discussing some of the critical features. For example, one instructor explained resonance structures as a "rapid equilibrium" before explaining, at a later time, that resonance structures do not exist in equilibrium. Furthermore, while discussing some of the critical features, such as *hybridization* and *pattern recognition*, most of the instructors used language (e.g., pushing and pulling electrons) that is typically associated with reaction mechanisms and not resonance structures, and thus, possibly could contribute to student misconceptions about resonance.

In conclusion, it is apparent that instructors are teaching many of the critical features of resonance that they deem important for their students to understand resonance in their General Chemistry I and Organic Chemistry I classrooms. However, both groups of instructors tended to give priority to the operational aspects of those critical features during classroom teaching. Thus, students in these classes had more opportunities to build their operational understandings of resonance than their conceptual understandings, as students only have the possibility to learn what is presented to them in class. In the next chapter, I will present what students ultimately came to understand about resonance after classroom instruction (i.e., the lived object of learning).

In a subsequent chapter, the information presented in this chapter—the enacted object of learning—will be compared to what instructors intended for students to learn about resonance (i.e., the intended object of learning). It will also compared to what students actually came to understand about resonance (i.e., the lived object of learning).

CHAPTER 7 ANALYSIS, RESULTS, AND DISCUSSION OF THE LIVED OBJECT OF LEARNING (RESEARCH QUESTION 3)

My third research question asks what do General Chemistry I and Organic Chemistry I students understand about resonance after learning about it in their General Chemistry I and Organic Chemistry I classrooms. Because this study was informed by variation theory, answering this research question involved interviewing fifteen General Chemistry I students and fourteen Organic Chemistry I students about what they understand about resonance. Table 15 lists the pseudonyms of the students and their associated courses and instructors alphabetically. Like the instructors, I found that the students' beliefs were not institutionally specific, meaning their beliefs were not dependent on the type of institution they attended. Thus, to protect their identities, I do not identify the students' institutions or institution types in the following discussion. I also recreated the students' artifacts to further protect their identity.

Overall, I found that students tended to focus on what they were expected to do with the critical features of resonance (i.e., operational aspects) rather than what they should know (i.e., conceptual aspects). Many students lacked both a scientifically accepted understanding of resonance as well as an understanding of *why* resonance was an important topic to learn about. While the two groups of students mentioned many of the same critical features, there were differences in the number of students who did so and the depth of their explanations. Overall, the Organic Chemistry I students tended to recall more information about resonance and gave more detailed responses to the interview questions. Nevertheless, relative to the instructor interviews, both groups of students gave far less detailed explanations to the interview questions. Sometimes, students gave long pauses before being unable to respond to a question at all. Furthermore, the students were less likely to draw examples of their explanations to interview questions, while the instructors did so readily; thus, while this chapter is based on more interviews than Chapter 5, it is similar in length for the reasons just mentioned.

Table 15

Student Pseudonyms and Their Associated Instructors

General Chemistry I Instructors and Associated General Chemistry I Students (N=15)	Organic Chemistry I Instructors and Associated Organic Chemistry I Students (N=14)
Annabelle • Bobbi • Ellie	Anthony • Ainsley • Julia
Destiny • Ashton • Brittany • Jacob • Kennedy • Lydia • Minnie • Phoebe	Brad • No students
Kory • Danielle • Ross	Dallas • Amy • Geneva • Tyler
Maryann • Brody • Rachel	Joe • Emmy • Jessie • Makynna • Olivia • Teva
Ryan • Arnold • Monica	Maryann • Erin • Joey • Katie • Rose

In the following sections, and in more detail than was described in Chapter 4, I will discuss how I analyzed the student interviews to elucidate students' understandings of resonance using the critical and non-critical features of resonance (as previously identified in Chapters 5 and 6, respectively) as a coding scheme. I will also describe how I analyzed the student interviews for additional non-critical features of resonance not identified by instructors in the previous chapter. Next, I will discuss how each of the eleven critical features (from Chapter 5) was or was not mentioned by the students I interviewed. Finally, there will be a discussion of students' perceptions of non-critical features of resonance.

Data Collection and Analysis of Students' Perceptions of the Critical and Non-Critical Features of Resonance

This component of the current study aims to identify the lived object of learning or, in other words, to investigate what General Chemistry I and Organic Chemistry I students understand about resonance after learning about it in their classes. This involves identifying what the students in this study perceive about the instructor-identified critical and non-critical features of resonance, as well as identifying any additional non-critical features of resonance discussed by students. To do so, I conducted a total of twenty-nine student interviews: fifteen General Chemistry I student interviews, and fourteen Organic Chemistry I student interviews. Most of the General Chemistry I and Organic Chemistry I students were interviewed within two weeks of taking the first exam that included resonance in their respective courses. One Organic Chemistry I student (Rose) was interviewed after she had completed the course due to scheduling conflicts. I should also mention that, unfortunately, no students were recruited from Brad's Organic Chemistry I classroom. The semester I had planned to recruit Brad's students, his department's course schedule changed, and he was no longer teaching that semester.

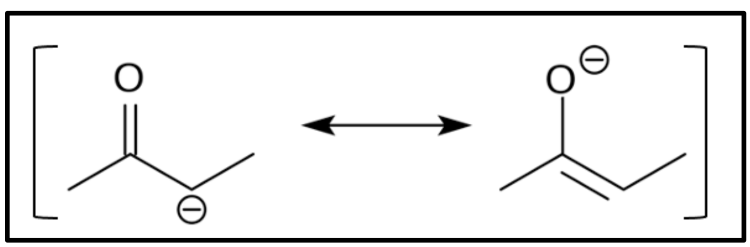
During the General Chemistry I and Organic Chemistry I student interviews, I asked the students questions about their understandings of resonance. For example, I asked, “How would you describe resonance in your own words?” I also showed students four chemical formulas and four Lewis structures for different chemical compounds. All General Chemistry I students were shown the same chemical compounds, and all the Organic Chemistry I students were shown the same chemical compounds (discussed in a section that follows). Students were provided with scratch paper, pencil, and a periodic table. I asked them to “identify which chemical compounds have resonance and why or why not.”

Furthermore, because I was aware that while all of the students who participated in this study were enrolled in General Chemistry I and Organic Chemistry I for the first time, many had taken preparatory general chemistry or preparatory organic chemistry before enrolling in their respective courses. Thus, some students had prior knowledge of resonance from these courses. To address this potential limitation, I asked students to recall their learning of resonance in previous courses (e.g., when do you remember learning about resonance for the first time?). I also asked direct questions about their current learning experiences related to resonance (e.g., what did your Organic Chemistry I teacher do/say while teaching you about resonance?).

The interviews were transcribed verbatim. I then coded the students’ responses to these questions using the instructor-identified critical features discussed in Chapter 5 and the instructor-identified non-critical feature discussed in Chapter 6 as a coding scheme. I should be clear that the lived object of learning concerns what students *actually* came to understand about resonance, regardless of whether that is correct or not. Thus, I coded any textual data from student transcripts related to what students know about and/or do with the critical and non-critical features of resonance, regardless of whether that information was considered scientifically accepted or not. For example, a couple of students described resonance structures as depicting the distribution of electron density in a molecule. This type of response was coded as "resonance structures." Other students indicated that they needed to be able to draw resonance structures. This type of response was also coded as "resonance structures." As another example, when I showed Jacob the resonance structures of enolate (Figure 64), he pointed to the double-headed arrow separating the resonance structures. He stated, "The arrow is trying to show that it's fluid between the two structures. It goes back and forth." This response was coded as "resonance arrow," which was a non-critical feature of resonance identified by some of the instructors in the previous chapter.

Figure 64

Resonance Structures of Enolate Shown to Students



I also coded the transcripts for student-identified non-critical features of resonance. That is, I coded for any additional features of resonance that students mentioned but that did not show up in the classroom observations. For example, during Kennedy's interview, she explained that she used resonance brackets as an indicator of a molecule exhibiting resonance. This response was coded as "resonance bracket."

To provide confirmability, I reached out to a fellow chemistry education researcher with a master's degree in analytical chemistry and a doctoral degree in chemistry education. I provided her with four transcripts (two from General Chemistry I students and two from Organic Chemistry I students), my coding system (i.e., the instructor identified critical and non-critical features of resonance), and a description of each code. I also provided her with drafts of Chapter 5 and Chapter 6, where I discuss each of the critical and non-critical features of resonance in detail. I asked her to apply the coding system to the student transcripts. After we independently coded the transcripts, we met to discuss the application of the coding scheme to the student transcripts. We reviewed any differences in the application of the coding scheme until we reached a consensus. Using this information, I independently coded the remaining transcripts.

Based on the analysis described above, the students in this study identified ten of the eleven critical features and the one non-critical feature (i.e., *resonance arrows*) previously identified by instructors in Chapters 5 and 6. Students also identified one additional non-critical feature of resonance during the student interviews. In the following sections, I discuss how/if the students identified the critical and non-critical features of resonance. When possible, I distinguish between what students believe they should know about the critical features and what students can do with the critical features. The critical features will be discussed using the same grouping assigned in Chapter 6 (GCI and OCI classrooms, GCI classrooms, OCI classrooms), as this reflects which critical features were made available for students to learn about in their respective classrooms. Within these groups, the critical features will be discussed in descending order of the total number of students who identified them. If this distinction is not possible, I will discuss them in the same order presented in Chapter 6. Student responses related to the two non-critical features will be discussed afterward.

The next section will focus on students' perceptions of the critical features of resonance. For ease, Table 16 lists the number and type of students who mentioned each critical feature during the student interviews in the order they are discussed in the following sections (please note that the non-critical features are not listed in this table, as they are discussed in a separate section).

Table 16

Number of Students that Mentioned Each Critical Feature during the Student Interviews

Mentioned by General Chemistry I (GCI) and Organic Chemistry I (OCI) Instructors, GCI Instructors, or OCI Instructors During Classroom Observations	Critical Feature	Mentioned by "X" Number of General Chemistry I Students During Student Interviews (N=15)	Mentioned by "X" Number of Organic Chemistry I Students During Student Interviews (N=14)
GCI and OCI Instructors			
	Lewis structures	15	14
	Resonance structures	15	14
	Formal charge	7	13
	Octet rule	12	7
	Delocalized and localized lone pairs	2	11
	Resonance hybrid	2	4
	Major and minor resonance contributors	3	3
	Curved arrows	0	6
GCI Instructors			
	Bond length	0	0
OCI Instructors			
	Pattern recognition	0	6
	Hybridization	0	4

Critical Features Presented in General Chemistry I and Organic Chemistry I Classrooms

The critical features in this category were mentioned in the General Chemistry I and Organic Chemistry I classrooms I observed for this study. Thus, the critical features in this category represent what was made available for both the General Chemistry I and Organic Chemistry I students participating in this study to learn about resonance. Here, I discuss how/if the General Chemistry I and/or Organic Chemistry students in this study identified any of the following critical features: *Lewis structures*, *resonance structures*, *formal charge*, *octet rule*, *delocalized and localized lone pairs*, *resonance hybrid*, *major and minor resonance contributors*, and *curved arrows*. As mentioned, the critical features will be discussed in descending order of the total number of students who identified them during the student interviews, which is the order in which they are listed in the previous sentence.

Lewis structures

While all of the General Chemistry I and Organic Chemistry I students in this study mentioned aspects of *Lewis structures* during the student interviews, only a few General Chemistry I and Organic Chemistry I students had a complete understanding of Lewis' model of chemical bonding (i.e., Lewis structures) and that a single Lewis structure cannot adequately represent the bonding in some molecules. That is, many of the students in this study did not articulate an understanding of the conceptual connection between *Lewis structures* and resonance whatsoever. In other words, most of the students did not explain *why* resonance was needed.

Lydia, a General Chemistry I student, was one of the few students who did so. When I asked Lydia what topics are important to understand before being able to understand resonance, she explained that Lewis structures are "a core concept behind resonance." She further explained that understanding the limitations of Lewis structures helped her better understand *why* resonance structures are drawn, as well as why there are instances in which one resonance structure is the “preferred structure” (however, she did not mention the resonance hybrid, a critical feature discussed further in a later section). Similarly, at the beginning of the interview, I asked Rose, an Organic Chemistry I student, to explain resonance in her own words. She explained:

> Resonance structures are used when one single Lewis structure does not suffice due to the electrons being delocalized, and so they are not connected to one specific atom as a Lewis structure would imply. So, by using resonance structures, we can better and more realistically visualize electron density distribution around atoms in compounds.

Unfortunately, most General Chemistry I and Organic Chemistry I students in this study viewed Lewis structures in less conceptual ways than Lydia and Rose, focusing more on what they use Lewis structures for rather than what they know about Lewis structures, likely because this is what was emphasized in class.

Students' conversations about *Lewis structures* were mostly during the middle portion of the interviews when I asked students to decide if a series of chemical compounds that I presented them with exhibited resonance. General Chemistry I and Organic Chemistry I students were shown different sets of chemical compounds. The rationale for choosing these can be found in Appendices N, O, P, and Q. First, I presented students with the chemical formulas for four different chemical compounds (Table 17). I asked students which exhibited resonance and why or why not (i.e., this task required students to draw the Lewis structures independently). Then, I presented students with the Lewis structures for four different chemical compounds and posed the same question (Figure 65). As previously mentioned, the students had a periodic table, paper, and pencil.

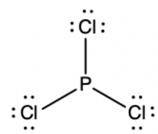
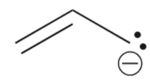
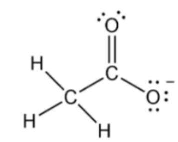
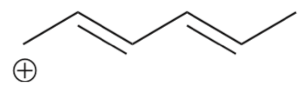
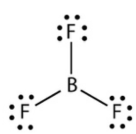
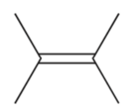
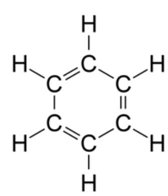
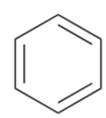
Table 17

Chemical Formulas Shown to General Chemistry I and Organic Chemistry I Students

Chemical Formulas Presented to General Chemistry I Students	Chemical Formulas Presented to Organic Chemistry I Students
O_3	C_6H_6
NCS^-	CH_3COOH
H_2O	H_2O
SO_3	HCO_2^-

Figure 65

Lewis Structures Shown to General Chemistry I and Organic Chemistry I Students

Lewis Structures Presented to General Chemistry I Students	Lewis Structures (i.e., bond-line structures) Presented to Organic Chemistry I Students
A. 	E. 
B. 	F. 
C. 	G. 
D. 	H. 

Through these tasks, I found that both the General Chemistry I and Organic Chemistry I students tended to describe Lewis structures as a way to visualize a molecule or ion and, based on structural cues in the molecular structure (e.g., double bond), decide if resonance was possible for a species (a future section will discuss students' reasoning related to identifying if a compound exhibits resonance). That is, when I presented students with the chemical formulas and asked them which ones had resonance, nearly all of the students made it clear that they needed to first visualize the molecule by drawing the Lewis structure and then, based on cues in the molecular structure, they could decide if resonance was possible. For example, after completing the tasks described in the previous paragraph, I asked Ashton, a General Chemistry I student, if he had a different strategy for identifying resonance when given the chemical formula versus the Lewis structures. He stated, "I mean, the harder part was trying to get the Lewis structure. Once I can *see the actual molecule*, it is easy to decide if there's resonance." I followed up on his response by asking how seeing the Lewis structure helps him decide whether the molecule or ion exhibits resonance. He replied, "I usually look for a double bond within the structure." I am assuming that Ashton believes a double bond indicates resonance. However, I am unclear if he means *any* double bond or, for example, a lone pair adjacent to a double bond (i.e., a pattern of resonance), as not all double bonds indicate resonance.

Despite students recognizing the importance of what they should do with Lewis structures (i.e., use them to visualize if a species exhibits resonance by looking for specific structural cues), most of students struggled to draw valid Lewis structures for the chemical formulas I presented to them during the interviews. For any given chemical formula (except H_2O, which, based on familiarity, nearly all students could draw a valid Lewis structure for), only about half of the General Chemistry I and Organic Chemistry I students could draw a valid Lewis structure, despite many of these compounds being common examples from General Chemistry I and Organic Chemistry I textbooks and/or presented in their respective classrooms (e.g., O_3). This led many students to guess what the Lewis structure should look like based on their memory or not to draw a Lewis structure and guess if the compound had resonance or give up on the task altogether. For example, a General Chemistry I student acknowledged that he needed to draw the Lewis structure for the compounds to decide if resonance was possible, but stated, “I can’t do any of these. Because I can’t draw the structure” (Arnold). While trying to decide if CH_3COOH had resonance, Joey, an Organic Chemistry I student, could not decide if/where to place a double bond in the structure, “I think there is going to be a double bond in that compound.” Ultimately, Joey was not able to draw the Lewis structure correctly and decided to assume there was a double bond somewhere and that the structure “probably had resonance.” I assume that Joey (like Ashton) used the presence of a double bond as an indication of resonance.

The students who could draw valid Lewis structures for the chemical formulas usually did so quickly and confidently. For example, while drawing the Lewis structure for O_3, Phoebe, a General Chemistry I student, walked me through her thought process while working aloud to draw the structure:

> For O_3, I know there are 18 valence electrons. Three oxygens are all connected to each other. You can start with one bond on each side [of the central oxygen atom], and you are left with 14 valence electrons. So, put some on the outside atoms and on the central oxygen. However, now you don’t have any electrons leftover, and your central atom doesn’t have an octet. So, you can start sharing electrons, and I will make a double bond. But you could make the same bond on the other side. So, that’s how I know it has resonance.

Phoebe is correct that O_3 has resonance, and based on the fact that she is in General Chemistry I her reasoning using the Lewis structure is similar to how resonance was presented to her in class.

The Organic Chemistry I students who could draw valid Lewis structures primarily did so based on recognition and did not discuss their thought process for doing so aloud as clearly as students in general chemistry. For example, Julia, an Organic Chemistry I student, saw the chemical formula C_6H_6, immediately recognized it as benzene, and drew a valid Lewis structure before identifying that the structure exhibited resonance because it was a "cyclical compound." Julia did not elaborate on this, however, it is possible that while the compound is cyclical she meant to say aromatic, as, in general, aromatic compounds exhibit resonance more often than cyclical ones. Not surprisingly many of the General Chemistry I and Organic Chemistry I students expressed that they had an easier time identifying resonance when given the Lewis structure versus the chemical formula. As Erin, an Organic Chemistry I student, stated, "There is a different level of confidence [when provided the Lewis structure]."

Overall, the majority of students in this study did not show a conceptual understanding of the connection between *Lewis structures* and resonance, as only Lydia and Rose directly addressed the limitations of Lewis' model. Instead, the students in this study focused on the importance of being able to draw valid Lewis structures and interpreting structural information from Lewis structures to identify resonance. Unfortunately, while aware of what their instructors expected them to do with resonance (i.e., use Lewis structures to identify resonance), when presented with the task they struggled to do so because they could not draw valid Lewis structures.

Resonance structures

All of the General Chemistry I and Organic Chemistry I students in this study mentioned aspects of this critical feature during the student interviews. Still, only a few students fully explained that resonance structures only differ in the placement of electrons (i.e., electron movement), not atoms, in scientifically correct ways. Minnie was one of the few General Chemistry I students who clearly explained what resonance structures represent. When I asked her to describe resonance in her own words, she replied:

> The way I understand it is that resonance is describing the same molecule because the only thing that changes between [resonance] structures is where the electrons are…For example, if you have three atoms connected to your center atom and there is a double bond on one side, that double bond is actually spread out around the entire molecule.

I should mention that later in the interview, Minnie told me that much of her understanding of resonance comes from a preparatory chemistry course she took and that her current general chemistry instructor (Destiny) often confuses her. When I asked Julia, an Organic Chemistry I student, this same question (how would you describe resonance in your own words?), she explained:

> Resonance is basically like, well, compounds can share charge […]. So basically, the idea is that electrons [in resonance structures] are not just fixed in one place on one atom, but they are also not flip-flopping between atoms. They [the electrons] are all in this cloud.

Julia's description shows that she understands what resonance structures represent. Interestingly, despite her instructor (Anthony) expressing the misconception that resonance structures exist in "rapid equilibrium" during instruction, Julia made a point to address this as a misconception while answering the question ("they [resonance structures] are not flip-flopping"). This was not the norm, as most of the General Chemistry I and Organic Chemistry I students who participated in this study expressed this misconception about resonance structures. Furthermore, both General Chemistry I and Organic Chemistry I students believed resonance structures were real entities that exist in nature and that the electrons literally move as a molecule transitions from one resonance structure to another. These misconceptions were identified multiple times throughout the interviews. When I asked Brody, a General Chemistry I student, why he believed resonance was important for students to learn about, he replied:

> I'm not a chemistry major, but I'm guessing resonance is important because there is not one specific way to draw a Lewis structure for some molecules. So, it [the molecule] can alternate, so it's good for students to know that there are other ways to draw it because the electrons are moving around the whole structure. And that's why we draw resonance structures.

The phrase "it [the molecule] can alternate" suggests that Brody believes resonance structures exist in nature and that the electrons move back and forth between atoms. When I showed Katie, an Organic Chemistry I student, a picture of the resonance structures for the enolate molecule (Figure 64) and asked her to describe the relationship between the two structures, she said, "These are resonance structures. Well, like the electrons aren't just stuck in one place. They are moving, so we have to draw two structures to show where they are moving to." Katie's description of the enolate molecule suggests that she believes electrons are literally moving between resonance structures instead of electron density being spread out amongst multiple atoms in the molecule. She does not connect the concept of resonance structures with the resonance hybrid.

Similarly, Joey was shown the Lewis structure of benzene (Figure 59) and asked if the compound had resonance and why or why not. He stated: "Benzene does have resonance…the double bonds can alternate. All three of them are not permanently placed." Like Katie, this description suggests Joey does not completely understand what resonance structures are being used to represent (i.e., the resonance hybrid). Joey and Katie were in the same Organic Chemistry I course, where their instructor expressed similar misconceptions while teaching about resonance.

While many of the General Chemistry I and Organic Chemistry I students who participated in this study did not demonstrate an understanding of what their instructors wanted them to *know* about resonance, the majority seemed to recognize and focus on what they were expected to *do* with this critical feature, draw resonance structures. As mentioned, during the interviews, General Chemistry I and Organic Chemistry I students were shown the chemical formulas for four different compounds (Table 17) and the Lewis structures for four different chemical compounds (Figure 65). The students were asked to decide if the compounds had resonance and to explain their reasoning. Students were provided with paper, a pencil, and a periodic table. While deciphering if a chemical compound had resonance, General Chemistry I and Organic Chemistry I students examined the Lewis structures of the chemical compounds for specific structural cues. In no particular order, General Chemistry I and Organic Chemistry I students asked themselves questions like these: (1) Are there one or more double bonds (i.e., *delocalized and localized lone pairs*)? (2) Is there a lone pair of electrons (i.e., *delocalized and localized lone pairs*)? (3) Is the octet rule being followed (i.e., *octet rule*)? (4) Is there a charge on any atoms in the structure (i.e., *formal charge*)? In addition to these structural cues just listed, the Organic Chemistry I students also looked for specific patterns in the molecular structure that typically indicate a resonance structure could be drawn (i.e., *pattern recognition*). These cues will be further explored alongside specific examples within the discussion of their relevant critical features, as indicated by the italicized text above.

When General Chemistry I and/or Organic Chemistry I students in this study recognized one of these cues when asked to decide if a chemical compound I presented them during the interview had resonance, they often tried to draw the resulting resonance structures. As they were taught in class, many Organic Chemistry I students used curved arrows. For example, when

Ainsley, an Organic Chemistry I student, explained why she believed the Lewis structure depicted in Figure 65 F exhibited resonance, she stated, "There is a charge and a double bond that can move, so there is resonance." After stating this, she correctly drew one (of three possible) resulting resonance structures using a single curved arrow (Figure 66). None of the General Chemistry I students used curved arrows while drawing resonance structures, despite some of their instructors doing so in class.

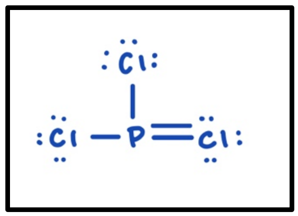
Figure 66

Ainsley's Resonance Structure Drawing with Curved Arrow

Unfortunately, even though General Chemistry I and Organic Chemistry I students participating in this study recognized the importance of being able to draw resonance structures, many of them struggled to do so. As discussed earlier, this was partly because they struggled to draw valid Lewis structures. Nevertheless, even when presented with valid Lewis structures and asked if the chemical compounds have resonance, some of the General Chemistry I and Organic Chemistry I students in this study still struggled to answer this question correctly. For example, when presented with the Lewis structure for PCl_3, Danielle, a General Chemistry I student, stated, "I'm going to say that PCl_3 does have resonance because of the extra lone pair [of electrons] on phosphorus." She then drew an invalid Lewis structure (broke the octet rule), where she moved the lone pair of electrons off phosphorus to make a double bond between phosphorus and one of the chlorine atoms (Figure 67). Danielle concluded that the double bond could have been drawn between any of the chlorine atoms.

Figure 67

Danielle's Invalid Resonance Structure for PCl_3



Formal charge

About half of the General Chemistry I and most of the Organic Chemistry I students in this study mentioned aspects of this critical feature, *formal charge*. Of these students, however, only a few of them did so in the ways their instructors intended. That is, only a couple of students explained that the concept of formal charge was fundamental to understanding the differences between resonance structures for the same species. Most of the students used formal charge as a cue that a molecule or ion exhibited resonance. Overall, all of the students who identified this critical feature focused on what their instructors wanted them to do with it, which was to calculate and use formal charge to identify the major resonance contributor (i.e., the most stable resonance structure with the lowest formal charges on individual atoms).

Monica was one of the students who identified *formal charge*. When I asked Monica, a General Chemistry I student, what topics she believed were important to understand resonance, she stated, “Formal charge […] because then you can decide which structure is better. I remember [my instructor] did talk about that.” When I asked Monica to elaborate on how formal charge affects molecular structure, she explained: “Well, depending on which atom the formal charge is on, that structure can be better or worse.” It was evident that Monica knew that formal charge affects molecular structure somehow, but she could not explain *why* formal charge does so. Lydia, another General Chemistry I student, shared a more sophisticated understanding of why one structure might be “better” than another. Lydia said, “There are some preferred structures. We learned that sometimes there is a more stable form of a structure, depending on the charge on the atoms.”

The Organic Chemistry I students shared similar remarks. For example, when I showed Jessie the resonance structures of the enolate molecule (Figure 64) and asked her to describe the relationship between the two structures, she said:

> These are resonance structures. I know that the structure on the right is a more stable resonance structure because the negative charge is on a more electronegative atom. So that structure is more stable, and it is the major structure.

As mentioned, a majority of the students who identified this critical feature did not do so in the way their instructors intended them to do so. Interestingly, during the interviews, when students were shown the chemical formulas and Lewis structures for different compounds and asked which structures had resonance and to explain their reasoning, none mentioned using formal charge to decide which resonance structure was the major resonance contributor.

Instead, most the students in this study associated the concept of formal charge with the delocalization of electrons within a molecule. In other words, as previously mentioned, while discussing *resonance structures*, students explained that they used formal charge as a way to identify if a chemical compound exhibits resonance or not (i.e., a cue). For example, while Brittany, a General Chemistry I student, was identifying if the four Lewis structures I showed her had resonance, she kept pointing out formal charges on individual atoms in the structures. I asked her why she kept mentioning formal charges. She replied, “The charges help tell me there’s resonance.” Another General Chemistry I student, Kennedy, also stated that she looks for formal charge to decide if a compound has resonance, “Whenever I see formal charge, I think there’s resonance.” When I asked Kennedy why this is the case, she explained that after doing many examples, she noticed it was “a pattern.” I should note that the General Chemistry I students were not taught *pattern recognition*; however, it seems that some of the General Chemistry I students are creating their own patterns and/or heuristics (e.g., charge indicates resonance) while trying to identify resonance.

While some of the Organic Chemistry I students in this study were taught *pattern recognition,* some still tried to create their own patterns for recognizing resonance and used similar heuristic reasoning to the General Chemistry I students. For example, while identifying which chemical formulas and Lewis structures exhibit resonance, Ainsley stated, “Formal charge helps me identify if electrons [within a molecule] can move or not.” Similarly, while Katie, an Organic Chemistry I student, was trying to decide if one of the chemical formulas I showed her (HCO_2^-) had resonance, she drew the Lewis structure. She said, “Well because there is a negative charge, that usually makes me think there is resonance. There are extra electrons that can move around." Almost every student in this study used formal charge as one of their main cues for deciding if a molecule or ion has resonance.

Octet rule

Most of the General Chemistry I and half of the Organic Chemistry I students in this study recognized that second-row elements cannot have expanded octets in Lewis structures. The students who identified this critical feature recognized its importance and applied their knowledge to decide if the chemical formulas and Lewis structures I showed them had resonance during the interviews. When I asked the students participating in this study what they believed students needed to understand before they could understand resonance, they often mentioned the octet rule. For example, when I asked Phoebe, a General Chemistry I student, this question, she said:

> I think you need to understand pretty much everything that has to do with Lewis structures and electrons. […] Why you need atoms to follow octets. It's important to know that hydrogen can only have two valence electrons. […] That type of stuff.

Earlier in the interview, Phoebe applied her knowledge of the octet rule to decide if H_2O exhibited resonance. She explained that H_2O does not exhibit resonance because any other arrangement of electrons would violate the octet rule, "So, water, I don't think has resonance because the hydrogens can only have two valence electrons."

While fewer Organic Chemistry I students identified this critical feature, those who did (like the General Chemistry I students) recognized its importance and applied their knowledge to decide if the chemical formulas and Lewis structure I showed them exhibited resonance. When I asked Teva, an Organic Chemistry I student, what he believed students needed to understand before they could understand resonance, he stated, "Definitely Lewis structures because you have to understand the octet rule." Like Phoebe, Teva applied this understanding during the interview while deciding if the Lewis structure shown in Figure 65 G exhibited resonance. He said, "It does not have resonance because of the octet rule." When I asked Teva to elaborate, he explained that carbon cannot have more than four bonds or the Lewis structure would be invalid.

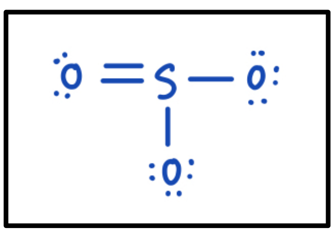
Delocalized and localized lone pairs

A few of the General Chemistry I and most of the Organic Chemistry I students who participated in this study identified aspects of this critical feature. None of the General Chemistry I or Organic Chemistry I students discussed *why* there are delocalized electrons or how this critical feature is related to hybridization. Instead, students focused on using this critical feature to identify if a chemical compound has resonance. More specifically, the General Chemistry I and Organic Chemistry I students used lone pairs of electrons and/or double bonds within a molecule or ion as a cue that it might exhibit resonance. It should be noted that just because there is a lone pair of electrons and/or a double bond in a compound, it does not automatically exhibit resonance, as these electrons are not always delocalized. For example, the structure shown in Figure 65 G has a double bond but does not exhibit resonance, as the electrons are not delocalized but confined between two atoms. Because students often grouped their understanding of delocalized lone pairs with double bonds, the same code (i.e., *delocalized and localized lone pairs*) was applied when students discussed either of these concepts.

Ross was among the few General Chemistry I students who mentioned this critical feature, possibly because he had one of the only General Chemistry I instructors who emphasized it in class (Kory). When I showed Ross the chemical formula of SO_3 and asked if the compound exhibited resonance and why or why not, Ross drew a valid Lewis structure for SO_3 (without including formal charge) (Figure 68) and stated, "SO_3 definitely has resonance because there's a double bond." Ross used this same reasoning when deciding if other compounds had resonance during the interview, which led me to ask him if it was something he looked for while trying to identify resonance. He responded, "Yeah, I feel like all of the examples of resonance [shown in Kory's class] had double bonds, so I just kind of assumed it." I should again note that the General Chemistry I students were not taught *pattern recognition*, however, as was presented during the discussion of *formal charge*, it does seem that some of the General Chemistry I students are creating their own patterns and/or heuristics (e.g., a double bond always indicates resonance) while trying to identify resonance.

Figure 68

Ross' Lewis Structure for SO_3



Organic Chemistry I students also said they look for lone pairs of electrons and double bonds while deciding if a compound has resonance. For example, when I asked Jessie what students need to understand before they can understand resonance, she said, "Figuring out where the double bonds and lone pairs and charges are." I followed up her response by asking how those aspects are related to resonance. She replied, "They usually mean there is resonance. You can start moving things around." Almost all of the other Organic Chemistry I students used similar reasoning. When deciding if C_6H_6 has resonance and why or why not, Olivia stated, "I will draw the structure…This one [C_6H_6] does [have resonance]. Pi bonds are usually something that makes me think resonance." While deciphering if CH_3COOH, Julia, an Organic Chemistry I student, drew the structure and stated, "CH_3COOH has resonance due to the fact that there is a charge and a double bond." Unfortunately, students often lacked the ability to discern when this reasoning would not work. When I showed the Organic Chemistry I students the structure shown in Figure 65 G, they often assumed it had resonance because of the presence of a double bond. For example, when I showed Makynna the structure and asked if it had resonance, she stated: "I think [it] does have resonance. The double bond can move." Makynna should have recognized that, in structure 65 G, the electrons participating in the double bond are not delocalized but confined between two atoms. Thus, while many students mention the same critical features identified by the instructors, they do not always understand them in the same (or correct) ways.

Resonance hybrid

A few General Chemistry I and Organic Chemistry I students in this study mentioned aspects of the *resonance hybrid*. Of these students, only two explicitly indicated that they understood that resonance structures are not real entities and do not exist in nature and that the actual structure is a combination of all the resonance structures, called the resonance hybrid. Some of the students suggested it was an equilibrium process (i.e., held misconceptions), while others did not mention the resonance hybrid at all. Interestingly, Lydia, a General Chemistry I student who demonstrated a conceptual understanding of how *Lewis structures* and resonance are connected, did not mention the *resonance hybrid*.

Rose, an Organic Chemistry I student who also demonstrated a conceptual understanding of how *Lewis structures* and resonance are connected, did identify this critical feature. Rose explained:

> I guess the main thing is that no one resonance structure is an accurate depiction of the compound. The actual molecule is a combination or an average of all the resonance structures. That's never really talked about. Oh, I guess there are sometimes major and minor resonance contributors.

Olivia was another student who discussed one of the more well-rounded understandings of the resonance hybrid. I showed Olivia, an Organic Chemistry I student, the resonance structures of the enolate molecule and asked her to describe the relationship between the two structures. She explained:

> Well, in the real world and not on a piece of paper, it's not just one structure or the other structure…What I am trying to say is that these electrons are flowing throughout all the atoms. So, it's not like having both of them.

While the use of the word "flowing" does suggest that she does not fully understand that the electron density is being spread out amongst multiple atoms, it was still one of the most holistic descriptions of the resonance hybrid by any of the students who participated in this study.

Other students mentioned the resonance hybrid during the interviews. However, these students expressed misconceptions while doing so. For example, when I showed Brittany, a student in Destiny's general chemistry course, the resonance structures of enolate (Figure 64) and asked her to describe the relationship between the two structures, she explained, "So between the two structures, what is changing is where the electrons and charges are. So, like they are moving back and forth between the two [structures]." Similarly, Erin, an Organic Chemistry I student, also shared this misconception of the resonance hybrid. She mentioned the resonance hybrid while discussing whether benzene had resonance. When I asked her to explain the resonance hybrid in a follow-up question, she stated, “So, basically, all the resonance structures combined is the resonance hybrid. So, the molecule likes to move around. So, because it’s always moving and there is a mixture, the most accurate structure is a combination of all the structures.” These students' use of the phrases “moving back and forth," “move around,” and “mixture” suggests that they believe resonance structures exist in equilibrium.

Interestingly, some students perceived the resonance hybrid as shorthand for drawing resonance structures instead of representing the actual molecule or ion. For example, when I showed Rachel, a General Chemistry I student, the Lewis structure of benzene and asked her if it had resonance and why or why not, she brought up the resonance hybrid. She explained that she recognized the Lewis structure I showed her but that a circle is usually drawn in the center as a circle instead of the individual double bonds (Figure 69). When I asked why she thought that was, she explained that it was a quicker way to draw the Lewis structure and that it was called the resonance hybrid. I followed up by asking her to describe the resonance hybrid, and she explained:

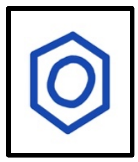
> So the hybrid structure is basically short form for like the full resonance structures. So especially for some molecules where there’s like six of them, instead of people having to write all six Lewis structures, they write the hybrid form as like a shorthand for the full structures.

It seems as though Rachel believes that individual resonance structures exist, and that the resonance hybrid is drawn for convenience, when in fact it can actually be rather complex to draw.

All in all, there was very little conversation about the resonance hybrid among students. This is likely related to the fact that many instructors did not emphasize it in class and made it clear to their students that they would not be tested on this critical feature.

Figure 69

Rachel's Description of How the Lewis Structure of Benzene is Drawn



Major and minor resonance contributors

While a focus of instruction in all of the classrooms I observed for this study, only a few of the General Chemistry I and Organic Chemistry I students identified aspects of this critical feature. I should mention that, like the instructors who participated in this study, the students used different terms to describe the major and minor resonance contributors, such as "best structure" or "preferred structure." Because it was obvious that the students were referring to the same thing, they were given the same code during analysis. The General Chemistry I and Organic Chemistry I students who mentioned this critical feature often did so briefly while identifying if the set of compounds I showed them exhibited resonance often in conjunction with their discussion of *formal charge*.

Interestingly, Lydia, a General Chemistry I student, identified aspects of this critical feature despite not identifying or discussing *resonance hybrid* during her interview. For example, as previously discussed, Lydia said at one point during the interview, "There are some preferred structures. We learned that sometimes there is a more stable form of a structure, depending on the charge on the atoms." While Lydia identified the fact that there are major and minor resonance contributors due to differences in how charge affects molecular stability, she did not explain or connect her understanding to the *resonance hybrid* (a critical feature she did not identify during her interview).

The Organic Chemistry I students had similar shortcomings in connecting their understandings of this critical feature to *resonance hybrid*. For example, as previously mentioned, when I showed Jessie the resonance structures of the enolate molecule (Figure 64) and asked her to describe the relationship between the two structures, she said:

> These are resonance structures. I know that the structure on the right is a more stable resonance structure because the negative charge is on a more electronegative atom. So that structure is more stable, and it is the major structure.

Overall, while the General Chemistry I and Organic Chemistry I students mentioned that there were instances in which one of the resonance structures was a better structure, only one Organic Chemistry I student (Rose) tied this idea to that of the resonance hybrid and only in a limited way. For example, as previously mentioned, when I asked Rose what students should know about resonance to be successful in organic chemistry, she replied:

> I guess the main thing is that no one resonance structure is an accurate depiction of the compound. The actual molecule is a combination or an average of all the resonance structures. That's never really talked about. Oh, I guess there are sometimes major and minor resonance contributors.

It is possible that the General Chemistry I students did not make this connection because none of the instructors in this study did so during instruction. However, most Organic Chemistry I students also did not make this connection despite their instructors doing so in class.

Curved arrows

None of the General Chemistry I students mentioned this critical feature despite some of them having an instructor who discussed it in class (i.e., Kory was the only General Chemistry I instructor who presented this critical feature in his class). Not surprisingly, nearly all the Organic Chemistry I students in this study used curved arrows to draw resonance structures while deciding if a chemical compound exhibited resonance. Nevertheless, only a few Organic Chemistry I students directly mentioned what curved arrows represent during the student interviews. As such, this code was only applied to textual evidence related to students verbally mentioning what they knew about and/or do with curved arrows during the interview.

Except for Anthony, all of the Organic Chemistry I instructors in this study spent time during class explaining what curved arrows represent. Curved arrows are a tool used to draw resonance structures; they do not represent the actual movement of electrons as in reaction mechanisms. Unfortunately, none of the Organic Chemistry I students could accurately describe this. The Organic Chemistry I students who identified this critical feature perceived curved arrows as the *actual* movement of electrons between resonance structures. During Katie's interview, she recalled her instructor (Maryann) explaining a difference between curved arrows used to draw reaction mechanisms and curved arrows used to draw resonance structures; however, when trying to explain the difference herself, she struggled to do so:

Researcher: Why do you think it's important for students to learn about resonance?

Katie: I think resonance is a good foundation for mechanisms. I know resonance and mechanisms aren't the same, but resonance helped me understand the concept of moving electrons around, which is what we do while drawing mechanisms. I do remember her [Maryann] mentioning that resonance arrows and mechanism arrows are different, though. I think she said they represent different things. But in both instances, we are moving electrons. So, that's what I try to remember. So, moving forward, I think resonance gave me a good foundation in organic chemistry.

Researcher: Do you remember why she [Maryann] said resonance arrows and mechanism arrows are different?

Katie: Well, I think resonance arrows are kind of showing a pattern of where the electrons can be found after they move. But reaction mechanisms show the potential movement of something that could take place in a chemical reaction. That's just my understanding.

Similarly, a student in Anthony's Organic Chemistry I class, Julia, also expressed similar misunderstandings about curved arrows. When I asked Julia to describe the differences she experienced learning about resonance in general and organic chemistry, she said:

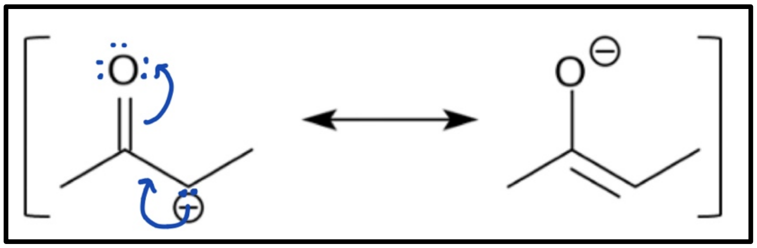
> It [resonance] was a little different. In gen chem, it was really just a basic overview of resonance structures […]. In organic chemistry, we use arrow pushing or the mechanism arrows [while drawing resonance structures] where we actually show the double bonds and lone pairs moving.

Julia does not perceive a difference between curved arrows used to draw resonance structures and curved arrows used to depict reaction mechanisms. This description surprised me as Julia described resonance in conceptually correct ways earlier in the interview. It should be mentioned that she was in Anthony's class; thus, she might have this disconnect because of a lack of instruction on it. Furthermore, in Julia's class, resonance was taught towards the end of the semester after reaction mechanisms had already been introduced. This fact compounded with no clear instruction on the differences between the two is likely why Julia assumed them to be the same.

The Organic Chemistry I students who identified this critical feature recognized that they needed to use curved arrows while drawing resonance structures. Ainsley pointed out that there were rules for doing so. When I asked Ainsley what topics students need to understand before understanding resonance, she said, "You need to know what you can and cannot do with curved arrows. You can't break single bonds." Amy was one of the few students who referenced her use of curved arrows while deciding if the resonance structures of the enolate molecule I showed her had resonance (Figure 64). In reference to the image, she said, "These are resonance structures. If I draw an arrow here [see Figure 70], I can show the pathway of movement." I followed up by asking Amy what the arrow she drew represented, and she replied, "It shows the movement of electrons. The arrow is like showing your work."

Figure 70

Amy's Use of Curved Arrows



It is possible these misunderstandings are because instructors are using language (e.g., "chasing the positive") that suggests actual electron movement (i.e., language associated with mechanisms) during classroom teaching.

Critical Feature Presented in General Chemistry I Classrooms

Bond length

Despite nearly all the General Chemistry I instructors discussing bond length during the classroom observations, none of the students participating in this study mentioned it during the student interviews.

Critical Features Presented in Organic Chemistry I Classrooms

The critical features in this category were only mentioned in the Organic Chemistry I classrooms I observed. Thus, the critical features in this category represent what was made available for Organic Chemistry I students participating in this study to learn about resonance (none of the General Chemistry I students identified these critical features). In the following sections, I discuss how/if the Organic Chemistry I students in this study identified the critical features of *pattern recognition* or *hybridization*. As mentioned, the critical features will be discussed in descending order of the total amount of students who identified them during the student interviews, which is the order in which they are listed in the previous sentence.

Pattern recognition

Some of the Organic Chemistry I students who participated in this study mentioned that resonance structures can be identified by recognizing specific patterns in molecular structure. The patterns that students broadly referred to were (1) an allylic lone pair, (2) an allylic positive charge, (3) a lone pair adjacent to a positive charge, (4) a π bond between two atoms of differing electronegativity, and (5) conjugated π bonds in a ring (Klein, 2012, p. 81) (see Figure 12). Interestingly, some Organic Chemistry I students who identified this critical feature explained that they did not believe it was focused on enough during instruction, which is perhaps why more students did not identify this critical feature. Geneva was an Organic Chemistry I student who found the five patterns of resonance particularly helpful. When I asked Geneva to pretend that she was a teacher and what problems she would foresee her students having about resonance, she said:

> I think they would have problems trying to draw the structures. I would show them [student] that there are patterns they can follow […]. I don't think a lot of professors ever teach these. Learning to recognize the five or six patterns of resonance really helped me pass my exam. I was able to see something and be like oh that's a pattern. So, I just followed that, and I ended up being correct.

Other Organic Chemistry I students in this study used these patterns while deciphering whether the chemical compounds I showed had resonance during the student interviews. Typically, the students who referred to any of the specific patterns by name while working through the task were able to correctly identify resonance. For example, while Tyler was deciphering if the Lewis structure shown in Figure 65 F had resonance, she explained, “This has resonance because there is an allylic carbocation.” She did not bother to draw the resulting resonance structures. When I asked Emmy to summarize her approach to deciding if the chemical compounds that I showed her had resonance, she stated, “After looking for double bonds and charges, I start to think about the patterns of resonance that are in my book.” I am assuming that Emmy is referring to the five patterns of resonance in Figure 12. Thus, I was surprised by this response as while she was working through the initial task (i.e., identifying which compounds had resonance) she had not mentioned any of the specific patterns aloud.

Hybridization

Some of the Organic Chemistry I students who participated in this study identified how hybridization affects whether a molecule exhibits resonance or not. Interestingly, despite nearly every instructor in this study at least mentioning this critical feature during instruction, all but one of the students who did so were in Joe’s Organic Chemistry I class. It should be noted that while other instructors mentioned hybridization, Joe and Anthony were the only instructors who emphasized the connection between hybridization and resonance during classroom observations. Thus, it was surprising that none of Anthony’s students mentioned hybridization during the student interviews. The one student who mentioned this critical feature who was not in Joe’s class was Rose. Rose explained that she learned about hybridization and its connection to resonance in a general chemistry course at a different institution than the one she currently attends. She did not recall learning about hybridization in Maryann’s Organic Chemistry I course.

Overall, the Organic Chemistry I students perceived hybridization as an underlying concept of resonance that allows them to better understand why a molecule exhibits resonance.

For example, when I asked Teva when he remembered learning about resonance for the first time, he recalled that it was in his preparatory organic chemistry course and that in this course, he only focused on using the patterns, not understanding the why behind those patterns:

> Back then [in preparatory organic chemistry], I didn't really understand the underlying concept of resonance with p orbitals and stuff. I just focused on the patterns. I didn't like know why there was a pattern or why I was moving electrons around. Now, understanding the orbitals and hybridization, I understand why those patterns exist.

Teva further explained that while he believes hybridization is important, he uses pattern recognition while drawing resonance structures, not hybridization. On the other hand, Olivia shared that she uses hybridization to draw resonance structures. When I asked Olivia how she was taught about resonance in her Organic Chemistry I classroom, she stated:

> Basically, my teacher just emphasized figuring out the hybridization of each atom to tell if there is resonance. So basically, what I do is I just go through the molecule and see if there are any sp^2 hybridized atoms because that means there is an empty p orbital, which means that electrons can transfer through that p orbital. I like bringing things to life to understand them. I have to say that is kind of hard with resonance. I have a hard time visualizing resonance. But basically, I just look for those empty p orbitals […]. I think about it [a p orbital] as a pipe, the p orbital, I mean, so if there's no pipe for electrons to go through, resonance can't happen.

Interestingly, later in the interview, when I showed Olivia four chemical formulas and four Lewis structures for different chemical compounds and asked her to decide which have resonance, she did not employ the reasoning just described. Instead, she looked for patterns that indicate resonance (a critical feature previously discussed) or what she described as her "gut instinct."

Jessie, another student in Joe's class, echoed ideas similar to Olivia's about hybridization. Jessie explained that her instructor emphasized hybridization "over and over." When I asked Jessie to explain resonance in her own words, she explained:

> You need to have a sp^2 hybridized atom because you need an empty p orbital to overlap in order for resonance to occur. So basically, when I look at a molecule and try to decide if there is resonance, I look at each atom's hybridization. And if I see a sp^2 hybridized atom, then I know resonance can happen. When I try to look on YouTube for extra help, I don't see it explained this way. I always see it as those five patterns or whatever. I mean, I guess [my instructor] mentioned looking for patterns too, but I hate memorizing. I mean, you get used to seeing some of them, but looking for the p orbitals actually makes sense.

Jessie did not mention sp hybridized atoms, likely because her instructor (Joe) did not discuss it in class. Furthermore, it should be mentioned that while sp^2 hybridized atoms in a structure are more likely to participate in resonance, it is not *always* the case, as Joe pointed out, using pyridine as an example (Figure 39).

Unlike Olivia, Jessie employed reasoning about hybridization when I asked her to explain if the chemical compounds I showed her had resonance. For example, while deciding if the chemical formula C_6H_6 exhibits resonance, she explained:

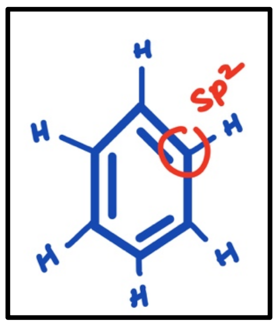
> The first thing I do is draw the structure to figure out the hybridizations. I need to draw the hydrogens, too [Figure 71]. And I want to see if there's a double bond. Yeah, so this

structure C_6H_6 would have resonance. All the atoms are sp^2, so I know I can move the double bonds.

I should note that none of the students in this study mentioned using the patterns that Dallas described as “(1) chasing the positive and (2) pushing the negative.”

Figure 71

Olivia’s Drawing of Benzene’s Lewis Structure



Non-critical Features of Resonance Discussed by General Chemistry I Students

The General Chemistry I students in this study—but no Organic Chemistry I students—discussed two non-critical features of resonance during the student interviews, *resonance arrow* and *resonance brackets*. In the current study, a non-critical feature is a feature that instructors did not deem essential to students developing a correct understanding of resonance. In other words, the instructor interviewees did not *verbally* mention either of these two features as essential to students' understanding of resonance, but students mentioned them during interviews. That being said, as discussed in Chapter 6, some instructors discussed *resonance arrows* during their classroom teaching. The other non-critical feature of resonance (i.e., *resonance brackets*) identified by one student interviewee was not verbally discussed by the instructors in their interviews or their classrooms (thus, it was not discussed in Chapter 6). These two non-critical features, their descriptions, and student counts are listed in Tables 18 and 19.

Table 18

Non-Critical Features of Resonance Identified by Students

Identified by General Chemistry I (GCI) and Organic Chemistry I (OCI) Students, GCI Students, or OCI Students during Student Interviews	Non-Critical Feature	Description of Non-Critical Feature
GCI Students		
	Resonance arrow	A resonance arrow is a double-headed arrow that denotes that the actual electron density distribution is a mental melding of the various resonance structures drawn.
	Resonance brackets	Resonance brackets are square brackets that are drawn on the left and right of resonance structures to denote that they are resonance contributors.

Table 19

Number of Students that Identified Each Non-Critical Feature during the Classroom Observations

Identified by General Chemistry I (GCI) and Organic Chemistry I (OCI) Students, GCI Students, or OCI Students during Student Interviews	Non-Critical Feature	Number of GCI Students Identifying Non-Critical Feature during Student Interviews (N=15)	Number of OCI Students Identifying Non-Critical Feature during Student Interviews (N=14)
GCI Students			
	Resonance arrow	2	0
	Resonance brackets	1	0

Non-Critical Feature Identified by Instructors and Students

Resonance Arrow

A few of the General Chemistry I students in this study pointed out the resonance arrow (↔) that was drawn between the two resonance structures of the enolate molecule that I showed them (Figure 64). Unfortunately, while describing the resonance arrow, the students described it in a way consistent with that of equilibrium. For clarity, resonance arrows are double-headed arrows drawn between resonance structures. They denote that the resonance structures are not separate entities but that the actual structure is a hybrid of the different resonance structures. Equilibrium arrows (⇌) denote a reversible chemical reaction; the reaction can proceed in both forward and reverse directions. Thus, if students confuse resonance and equilibrium arrows, it can profoundly impact their overall understanding of resonance, as can be seen in the examples that follow. Jacob, a General Chemistry I student in Destiny's class, stated in reference to Figure 64, "The arrow is trying to show that it's fluid between the two structures. They go back and forth." Another student in Destiny's class, Kennedy, explained similar incorrect ideas when shown the same figure. She explained, "So I see the arrow between them, so I know it's definitely a resonance structure. So essentially, the structures are the same, and they could swap back and forth." It might be worth noting that equilibrium arrows are not introduced to general chemistry students until General Chemistry II. So it is likely that these General Chemistry I students either learned about equilibrium arrows in a previous course or they are making up their own rules about what equilibrium arrows mean.

Non-Critical Feature Identified by a Student

Resonance Brackets

One General Chemistry I student, Kennedy, pointed out resonance brackets during her interview. Resonance brackets are square brackets that are drawn on the left and right of resonance structures to denote that they are resonance contributors. These brackets are different than those used to denote the charge of an ion. Kennedy explained that she uses those brackets as an indicator for resonance. For example, when I asked Kennedy what she would tell a friend coming into general chemistry that they would need to know about resonance to be successful, she explained many things other students shared, such as Lewis structures and formal charge. However, she also stated, "Maybe learn what the brackets mean so that you can keep an eye out for resonance." When I asked Kennedy why this might be helpful, she was not able to give a response.

Conclusions

Through interviews with General Chemistry I and Organic Chemistry I students, I identified what students understand about resonance (i.e., the lived object of learning). All in all, I found that the students identified many of the same critical and non-critical features mentioned in the instructor interviews and classroom observations. Additionally, the students identified one other non-critical feature that instructors did not previously identify during the classroom observations (i.e., *resonance brackets*). I found that both groups of students identified many of the same critical features. The Organic Chemistry I students identified three critical features (*pattern recognition,* and *hybridization*) that the General Chemistry I students did not identify. This was unsurprising as these critical features are typically only taught in organic chemistry courses, as was mostly the case in this study.

Despite identifying nearly all the instructor-identified critical features, many students often expressed incorrect or incomplete understandings of them. It seems as though students' misconceptions about resonance persist throughout their chemistry courses, as the Organic Chemistry I students expressed many of the same misunderstandings about resonance as the General Chemistry I students. The students' depth of description related to the critical features mostly depended on the course they were enrolled in. Overall, the Organic Chemistry I students tended to recall more information about resonance and gave more detailed responses to the interview questions. This was unsurprising as the Organic Chemistry I students have had more experience with resonance.

Both groups of students struggled to understand and explain the conceptual aspects of resonance and tended to focus on the operational aspects. For example, only a few students explained *why* resonance structures are drawn (i.e., the limitations of Lewis structures) or *why* the "best" resonance structure has the lowest formal charge. Only a handful of students in either course mentioned the *resonance hybrid* during the student interviews. Those students who did mention the *resonance hybrid* often lacked a clear and correct understanding of it. Some students perceived the resonance hybrid as shorthand for drawing resonance structures instead of representing the actual molecule or ion. General Chemistry I and Organic Chemistry I students also held misconceptions about what resonance structures represent, often describing resonance as an equilibrium process.

As mentioned, the students tended to focus on the operational aspects of resonance. This was a trend throughout all of the interviews. Both General Chemistry I and Organic Chemistry I students discussed specific structural features that they look for while trying to identify if a chemical compound has resonance. For example, similar to what has been reported in the research literature (e.g., Finkenstaedt-Quinn et al., 2020; Petterson et al., 2020; Watts et al., 2021), the students in this study often explained that they look to see if the structure has a double bond or charge to decide if it exhibits resonance. Students in both courses explained that they do so based on patterns they have noticed while working on practice problems (i.e., they were not necessarily using the five patterns of resonance that were taught in some of their classes). I should note that the General Chemistry I students were not taught *pattern recognition,* and that only about half of the Organic Chemistry I instructors taught *pattern recognition* in their classes. However, it seems that some of the students are creating their own patterns and/or heuristics (e.g., charge indicates resonance) while trying to identify resonance. These student-generated patterns are often built on incomplete understandings and lead students astray.

In conclusion, many of the students in this study tended to focus on the operational aspects of resonance and lacked a conceptual understanding of resonance. Unfortunately, despite students' focus on the operational understandings/tasks (i.e., identifying resonance) over conceptual understandings, many of them struggled to correctly identify resonance when asked to do so during the interview. This aligns with the research literature, as Braun et al. (2022)

showed that students who do not have good conceptual understandings struggle with correctly using resonance in operational ways.

In the following chapter, the information presented here is compared to what instructors intended for students to understand about resonance (i.e., the intended object of learning). It is also compared to what students were presented with in class (i.e., the enacted object of learning). These comparisons provide possible reasons why students tend to focus on the operational aspects of resonance.

CHAPTER 8 CONCLUSIONS AND IMPLICATIONS

The overarching aim of this study was to investigate students' understandings of resonance in General Chemistry I and Organic Chemistry I. The study was informed by variation theory (Bussey et al., 2013). This framework focuses on how and why people can experience the same phenomenon differently and how that information can inform classroom teaching and learning (Bussey et al., 2013; Tan, 2009). The following three research questions were addressed:

- (1) What do General Chemistry I and Organic Chemistry I instructors intend for their students to understand about resonance?
- (2) What is possible for General Chemistry I and Organic Chemistry students to understand about resonance in General Chemistry I and Organic Chemistry classrooms based on the information presented to them in their classes?; and
- (3) What do General Chemistry I and Organic Chemistry I students understand about resonance in General Chemistry I and Organic Chemistry I classrooms after learning about them in their General Chemistry I and Organic Chemistry I classrooms?

Because I was interested in examining students' understandings of resonance from three different perspectives (instructor, classroom, and student), the methods for each research question were slightly different. They are briefly reviewed below, along with the major findings of each research question and how those findings relate to the research literature. Next, I compare each of the findings of these research questions to draw overarching results and provide suggestions to improve instructional materials and teaching practices related to resonance. Finally, I discuss the future research directions and implications for teaching resonance.

Overview of Research Questions

Research Question 1 Methodology and Major Findings

To investigate what General Chemistry I and Organic Chemistry I instructors intend for their students to understand about resonance, I conducted semi-structured interviews with 5 General Chemistry I and 5 Organic Chemistry instructors. I asked them questions about what they believed to be the most important features of resonance for students to understand, student difficulties they noticed with resonance, etc. The analysis of this data helped me identify what instructors believe to be the most important features of resonance (i.e., the critical features of resonance) and what instructors intend for their students to understand about resonance at both the general chemistry and the organic chemistry levels.

The instructors identified a total of eleven critical features of resonance (Table 10). I found that both groups of instructors shared many of the same beliefs on what was important for students to learn about resonance. However, there were also critical feature(s) identified by only General Chemistry I instructors and critical features identified by only Organic Chemistry I instructors.

Overall, I found that both groups of instructors tended to emphasize what they wanted students to do with resonance (i.e., operational aspects) over what they wanted students to know about resonance (i.e., conceptual aspects). That said, while neither type of instructor focused on conceptual understandings of resonance relative to operational understandings, the General Chemistry I instructors in the current study reported discussing critical features that address students' conceptual understandings of resonance more often than did the Organic Chemistry I instructors.

Research Question 1 and Main Connections to The Research Literature

As mentioned, the instructors I interviewed identified eleven critical features of resonance (Table 10). The data related to this research question represents the first publication of information regarding what General Chemistry I instructors intend for their students to understand about resonance via instructor interviews. It also further contributes to the limited literature related to what Organic Chemistry I instructors intend for their students to know about resonance (e.g., Xue & Stains, 2020; Atieh et al., 2022).

Overall, the results from the current study align with previous reports on what students should know about and be able to do with the concept of resonance, as described in Chapter 2 of this dissertation. I should note that while the instructors in this study indicated the importance of the resonance hybrid, none expected students to be able to draw the resonance hybrid, nor did they assess students' understanding of the resonance hybrid (aside from Annabelle asking students to predict the bond length for certain molecules or ions). In other words, the instructors tended to emphasize the operational aspects of resonance over the conceptual aspects. These results align with similar findings in the research literature that indicate that instructors believe the resonance hybrid is important—yet not all instructors believe they should assess what students know about it or if they can draw it (Xue & Stains, 2020; Atieh et al., 2022). In the current study, I also identified additional critical features of resonance not yet reported in the research literature: *octet rule*, *formal charge*, and *delocalized and localized lone pairs.*

Research Question 2 Methodology and Major Findings

To investigate what is possible for General Chemistry I and Organic Chemistry I students to understand about resonance based on what takes place in the classroom, I conducted observations of 5 General Chemistry I classrooms and 5 Organic Chemistry I classrooms. The analysis of this data involved using the instructor-identified critical features as a coding scheme. I found that many of the instructors mentioned the same critical features in their classrooms that they had previously identified during the instructor interviews. There were, however, some inconsistencies between what instructors identified during the interviews and what they actually taught in their classes (which will be further discussed in a later section). For example, two critical features (*curved arrows* and *delocalized and localized lone pairs*) were initially only identified by Organic Chemistry I instructors (during instructor interviews). Still, they were discussed in both the General Chemistry I and Organic Chemistry I classrooms I observed. A couple of the instructors in this study identified one additional non-critical feature of resonance during the classroom observations: *resonance arrow*.

Research Question 2 and Main Connections to The Research Literature

To my knowledge, no studies have used classroom observations to examine the teaching and learning of resonance in General Chemistry I or Organic Chemistry I. That being said, Carle and Flynn's (2020) study focused on what students can learn about resonance in Organic Chemistry I and II classrooms through a textbook content analysis of organic chemistry textbooks (currently, there have been no similar studies done using general chemistry textbooks). Because textbooks often influence what/how instructors present information to students, the information presented in their study closely represents what students can learn about resonance in organic chemistry classrooms (Bussey et al., 2013). Carle and Flynn (2020) identified ten essential learning outcomes related to resonance and analyzed how those essential learning outcomes are taught and practiced in the textbooks analyzed, as well as how those essential learning outcomes are assessed on exams (i.e., they asked professors to provide summative assessments for this analysis). They found that the essential learning outcomes that addressed more conceptual aspects of resonance (e.g., the resonance hybrid) were underrepresented in textbook explanations and practice questions, as well as the assessments. For example, only 0.7% of the practice questions in the textbooks analyzed were directly related to the resonance hybrid. More operational aspects of resonance (e.g., drawing resonance structures) were well-represented in the textbooks and assessments. Similarly, while teaching, the instructors in the current study also tended to emphasize the operational aspects of resonance rather than the conceptual aspects of resonance.

Research Question 3 Methodology and Major Findings

To investigate what General Chemistry I and Organic Chemistry I students actually understand about resonance after learning about it in their General Chemistry I and Organic Chemistry I classrooms, I conducted semi-structured interviews with 15 General Chemistry I students and 14 Organic Chemistry I students. I asked them questions about what they think are the most important things to learn about resonance, what resonance is, their thought processes while identifying resonance, etc. The analysis of this data also involved using the instructor-identified critical and non-critical features as a coding scheme, through which I identified what students actually came to understand about resonance.

Additionally, I coded the student transcripts for student-identified non-critical features of resonance. That is, I coded for any additional features of resonance that students mentioned but that did not show up in the instructor interviews.

Research Question 3 and Connections to The Research Literature

My findings align with what has previously been reported in the research literature related to students' difficulties with resonance and what students focus on while learning about resonance (e.g., Atieh et al., 2022; Betancourt- Perez, et al., 2010; Brandfonbrener et al., 2021; Braun et al., 2022; Finkenstaedt-Quinn et al., 2020; Kim et al., 2019; Petterson et al., 2020; Tetschner & Nedungadi, 2023; Xue & Stains, 2020). The students in my study struggled to describe resonance in conceptually correct ways. They often described resonance structures as real entities that exist in nature, alternating back and forth between resonance structures (Taber, 2002; Kim et al., 2019; Xue & Stains, 2020). They also struggled to identify if a compound exhibited resonance. Many focused on looking for specific structural cues indicating resonance, such as a charge or a double bond (Finkenstaedt-Quinn et al., 2020; Petterson et al., 2020; Watts et al., 2021). This difficulty was exacerbated when the students were only given the chemical formula rather than the initial Lewis structures. Many students were unsure if/where to place double bonds or struggled to calculate formal charge while drawing the initial Lewis structure of a compound, ultimately resulting in many students not being able to identify if a compound exhibited resonance. This difficulty emphasizes the connection between students' difficulties drawing Lewis structures and resonance (Cooper et al., 2010).

Furthermore, similar to Brandfonbrener et al.'s (2021) study, the students in our study tended to focus on the operational rather than the conceptual aspects of resonance. While discussing resonance, students focused on what they needed to do with it rather than what they needed to understand or know about it. This was largely illustrated when I presented students with the resonance structures of enolate and asked them to describe the relationship between the two structures. Instead of focusing on the conceptual aspects (i.e., the two structures melded together represent the real molecule), the students focused on the physical differences between the two structures, such as the movement of the double bond or charge.

Comparisons of the Objects of Learning

The findings related to these research questions will now be compared to draw overarching results and provide suggestions to improve instructional materials and teaching practices related to resonance (Bussey et al., 2013). First, I will examine how the instructor-identified critical features aligned with what was presented in the classrooms I observed (the intended and enacted learning objects). This comparison focuses on identifying potential differences in what instructors intend to teach about resonance versus what they actually taught about resonance in their classes. Second, I will examine how the instructor-identified critical features align with what students are actually coming to understand about resonance in the classroom (the intended and the lived objects of learning). This comparison focuses on identifying differences in what instructors intend students to understand about resonance versus students' understandings of resonance. Third, I will compare what students are presented with in the classroom and what they ultimately integrate into their understanding of resonance (the enacted and the lived objects of learning), which provides insight into what students typically pay attention to while learning about resonance in the classroom. Finally, these perspectives will be considered to identify potential reasons why students might not have come to the intended understanding of resonance.

Comparison of Intended and Enacted Objects of Learning

This comparison examines how the instructor-identified critical features (the intended object of learning) align with what was presented to students in the classrooms I observed (the enacted object of learning). It focuses on the similarities and differences between what instructors intend to teach about resonance and what was actually presented to students in the classroom (i.e., what students actually had the opportunity to learn about resonance).

Instructors Emphasized the Operational Aspects of Resonance

One of the most common themes throughout instructor interviews and classroom observations was that instructors consistently emphasized the operational aspects of resonance over the conceptual aspects. The instructors I interviewed identified eleven critical features of resonance. During the instructor interviews, they discussed both what they wanted students to know (conceptual understandings) and what they wanted students to do (operational understandings) with the critical features. That said, despite believing that the conceptual aspects of resonance are important for students to understand, in identifying these critical features, instructors often prioritized what students should do with resonance over what students should know. For example, while many instructors in this study clearly explained during the instructor interviews that they wanted students to use formal charge to identify the major and minor resonance contributors, they were relatively vague when describing what they wanted students to know about formal charge's relationship to resonance. This emphasis paralleled what happened in their classrooms. For example, while all the instructors in this study mentioned the resonance hybrid in class, they did so briefly (some even expressed misconceptions while doing so). One instructor teaching organic chemistry did not mention the resonance hybrid until the final few minutes of instruction on resonance. Overall, in both the instructor interviews and classroom observations, the instructors prioritized what they wanted students to do with resonance over what they wanted students to know about it.

Instructors Used Mechanistic Language While Discussing Some of the Critical Features

I noticed that both during the interviews and while teaching, instructors used language commonly associated with mechanisms to discuss some of the critical features of resonance. This was most often done while discussing the critical features *curved arrows*, *pattern recognition,* and *hybridization*. For example, during the interviews, when I asked Anthony how he typically teaches resonance in his class, he said, “So teaching resonance in organic chemistry is really about the arrow pushing [i.e., curved arrows], I guess, for me to show how the electrons move.” This explanation suggests that curved arrows depict the actual movement of electrons in nature, which is incorrect. In the context of resonance, curved arrows do not represent the actual movement of electrons (i.e., they are merely a tool used to draw resonance structures). In the classroom, while teaching *hybridization*, Anthony described sp^3 hybridized atoms as “roadblocks.” He stated, “Electrons can’t move through a sp^3 [carbon atom]. It acts as a roadblock…there is no electron delocalization [resonance].”

Similarly, while discussing *pattern recognition,* some instructors used language that is typically associated with mechanisms. These instructors described the electrons as *actually* moving and used curved arrows to depict the movement they were describing. For example, Dallas used the phrases “Chasing the positive” and “Pushing the negative,” while Brad stated, “Electrons flow more to less.” The instructors are likely just trying to describe what is happening on paper while drawing resonance structures. However, this mechanistic language can make students think actual reactions are, in fact, happening. Interestingly, Dallas was aware of the fact that students might hold this misconception. Still, he seemed to connect the confusion students have to formal charge and not the mechanistic language he used to describe curved arrows. He stated, “It’s really easy to get lost in resonance structures. I always try to remind my students to remember formal charges; no reactions are occurring, so there should be the same sum of formal charges across every resonance structure.” Thus, like Dallas, it is possible that other instructors are also unaware of the confusion this type of language might cause students and how that might affect their conceptual understandings of resonance.

Inconsistency Between Instructor Identified and Enacted Critical Features

Another common theme that emerged from this comparison is the fact that there were differences in what instructors did or did not identify as important during the instructor interviews versus what they presented to students during classroom teaching. For example, only two of the General Chemistry I instructors had identified *major and minor resonance contributors* as a critical feature of resonance. Still, all of the instructors presented it to students in their classes. Only two General Chemistry instructors mentioned *bond length* during the instructor interviews, but four instructors mentioned it during the classroom observations. Similarly, only one Organic Chemistry I instructor identified *hybridization* as a critical feature, but four instructors taught students about it in their classes. The opposite was also true; all of the Organic Chemistry I instructors identified *pattern recognition* during their interviews, but only three instructors taught students about this critical feature.

There are many possible reasons for these inconsistencies. One possible reason instructors mentioned critical features during classroom teaching that they had not previously identified is that participating in the interview caused instructors to go back and re-evaluate what they wanted to teach students about resonance. This could also be true for why instructors identified critical features that they did not ultimately teach. Instructors might have also run out of time in the class I observed to do so. Nevertheless, these results indicate the importance of instructors spending adequate time reflecting on what they truly intend for students to understand about resonance and how that does or does not align with their classroom teaching.

Instructors Presented an Additional Feature of Resonance during Classroom Teaching

Through this comparison, I found that instructors discussed one additional feature of resonance (i.e., *resonance arrows*) during the classroom observations that none of the instructors previously identified in their interviews. Thus, because an understanding of *resonance arrows* had not been deemed essential to students' understandings of resonance, it was coded as a non-critical feature. Nevertheless, some instructors discussed this non-critical feature during classroom instruction as a way to dispel the common misconception that resonance is an equilibrium process. Unfortunately, one instructor, Anthony, actually promoted this misconception by incorrectly referring to the resonance arrow drawn between resonance structures as an equilibrium arrow. Overall, identifying this non-critical feature was important. As will be discussed in a section that follows, this feature might be distracting to students and might promote student misconceptions, especially if not taught properly.

Overview of the Comparison Between the Intended and Enacted Objects of Learning

Students' understandings of resonance are affected not only by what instructors intend for them to learn about resonance but also by what is actually presented to them about resonance in the classroom. This comparison shows that both General Chemistry I and Organic Chemistry I instructors are consistent in their prioritization of the operational aspects of resonance. This comparison also showed inconsistencies regarding which critical features instructors intend for students to learn versus which critical features instructors actually present to students in class. I also found that many instructors used language associated with mechanisms while discussing resonance in the interviews and during classroom teaching, which could possibly be contributing to misconceptions about resonance.

Comparison of Intended and Lived Objects of Learning

This comparison examines how the instructor-identified critical features (the intended object of learning) align with what students actually came to understand about resonance (the lived object of learning). That is, how do students' understandings of resonance compare with what their instructors intended for them to learn about resonance?

All of the Instructors and Students Identified Resonance Structures and Lewis Structures

I found that students' understandings of specific critical features did not always align with what their instructors intended for them to learn. Only two critical features were mentioned by all of the instructors and all of the students interviewed for this study: *Lewis structures* and *resonance structures*. Regarding *Lewis structures*, the instructors intended for students to understand Lewis' model of chemical bonding (i.e., Lewis structures) and that a single Lewis structure cannot adequately represent the bonding in some molecules. They also intended students to be able to draw Lewis structures and use them to identify resonance. Unfortunately, while all of the students in this study mentioned aspects of *Lewis structures* during the student interviews, only a few General Chemistry I and Organic Chemistry I students had a complete understanding of Lewis' model of chemical bonding (i.e., Lewis structures) and that a single Lewis structure cannot adequately represent the bonding in some molecules. That is, students focused on needing to draw or use Lewis structures to identify resonance and did not articulate an understanding of the conceptual connection between *Lewis structures* and resonance. In other words, other than Lydia and Rose, students did not explain that resonance was needed to account for the limitations of Lewis structures. Nevertheless, despite students' focus on what they should do with Lewis structures (i.e., use them to visualize if a species exhibits resonance by looking for specific structural cues), most of the students struggled to draw valid Lewis structures for the chemical formulas I presented to them during the interviews.

Regarding *resonance structures*, the instructors intended for students to understand that resonance structures only differ in the placement of electrons (i.e., electron movement), not atoms, and they expected students to be able to identify and draw correct resonance structures. Unfortunately, like *Lewis structures*, only a few students focused on what they were meant to *know* about the *resonance structures*. Students who did try to explain the conceptual aspects of this critical feature did so incorrectly. Many of the students in this study expressed the misconception that resonance structures are real entities that exist in nature, alternating back and forth. Throughout the interview, most students seemed to recognize and focus on what they were expected to *do* with this critical feature: draw resonance structures. That being said, this seemed to be a rather difficult task for most of the General Chemistry I and Organic Chemistry I students in this study. As discussed earlier, this was partly because they struggled to draw valid Lewis structures. Nevertheless, even when presented with valid Lewis structures and asked if the chemical compounds I showed them during the interview exhibit resonance, quite a few of the General Chemistry I and Organic Chemistry I students in this study still struggled to answer this question correctly. The students often clung to specific structural cues (e.g., lone pair or double bond) that they believed indicated resonance. It seemed as though some students were trying to create their own patterns or heuristics to identify resonance.

All in all, while both instructors and students identified the critical features *Lewis structures* and *resonance structures*, there were noticeable differences in what instructors intended for students to know about and be able to do with them versus what students actually knew about and could do with them. Students were task-orientated when discussing *Lewis structures* and *resonance structures*, as they focused on what they were meant to do with the critical features rather than know (which parallels what their instructors emphasized in class).

Unfortunately, even while aware of what they were meant to do with this critical feature, many students struggled to do so.

Nearly All of the Instructors but Few of the Students Identified Resonance Hybrid

Again, from this comparison, I found that students' understandings of specific critical features did not always align with what their instructors intended for them to learn. All of the instructors in this study, except one, identified *resonance hybrid* as a critical feature of resonance they intended for students to learn. Many of the instructors who identified this critical feature indicated the importance of understanding that resonance structures are not real entities and do not exist in nature, as well as the importance of understanding that the actual, most correct structure, the resonance hybrid, is a mental melding of the different resonance structures. As previously mentioned, while neither type of instructor focused on conceptual understandings of resonance relative to operational understandings, the General Chemistry I instructors in the current study reported discussing critical features (e.g., *resonance hybrid*) that address students' conceptual understandings of resonance more often than did the Organic Chemistry I instructors. Some of the instructors also indicated the importance of addressing common misconceptions related to this critical feature, such as resonance being an equilibrium process.

While nearly all of the instructors had intended for their students to understand this critical feature in the ways just described, only two General Chemistry I students and four Organic Chemistry I students identified it during the student interviews. It was surprising to see that more Organic Chemistry I students identified this critical feature than General Chemistry I students, as the General Chemistry I instructors spent more time emphasizing its importance during the instructor interviews. Of the students who identified this critical feature, only two explicitly indicated that they understood that resonance structures are not real entities and do not exist in nature and that the actual structure is a combination of all the resonance structures, called the resonance hybrid. Some of the students suggested resonance was an equilibrium process (i.e., held misconceptions), while others did not mention the resonance hybrid at all. Interestingly, Lydia, a General Chemistry I student who demonstrated a conceptual understanding of how *Lewis structures* and resonance are connected, did not mention *resonance hybrid*. This highlights the importance of instructors reflecting on and helping students understand how the critical features are connected and related to each other.

All in all, this was one of the clearest examples of differences between what instructors intend for students to understand about a critical feature versus what students actually came to understand about it. Despite all of the instructors identifying *resonance hybrid,* most of the students in this study did not even mention it throughout the entirety of their interviews. Furthermore, those students who did mention it often expressed misconceptions while doing so.

Overview of the Comparison Between the Intended and Lived Objects of Learning

This comparison shows differences between what instructors intend for students to learn about resonance and what students actually understand about resonance. Overall, while discussing each of the eleven critical features, most students did not mention what their instructors expected them to *know* about them. In certain instances, students were at least partially aware of what they were meant to *do* with specific critical features, most notably *Lewis structures* and *resonance structures*. That said, when asked to identify resonance for different chemical compounds during the student interviews, most students struggled to do so correctly. Furthermore, all but one instructor identified the critical feature *resonance hybrid*, but relatively few students mentioned it during their interviews. Students who did mention it often did so with misconceptions.

Comparison of Lived and Enacted Objects of Learning

This comparison examines what happened in the classroom (the enacted object of learning) and what students ultimately integrated into their understanding of resonance (the lived object of learning). This comparison highlights what students paid attention to when learning about resonance. That is, are students focusing on the critical features of resonance identified by their instructors, or are they focusing on other, perhaps, less important features that were presented in their classes?

Students Emphasized the Operational Aspects of Resonance

The students in this study focused on the operational aspects of resonance. That is, while discussing resonance during their interviews, the students tended to focus on how each of the critical features they identified related to the drawing of resonance structures. This was unsurprising as the operational aspects of resonance were emphasized during classroom teaching. For example, while many of the instructors had identified highly conceptual critical features (e.g., *resonance hybrid* and *bond length*), they dedicated little class time to teaching those critical features. Thus, because students had more opportunities to build their operational understandings of resonance than conceptual understandings of resonance in class, it is unsurprising that students chose to focus on these aspects during their interviews. Furthermore, during class, the instructors informed students that they would not be tested on the conceptual aspects of resonance. As students tend to pay more attention to skills and concepts that will be assessed, the instructors' assessment practices likely played a part in reinforcing students' developing operational understandings of resonance over their conceptual understandings (Van Etten, Freebern, & Pressley, 1997)

Students Expressed Misconceptions about Resonance

As has been discussed throughout this dissertation, students held misconceptions about resonance, most often expressing these while discussing the critical features *resonance structures*, resonance *hybrid,* and *curved arrows.* These misconceptions are likely tied to how their instructors discussed the critical features of resonance in their classes. For example, students in both General Chemistry I and Organic Chemistry I believed resonance structures were real entities that exist in nature and that the electrons literally move as a molecule transitions from one resonance structure to another. These types of misconceptions were identified multiple times throughout the student interviews and are, unfortunately, likely tied to instruction. That is, while teaching, some instructors expressed similar misconceptions themselves. For example, while introducing resonance in her general chemistry classroom using ozone as an example, Destiny stated, "Both resonance structures of ozone exist in equal percentages, so 50% and 50%." An organic chemistry instructor shared a similar misconception with students while discussing benzene. He described the resonance structures of this molecule as being in "rapid equilibrium" (before explaining, at a later time, that resonance structures do not exist in equilibrium).

Furthermore, as previously discussed, students' misconceptions about resonance might also be tied to instructors' use of mechanistic language to describe resonance. For example, while discussing some of the critical features, such as *curved arrows, hybridization, and pattern recognition,* most of the instructors used language (e.g., pushing and pulling electrons) that is typically associated with reaction mechanisms and not resonance structures and thus, possibly could contribute to student misconceptions about resonance.

Students Identified Non-Critical Features

During the student interviews, a few of the General Chemistry I students identified non-critical features of resonance: *resonance arrow* and *resonance brackets*. These are features of resonance that instructors did not deem critical for students to understand about resonance. Some instructors discussed *resonance arrows* during their classroom teaching. Unfortunately, *resonance arrow* was a source of confusion, as the students who identified this critical feature did so in a way consistent with that of equilibrium, something Wheland warned about in his book *Resonance in Organic Chemistry* (1955). Because of this, instructors might consider pointing out to students that resonance arrows are double-headed arrows drawn between resonance structures and that they denote that the resonance structures are not separate entities but that the actual structure is a hybrid of the different resonance structures. They might also consider heeding Kerber's advice, he suggests not using a resonance arrow but rather a comma or even the word "and" between the structures (2006).

The other non-critical feature of resonance (i.e., *resonance brackets*) identified by one General Chemistry I student interviewee was not verbally discussed by the instructors in their classrooms. This student pointed out resonance brackets during her interview. Resonance brackets are square brackets that are drawn on the left and right of resonance structures to denote that they are contributors to the resonance hybrid. These brackets are different than those used to denote the charge of an ion. While the student who identified this critical feature explained that she uses those brackets as an indicator for resonance, instructors might consider using them as an opportunity to focus on the conceptual aspects of resonance by pointing out what resonance brackets are meant to represent.

Comparison of Intended, Enacted, and Lived Objects of Learning

This comparison examines potential reasons why students did not come to understand resonance in the way that the instructors intended them to by comparing each of the objects of learning together. This comparison allowed me to identify the information that students paid attention to during instruction and what they ultimately integrated into their understanding.

Students Focused on the Operational Aspects of Resonance Because of What is Presented in Class

The instructors in this study identified both what they wanted students to know (conceptual understandings) and what they wanted students to do (operational understandings) with the critical features of resonance. That said, in identifying these critical features during the interviews and presenting them in class, instructors often prioritized what students should do with resonance over what students should know. The two critical features identified and taught by all the instructors and all the students in this study were those closely associated with operational understandings of resonance, *Lewis structures,* and *resonance structures.* As previously stated, students had more opportunities to build their operational understandings of resonance than conceptual understandings of resonance in class, as instructors put an emphasis on reviewing how to identify resonance and draw resonance structures. Thus, it is unsurprising that this is what students ultimately drew their attention to while learning about resonance. Furthermore, during class, the instructors informed students that they would not be tested on the conceptual aspects of resonance (e.g., drawing the resonance hybrid). As students tend to pay more attention to skills and concepts that will be assessed, the instructors' assessment practices likely played a part in reinforcing students' developing operational understandings of resonance over their conceptual understandings (Van Etten et al., 1997).

Students Created their Own Patterns for Identifying Resonance

I found that while students were explaining their thought processes behind whether a chemical compound that I showed them during the interview exhibited resonance or not, both General Chemistry I and Organic Chemistry I students relied on specific structural cues of molecules they believed indicated resonance. For example, students often explained that they look for double bonds, lone pairs, and charges to help them identify resonance, and when they see these structural cues, there is resonance. I should point out that while some of the Organic Chemistry I students in this study were taught *pattern recognition*, some still tried to create their own patterns as they used heuristic reasoning similar to that of the General Chemistry I students. It is important for instructors to point out to students that just because there are double bonds, lone pairs, or charges present, it does not automatically mean the molecule exhibits resonance. Instructors might also consider further elaborating on why a molecule with one of these structural cues might exhibit resonance while another with these structural cues might not. In other words, instructors should help students understand the underlying reasons why a compound might exhibit resonance.

Students Expressed Misconceptions about Resonance

As mentioned, many of the students in this study expressed scientifically inaccurate conceptions of resonance. There are multiple possible origins of these misconceptions. First, instructors do not spend adequate time discussing the conceptual aspects of resonance. For example, while all of the instructors identified *resonance hybrid* as a critical feature of resonance, they spent very little class time discussing it. The instructors also made it clear to students that it would not be something they would be assessed on. Thus, it is unsurprising that students put little effort towards understanding it. Another reason students might express misconceptions about resonance is the fact that some of the instructors did so as well, most often while discussing *resonance hybrid* and *major and minor resonance contributors*. For example, Destiny stated, “Both resonance structures of ozone exist in equal percentages, so 50% and 50%.” An organic chemistry instructor shared a similar misconception with students while discussing benzene. He described the resonance structures of this molecule as being in “rapid equilibrium.” Another source of these misconceptions might be how instructors choose to discuss *curved arrows*, *hybridization,* and *pattern recognition*. That is, while discussing these critical features in class, instructors used language that is associated with reaction mechanisms. For example, no matter which instructor was discussing resonance, they described it as the actual movement of electrons or, for example, the “pushing and pulling of electrons.” This use of these words likely promotes and/or reinforces students’ misconceptions of resonance.

Implications for Teaching and Future Research

The current study has focused on the teaching and learning of resonance in General Chemistry I and Organic Chemistry I from the instructor, classroom, and student perspectives. Overall, I found that while instructors desire for their students to have both conceptual and operational understandings of resonance, their teaching practices do not fully support the development of both types of understandings. Based on the comparisons of the intended, enacted, and lived objects of learning and the prior research literature, I provide suggestions that might aid in improving the teaching of resonance and ultimately help more students come to the desired understanding of resonance. I also provide suggestions for the future research of students’ understandings and uses of resonance in General Chemistry I and Organic Chemistry I.

Implications for Teaching

Instructors Should Evaluate Students’ Understandings of Lewis Structures

Educational researchers (Betancourt-Perez et al., 2010; Cooper et al., 2010) have identified the ability to draw and use Lewis structures as a prerequisite to drawing resonance structures. My findings align with the research literature indicating that both general chemistry and organic chemistry students have difficulties understanding and using Lewis structures (Betancourt-Perez et al., 2010; Bodner & Shane, 2006; Brady et al.,1990; Cooper et al., 2010; Kaufmann et al., 2017; Taber, 1997, 1998; Underwood et al., 2015). Unfortunately, being unable to draw valid Lewis structures ultimately kept many of the general chemistry and organic chemistry students in this study from being able to identify if a compound exhibited resonance. Most of the students in my study also lacked an understanding of the limitations of Lewis structures and why resonance is needed.

Based on these findings, I suggest that general chemistry instructors separate their initial introduction of Lewis structures and resonance by at least a class period to give students in this course more time to practice drawing Lewis structures with molecules and ions that do not exhibit resonance. That is, having time to master or at least practice Lewis structures before learning about other complexities, such as resonance (i.e., the limitations of Lewis structures), will arguably lower students' overall cognitive load, making it easier for them to understand how and why resonance structures are drawn (Tiettmeyer et al., 2017). I suggest that those teaching organic chemistry assess students' prior knowledge of Lewis structures via a short online or in-class quiz to determine how much time they should dedicate to re-introducing the topic in class or, if class time is an issue, how much supplementary learning materials they provide students with (e.g., extra practice problems, instructional videos, etc.). Those teaching organic chemistry often assume that students have mastered the skill of drawing and using Lewis structures.

However, students entering organic chemistry have likely not been asked to draw Lewis structures in some time.

Furthermore, many of the students in this study lacked an understanding of the limitations of Lewis structures and why resonance is needed. Thus, I suggest that General Chemistry I and Organic Chemistry I instructors spend time first emphasizing that we draw Lewis structures so that we can use them to predict structure-property relationships. Then, they should explain why just one Lewis structure cannot be used to do so for all molecules or ions because some exhibit resonance. Instructors might consider using Cooper, Underwood, and Hilley's (2012) Implicit Information from Lewis Structures Instrument (IILSI) to evaluate their student's abilities to use Lewis structures to make structure-property connections. The IILSI is a survey instrument that instructors can easily implement to determine students' beliefs about the type of information Lewis structures contain. Instructors might also consider using curricula that focuses on building structure-property connections, such as the general chemistry textbook *CLUE: Chemistry, Life the Universe and Everything* (CLUE) (Cooper & Klymkowsky, 2013). This book and its associated materials (e.g., video lectures, assessment, recitation worksheets) are available online free of charge for students.

Instructors Should Help Students Understand and Use the Patterns for Identifying Resonance

Both General Chemistry I and Organic Chemistry I students' reasoning for what they should look for to decide if a molecule or ion has resonance mostly focused on specific patterns in molecular structure. In other words, students are focusing on surface features instead of underlying concepts. While deciphering if a chemical compound exhibits resonance, General Chemistry I and Organic Chemistry I students examined the Lewis structures of the chemical compounds for specific structural cues. In no particular order, General Chemistry I and Organic

Chemistry I students asked themselves questions like these: (1) Are there one or more double bonds? (2) Is there a lone pair of electrons? (3) Is the octet rule being followed? (4) Is there a charge on any atoms in the structure? Often, if students noticed any of these aspects, they decided the compound exhibited resonance. This, of course, often leads students astray as this reasoning is incomplete. It is unsurprising that the General Chemistry I students tried to come up with their own patterns of resonance as they are not taught *pattern recognition* in their course. Some of the Organic Chemistry I students in this study were taught *pattern recognition.* Still, they struggled to apply the appropriate patterns. They often cherry-picked specific structural cues over using the complete group of structural cues (i.e., the five patterns of resonance) that suggest resonance.

To help students understand that, for example, just a double bond or a lone pair of electrons by itself does not indicate resonance, I suggest that instructors show students a mixture of compounds that have those structural cues, some of which exhibit resonance and some of which do not, and then discuss why. For example, some of the students in this study believed that PCl_3 exhibits resonance because of the presence of lone pairs on the phosphorus atom. This resulted in students drawing invalid Lewis structures that broke the octet rule. Instructors might consider using PCl_3 as an example of why a structure with a lone pair of electrons does not always exhibit resonance. It might also be helpful for those teaching general chemistry to limit their initial examples of Lewis structures and resonance structures to those that follow the octet rule. That way, when students try to decide if a lone pair of electrons can be re-written as a double bond, they can consider the octet rule without being confused by its exceptions.

Organic Chemistry I instructors might also consider this approach. For example, those teaching organic chemistry might show students the Lewis structure for ethene and explain why, despite having a double bond, the structure does not exhibit resonance. Furthermore, because *pattern recognition* is often taught to students in organic chemistry, as Braun et al. (2022) suggested, instructors should spend more time helping students learn and recognize *why* these patterns typically indicate resonance (e.g., using *hybridization*). That way, students do not just cherry-pick bits and pieces of these patterns but understand them as a whole.

Instructors Should Engage Students in Activities Focused on Conceptual Aspects of Resonance

One of the most common themes throughout this study and the research literature is that instructors prioritize the operational aspects of resonance over the conceptual aspects both in teaching and assessments. This is likely because while instructors believe a conceptual understanding of resonance to be important, they believe that actually being able to draw resonance structures (and then eventually use resonance structures in a context) is the skill they are most worried about students developing. What instructors might not realize is that the research literature suggests that students who lack an underlying understanding of the conceptual aspects of resonance have more difficulties drawing and using resonance structures (Braun et al., 2022). Thus, taking the time to teach students about and assess their understandings of the conceptual aspects of resonance might actually help develop their operational understandings of resonance.

Thus, I suggest that instructors incorporate activities similar to those reported by Kim et al. (2019) and Brandfonbrener et al. (2021). These two studies were previously described in Chapter 2 of this dissertation. They provide useful teaching interventions/strategies that address students' conceptual understandings of resonance using research-based information. Specifically, according to Kim et al. (2019), instructors should focus on developing students’ metarepresentational competence related to resonance. This involves having students create their own representations of resonance and discussing the representations' strengths and weaknesses. A writing-to-learn assignment (Hayes, 1996) similar to that designed by Brandfonbrener et al. (2021) might also be useful in developing students' conceptual understanding of resonance. Such an assignment should encourage students to articulate, reflect, and elaborate on their conceptual understandings of resonance. Finally, considering that some of the instructors in our study expressed misconceptions about the resonance hybrid, I encourage instructors to reflect on their own conceptual understandings of resonance, as these misunderstandings could profoundly impact student learning and should be addressed before leading student discussions on the concept.

Instructors Should Assess Students' Conceptual Understandings of Resonance

Aside from the activities described in the previous paragraphs, it is also important for instructors to assess students' conceptual understandings of resonance. It seems reasonable that instructors would assess students in their classrooms as they have experienced in the past. If this is true, it is possible that instructors do not have experience with conceptual assessments of resonance. Thus, despite believing a conceptual understanding of resonance to be important, it might not be reflected in their practice and homework problems or their assessments of the concept. I suggest that instructors examine their assessment questions to ensure that they match what they intend for students to learn about resonance. Tetschner and Nedungadi's (2023) resonance concept inventory provides examples of the types of questions that could be used to elicit and assess students' conceptual understandings of resonance.

Instructors Should Evaluate How/If Their Teaching Practices and Assessments Align with the Critical Features

The eleven critical features of resonance identified in this study can be used by instructors to guide their teaching and assessment practices. Instructors might reflect on how their teaching practices and assessments address or do not address the critical features and make the necessary adjustments to align the three. For example, if students are not understanding something the instructor intends them to understand, the instructor might reflect on why that is. They might ask themselves: ‘‘Why is that? Am I not teaching it? Am I not emphasizing it enough? Am I teaching it in a way that promotes misconceptions?’’ The critical features might also help guide textbook selections that best address all of (or most of) the critical features of resonance. Instructors might also consider providing students with the critical features of resonance to communicate what they expect students to understand about resonance in their classes.

Instructors Should Consider Replacing the Arrow Between Resonance Structures with a Comma or the Word "and"

A resonance arrow is a double-headed arrow (↔) used between resonance structures to denote that the actual electron density distribution is a mental melding of the various resonance structures drawn. Some instructors pointed this out to students and explained what it meant. Unfortunately, one instructor promoted the misconception that the arrow indicates equilibrium. *Resonance arrow* was also a source of confusion for some of the students in this study. That is, a couple of the general chemistry students held misconceptions about the resonance arrow, explaining that it indicates that the resonance structures "go back and forth." I suggest that instructors spend adequate time explaining what the arrow between resonance structures represents while discussing the conceptual aspects of resonance. This will hopefully keep students from making their own incorrect interpretations of the arrow. As previously mentioned, instructors might also consider heeding Kerber's advice. He suggests not using a resonance arrow but rather a comma or even the word "and" between the structures (2006).

Implications for Future Research

This study was designed to investigate the teaching and learning of resonance in General Chemistry I and Organic Chemistry I by examining it from the instructor, classroom, and student perspectives. I suggest that future work focuses on further examining and developing curricular materials that address both the conceptual and operational aspects of the critical features of resonance in General Chemistry I and Organic Chemistry. In the paragraphs that follow, I first discuss the future research suggestions directly tied to the current study. Then, I discuss the future research suggestions that are more broadly tied to the current study.

Future Research Suggestions Directly Tied to the Current Study

I have three recommendations for future research that follow directly from the finding of the current study. First, because instructors in this study often used mechanistic language to describe resonance, I suggest that researchers examine how the language used to talk about resonance affects students' understandings of resonance. Researchers might also compare students' understandings of mechanisms versus resonance. Second, future research might examine instructors' perceptions of the non-critical features of resonance. That is, if instructors are presented with a list of all of the features of resonance identified in this study, would they deem *resonance arrows* and *resonance brackets* as critical features? What does it tell us if they do or do not? That is, should we continue to use these features while teaching resonance? Finally, researchers should examine how the teaching interventions I suggested in this chapter affect students' understandings of resonance. For example, how does spending more time making sure students understand structure-property relationships affect students conceptual and operational understandings of resonance. How does spending time in class emphasizing and discussing the conceptual aspects of resonance affect students' understanding of resonance? How does assessing students on the conceptual aspects of resonance affect their learning of the topic? Does reviewing why or why not specific structural features indicate resonance help students draw valid resonance structures?

Future Research Suggestions Broadly Tied to the Current Study

I also have recommendations for future work that is more broadly related to the current project. I suggest that future work analyze how resonance is taught, practiced, and assessed in general chemistry textbooks. As Carle and Flynn (2020) showed using content analysis, many popular organic chemistry textbooks do not adequately explain or assess students on the conceptual aspects of resonance (e.g., the resonance hybrid). To explore how this finding relates to general chemistry textbooks, I suggest that a content analysis similar to that performed by Carle and Flynn (2020) be used to examine how general chemistry textbooks approach the teaching and learning of resonance with respect to how each of the critical features of resonance are being taught, practiced, and assessed. Researchers might also examine General Chemistry I assessments of resonance to further compare how each critical feature is being addressed in the course.

It might also be interesting to investigate how students' understandings of the critical features progress from preparatory chemistry to higher-level chemistry courses, such as biochemistry, and finally to the instructor level. That is, do students' understandings of resonance progress as they learn more about chemistry? How do their perceptions of the purposes of resonance change over time? Why do students' misconceptions of resonance persist over time? Researchers might consider using Perry's Scheme of Intellectual and Ethical

Development as a framework to explore this question (Perry, 1968). This information might help instructors address their own misconceptions about resonance and approach resonance in ways that are developmentally appropriate for students. It might also provide information regarding how much information about resonance students are retaining as they progress from general chemistry to organic chemistry.

Finally, I also suggest that researchers investigate the teaching and learning of resonance in preparatory general chemistry and preparatory organic chemistry. These are two courses that many of the students who participated in my study took prior to enrolling in their respective courses. Thus, a limitation of this study was the fact that I was not able to examine how much of a participant's understanding of resonance was from the course they were enrolled in versus a previous course. Students often recalled these courses as being critical to their current understandings of resonance.

Limitations

I have identified several possible limitations to my study. While this study was not limited to a single institution, it was limited to a specific region of the Southwestern United States with a limited sample of student and instructor participants. Furthermore, while the student participants were enrolled in either General Chemistry I or Organic Chemistry I for the first time, some mentioned taking preparatory general chemistry and/or preparatory organic chemistry courses before enrolling, which likely influenced their understandings of resonance coming into their respective courses. The original developers of variation theory do not address students' prior knowledge; thus, aside from asking students where/how they remember learning about resonance for the first time, I could not fully capture their prior understanding of resonance. However, it is likely that many other students have taken similar courses before enrolling in either General Chemistry I or Organic Chemistry I.

I should also mention that the findings from this study represent my interpretation of the instructors' and students' perceptions of resonance. While I believe I captured the most accurate representations of the instructors' and students' perceptions, there were interview questions to which both instructors and students gave short or vague responses, making it difficult to capture their beliefs fully. It is also possible that despite my best efforts to put students at ease, they were nervous or embarrassed while trying to answer a question they might not know; thus, it is possible that some students did not fully explain their thought processes aloud during the interview. Finally, despite my best efforts to put instructors at ease, it is possible that while teaching resonance, instructors felt nervous or embarrassed to have me observe their teaching. This could potentially affect their teaching for that day. Furthermore, knowing I would observe their classrooms could have influenced the instructors to reflect on their teaching practices and/or change how they would naturally approach teaching. All in all, the transferability of these results should be thoughtfully considered based on the information provided.

APPENDIX A

IRB Exempt Notice

Date: 12-3-2023

IRB #: UNLV-2022-239
Title: An Examination of the Teaching and Learning of Resonance in General Chemistry I and Organic Chemistry I Using Variation Theory
Creation Date: 5-2-2022
End Date:
Status: Approved
Principal Investigator: MaryKay Orgill
Review Board: Biomedical
Sponsor:

Study History

Submission Type	Initial	Review Type	Exempt	Decision	Exempt
Submission Type	Modification	Review Type	Exempt	Decision	Exempt

APPENDIX B

Email Instructor Recruitment Script

UNLV

Principal Investigator: MaryKay Orgill
Contact Information: marykay.orgill@unlv.edu

Instructor Recruitment Script—Email

Dear ____________,

Hi, my name is Sabrina Barakat, and I am a graduate student researcher working under Dr. MaryKay Orgill in the Department of Chemistry and Biochemistry at the University of Nevada, Las Vegas (UNLV). We are a group of Discipline Based Education Researchers focused on the teaching and learning of chemistry. Specifically, I am interested in examining how/ why there are differences in students' understandings of resonance in general and organic chemistry I by evaluating the concept from three different perspectives—the instructor, classroom, and student. Ideally, results from my study can be used to improve the teaching practices and instructional materials related to resonance in these courses. Potentially, resulting in more students coming to a scientifically meaningful understanding of the topic.

The purpose of this email is to ask you to take part in my research study, as your insight can help me better understand what [general and/or organic chemistry I] instructors intend for their students to learn about resonance. For example, I am interested in conducting an interview with you about how you teach resonance in your classroom, what you think are the most important aspects of resonance for students to understand, and student difficulties that you have noticed with resonance. I would audio-record the interview and take notes.

Furthermore, because I am also interested in the teaching and learning of resonance from the classroom perspective, I would also like to ask you to allow me to observe your classroom when you introduce resonance for the first time. I would audio-record your class period and take notes but would strictly act as an observer (i.e., will not participate in the class in any way).

Please let me know if you would be willing to participate in my research study. If so, please reply to this email and indicate if you are willing to (option 1) participate in a one-on-one interview only (please specify if you would like to meet in person at UNLV or via web-conference technology) or (option 2) a one-on-one interview and a classroom observation. Please note that I do not expect the interview to last more than an hour and I would only observe your classroom on the day and time that you first introduce resonance. The interview would be scheduled for a date and time that is most convenient for you. Your identity as a research participant would be kept completely confidential, and any data published will maintain that confidentiality.

Thank you for taking the time to read this email and considering participation in my research study. Pleases do not hesitate to reach out with questions or concerns that I may address. I am looking forward to hearing from you.

Best,

Sabrina Barakat
Graduate Researcher
UNLV-Department of Chemistry and Biochemistry
barakat4@unlv.nevada.edu

APPENDIX C

Informed Consent for General Chemistry I Instructor Interview

Informed Consent
Department of Chemistry and Biochemistry

Title of Study: An examination of the teaching and learning of resonance in General Chemistry I and Organic Chemistry I using variation theory
Investigator(s): Dr. Marykay Orgill (PI) and Sabrina Barakat
For questions or concerns about the study, you may contact MaryKay Orgill at marykay.orgill@unlv.edu.

For questions regarding the rights of research subjects, any complaints or comments regarding the manner in which the study is being conducted, contact **the UNLV Office of Research Integrity – Human Subjects at 702-895-0020 or via email at IRB@unlv.edu.**

It is unknown as to the level of risk of transmission of COVID-19 if you decide to participate in this research study. The research activities will utilize accepted guidance standards for mitigating the risks of COVID-19 transmission: however, the chance of transmission cannot be eliminated.

PURPOSE OF THE STUDY

You are invited to participate in a research study. The purpose of this study is to examine the teaching and learning of resonance in general chemistry I and organic chemistry I. I will focus on identifying how/ why there are differences in students' understandings of resonance by evaluating the teaching and learning of resonance from three different perspectives—the instructor, classroom, and student perspectives.

PARTICIPANTS

You are being asked to participate in the study because you fit these criteria: general chemistry I instructor, over 18 years of age and have taught general chemistry I at the tertiary level.

PROCEDURES

If you volunteer to participate in this study, you will be asked to do the following: participate in an approximately 60-minute interview where we discuss the teaching and learning of resonance. The interview will take place in an office in the chemistry building on the University of Nevada, Las Vegas Maryland campus, or as an option, interviews could take place using web-conference technology. The entire interview will be audio-recorded. If web-based you will be asked to leave your web camera on for the duration of the interview, but you will be audio-recorded only.

BENEFITS OF PARTICIPATION

There may be direct benefits to you as a participant in this study. However, we hope to learn how to improve the teaching and learning of resonance.

RISKS OF PARTICIPATION

There are risks involved in all research studies. This study may include only minimal risks. There are no physical or social risks associated with participating in this study. There is a small chance of psychological risk due to the nature of the study which may include stress, discomfort and embarrassment resulting from a feeling of uncertainty or lack of knowledge about the topic of discussion. You will be asked questions about resonance that may cause anxiety. To minimize this risk, you do not have to answer any questions that make you feel uncomfortable. You can end the interview at any time.

COST /COMPENSATION

There may not be financial cost to you to participate in this study. The study will take approximately 60 minutes of your time. You will not be compensated for your time.

CONFIDENTIALITY

All information gathered in this study will be kept as confidential as possible. No reference will be made in written or oral materials that could link you to this study. All records will be stored in a locked facility at UNLV for 3 years after completion of the study. After the storage time the information gathered will be physically destroyed by shredding and deleted electronically.

VOLUNTARY PARTICIPATION

Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study. You may withdraw at any time without prejudice to your relations with UNLV. You are encouraged to ask questions about this study at the beginning or any time during the research study.

PARTICIPANT CONSENT:

I have read the above information and agree to participate in this study. I have been able to ask questions about the research study. I am at least 18 years of age. A copy of this form has been given to me.

______________________________ ______________________

Signature of Participant Date

____

Participant Name (Please Print)

Audio/Video Taping:

I agree to be audio taped for the purpose of this research study.

Signature of Participant | Date

Participant Name (Please Print)

APPENDIX D

Informed Consent for Organic Chemistry I Instructor Interview

UNLV

Informed Consent
Department of Chemistry and Biochemistry

Title of Study: An examination of the teaching and learning of resonance in General Chemistry I and Organic Chemistry I using variation theory

Investigator(s): Dr. Marykay Orgill (PI) and Sabrina Barakat
For questions or concerns about the study, you may contact MaryKay Orgill at marykay.orgill@unlv.edu.

For questions regarding the rights of research subjects, any complaints or comments regarding the manner in which the study is being conducted, contact **the UNLV Office of Research Integrity – Human Subjects at 702-895-0020 or via email at IRB@unlv.edu.**

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It is unknown as to the level of risk of transmission of COVID-19 if you decide to participate in this research study. The research activities will utilize accepted guidance standards for mitigating the risks of COVID-19 transmission: however, the chance of transmission cannot be eliminated.

PURPOSE OF THE STUDY

You are invited to participate in a research study. The purpose of this study is to examine the teaching and learning of resonance in general chemistry I and organic chemistry I. I will focus on identifying how/why there are differences in students' understandings of resonance by evaluating the teaching and learning of resonance from three different perspectives—the instructor, classroom, and student perspectives.

PARTICIPANTS

You are being asked to participate in the study because you fit these criteria: organic chemistry I instructor, over 18 years of age and have taught organic chemistry I at the tertiary level.

PROCEDURES

If you volunteer to participate in this study, you will be asked to do the following: participate in an approximately 60-minute interview where we discuss the teaching and learning of resonance. The interview will take place in an office in the chemistry building on the University of Nevada, Las Vegas Maryland campus, or as an option, interviews could take place using web-conference technology. The

entire interview will be audio-recorded. If web-based you will be asked to leave your web camera on for the duration of the interview, but you will be audio-recorded only.

BENEFITS OF PARTICIPATION

There may be direct benefits to you as a participant in this study. However, we hope to learn how to improve the teaching and learning of resonance.

RISKS OF PARTICIPATION

There are risks involved in all research studies. This study may include only minimal risks. There are no physical or social risks associated with participating in this study. There is a small chance of psychological risk due to the nature of the study which may include stress, discomfort and embarrassment resulting from a feeling of uncertainty or lack of knowledge about the topic of discussion. You will be asked questions about resonance that may cause anxiety. To minimize this risk, you do not have to answer any questions that make you feel uncomfortable. You can end the interview at any time.

COST /COMPENSATION

There may not be financial cost to you to participate in this study. The study will take approximately 60 minutes of your time. You will not be compensated for your time.

CONFIDENTIALITY

All information gathered in this study will be kept as confidential as possible. No reference will be made in written or oral materials that could link you to this study. All records will be stored in a locked facility at UNLV for 3 years after completion of the study. After the storage time the information gathered will be physically destroyed by shredding and deleted electronically.

VOLUNTARY PARTICIPATION

Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study. You may withdraw at any time without prejudice to your relations with UNLV. You are encouraged to ask questions about this study at the beginning or any time during the research study.

PARTICIPANT CONSENT:

I have read the above information and agree to participate in this study. I have been able to ask questions about the research study. I am at least 18 years of age. A copy of this form has been given to me.

_______________________________________ _______________________

Signature of Participant Date

____

Participant Name (Please Print)

Audio/Video Taping:

I agree to be audio taped for the purpose of this research study.

_______________________________________ _______________________

Signature of Participant Date

Participant Name (Please Print)

APPENDIX E

Instructor Interview Guide

Research Question #1: What do General Chemistry I and Organic Chemistry I instructors intend for their students to understand about resonance?

Informed Consent

- First, I want to say thank you for your willingness to participate in my research study. My name is Sabrina, and I am a graduate student at the University of Nevada, Las Vegas (UNLV) working to complete a Ph.D. in chemistry. This study is about the teaching and learning of resonance. This interview will be audio recorded so that I may reference our discussion later. What we will discuss today will be potentially published as part of a research report. Your identity of any information that could identify you as a participant will remain confidential.

- Take a few moments to look over the form and let me know if you have any questions. And then please sign the form indicating that you consent to be interviewed and audio recorded. I am supplying this informed consent document to you for your records. Thank you! Now we will begin the interview by talking about your background.

Participant Background

- Tell me about yourself.
    - Where did you go to college?
    - What did you study?
    - What's your position at [CSN, NSC, or UNLV] and what do you do? [Response will direct follow-up questions]
        - What are your research interests? What are you currently working on?
    - What courses do you typically teach? How long have you been teaching? What do you typically teach?
    - What has shaped your approach to teaching?

- Today we will mostly be talking about resonance.

What Students Should Know about Resonance

- How would you describe resonance in your own words?
- Why do you think it's important for students to learn about resonance?
- What do you expect your students to already know about resonance before coming into your classroom?
    - So, that's what you expect them to know. What do you they usually know about resonance when they come into your classroom?
- Now let's shift a little to talk about how you teach resonance concepts in your classroom.
- When do you typically teach resonance in the semester?
- Pretend I'm a student in your class. How would you teach me about resonance? What would you tell me? Show me? Feel free to use the paper and pencil if you like.
    - How long do you spend talking about it initially?

    - How often do you refer to it again when you are teaching?
    - I have noticed that textbooks and other practitioners will use analogies to teach about resonance. What do you think about this approach?
        - Do you use any specific analogies when teaching resonance in your class?
- What do you think students should be able to understand/ do related to the topic of resonance in your class?
- What type of practice or homework problems do you typically ask students to do that involve resonance? What about test questions?
- When you think about your students, what do they really understand when you teach them about resonance?
- What do you think they have a hard time understanding?
  What types of misunderstandings do they tend to develop about resonance? Where do you think these misunderstandings come from? What do you do to help students avoid or overcome these misunderstandings?
- What do you typically do when you notice students are having difficulties understanding resonance?
- Students, especially beginning ones, might not learn everything about a given topic. What do you think is really important for students to understand about resonance at _____level? What isn't so important?

Reflection and Final Remarks

- I am going to ask you a final question to finish up the interview.
    - What would you tell a student coming into the class they would need to know about resonance to be successful?

- Okay, those are all the questions I have for you. Do you have any final thoughts? I really appreciate you taking the time to sit down and talk with me. Have a great rest of your day.

APPENDIX F

Informed Consent for General Chemistry I Classroom Observation

UNLV

Informed Consent
Department of Chemistry and Biochemistry

Title of Study: An examination of the teaching and learning of resonance in General Chemistry I and Organic Chemistry I using variation theory
Investigator(s): Dr. Marykay Orgill (PI) and Sabrina Barakat
For questions or concerns about the study, you may contact MaryKay Orgill at marykay.orgill@unlv.edu.

For questions regarding the rights of research subjects, any complaints or comments regarding the manner in which the study is being conducted, contact **the UNLV Office of Research Integrity – Human Subjects at 702-895-0020 or via email at IRB@unlv.edu.**

It is unknown as to the level of risk of transmission of COVID-19 if you decide to participate in this research study. The research activities will utilize accepted guidance standards for mitigating the risks of COVID-19 transmission: however, the chance of transmission cannot be eliminated.

PURPOSE OF THE STUDY

You are invited to participate in a research study. The purpose of this study is to examine the teaching and learning of resonance in general chemistry I and organic chemistry I. The researcher (Sabrina Barakat) will focus on identifying how/ why there are differences in students' understandings of resonance by evaluating the teaching and learning of resonance from three different perspectives—the instructor, classroom, and student perspectives.

PARTICIPANTS

You are being asked to participate in the study because you fit these criteria: general chemistry I instructor, over 18 years of age and have taught general chemistry I at the tertiary level.

PROCEDURES

If you volunteer to participate in this study, you will be asked to do the following: either (1) allow the researcher to conduct a classroom observation while you introduce resonance for the first time in your in-person or web-live course or (2) provide the researcher with a copy of your pre-recorded lecture. If observing your in-person or web-live course the researcher will post a sign on the classroom door or a comment in the chat box (if teaching web-live) indicating to others in attendance that the class period will be audio recorded for research purposes. Your entire in-person or web-live class period will be audio-recorded. If needed the researcher will take pictures with her iPad of your class materials (PowerPoint/ Presentation slides and/ or notes written on the board).

BENEFITS OF PARTICIPATION

There may be direct benefits to you as a participant in this study. However, the researchers hope to learn how to improve the teaching and learning of resonance.

RISKS OF PARTICIPATION

There are risks involved in all research studies. This study may include only minimal risks. There are no physical or social risks associated with participating in this study. There is a small chance of psychological risk due to the nature of the study which may include stress, discomfort and embarrassment resulting from a feeling of uncertainty or lack of knowledge about the topic of discussion. The researcher will minimize risk to privacy and confidentially by taking special caution not to get any individuals in pictures that the researcher takes during the class period. If an individual does get in the camera frame, the researcher will immediately either crop them out or delete the image altogether. The researcher will exclude any questions that students might ask from my audio transcription as the researcher will not have students' permission to include their questions in my data analysis. In place of their questions, the researcher will insert the phrase "student question" in the transcript.

COST /COMPENSATION

There may not be financial cost to you to participate in this study. The study will take approximately 60 minutes of your time. You will not be compensated for your time.

CONFIDENTIALITY

All information gathered in this study will be kept as confidential as possible. No reference will be made in written or oral materials that could link you to this study. All records will be stored in a locked facility at UNLV for 3 years after completion of the study. After the storage time the information gathered will be physically destroyed by shredding and deleted electronically.

VOLUNTARY PARTICIPATION

Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study. You may withdraw at any time without prejudice to your relations with UNLV. You are encouraged to ask questions about this study at the beginning or any time during the research study.

PARTICIPANT CONSENT:

I have read the above information and agree to participate in this study. I have been able to ask questions about the research study. I am at least 18 years of age. A copy of this form has been given to me.

______________________________________ ____________________

Signature of Participant Date

____

Participant Name (Please Print)

Audio/Video Taping:

I agree to be audio taped for the purpose of this research study.

______________________________________ ____________________
Signature of Participant Date

____
Participant Name (Please Print)

APPENDIX G

Informed Consent for Organic Chemistry I Classroom Observation

Informed consent
Department of Chemistry and Biochemistry

Title of Study: An examination of the teaching and learning of resonance in General Chemistry I and Organic Chemistry I using variation theory
Investigator(s): Dr. MaryKay Orgill (PI) and Sabrina Barakat
For questions or concerns about the study, you may contact MaryKay Orgill at marykay.orgill@unlv.edu.

For questions regarding the rights of research subjects, any complaints or comments regarding the manner in which the study is being conducted, contact **the UNLV Office of Research Integrity – Human Subjects at 702-895-0020 or via email at IRB@unlv.edu.**

It is unknown as to the level of risk of transmission of COVID-19 if you decide to participate in this research study. The research activities will utilize accepted guidance standards for mitigating the risks of COVID-19 transmission: however, the chance of transmission cannot be eliminated.

PURPOSE OF THE STUDY

You are invited to participate in a research study. The purpose of this study is to examine the teaching and learning of resonance in general chemistry I and organic chemistry I. The researcher (Sabrina Barakat) will focus on identifying how/ why there are differences in students' understandings of resonance by evaluating the teaching and learning of resonance from three different perspectives—the instructor, classroom, and student perspectives.

PARTICIPANTS

You are being asked to participate in the study because you fit these criteria: organic chemistry I instructor, over 18 years of age and have taught organic chemistry I at the tertiary level.

PROCEDURES

If you volunteer to participate in this study, you will be asked to do the following: either (1) allow the researcher to conduct a classroom observation while you introduce resonance for the first time in your in-person or web-live course or (2) provide the researcher with a copy of your pre-recorded lecture. If observing your in-person or web-live course the researcher will post a sign on the classroom door or a comment in the chat box (if teaching web-live) indicating to others in attendance that the class period will be audio recorded for research purposes. Your entire in-person or web-live class period will be audio-recorded. If needed the researcher will take pictures with her iPad of your class materials (PowerPoint/ Presentation slides and/ or notes written on the board).

BENEFITS OF PARTICIPATION

There may be direct benefits to you as a participant in this study. However, we hope to learn how to improve the teaching and learning of resonance.

RISKS OF PARTICIPATION

There are risks involved in all research studies. This study may include only minimal risks. There are no physical or social risks associated with participating in this study. There is a small chance of psychological risk due to the nature of the study which may include stress, discomfort and embarrassment resulting from a feeling of uncertainty or lack of knowledge about the topic of discussion. The researcher will minimize risk to privacy and confidentially by taking special caution not to get any individuals in pictures that the researcher takes during the class period. If an individual does get in the camera frame, the researcher will immediately either crop them out or delete the image altogether. The researcher will exclude any questions that students might ask from my audio transcription as the researcher will not have students' permission to include their questions in data analysis. In place of their questions, the researcher will insert the phrase "student question" in the transcript.

COST /COMPENSATION

There may not be financial cost to you to participate in this study. The study will take approximately 60 minutes of your time. You will not be compensated for your time.

CONFIDENTIALITY

All information gathered in this study will be kept as confidential as possible. No reference will be made in written or oral materials that could link you to this study. All records will be stored in a locked facility at UNLV for 3 years after completion of the study. After the storage time the information gathered will be physically destroyed by shredding and deleted electronically.

VOLUNTARY PARTICIPATION

Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study. You may withdraw at any time without prejudice to your relations with UNLV. You are encouraged to ask questions about this study at the beginning or any time during the research study.

PARTICIPANT CONSENT:

I have read the above information and agree to participate in this study. I have been able to ask questions about the research study. I am at least 18 years of age. A copy of this form has been given to me.

____ ______________________

Signature of Participant Date

____

Participant Name (Please Print)

Audio/Video Taping:

I agree to be audio taped for the purpose of this research study.

____ ______________________

Signature of Participant Date

____

Participant Name (Please Print)

APPENDIX H

Research in Progress Classroom Observation Sign

UNLV

Department of Chemistry and Biochemistry

TITLE OF STUDY: AN EXAMINATION OF THE TEACHING AND LEARNING OF RESONANCE IN GENERAL CHEMISTRY I AND ORGANIC CHEMISTRY I USING VARIATION THEORY

Principal Investigator: MaryKay Orgill
Contact Information: marykay.orgill@unlv.edu

ATTENTION: Audio recording in progress for research purposes during this class period.

APPENDIX I

In-Class Student Recruitment Script

UNLV

Principal Investigator: MaryKay Orgill
Contact Information: marykay.orgill@unlv.edu

Student Recruitment Script-Verbal

Hi! My name is Sabrina Barakat, and I am a graduate student working with Dr. MaryKay Orgill in the Department of Chemistry and Biochemistry at the University of Nevada, Las Vegas (UNLV). I am conducting a research study about the teaching and learning of a chemistry concept called resonance.

I know that chemistry can be a difficult course so I am interested in collecting information that will help me to improve how chemistry is taught in the future. Specifically, I am interested in students' understandings of resonance, which means that I need to conduct interviews with students to talk about your experiences with the topic. The interview will be audio recorded and shouldn't take longer than an hour, we would chat about your experiences learning about resonance in your [general or organic] chemistry course.

The interview is confidential, and any data published for research purposes will maintain that confidentiality. I am going to hand out a notecard to all of you [Sabrina Barakat will hand out 3 x 3 notecards]. Please either right "no" indicating that you are not interested in participating in my study or "yes" along with your name and preferred email address indicating that you are interested in participating in my study. When you are done, please turn your notecards over and I will collect all of them. This is to ensure that no one knows if you volunteered for the study or not.

If you wrote "yes" than I will contact, you directly with a few interview dates and times to choose from that work the best for your schedule. If you wrote "no" I will immediately shred your notecard. The interview can be conducted in an office on campus at UNLV, or via web conference software, whichever is most convenient.

I really appreciate your help! Here is my name and email address in case you would like to ask any questions before the interview [provide the participant with my contact information]. Thank you for helping me make chemistry easier for future students to learn!

APPENDIX J

Informed Consent for General Chemistry I Student Interview

UNLV

Informed consent
Department of Chemistry and Biochemistry

Title of Study: An examination of the teaching and learning of resonance in General Chemistry I and Organic Chemistry I using variation theory
Investigator(s): Dr. MaryKay Orgill (PI) and Sabrina Barakat
For questions or concerns about the study, you may contact MaryKay Orgill at marykay.orgill@unlv.edu.

For questions regarding the rights of research subjects, any complaints or comments regarding the manner in which the study is being conducted, contact **the UNLV Office of Research Integrity – Human Subjects at 702-895-0020 or via email at IRB@unlv.edu.**

It is unknown as to the level of risk of transmission of COVID-19 if you decide to participate in this research study. The research activities will utilize accepted guidance standards for mitigating the risks of COVID-19 transmission: however, the chance of transmission cannot be eliminated.

PURPOSE OF THE STUDY

You are invited to participate in a research study. The purpose of this study is to examine the teaching and learning of resonance in general chemistry I and organic chemistry I. I will focus on identifying how/why there are differences in students' understandings of resonance by evaluating the teaching and learning of resonance from three different perspectives—the instructor, classroom, and student perspectives.

PARTICIPANTS

You are being asked to participate in the study because you fit these criteria: general chemistry I student, over 18 years of age and are enrolled in general chemistry I for the first time.

PROCEDURES

If you volunteer to participate in this study, you will be asked to do the following: participate in an approximately 60-minute interview where we discuss the teaching and learning of resonance. The interview will take place in an office in the chemistry building on the University of Nevada, Las Vegas Maryland campus, or as an option, interviews could take place using web-conference technology. The

entire interview will be audio-recorded. If web-based you will be asked to leave your web camera on for the duration of the interview, but you will be audio-recorded only.

BENEFITS OF PARTICIPATION

There may be direct benefits to you as a participant in this study. However, we hope to learn how to improve the teaching and learning of resonance.

RISKS OF PARTICIPATION

There are risks involved in all research studies. This study may include only minimal risks. There are no physical or social risks associated with participating in this study. There is a small chance of psychological risk due to the nature of the study which may include stress, discomfort and embarrassment resulting from a feeling of uncertainty or lack of knowledge about the topic of discussion. You will be asked questions about resonance that may cause anxiety. To minimize this risk, you do not have to answer any questions that make you feel uncomfortable. You can end the interview at any time.

COST /COMPENSATION

There may not be financial cost to you to participate in this study. The study will take approximately 60 minutes of your time. You will not be compensated for your time.

CONFIDENTIALITY

All information gathered in this study will be kept as confidential as possible. No reference will be made in written or oral materials that could link you to this study. All records will be stored in a locked facility at UNLV for 3 years after completion of the study. After the storage time the information gathered will be physically destroyed by shredding and deleted electronically.

VOLUNTARY PARTICIPATION

Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study. You may withdraw at any time without prejudice to your relations with UNLV. You are encouraged to ask questions about this study at the beginning or any time during the research study.

PARTICIPANT CONSENT:

I have read the above information and agree to participate in this study. I have been able to ask questions about the research study. I am at least 18 years of age. A copy of this form has been given to me.

____ _______________________

Signature of Participant Date

____

Participant Name (Please Print)

Audio/Video Taping:

I agree to be audio taped for the purpose of this research study.

____ _______________________

Signature of Participant Date

Participant Name (Please Print)

APPENDIX K

Informed Consent for Organic Chemistry I Student Interview

Informed consent
Department of Chemistry and Biochemistry

Title of Study: An examination of the teaching and learning of resonance in General Chemistry I and Organic Chemistry I using variation theory
Investigator(s): Dr. MaryKay Orgill (PI) and Sabrina Barakat
For questions or concerns about the study, you may contact MaryKay Orgill at marykay.orgill@unlv.edu.

For questions regarding the rights of research subjects, any complaints or comments regarding the manner in which the study is being conducted, contact **the UNLV Office of Research Integrity – Human Subjects at 702-895-0020 or via email at IRB@unlv.edu.**

It is unknown as to the level of risk of transmission of COVID-19 if you decide to participate in this research study. The research activities will utilize accepted guidance standards for mitigating the risks of COVID-19 transmission: however, the chance of transmission cannot be eliminated.

PURPOSE OF THE STUDY

You are invited to participate in a research study. The purpose of this study is to examine the teaching and learning of resonance in general chemistry I and organic chemistry I. I will focus on identifying how/ why there are differences in students' understandings of resonance by evaluating the teaching and learning of resonance from three different perspectives—the instructor, classroom, and student perspectives.

PARTICIPANTS

You are being asked to participate in the study because you fit these criteria: organic chemistry I student, over 18 years of age and are enrolled in organic chemistry I for the first time.

PROCEDURES

If you volunteer to participate in this study, you will be asked to do the following: participate in an approximately 60-minute interview where we discuss the teaching and learning of resonance. The interview will take place in an office in the chemistry building on the University of Nevada, Las Vegas Maryland campus, or as an option, interviews could take place using web-conference technology. The

entire interview will be audio-recorded. If web-based you will be asked to leave your web camera on for the duration of the interview, but you will be audio-recorded only.

BENEFITS OF PARTICIPATION

There may be direct benefits to you as a participant in this study. However, we hope to learn how to improve the teaching and learning of resonance.

RISKS OF PARTICIPATION

There are risks involved in all research studies. This study may include only minimal risks. There are no physical or social risks associated with participating in this study. There is a small chance of psychological risk due to the nature of the study which may include stress, discomfort and embarrassment resulting from a feeling of uncertainty or lack of knowledge about the topic of discussion. You will be asked questions about resonance that may cause anxiety. To minimize this risk, you do not have to answer any questions that make you feel uncomfortable. You can end the interview at any time.

COST /COMPENSATION

There may not be financial cost to you to participate in this study. The study will take approximately 60 minutes of your time. You will not be compensated for your time.

CONFIDENTIALITY

All information gathered in this study will be kept as confidential as possible. No reference will be made in written or oral materials that could link you to this study. All records will be stored in a locked facility at UNLV for 3 years after completion of the study. After the storage time the information gathered will be physically destroyed by shredding and deleted electronically.

VOLUNTARY PARTICIPATION

Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study. You may withdraw at any time without prejudice to your relations with UNLV. You are encouraged to ask questions about this study at the beginning or any time during the research study.

PARTICIPANT CONSENT:

I have read the above information and agree to participate in this study. I have been able to ask questions about the research study. I am at least 18 years of age. A copy of this form has been given to me.

____ _________________________

Signature of Participant Date

____

Participant Name (Please Print)

Audio/Video Taping:

I agree to be audio taped for the purpose of this research study.

____ _________________________

Signature of Participant Date

Participant Name (Please Print)

APPENDIX L

Student Interview Guide

Research Question #3: What do General Chemistry I and Organic Chemistry I students understand about resonance after learning about it in General Chemistry I and Organic Chemistry I classrooms?

Informed Consent

- First, I want to say thank you for your willingness to participate in my research study. My name is Sabrina, and I am a graduate student at the University of Nevada, Las Vegas (UNLV) working to complete a Ph.D. in chemistry. This study is about the teaching and learning of resonance. This interview will be audio recorded so that I may reference our discussion later. What we will discuss today will be potentially published as part of a research report. Your identity of any information that could identify you as a participant will remain confidential.

- Take a few moments to look over the form and let me know if you have any questions. And then please sign the form indicating that you consent to being interviewed and audio recorded. I am supplying this informed consent document to you for your records. Thank you! Now we will begin the interview by talking about your background.

Participant Background

- Tell me about yourself.
    - Where are you from?
    - What brought you to [CSN, NSC, or UNLV]
    - What year are you in school? (Freshman, Sophomore, …)
    - What are you majoring in?
    - What do you want to do with your degree once you graduate?

Introduction to Interview Topic

- You know that I am interested in how students learn chemistry topics. What chemistry courses have you taken so far?
- Today I would like to talk to you about a chemistry topic called resonance. I know you were already tested on the topic, but have you had a chance to look at your exam yet? How do you feel about it?
- I have paper and pencil please feel free to use them whenever you want throughout the entire interview.

Students' Understandings of Resonance

- Questions for General and Organic Chemistry Students
    - How would you describe resonance using your own words?
    - What do you think is the relationship between the two structures shown? [Show students resonance structures of enolate]

- How were you taught about resonance in your classroom? Feel free to use the paper and pencil if you like. What did your teacher do and say when they taught resonance? What did your teacher emphasize?
- Why do you think it's important for students to learn about resonance?

Questions for General Chemistry I Students

- Next, I am going to show you the chemical formulas for four different compounds (at the same time), and I am going to ask you to identify which, if any, have resonance.
  - Feel free to draw or write anything down directly on the notecard or paper. I also have a periodic table in case you want or need to reference it.
  - See Appendix A for chemical formulas
- How did you actually go about identifying if those compounds have resonance or not?
  - Please explain your reasoning.
- Now, same thing but I am going to show you the Lewis structures of each of the different compounds (at the same time), and I am going to ask you to identify which, if any, have resonance.
  - Feel free to draw or write anything down directly on the notecard or paper. I also have a periodic table in case you want or need to reference it.
  - See Appendix A for representations of chemical compounds
- How did you go about identifying if those compounds have resonance or not? Was it the same as last time?
  - Please explain your reasoning.

Questions for Organic Chemistry I Students

- Next, I am going to show you the chemical formulas for four different compounds, and I am going to ask you to identify which, if any, have resonance.
  - Feel free to draw or write anything down. I also have a periodic table in case you want or need to reference it.
  - See Appendix B for chemical formulas
- How did you go about identifying if those compounds have resonance or not? Was it the same as last time?
  - Please explain your reasoning.
- Now, same thing but I am going to show you the Lewis structures of the four different compounds, and I am going to ask you to identify which, if any, have resonance. Feel free to draw or write anything down. I also have a periodic table in case you want or need to reference it.
  - See Appendix B for representations of chemical compounds
- How did you actually go about identifying if those compounds have resonance or not?
  - Please explain your reasoning.

Reflections and Final Remarks

- Now that we have talked a little bit more about resonance, what topics that you think you need to understand before you can really understand resonance?
  - Can you recall when you learned about resonance for the first time?

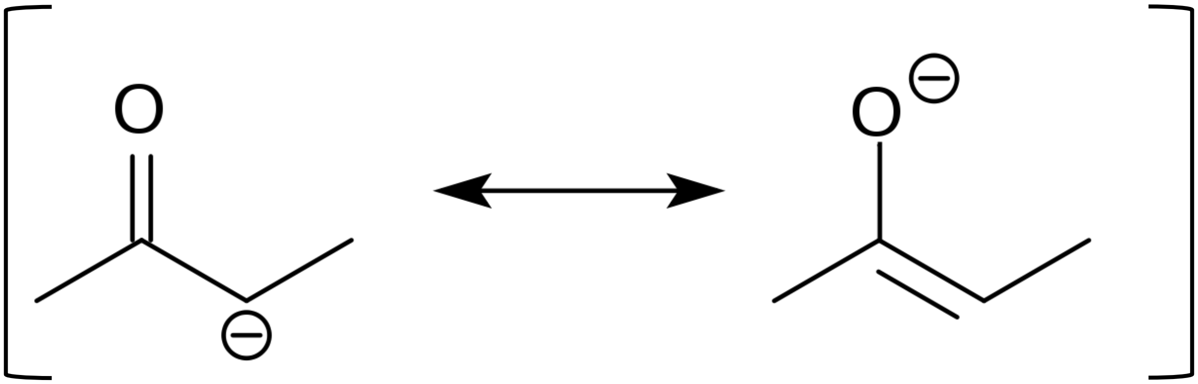
- Hypothetically, if you were a teacher, what problems do you foresee your students having while trying to understand resonance?
- What do you think would be helpful to tell a student that is struggling to understand resonance?

Additional Questions for Organic Chemistry Students

- [Phrase this question differently depending on if they remembered learning about resonance in general chemistry or not] You learned about resonance in general chemistry and then again at the beginning of organic chemistry. Why do you think it was important to learn about it in general chemistry?
- What was similar about how you learned about resonance in general and organic chemistry? What was different?
- I am going to ask you a final question to finish up the interview.
    - What would you tell a friend coming into the class they would need to know about resonance to be successful?
- Okay, those are all the questions I have for you. Do you have any final thoughts? I really appreciate you taking the time to sit down and talk with me. Have a great rest of your day.

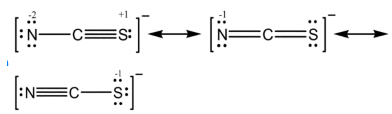
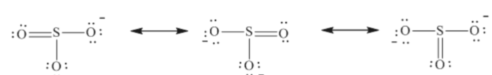
APPENDIX M

Resonance Structures of Enolate Shown to Students



APPENDIX N

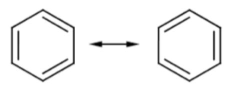
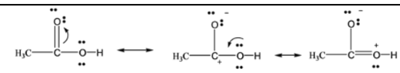
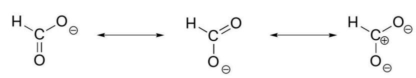
Chemical Formulas and Lewis Structures Shown to General Chemistry I Participants

Chemical Formula Shown to Students	Correct Resonance Structures	Rationale
O_3		• Identified from a general chemistry textbook (Brown et al., 2018) • Requires students to notice that the placement of electrons can differ with the same atoms bonded together
NCS^-		• Identified from a general chemistry textbook (Brown et al., 2018) • Requires students to notice that the placement of electrons can differ with the same atoms bonded together • Requires students to draw more than two resonance structures
H_2O	N/A	• Identified from a general chemistry textbook (Brown et al., 2018) • No resonance structures can be drawn for this compound
SO_3		• Identified from a general chemistry textbook (Brown et al., 2018) • Requires students to notice that the placement of electrons can differ with the same atoms bonded together • Requires students to draw more than two resonance structures

Note. The chemical formulas were typed on a piece of paper and shown to students.

APPENDIX O

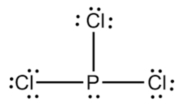
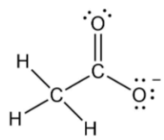
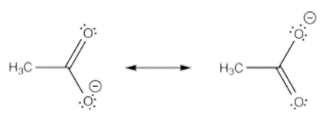
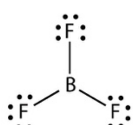
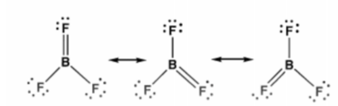
Chemical Formulas and Lewis Structures Shown to Organic Chemistry I Participants

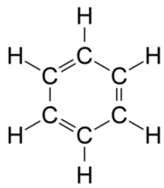
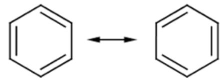
Chemical Formula	Correct Resonance Structures	Rationale
C_6H_6		• Identified from an organic chemistry textbook (Klein, 2012) • Requires students to recognize that the placement of electrons can differ with the same atoms bonded together
CH_3COOH		• Identified from an organic chemistry textbook (Klein, 2012) • Requires students to recognize that the placement of electrons can differ with the same atoms bonded together • Requires students to draw more than two resonance structures
H_2O	N/A	• Identified from an organic chemistry textbook (Klein, 2012) • No resonance structures can be drawn for this compound
HCO_2^-		• Identified from an organic chemistry textbook (Klein, 2012) • Requires students to recognize that the placement of electrons can differ with the same atoms bonded together • Requires students to draw more than two resonance structures

Note. The chemical formulas were typed on a piece of paper and shown to students.

APPENDIX P

Lewis Structures Shown to General Chemistry I Participants

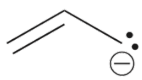
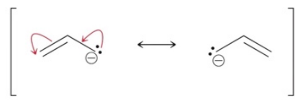
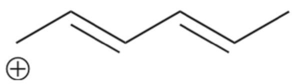
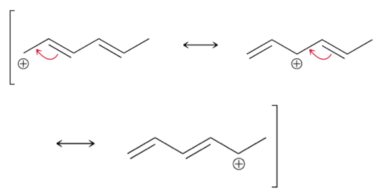
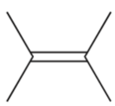
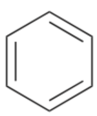
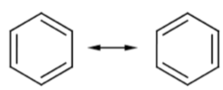
Lewis Structure Shown to Students	Correct Resonance Structures	Rationale
	N/A	• Identified from a general chemistry textbook (Brown et al., 2018) • No resonance structures can be drawn for this compound
	 *Note.* Students might include formal charges or not	• Committee agreed that acetate would be good structure to show students. • Requires students to recognize that the placement of electrons can differ with the same atoms bonded together • Requires students to consider formal charges, which could potentially change their approach to drawing the resonance structures. • Requires students to draw more than two resonance structures
		• Identified from a general chemistry textbook (Brown et al., 2018) • Requires students to recognize that the placement of electrons can differ with the same atoms bonded together • Requires students to draw more than two resonance structures

		• Identified from a general chemistry textbook (Brown et al., 2018). • Requires students to recognize that the placement of electrons can differ with the same atoms bonded together. • Used in the literature to investigate both general chemistry and organic chemistry students' understanding of resonance (e.g., Kim et al., 2019; Taber, 2002)

Note. The Lewis structures were typed on a piece of paper and shown to students.

APPENDIX Q

Lewis Structures (In Bond Line Form) Shown to Organic Chemistry I Participants

Chemical Compound	Correct Resonance Structures	Rationale
		• Compound identified from an organic chemistry textbook (Klein, 2012). • Requires students to identify lone pairs in the allylic position
		• Compound identified from an organic chemistry textbook (Klein, 2012). • Requires students to identify an allylic positive charge • Requires students to draw more than two resonance structures
	N/A	• Compound identified from an organic chemistry textbook (Klein, 2012) • No resonance structures can be drawn for this compound
		• Compound identified from a general chemistry textbook (Brown et al., 2018) • The literature used benzene in studies investigating both general chemistry and organic chemistry students' understanding of resonance (e.g., Kim et al., 2019; Taber, 2002)

Note. The structures were typed on a piece of paper and shown to students.

APPENDIX R

Permissions for Figures

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Abel and Hemmerlin (1991)
Betancourt-Perez et al. (2010)
Brandfonbrener et al. (2021)
Carle and Flynn (2020)
Fergusen and Bodner (2008)
Kim et al. (2019)
Klein (2012)
Lin (2007)
Lovvik et al. (2010)
McClary and Talanquer (2011a)
McClary and Talanquer (2011b)
Petterson et al. (2020)
Silverstein (1999)
Starkey (1995)
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Explaining resonance - a colorful approach

Author: Kenton B. Abel, William M. Hemmerlin
Publication: Journal of Chemical Education
Publisher: American Chemical Society
Date: Oct 1, 1991

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Assessment of Organic Chemistry Students' Knowledge of Resonance-Related Structures

Author: Rosa Betancourt-Pérez, Luis Javier Olivera, Julio E. Rodríguez
Publication: Journal of Chemical Education
Publisher: American Chemical Society
Date: May 1, 2010

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Organic Chemistry Students' Written Descriptions and Explanations of Resonance and Its Influence on Reactivity

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Author: Paul B. Brandfonbrener, Field M. Watts, Ginger V. Shultz
Publication: Journal of Chemical Education
Publisher: American Chemical Society
Date: Nov 1, 2021

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Publication Title	Chemistry education research and practice	**Publication Type**	e-Journal
Article Title	Essential learning outcomes for delocalization (resonance) concepts: How are they taught, practiced and assessed in Organic Chemistry?	**Start Page**	622
Author/Editor	Royal Society of Chemistry (Great Britain)	**End Page**	637
Date	01/01/2003	**Issue**	2
Language	English	**Volume**	21
Country	United Kingdom of Great Britain and Northern Ireland	**URL**	http://www.rsc.org/Education/CERP/index.asp
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Instructor Name	Sabrina Barakat	**Expected Presentation Date**	2024-05-01

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Editor of Portion(s)	Carle, Myriam; Flynn, Alison B.	**Author of Portion(s)**	Carle, Myriam; Flynn, Alison B.
Volume / Edition	21	**Issue, if Republishing an Article From a Serial**	2
Page or Page Range of Portion	622-637	**Publication Date of Portion**	2019-12-31

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Article Title	Making sense of the arrow-pushing formalism among chemistry majors enrolled in organic chemistry	**Start Page**	102
Author/Editor	Royal Society of Chemistry (Great Britain)	**End Page**	113
Date	01/01/2003	**Issue**	2
Language	English	**Volume**	9
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		Start Page	659
Article Title	An examination of students' perceptions of the Kekulé resonance representation using a perceptual learning theory lens	**End Page**	666
		Issue	4
		Volume	20
		URL	http://www.rsc.org/Education/CERP/index.asp
Author/Editor	Royal Society of Chemistry (Great Britain)		
Date	01/01/2003		
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Title of the Article / Chapter the Portion Is From	Molecular Representations in Organic Chemistry
Author of Portion(s)	Klein, David R.
Publication Date of Portion	2013-12-30

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Aromatic Bagels: An Edible Resonance Analogy

Author: Shirley Lin
Publication: Journal of Chemical Education
Publisher: American Chemical Society
Date: May 1, 2007

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Article Title	Eliciting Student Thinking About Acid-Base Reactions via App and Paper-Pencil Based Problem Solving	**Start Page**	878
Author/Editor	Royal Society of Chemistry (Great Britain)	**End Page**	892
Date	01/01/2003	**Issue**	3
Language	English	**Volume**	21
Country	United Kingdom of Great Britain and Northern Ireland	**URL**	http://www.rsc.org/Education/CERP/index.asp
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The "Big Dog-Puppy Dog" Analogy for Resonance

Author: Todd P. Silverstein
Publication: Journal of Chemical Education
Publisher: American Chemical Society
Date: Feb 1, 1999

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Resonance Analogy Using Cartoon Characters

Author: Ronald Starkey
Publication: Journal of Chemical Education
Publisher: American Chemical Society
Date: Jun 1, 1995

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Instructor Name	Sabrina Barakat
Institution Name	University of Nevada, Las Vegas
Expected Presentation Date	2024-05-01

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Exploring Students' Understanding of Resonance and Its Relationship to Instruction

Author: Dihua Xue, Marilyne Stains
Publication: Journal of Chemical Education
Publisher: American Chemical Society
Date: Apr 1, 2020

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CURRICULUM VITAE

Name: Sabrina Barakat
Email: sabrinamariebarakat@gmail.com

Educational Background:

Ph.D. Chemistry (Chemistry Education) — May 2024
University of Nevada Las Vegas, Las Vegas, NV

B.S. Biological Sciences — May 2017
University of Nevada Las Vegas, Las Vegas, NV
B.S. Concentration: Ecology and Evolution

Professional Experience:

Research Experience:

Graduate Chemistry Education Researcher — 2017-current
Performed preliminary textbook analysis and conducted interviews in order to determine student and instructor perceptions of resonance (pilot study). Successfully defended prospectus to begin dissertation work focused on investigating the teaching and learning of a fundamental chemistry concept called resonance. Department of Chemistry, University of Nevada Las Vegas Las Vegas, NV.

Undergraduate Chemistry Education Researcher — 2015-2017
Performed transcript analysis on the ChANgE Chem project (an NSF funded project) focusing on interdisciplinary collaboration in order to determine what factors attributed to the success of an interdisciplinary collaboration. Department of Chemistry, University of Nevada Las Vegas Las Vegas, NV.

General Chemistry Curriculum Committee Team Member — 2015-2016
Assisted in finding and testing potential General Chemistry II laboratory activities. Department of Chemistry, University of Nevada Las Vegas Las Vegas, NV.

Work/ Teaching Experience:

Graduate Teaching Assistant — 2017-current
Taught lectures, facilitated laboratory experiments, held weekly office hours, and graded laboratory reports, quizzes, and exams in an introductory chemistry course. Department of Chemistry, University of Nevada Las Vegas Las Vegas, NV.

Instructor of Record — Fall 2020, 2021, 2022, Spring 2024

Developed course materials (e.g., syllabi, exams), taught lectures, held weekly office hours, and graded quizzes and exams in a 3-credit preparatory chemistry course (online learning) and a 4-credit introductory chemistry course (hybrid)
Department of Chemistry, University of Nevada Las Vegas Las Vegas, NV.

Substitute Lecturer Spring 2018
Taught "General Chemistry II" while instructor was out of town (1 lecture). Department of Chemistry, University of Nevada Las Vegas Las Vegas, NV.

Substitute Lecturer Spring 2018
Taught "Preparatory Chemistry" while instructor was at jury duty (3 lectures). Department of Chemistry, University of Nevada Las Vegas Las Vegas, NV

Substitute Lecturer Fall 2017
Taught "General Chemistry I" while instructor was sick (2 lectures). Department of Chemistry, University of Nevada Las Vegas Las Vegas, NV

Supplemental Instruction Leader 2015-2017
Provided students with a deeper insight into the concepts presented in lecture by creating an engaging and collaborative learning environment while implementing the most effective and best teaching practices (general biology and chemistry). Academic Success Center, University of Nevada Las Vegas, Las Vegas, NV.

Practicum I Teacher Spring 2016
Provided assistance to veteran teacher by providing classroom management skills, co-teaching lectures, running laboratory projects, and preparing and grading examinations (high school biology). Valley High School, Las Vegas, NV.

Tutor 2015-2016
Provided group tutoring to students (biology and chemistry). Academic Success Center, University of Nevada Las Vegas, Las Vegas, NV.

Front Desk Manager 2014-2015
Provided management skills for the SI program by assisting with marketing, data collection, and policy enforcement. Academic Success Center, University of Nevada Las Vegas, Las Vegas, NV.

Undergraduate Teachers Assistant Spring of 2014 and 2015
Aided teacher assistants in the fields of general and microbiology by having laboratory set up with necessary materials before each class, teaching, and proctoring and grading examinations. School of Life Sciences, University of Nevada Las Vegas, Las Vegas, NV.

Leadership Experience:

Graduate Student Mentor 2021-2022

Successfully completed the Graduate Mentorship Certification, which required the mentorship of an undergraduate student for one academic year. Provided a first-generation college student with guidance on coursework and interpersonal relationships/ communication skills. The Grad Academy, University of Nevada Las Vegas, Las Vegas, NV.

Mentor SI Leader 2016-2017

Provided new tutors with guidance and mentorship and assisted management in planning and running team meetings and projects as assigned. Academic Success Center, University of Nevada Las Vegas, Las Vegas, NV.

Certificates

Graduate Mentorship Certification May 2022
Online Teaching Essentials Fall 2020

Grant/ Funding Activities:

Wolzinger Family Research Scholarship Fall 2023
Harold and Mayme Stocker Fall 2023
Professional Development Grant Spring 2022

Received a grant to begin initial proposal and development of a professional development (for secondary education science teachers) focused on superconductivity.

GPSA Travel Award July 2018

Applied for and received a travel grant to attend the 25th Biennial Conference on Chemical Education. (Funded for $400)

CSUN Travel Award Spring 2016

Applied for and received a travel grant to attend the 24th Biennial Conference on Chemical Education. (Funded for $500)

Millennium Scholar Fall 2012

Professional Societies:

American Chemical Society 2016-current

Conferences Attended:

American Chemical Society Western Regional Meeting October 2022
25th Biennial Conference on Chemical Education July 2018
253rd American Chemical Society April 2017
24th Biennial Conference on Chemical Education August 2016

Publications:

Barakat, S. & Orgill, M. (2024). Identifying the critical features of resonance: Instructors' intentions for the teaching and learning of resonance in General Chemistry I and Organic Chemistry I. *Chemistry Education Research and Practice*. Advance Article. DOI: 10.1039/d3rp00289f

Presentations:

Barakat, S., & Orgill, M. (2022, October). Variation theory: A useful framework for investigating the teaching and learning of chemistry. *Presented at the 2022 ACS Western Regional Meeting, Las Vegas, NV.*

Barakat, S., & Orgill, M. (2018, July). How organic chemists' understandings of resonance progress over time: A pilot study. Poster presented at the 25th Biennial Conference on Chemical Education, South Bend, IN.

Barakat, S., Millick, N., & Orgill, M. (2017, April). Examining the connection between what the team members of an interdisciplinary collaboration identified as their goals and how they thought those goals should be evaluated: The ChANgE Chem project. Poster presented at the 253rd National Meeting of the American Chemical Society, San Francisco, CA.

Millick, N., Barakat, S., & Orgill, M. (2017, April). Team members' perceptions of how communication relates to the success of an interdisciplinary grant collaboration: The ChANgE Chem project. Presented at the 253rd National Meeting of the American Chemical Society, San Francisco, CA.

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Barakat, S., Millick, N., & Orgill, M. (2016, August). *Perceived goals and outcomes of an interdisciplinary collaboration focused on bridging the educational research/practice gap: The ChANgE Chem project*. Poster presented at the 24th Biennial Conference on Chemical Education, Greeley, CO.

Service:

Symposium Organizer — Spring 2023

Selected by the program chair to review and arrange abstracts submitted to the symposium Research in Chemistry Education. American Chemical Society, Indianapolis, IN.

Curriculum Development Committee Member 2015-2016

Assisted in finding and testing potential General Chemistry II laboratory activities. Department of Chemistry, University of Nevada Las Vegas Las Vegas, NV.