January 2016

PROCESSES FOR IDENTIFYING IMPORTANT CHEMISTRY AND BIOCHEMISTRY CONCEPTS AND REPRESENTATIONS AND THEIR QUALITATIVE ASSESSMENT IN UNDERGRADUATE BIOLOGY COURSES

Rethabile Reginalda Tekane
Purdue University

Graduate School Form 30
(Updated 11/20/2014)

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Rethabile Reginalda Tekane

Entitled PROCESSES FOR IDENTIFYING IMPORTANT CHEMISTRY AND BIOCHEMISTRY CONCEPTS AND REPRESENTATIONS AND THEIR QUALITATIVE ASSESSMENT IN UNDERGRADUATE BIOLOGY COURSES

For the degree of Doctor of Philosophy

Is approved by the final examining committee:

Trevor Ryan Anderson

George M. Bodner

Brenda Capobianco

Nancy Pelaez

To the best of my knowledge and as understood by the student in the Thesis/Dissertation Agreement, Publication Delay, and Certification/Disclaimer (Graduate School Form 32), this thesis/dissertation adheres to the provisions of Purdue University's "Policy on Integrity in Research" and the use of copyrighted material.

Approved by Major Professor(s): Trevor Ryan Anderson

Approved by: Timothy Zwier 07/15/2016

Head of the Department Graduate Program Date

PROCESSES FOR IDENTIFYING IMPORTANT CHEMISTRY AND BIOCHEMISTRY CONCEPTS AND REPRESENTATIONS AND THEIR QUALITATIVE ASSESSMENT IN UNDERGRADUATE BIOLOGY COURSES

A Dissertation

Submitted to the Faculty

of

Purdue University

by

Rethabile Reginalda Tekane

In Partial Fulfillment of the

Requirements of the Degree

of

Doctor of Philosophy

August 2016

Purdue University

West Lafayette, Indiana

22/06/2015, on this day, you went back home. On this day, I cried when you passed away. I cry today still. Although I loved you dearly, I couldn't make you stay. A golden heart stopped beating, hard working hands at rest. God broke my heart to prove to me that He only takes the best. Rest in peace mama. *Adapted from anonymous author*

ACKNOWLEDGMENTS

Firstly, I would like to thank the LORD ALMIGHTY for being with me every step of the way (Jeremiah 29:11). Secondly, I would like to thank my Ph.D. advisor, Professor Trevor Anderson for his support, advice and guidance throughout this five-year journey. Thirdly, I would like to thank members of my committee, past and present, Professor Marc Loudon, Professor George Bodner, Dr. Brenda Capobianco and Dr. Nancy Pelaez, for their support and guidance. Fourthly, I would like to thank members of VIBE research group, past and present, specifically, Kathleen Jeffery, Stefan Irby, Carly Schnoebelen, Sara Johnson, Franziska Lang and Yi Kong. Guys, your never-ending edits, research related discussions, encouragement, and laughter will forever be truly appreciated. Sara, thank you very much for your patience and your never-ending support and fruitful discussions. Stefeen, you guys are the best. Fifthly, I would like to thank the biology instructors who participated in this study because without their participation, there would be no data to present.

Sixthly, I would like to thank my family for their never-ending support and encouragement throughout this five-year journey. Although this past year dropped a bomb-shell that tore our hearts deeply, your support has been ceaseless. Khwabane, abuti Lazaro, Melita, and rakhali Mosele, you guys are the best. Lebo, Palulu, Buta, Khethi, Nhlanhla, you guys are loved. Mama, kea leboha.

Seventhly, I would like to thank Fundzile Menon, Thembi Mdluli, Rosemary Masu, Dr. Shay, Dr. Sheran Oradu, Dr. Charity Wayua, Sepinare Lenkoe, Hopolang Lents'a, Moipone Ranyali, Dr. Mapitsi Thantsha and Skeem Sam: guys, thank your unchanging love, support and encouragement.

Eighthly, DeLean Tolbert, my writing partner, mahn, we surely burnt the midnight oil, thank you for keeping me company and encouraging me when my motivation levels hit 0%. Finally, I would like to thank HHMI for funding the early stages of this research and the Department of Chemistry, Purdue University for TA funding and particularly their sponsorship of my various summer salaries that enabled me to complete this work on time.

TABLE OF CONTENTS

Page

Page

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

ABSTRACT

Tekane, Rethabile Reginalda. Ph.D., Purdue University, August 2016. Processes for Identifying Important Chemistry and Biochemistry Concepts and Representations and their Qualitative Assessment in Undergraduate Biology Courses. Major Professor: Trevor R Anderson.

Biology has become increasingly more interdisciplinary in nature. Therefore, the Association of American Medical Colleges-Howard Hughes Medical Institute, and the National Research Council have called for reform in biology curricula. In particular, the Vision and Change report emphasized the importance of integrating biology with physical sciences such as chemistry and biochemistry in order to help biology majors understand the importance of biochemistry and chemistry to biology. The report also stipulated the need to design assessments that are informed by learning objectives in order to assess if students have attained the targeted conceptual knowledge. Currently, meetings and workshops have, and are still being used to collect curriculum related data regarding the chemistry and biochemistry concepts to include in chemistry or biochemistry courses designed for biology majors. Furthermore, studies have reported that most of the designed assessments still do not address the intended learning objectives. Therefore, the current study was conducted in order to address the following goals: (i) Goal 1, to design and test a simple three-stage process for identifying the

chemistry and biochemistry concepts, representations, and ways of reasoning important to biology courses; Goal 2, to investigate the specific acid-base content that the biology instructors consider to be important for their courses and how they expect students to use the acid-base knowledge; and Goal 3, to design a model that instructors could use for the design, evaluation, and validation of assessments. In order to address Goal 1, the following research questions were explored: (i) Which biochemistry and chemistry concepts do the biology instructors at a Midwestern university consider relevant to the courses they teach; (ii) How do these biology instructors expect students to use the identified concepts in the courses they teach; (iii) Which biochemistry and chemistry representations do the biology instructors at a Midwestern university consider relevant to the courses they teach; and (iv) How do these biology instructors expect students to use the identified representations in the courses they teach? Application of the three-stage process yielded 74 concepts which were grouped into 6 consensus themes: properties of water, chemical bonds and biomolecular structure and function; (bio)chemical reactions, enzymes, cellular processes and their regulation; thermodynamics including chemical equilibrium, ATP and membrane transport; acids and bases; solutions, mixtures and analytical techniques; and atomic theory and structure and the gas laws. Types of representations include a range of particulate models, graphs, chemical equations, and mathematical equations. Instructors also expect students to develop skills such as the ability to integrate, transfer and apply knowledge in order to develop sound explanatory frameworks, and the ability to decode representations, interpret and use them to explain and solve biological problems. To address Goal 2, the following research questions were addressed: (i) How is knowledge of concepts and ways of reasoning about acid-base used by instructors in their particular biology courses; and (ii) How are visual representations and ways of reasoning with acid-base representations used by instructors' in their particular biology courses? The results showed that the instructors wanted the students to have both declarative and procedural knowledge. That is, the biology instructors want their students to not only know the factual knowledge related to the acid-base concepts, instead they also want them to be able to reason with the acid-base knowledge to explain how biological processes work. Regarding Goal 3, the following research questions were addressed: (i) What is an appropriate model for designing and validating assessment tasks; and (iii) Do acid-base assessments designed by an organic chemistry instructor support the validity of this model? The results suggested that using the organic chemistry acid-base assessments to validate the assessment design model was good because it revealed the strengths and weaknesses of the assessment design model. The strengths include the fact that the model helps instructors to qualitatively validate the assessments whereas the weaknesses include the fact that the model cannot help the instructors to design assessments that explicitly reveal the reasoning and visual skills that students lack. In general, although the three-stage process and the assessment design model can be used by instructors at any institution, more studies need to be conducted to more fully establish their usefulness in the field.

CHAPTER 1: INTRODUCTION, RATIONALE AND RESEARCH QUESTIONS

1.1 Background

Biology has been defined as the discipline that "encompasses all of the disciplines devoted to the study of living organisms" (Mayr, 1999). Biology research has become increasingly more interdisciplinary in nature (Gross, 2004; Kennedy & James, 2003; Van Wylen, Abdella, Dickinson, Engbrecht, & Vandiver, 2013) as it "…. has become critically dependent on concepts and methods drawn from other scientific disciplines and furthermore, connections between the biological sciences and the physical sciences, mathematics, and computer science are rapidly becoming deeper and more extensive," (NRC, 2003, p. 1). Although biological research is radically changing, biology education has not experienced dramatic changes in the past decades (Bialek & Botstein, 2004; Depelteau, Joplin, Govett, Miller, & Seier, 2010). As a result, there is a need to bridge the gap between biological research and biology education to ensure that the biology taught in classrooms reflects the latest biological research trends, particularly the interdisciplinary nature of such research (Caldwell, Rohlman, & Benore-parsons, 2004; Thompson, Nelson, Marbach-ad, Keller, & Fagan, 2010). For this reason, the National Research Council (NRC) and others have called for reform in biology curricula

(Association of American Medical Colleges-Howard Hughes Medical Institute, 2009; NRC, 2003; Brewer & Smith, 2011) to meet modern trends and demands that biology graduates might face. In particular, the Vision and Change report (Brewer & Smith, 2011) emphasized the importance of integrating more mathematics and physical science into biology in order to promote the quantitative skills of future biologists (Bialek & Botstein, 2004; Matthews, Adams, & Goos, 2010; Speth et al., 2010), their "adaptive expertise" (Redish & Hammer, 2009), and their deep understanding of biological knowledge and other disciplines (Labov, Reid, & Yamamoto, 2010).

In response to these calls for curriculum reform, a group of chemistry and biochemistry instructors at Purdue, a large, research university in the Midwest of the United States decided to revise the introductory courses taken by biology students with the aim of better equipping them with the chemistry and biochemistry knowledge of relevance to the modern biology they are studying (Thompson, Chmielewski, Gaines, Hrycyna, & LaCourse, 2013). At this research university, biology majors are now required to take one semester of general chemistry, followed by two semesters of organic chemistry and one semester of biochemistry. The instructors who created this course sequence aimed to incorporate more applications of biological examples that would not only help students make more connections between biology, biochemistry and chemistry, but also help biology instructors avoid re-teaching some of the biochemistry and chemistry concepts that are relevant to their biology courses. This begs the question, though, which biochemistry and chemistry concepts are key to studies in the various biology majors at the institution under investigation? Using educational research to identify such concepts and related representations and ways of reasoning was therefore

Goal One of this project (see Chapter 4) in an attempt to respond to the various calls for the modernization of the biology undergraduate curriculum.

The tenets of curriculum theory (e.g. Anderson & Rogan, 2011; Prideaux, 2003;) advocate that course curricula should ideally be negotiated by all stakeholders and curricular decisions should be informed by research rather than only intuition and experience. In this regard, although various authors and sponsored projects (e.g. AAMC-HHMI, 2009; Loertscher, Green, Lewis, Lin, & Minderhout, 2014; Rowland, Smith, Gillam, & Wright, 2011; Tansey et al., 2013; White, Benore, Sumter, Caldwell, & Bell, 2013; Wright, Provost, Roecklin-Canfield, & Bell, 2013) have exhaustively identified the key chemistry and biochemistry concepts and competencies important for teaching and learning of biochemistry and molecular biology, they did not focus on other areas of biology like the present study. Furthermore, the identification of these concepts and representations was mainly done via meetings and workshops and not substantiated by educational research. In the present study, therefore, I aimed to add to existing knowledge by deploying educational research to survey instructor opinion from a wider range of biology disciplines (Chapter 4).

When performing curriculum development at a particular institution with its own unique context, it is additionally important to identify the specific content needs of that context because, given the nature of instruction at a particular institution, what instructors consider to be important at one institution may differ from what is deemed most important at another institution. Thus the goal of the present study was not to come up with information about concepts and representations that could necessarily be generalized across all institutions, but rather to develop and test a simple, efficient three-step process that could be used to launch curricular discussions regarding the concepts and competencies important to include in that institution's curriculum (See Chapter 4). In this way curriculum discussions would be directly informed by empirical data from the same context.

Besides knowing which biochemistry and chemistry concepts and representations are key prerequisite knowledge for students entering the various biology major courses, it was also important to investigate how biology instructors actually use such knowledge when teaching their courses. Since investigating all the concepts identified in the first study would be too extensive for a single dissertation, I decided to select one topic, namely acid-base theory, to address this Goal 2 (See Chapter 5).

The NRC, ASBMB and AAMC-HHMI have also stipulated the need to design and validate assessment tasks that will help develop students' reasoning and visual abilities and assess their understanding of science concepts (AAMC-HHMI, 2009; Bell, 2010; Brewer & Smith, 2011; NRC, 2001, 2003;). In education, assessments are considered important because they: (i) promote learning (Briggs et al., 2015; Pellegrino, 2014); (ii) monitor students' progress during the course (Anderson, 2007) and; (iii) can be used for assessing students' cognitive skills (Kane & Bejar, 2014; Masters, 2013). Whether formative or summative, the design of assessments is informed by various guidelines, models/systems and frameworks (Anderson & Rogan, 2010; Brewer & Smith, 2011; Briggs et al., 2015; Kennedy, 2005; NRC, 2001, 2003; Oates, 2009; Pellegrino, 2014;). There is a consensus, however, that most assessments are: i) not valid and reliable; ii) poorly written; and iii) not informed by learning objectives and the desired learning outcomes and thus do not measure students' achievement of each learning objective (e.g. DeBoer, Abell, Regan, & Wilson, 2008). Thus it is essential to design valid assessments that are informed by learning objectives and the desired learning outcomes because these will inform instructors whether students have attained the desired or targeted learning outcomes (Anderson, 2007; Brewer & Smith 2011; NRC 2001, 2003; Pellegrino 2014). In the present study, my Goal 3 was, therefore, to design a model that could be used for designing validated assessments that could have important future applications in the teaching of life science. To limit the scope of this dissertation, I chose to focus on evaluating the assessment model against a limited sample of organic chemistry students studying acid-base concepts (See Chapter 6).

1.2. Research Questions

Toward achieving Goal 1, that is, to design and test a simple three-stage process for identifying the chemistry and biochemistry concepts, representations and ways of reasoning important to biology courses, I addressed the following research questions:

- Which biochemistry and chemistry concepts do the biology instructors at a Midwestern university consider relevant to the courses they teach? (RQ-1),
- How do these biology instructors expect students to use the identified concepts in the courses they teach? (RQ-2).
- Which biochemistry and chemistry representations do the biology instructors at a Midwestern university consider relevant to the courses they teach? (RQ-3),

- How do these biology instructors expect students to use these representations in the courses they teach? (RQ-4).

These research questions were addressed by collecting data from biology instructors at a large research university in the Midwest of USA.

Towards achieving Goal 2, I addressed the following research questions:

- How is knowledge of concepts and ways of reasoning about acid-base used by instructors in their particular biology courses? (RQ-5)
- How are visual representations and ways of reasoning with acid-base representations used by instructors' in their particular biology courses? (RQ-6)

Towards achieving Goal 3, that is, to design a model that instructors could use for the design, evaluation and validation of assessments, I addressed the following research questions:

- What is an appropriate model for designing and validating assessment tasks? (RQ-7)
- Do acid-base assessments designed by an organic chemistry instructor support the validity of this model? (RQ-8)

As described in Chapters 3 and 6, the design of the assessment model was informed by the modeling process of Justi and Gilbert (2002) and validated by collecting data from Pharmacy students studying acid-base as part of an organic chemistry course.

Figure 1.1 shows an overview of the structure of this dissertation including the relationship between the chapters of this study. As discussed above, in order to address my stated goals, the study was divided in to three mini-studies presented in Chapters 4, 5 and 6. Since different data collection methods were used for each mini-study, each of these methods is discussed within the relevant mini-study. The methods chapter (Chapter 3) will discuss general data analysis and theoretical framework(s) that were applicable to all the three mini-studies. The literature review chapter (Chapter 2) provides a more detailed motivation for the goals and research questions of this study.

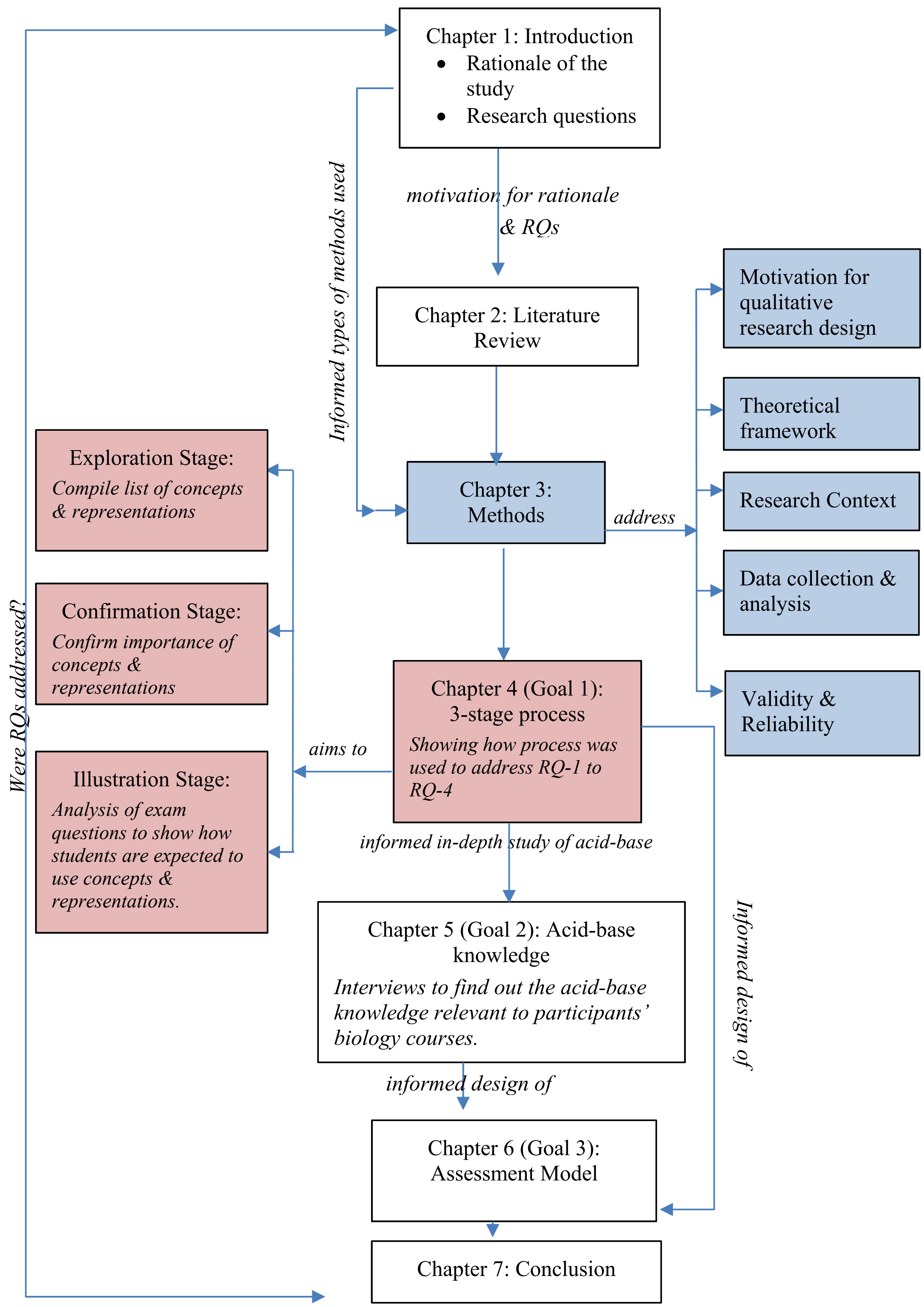


Figure 1.1 Overview of the Study Design

CHAPTER 2: LITERATURE REVIEW

The purpose of this chapter is to review the literature that is relevant to the current study and motivate why it was important to address the goals stated in Chapter 1. Therefore, I chose to first discuss literature pertaining to biology curriculum reform in order to paint a picture of why biology curriculum reform is necessary. Second, I will discuss research related to integrating biology with the physical sciences and mathematics in order to demonstrate the importance of integrating biology with these other disciplines. Third, I will review research related to the identification of biochemistry and chemistry concepts considered important and/or relevant for biology courses. Fourth, I will discuss research related to representations in biology to inform us about how representations aid the learning of biology. Fifth, I will provide a brief history of acid-base chemistry in order to show the importance of acid-base chemistry to biology. Finally, I will discuss the importance of assessment design in science education. This will include a discussion of the various assessment design guidelines and assessment design frameworks.

2.1 Motivation for Goal 1: The Need to Design a Three-Stage Process

2.1.1 Biology Curriculum Reform

There have been numerous calls for the reform of the undergraduate science curriculum for life science majors and pre-medical students (Association of American Medical Colleges-Howard Hughes Medical Institute, 2009; Brewer & Smith, 2011; NRC, 2001, 2003). These calls have emphasized the need to develop courses that will help students recognize the interdisciplinary nature of life science courses. Furthermore, these reports have stipulated the importance of designing assessments that address targeted learning objectives in order to assess whether students have attained the intended conceptual knowledge. Examples of such calls include those reported in the (i) AAMC-HHMI report (AAMC-HHMI, 2009); (ii) the Bio2010 report (NRC, 2003); and (iii) the Vision and Change report (Brewer & Smith, 2011).

2.1.1.1 The AAMC-HHMI Report

The AAMC-HHMI Scientific Foundations for Future Physicians report (AAMC-HHMI, 2009) was mainly geared towards the improvement of pre-medical and medical curricula. The report indicated the need to move from prescribed-course(s) curricula to a competency-based curriculum because the latter allows for "…the development of more interdisciplinary and integrative courses that maintain scientific rigor, while providing a broad education," (AAMC-HHMI, 2009, p. 38). The report also provided eight competencies (Table 2.1) that pre-medical students should have acquired by the time they

Table 2.1: Competencies Important for Pre-medical and Medical Students (From AAMC-HHMI, 2009)

Competencies	
Pre-medical students	Medical students
1. *Competency E1:* Apply quantitative reasoning and appropriate mathematics to describe or explain phenomena in the natural world.	1. *Competency M1:* Apply knowledge of molecular, biochemical, cellular, and systems-level mechanisms that maintain homeostasis, and of the dysregulation of these mechanisms, to the prevention, diagnosis, and management of disease.
2. *Competency E2:* Demonstrate understanding of the process of scientific inquiry, and explain how scientific knowledge is discovered and validated.	2. *Competency M2:* Apply major principles of physics and chemistry to explain normal biology, the pathobiology of significant diseases, and the mechanism of action of major technologies used in the prevention, diagnosis, and treatment of disease.
3. *Competency E3:* Demonstrate knowledge of basic physical principles and their applications to the understanding of living systems.	3. *Competency M3:* Use the principles of genetic transmission, molecular biology of the human genome, and population genetics to infer and calculate risk of disease, to institute an action plan to mitigate this risk, to obtain and interpret family history and ancestry data, to order genetic tests, to guide therapeutic decision making, and to assess patient risk.
4. *Competency E4:* Demonstrate knowledge of basic principles of chemistry and some of their applications to the understanding of living systems.	4. *Competency M4:* Apply the principles of the cellular and molecular basis of immune and non-immune host defense mechanisms in health and disease to determine the etiology of disease, identify preventive measures, and predict response to therapies.
5. *Competency E5:* Demonstrate knowledge of how biomolecules contribute to the structure and function of cells.	5. *Competency M5:* Apply the mechanisms of general and disease-specific pathological processes in health and disease to the prevention, diagnosis, management, and prognosis of critical human disorders
6. *Competency E6:* Apply understanding of principles of how molecular and cell assemblies, organs, and organisms develop structure and carry out function.	6. *Competency M6:* Apply principles of the biology of microorganisms in normal physiology and disease to explain the etiology of disease, identify preventive measures, and predict response to therapies.

Table 2.1, continued

Competences	
Pre-medical students	Medical students
7. *Competency E7:* Explain how organisms sense and control their internal environment and how they respond to external change.	7. *Competency M7:* Apply the principles of pharmacology to evaluate options for safe, rational, and optimally beneficial drug therapy
8. *Competency E8:* Demonstrate an understanding of how the organizing principle of evolution by natural selection explains the diversity of life on earth.	*8. Competency M8:* Apply quantitative knowledge and reasoning—including integration of data, modeling, computation, and analysis—and informatics tools to diagnostic and therapeutic clinical decision making.

enter medical school and eight competencies (Table 2.1) that medical students should have learnt by the time they leave medical school. It is envisioned that the inclusion of these competencies in pre-medical and medical curricula will ensure the development of curricula that foster "…scholastic rigor, analytical thinking, quantitative assessment and analysis of complex systems in human biology," (p. 38). In response to the call from HHMI, the National Experiment on Undergraduate Science Education (NEXUS) (https://www.hhmi.org/programs/national-experiment-in-undergraduate-science-education) project was initiated.

The goal of NEXUS was to develop interdisciplinary science courses as well as assessments that would assess students' competency; that is, their conceptual understanding and ability to apply what they have learnt when explaining phenomena and solving problems. In order to achieve this goal, NEXUS funded four universities to design curricula that would help students develop and use high-order cognitive skills, including for example, integrative thinking (https://www.hhmi.org/programs/national-experiment-in-undergraduate-science-education; Thompson et al., 2013). One of the NEXUS projects was at Purdue University, and involved the design of a chemistry course that would help life science students understand the importance of chemistry to biology. Another NEXUS project was at the University of Maryland, College Park, and involved the design of a physics course that would assist life science students, specifically biology majors, to understand the connections between physics and biology. The University of Maryland, Baltimore County, was asked to focus on developing a biology course that addressed the importance of mathematics in biology. The University of Miami was asked to focus on developing biomedical case studies that would require students to integrate knowledge from biology, physics, and chemistry when analyzing disease and human health.

2.1.1.2 The Bio2010 Report

The Bio2010 project (NRC, 2003) concentrated on how future biological researchers, specifically biomedical researchers, could be equipped to become competent researchers. This is important because biological research has become highly interdisciplinary in nature, depending on knowledge from mathematics, physics, and chemistry because the instrumentation used and the analysis of biological data is primarily rooted in mathematics and the physical sciences (chemistry and physics). Although biological research is radically changing, biology education has not experienced similar changes in recent decades (NRC, 2003). As a result, there is a need to bridge the gap between biological research and biology education to ensure that the biology taught in classrooms reflects the latest biological research trends, and particularly the interdisciplinary nature of biology. Furthermore, there is a need to identify the skills and concepts to teach to life science students in order to help them understand the importance of mathematics and the physical sciences to biology, as well as prepare them for careers in modern biology. To ensure that the biology taught in classrooms reflects the interdisciplinary nature of biology, Bio2010 recommended integrating biology with mathematics and physical sciences such as chemistry, biochemistry, computational sciences, and physics. According to this report, it is important to integrate biology with chemistry because "modern molecular biology and cell biology focus on understanding the chemistry of genes and of cell structure…biomedical engineering draws on chemistry for new materials and thus it is evident that future research biologists will need to have a thorough grounding in chemistry to make their research possible and to understand the work of others," (NRC, 2003, p. 34). Besides designing curricula that integrate biology with physical sciences such as chemistry, the report also emphasized the importance of accompanying newly designed curricula with assessments that will help assess student learning.

2.1.1.3 The Vision and Change Report

The Vision and Change report (Brewer & Smith, 2011) emphasizes that the biology taught in classrooms does not reflect modern practices implemented in biology research. Thus, according to the report, there is a need to design introductory curricula that will better equip life science students with skills that will enable them to apply their knowledge of science to real world problems, and think across various scientific disciplines. The report further identified five core concepts and six competencies that should be integrated in biology curricula. The five core concepts include evolution; structure and function; information flow, exchange and storage; systems; and pathways and transformation of energy and matter. According to the report, knowledge of these concepts is essential as it will enable students to explain biological phenomena. For instance, “knowledge of chemical principles can help inform the production of microorganisms that can synthesize useful products or remediate chemical spills, as well as the bioengineering of plants that produce industrially important compounds in an ecologically benign manner,” (Brewer & Smith, 2011, p. 13). The suggested six core competencies include the ability to: (i) apply the process of science; (ii) use quantitative reasoning; (iii) use modelling and simulation; (iv) tap into the interdisciplinary nature of science; (v) communicate and collaborate with other disciplines; and (vi) understand the relationship between science and society. In addition to the core concepts and competencies, the report emphasized the importance of using different forms of assessments for measuring student learning. According to the report, “upfront planning helps ensure that assessment aligns with a course’s objectives and with the strategies employed to foster learning. Assessments that do not align with learning goals and class activities undermine both student learning and faculty evaluation of the effectiveness of classroom teaching,” (Brewer & Smith, 2011, p. 24).

2.1.2 Relevance of the Reports to the Current Study

All three reports emphasize the importance of integrating biology with physical sciences such as chemistry and biochemistry in order to help life science students understand the interdisciplinary nature of biology. Furthermore, these reports provide examples of chemistry concepts and/or competencies that are important for biology courses and suggest using them as "a framework for initiating conversations about curricular evaluation and revision within biology departments and for catalyzing cross-departmental discussions about interdisciplinary programming," (Brewer & Smith, 2011, p. 17). Although the identification of concepts and/or competencies was done through meetings and workshops, there needs to be a simple and efficient step-by-step process that instructors at any university can use in order to collect data that can service as the basis of curriculum related discussions. This is significant because it is important to identify the specific content needs of the particular context when performing curriculum development at a given institution with its own unique context. In the present study, I therefore chose to design a simple, three-stage process that could be used by instructors at any institution in order to collect data to initiate curriculum discussions regarding the concepts and competencies to include in a curriculum (Goal1; Chapter 4). In this way, curriculum discussions would be directly informed by empirical data from the same context. What people consider to be important at one institution may differ from what is deemed most important at another institution.

The reports described above also indicate the importance of designing assessment tasks that actually assess students' learning and their understanding of stated course objectives. Thus, in the present study, I decided to design an assessment model that instructors can use for designing assessments that address the intended learning outcomes and also validating the assessments to ensure that they probe what they are intended to probe (Goal 3; Chapter 6).

2.1.3 Integration of Biology, Physical Sciences, and Mathematics

A number of studies related to the integration of biology and physical sciences, and biology and mathematics have been conducted in response to the biology curriculum reform calls (NRC, 2003; Brewer & Smith, 2011; AAMC-HHMI, 2009). Depelteau et al. (2010) designed a curriculum in which mathematics was integrated into an undergraduate introductory biology course. The developed curriculum, consisted of three symbiosis modules: symbiosis I (integrated biology and statistics); symbiosis II (integrated biology and calculus); and symbiosis III (integrated biology and discrete math). Results from piloting the curriculum showed that the "symbiosis material could be used in introducing college and precollege students to an integrated approach to quantitative biology," (p. 343). Similarly, Matthews and colleagues (2010) developed a curriculum for SCIE1000, an undergraduate introductory biology course, which incorporated mathematics and computer programming into biology. The curriculum was developed in order to assess its impact on students' perceptions of mathematics and computer programming in the context of science, specifically biology; and whether exposing students to an integrated curriculum would motivate them to register for higher-level quantitative courses. Analysis of the results showed that although enrolling in SCIE1000 helped students realize the importance of mathematics to biology, few students were interested in registering for higher-level quantitative courses. In response to students' lack of quantitative skills, Speth et al. (2010) designed a curriculum by incorporating quantitative concepts into an already existing undergraduate introductory biology course. The effectiveness of the curriculum was assessed by exposing students to test questions which required them to perform calculations and draw graphs. Analysis of the results showed that students' quantitative skills and graphical presentation skills improved. Thompson and colleagues (2010) similarly incorporated online MathBench biology modules into undergraduate introductory laboratory curriculum. The modules were aimed at reinforcing biological concepts and the importance of mathematics in biology, and assessment of their effectiveness revealed that the modules helped promote students' quantitative skills.

Unlike the integration of biology with mathematics, limited studies have been done regarding the integration of biology with chemistry. Examples of such studies include those done by Abdella, Walczak, Kandl, and Schwinefus (2011); Reingold (2001); Van Hecke, Karukstis, Haskell, McFadden, and Wettack (2002); and Wolfson, Hall & Allen (1998). Abdella et al. (2011) developed a curriculum for an undergraduate introductory biology course by integrating chemistry into an existing biology course. The developed curriculum addressed the relevance of chemical concepts, thermodynamics and kinetics to biology. When the effectiveness of the developed curriculum was assessed, results showed that the curriculum helped students gain a broader understanding of the interdisciplinary nature of science, specifically biology. Furthermore, Wolfson and colleagues (1998) designed a mini-cluster curriculum consisting of one section of introductory biology and one section of introductory chemistry. The mini-cluster curriculum was designed in order to make students aware of the interdisciplinary connections between chemistry and biology. Results from the attitudinal surveys showed that students appreciated the mini-cluster curriculum. Moreover, Van Hecke and colleagues (2002), designed an interdisciplinary laboratory course that integrated chemistry, biology and physics. The laboratory course was designed for introductory science and engineering majors. The goal of this laboratory course was to demonstrate the interdisciplinary nature of methods and laboratory techniques used in chemistry, biology and physics. Results from the assessment questionnaires showed that the interdisciplinary laboratory course helped students “develop the ability to recognize the interdisciplinary nature,” of chemistry, biology and physics (p. 843). Additionally, Reingold (2001) proposed a new approach for college chemistry curricula. This approach involved teaching organic chemistry at freshmen level. However, according to Reingold, the organic chemistry should only concentrate on topics that are relevant to life scientists, and “integrate biology-related topics as much as possible,” (p. 870). By so doing, Reingold believes that life science students, specifically, biology majors will be exposed to an organic chemistry that is more relevant to their major.

Studies have also been conducted in physics education in order to assess how biology can be incorporated into physics in order to help life science students, specifically biology majors, understand the importance of physics to biology (e.g. Meredith & Redish, 2013; Redish & Hammer, 2009; Watkins, Coffey, Redish, & Cooke, 2012). One of the most crucial discoveries made by these studies was the importance of having discussions between physics and biology instructors in order to decide what to include in the curriculum. This is important because different stakeholders can have different ideas regarding what to include in the curriculum (Redish et al., 2014; Watkins et al., 2012).

Based on the above studies, it can be deduced that most research in this area has involved the integration of biology and physics or math, while only limited research has been done involving the integration of biology with chemistry or biochemistry.

Furthermore, scholars such as Redish and Cooke (2013), Redish et al. (2014), Meredith and Redish (2013) have stipulated the importance of having discussions between the relevant stakeholders in order to decide what to include in the integrated curriculum. Therefore, there is a need for a simple process that instructors at any institution can use in order to collect data that they could use to initiate curriculum related discussions. Thus, in the present study, I found it important to design a simple, three-stage process that could be used by instructors in order to collect data that they could use to initiate discussions regarding, for example, the chemistry/biochemistry concepts and representations to include in a chemistry course designed for the life sciences, specifically biology majors.

2.1.4 Identification of Biochemistry and Chemistry Concepts Important for Biology Courses: A discussion of Studies done by ASBMB

A number of studies have been conducted in order to identify foundational concepts to include in the curriculum. One project that has received great attention regarding the identification of such concepts is the ‘concept-driven teaching project’ run by the American Society of Biochemistry and Molecular Biology (ASBMB) (Bell, 2010). The project is intended to promote concept-driven teaching by focusing on the following goals: (i) identifying the key concepts and skills required to understand biochemistry and molecular biology; (ii) creating a taxonomy of key concepts and skills, and linking these to topics outlined in ASBMB’s undergraduate curriculum; and (iii) designing concept inventories that will be used for assessing student understanding and learning. The major goal of the ASBMB (Bell, 2010) project is to develop an online database of instructional resources for biochemistry and molecular life sciences educators that will include a collection of all the identified foundational concepts, key concepts, skills, and the designed concept inventories and develop an online database of instructional resources that will be useful for biochemistry and molecular life sciences educators.

Several studies have been conducted in response to the ASBMB call for the concept-driven teaching approach. Wright and colleagues (2013) conducted a study in which they compiled a list of foundational concepts from chemistry, mathematics, and physics that biochemistry and molecular biology majors should have been taught by the time they graduate. The foundational concepts identified were classified into the folowing five categories: (i) foundational mechanical concepts from physics; (ii) foundational energy and thermodynamic concepts from physics and chemistry; (iii) foundational concepts of structure from chemistry; (iv) foundational concepts of reactions from chemistry; and (v) essential mathematics. These foundational concepts were further classified into sub-foundational concepts which, according to the authors, could become course objectives that could inform the design of assessments. The authors indicated the latter is important because assessments must be designed to assess students' understanding of the targeted learning objectives. Conversely, Tansey and colleagues (2013) conducted a study in which they compiled a list of learning outcomes relevant to the following five foundational core concepts: (i) evolution; (ii) matter and energy transformation; (iii) homeostasis; (iv) information flow; and (v) macromolecular stucture and function. According to the authors, the developed learning outcomes were meant to serve as examples that instructors can use as guides when developing their own learning outcomes and assessment tasks. White and colleagues (2013) compiled a list of skills that biochemistry and molecular biology students ought to have attained upon graduation.

These skills were divided into the following three categories: (i) process of science; (ii) communication and comprehension of science; (iii) and community of practice aspects of science. According to the authors, these skills "can be used as a basis for development of appropriate assessment tools that focus on the essential concepts encompassed by these three areas." Other studies focused solely on biochemistry majors rather than both biochemistry and molecular biology majors. Such studies include those that concentrated on the identification of threshold concepts for biochemistry (Loertscher et al., 2014), and the identification of core biochemistry concepts and the development of a biochemical concept map and a teaching module framework that can be used for an introductory biochemistry course (Rowland et al., 2011).

In order to identify the stated concepts and skills, ASBMB held meetings and workshops throughout the country. However, besides holding meetings and workshops, there needs to be a simple and efficient process that can be used by instructors at any institution in order to identify concepts and skills they consider to be important for the topic under study. Therefore, one of the goals (Goal 1) of this study was to design a simple three step process that can be used by instructors at any university in order to collect data that can be used to launch curriculum related discussions so as to identify concepts and skills to include in a curriculum.

2.1.5 Importance of Representations in Science and Science Learning

Visual representations (or external representations) are physical or molecular models, or pictorial, diagrammatic, graphical or symbolic representations of scientific phenomena in the external world (Schönborn & Anderson, 2006). Visual representations are usually used as a means of communicating scientific data (Watson & Lom, 2008) and "displaying multiple relationships and processes that are difficult to describe," (Cook, 2011). Numerous studies in science education have established that visual representations are essential for constructing knowledge (e.g. Peña & Quílez, 2001; Treagust Chittleborough & Mamiala, 2002) and promoting conceptual understanding and visualization of abstract phenomena (e.g. Kozma, 2000; Schönborn & Anderson, 2009). This is because visual representations are believed to aid students in constructing meaningful mental models of scientific phenomena (Anderson, Schönborn, du Plessis, Gupthar, & Hull, 2013; Cheng, Kennedy, & Kazmierczak, 2010). Using multiple representations also helps students understand different aspects of the concept represented (Ainsworth, 2006; Schönborn & Anderson, 2010; Schönborn & Bögeholz, 2009). Although beneficial, it has been reported that most students have difficulties translating between multiple representations (e.g. Ainsworth, 1999). According to Mayer (1997), representations become even more helpful to students if: (i) extraneous, unnecessary material is excluded from the representation (known as the coherence effect); (ii) words corresponding to the representation are placed next to the representation (known as the spatial contiguity effect); and (iii) words describing the representation are more conversational as opposed to being formal (known as the personalization effect).

2.1.5.1 Importance of Representations in Learning Biology

Research has shown that using various types of representations in biology helps students construct and develop a deeper understanding of biological concepts (Tsui & Treagust, 2013). For instance, Yarden and Yarden (2013) showed that using animations helped improve students' understanding of biotechnological methods, whereas Griffard (2013) showed that the use of different types of complex diagrams helped improve pre-medical students' understanding of molecular biology. The use of representations in biology teaching and learning is necessary because biological phenomena are complex since they involve physical and abstract systems and processes that need to be viewed, studied, and understood at the micro and macro levels (Eilam, 2013). According to Johnstone (1991), learning science always involves an interaction between three levels of representation. For instance, in physics, the conventional three levels of representation are the macro, the invisible, and the symbolic levels. In chemistry, the accepted three levels of representation are the macro, the submicro, and the symbolic levels, whereas in biology the levels of representation are the macro, the micro, and the biochemical levels. In contrast, Tsui and Treagust (2013) argued that learning biological knowledge is more complex than learning chemical knowledge; hence Johnstone's triple levels of representations do not fully describe how learning occurs in biology. According to Tsui and Treagust (2013), learning biological knowledge is more complex because biological knowledge involves "hierarchically organized levels of nested but different biological entities. That is, cells are nested within tissues, which are in turn nested within organs and then within the next level systems, organisms, populations, communities, ecosystems and up to the top level of the biosphere" (p. 8). Therefore, Tsui and Treagust (2013) suggested that learning in biology involves four levels of representations: the macroscopic level; the cellular or subcellular level; the molecular level; and the symbolic level. The fact that learning in biology involves four levels of representations implies that students are expected to be able to "acquire knowledge and understanding that is diverse and embedded at different levels of complexity and abstraction; flexibly transfer knowledge during problem-solving; and interpret and translate across multiple external representations," (Schönborn & Bögeholz, 2009, p. 931). Therefore, there is a need to expose students to teaching practices that will develop their visual literacy skills so that they are able to meaningfully learn with the various multiple representations used in biology (Rybarczyk, 2011).

In order to address research Goal 1, I asked the biology instructors to provide examples of representations they considered to be important for the biology courses they taught and also state ways they expected students to reason with the representations. Knowing the representations that the biology instructors considered to be relevant as well as ways they expected the students to reason with the representations was important because literature contains limited studies in these areas. Furthermore, although it is apparent that representations are indistinguishable from their related concepts as shown in numerous textbooks, I still found it important to ask the biology instructors about the representations because not all instructors at the present institution use representations from textbooks; instead, some use representations from published articles.

2.2 Motivation for Goal 2: The need to Identify the Acid-Base Content Important for Biology Courses

2.2.1 Overview of Acid-Base Chemistry

In 1776 Antoine Lavoisier, a French scientist, suggested that acidity was caused by the presence of oxygen in a compound (Lesney, 2003). However, in 1810, the British Scientist Sir Humphry Davy discovered that not all acids contained oxygen (Lesney, 2003). Furthermore, in 1838, Justus von Liebig, a German scientist, theorized that acids were hydrogen-containing substances whose hydrogen could be displaced by metals (Kousathana, Demerouti, & Tsaparlis, 2005). The most important thing to mention is the fact that Liebig's theory formed a foundation for other acid-base theories that were developed after 1838. One such theory, developed in 1838 by the Swedish chemist Svante August Arrhenius, defined acids as substances that increased the concentration of hydrogen ions when dissolved in aqueous solutions (Story, 2004). Arrhenius further suggested that: (i) acids were substances that dissociate into positively charged hydrogen ions in aqueous solutions, (ii) bases were substances that dissociate into negatively charged hydroxide ions in aqueous solutions, and (iii) acids and bases react to form water and a salt, a process referred to as neutralization (Lesney, 2003). Inspired by Arrhenius's work, Johannes Nicolaus Brønsted and Thomas Martin Lowry each developed another definition for acids and bases in 1923. These scientists defined acids as those substances that could donate hydrogen ions, whereas bases were those substances that could accept hydrogen ions, (Lesney, 2003; Story, 2004; Kousathana et al., 2005). The Brønsted-Lowry theory introduced the concept of conjugate acid-base pairs. However, in 1938, Lewis developed another definition in which he defined an acid as an electron pair acceptor, and a base as an electron pair donor (Lesney, 2003; Kousathana et al., 2005; Story, 2004). It is important to point out that all three models are concurrently being used in chemistry education to teach learners about acid-base theory (Story, 2004). Furthermore, of the three models, the Brønsted-Lowry model is extensively used in acid-base physiology (Story, 2004). This is because "in the 1950s clinical chemists combined the Henderson-Hasselbalch equation and the Brønsted-Lowry definition of an acid to produce the current bicarbonate ion-centered approach to metabolic acid–base disorders," (Story, 2004). The Henderson-Hasselbalch equation, which shows, how mathematically, pH, partial pressure of carbon-dioxide and bicarbonate concentration ($pH= pK_a + \log_{10}[HCO_3^-]/\alpha pCO_2$) are related, also shows the relationship between pH and the ratio of the acid concentration to the concentration of its conjugate base (Story, 2004). The latter is important because it helps explain why changes in partial pressure of carbon-dioxide cause acidosis or alkalosis (Story, 2004).

Various education researchers have reported that acid-base theory is an important topic because it is a fundamental theory that is encompassed within various chemistry topics such as the nature of inorganic oxides of metals and non-metals, phenols and carboxylic acids (Halstead, 2009); and it is the basic theory upon which explanations of cellular processes such as homeostasis are built (Story, 2004). Research in chemistry education has established that students have misconceptions related to the various acid-base concepts (e.g. Cartrette & Mayo, 2011; Kousathana et al., 2005; Muchtar, 2012; Orgill & Sutherland, 2008; Sheppard, 2006; Watters & Watters, 2006). Besides research done on students' acid-base misconceptions, some studies conducted in chemistry education include the use of various teaching strategies in order to help remediate students' misconceptions and promote conceptual understanding of acid-base concepts (e.g. Demircioğlu, Ayas, & Demircioğlu, 2005; Halstead, 2009; Nakhleh & Krajcik, 1994). Some studies have concentrated on developing acid-base concept inventories (McClary & Bretz, 2012).

2.2.2 Biological Importance of Acid-Base Chemistry

Acid-base chemistry is important to biology because it can be used to build explanations that portray how the body functions. For instance, acid-base homeostasis refers to the appropriate balance between acids and bases; that is the proper balance of cellular pH. This balance is crucial because cells and their components are very sensitive to pH changes, because enzymes or other proteins can denature or lose their ability to function at pH values above their acceptable range (Halstead, 2009). Since enzymes are the major controlling entities in our metabolic pathways (e.g. glycolysis & gluconeogenesis pathways), so loss of function could be fatal. Therefore, in order to maintain this balance, the body uses buffering systems. Buffers are solutions composed of weak conjugate acid-base pairs, that resist change in their pH and are composed of weak conjugate acid-base pairs (Garrett & Grisham, 2010). Thus, when making a buffer, it is advisable to use a weak acid that has a pK_a that is close to the desired pH because it is at the pK_a that the "buffer system shows its greatest buffering capacity," (Garrett & Grisham, 2010).

Because maintenance of pH is vital for cell, organisms make use of various buffering systems such as the phosphate buffer system and the bicarbonate buffer system.

The phosphate buffer system maintains the intracellular pH of cells (Garrett & Grisham, 2010) whereas the bicarbonate buffer system maintains the pH of blood within the 7.35-7.45 range (Modell et al., 2015). If the pH rises above this range, then alkalosis occurs. On the other hand, if the pH drops below this value, then acidosis occurs; these two conditions may be fatal (Garrett & Grisham, 2010). Since buffers are important in biological systems and are regularly used in research, they are "covered in many classes in a typical chemistry undergraduate degree program," (Orgill & Sutherland, 2008, p. 131; Rhodes, 2006). Furthermore, due to the importance of buffers in chemistry and biology, it is important for chemistry and biology majors to understand them (Orgill & Sutherland, 2008).

Although acid-base chemistry is crucial for biological systems, it is surprising that, at the time of writing, more studies that had reported the content related to the various acid-base concepts were in chemistry and biochemistry education, whereas very limited studies had been done in biological sciences (Haudek, Prevost, Moscarella, Merrill, & Urban-Lurain, 2012; Modell et al., 2015). There is an urgent need to conduct more studies in biology education in order to know what biology instructors consider to be the relavent acid-base for the courses they teach. In the present study, I therefore decided to interview biology instructors in order to find out what acid-base knowledge they consider to be important for the various biology courses they teach and how they use such knowledge to teach biology. Data collected will contribute to the knowledge that has already been reported in the Bio2010 report, the Vision and Change report and the various studies done in ASBMB.

2.3 Motivation for Goal 3: The Need to Design a Simple Assessment Design Model

2.3.1 Assessment Types and Purposes

Like many terms used in science education, "assessment" can be defined in different ways. It can be defined as "the systematic collection, review and use of information about educational programs undertaken for the purpose of improving student learning and development" (Palomba & Banta, 1999). Or it can be defined as "the process of providing credible evidence of resources, implementation actions, and outcomes undertaken for the purpose of improving the effectiveness of instruction, programs and services," (Banta, Palomba & Jillian, 2014). Regardless of the definition used, assessments provide students, instructors, policy makers, researchers, and educators with information related to student learning thus helping them make decisions about implications and decision making. Because assessments can be used for various purposes, the definition that one decides to use depends on the purpose of the assessment they intend to use or design. For instance, assessments can be used to assist learning, evaluate individual student performance, and evaluate programs (Pellegrino, 2014). Although various types of assessments are used to monitor student progress, formative and summative assessments are examples of assessments that are often used in classrooms to assist and evaluate student learning. Formative assessments are implemented during a course and can be used by both the instructors and students in order to measure student learning (Anderson, 2007; Briggs et al., 2015; Masters, 2013). Students can use formative assessments as diagnostic tools to help measure their performance regarding the concepts being taught (Aboulsoud, 2011; Masters, 2013). This becomes more effective and useful if continuous feedback is provided. Instructors, on the other hand, use formative assessments in order to monitor the impact of their teaching on students' understanding of concepts (Aboulsoud, 2011; Anderson, 2007). Summative assessments, on the other hand, are implemented at the end of a course in order to establish what students have learnt throughout the course (Anderson, 2007; Masters, 2013). Whether formative or summative, it is important to design assessments that directly address the learning objectives (AAMC-HHMI, 2009; Anderson, 2007; Brewer & Smith, 2011; Kennedy 2005; NRC, 2001, 2003). This is crucial because it informs instructors whether students can demonstrate that they have understood the targeted learning objectives. Therefore, in order to help instructors design assessments, a variety of frameworks and guidelines have been developed (Anderson & Rogan, 2010; Briggs et al., 2015; Kennedy, 2005; NRC, 2001, 2003; Pellegrino, 2014).

2.3.2 Assessment Design

As stated previously, various assessment design frameworks and guidelines have been created in order to help instructors to design assessments. According to the Anderson and Rogan (2010) guidelines, when designing or evaluating an assessment it is important to ensure that it assesses the targeted learning objectives and the desired learning outcomes, which can be achieved by checking if the assessment questions align with the learning objectives and the desired learning outcomes. Furthermore, it is essential to ensure that the assessment probes relevant concepts and the desired cognitive skills; this can be achieved by checking if the assessment questions align with the targeted concepts and cognitive skills. If representations are included in the assessment, it is important to ensure that they are not too complex and can be understood by the students (Anderson & Rogan 2010). The quality of the assessment can be checked qualitatively via, for instance, analyzing student responses. Qualitative analysis of student data is important as it reveals existing conceptual difficulties and whether or not the assessment assessed the targeted content.

The assessment triangle is another example of an assessment design framework, developed by the National Research Council (2001). The assessment triangle serves as a framework that educators can use in order to determine if their assessments address the targeted learning outcomes. It consists of three interdependent components, namely *cognition*, *observation* and *interpretation*. *Cognition* refers to the theories of learning knowledge and skills within a subject domain. According to this component, when designing an assessment, “a theory of learning in the domain is needed to identify the set of knowledge and skills that is important to measure for the intended context of use, whether that be to characterize the competencies students have acquired at some point in time to make a summative judgment, or to make formative judgments to guide subsequent instruction so as to maximize learning,” (Pellegrino 2014 pg. 69). *Observation,* on the other hand, refers to the activities or tasks that students engage in so as to illustrate their knowledge and skills. This component of the triangle has a set of specifications regarding how assessments can be carefully designed in order to ensure that they “provide evidence that is linked to the cognitive model of learning and to support the kinds of inferences and decisions that will be made on the basis of the assessment results,” (Pellegrino 2014 pg. 69). Conversely, *interpretation* refers to the various methods or processes used to make sense of the data collected using assessments.

This component shows how “the observations derived from a set of assessment tasks constitute evidence about the knowledge and skills being assessed (Pellegrino 2014 pg. 69).”

The learning progression framework (Briggs et al., 2015) is another example of an assessment design framework that can be used for designing assessments. This framework is informed by the assessment triangle described above. The learning progression framework also has three components, namely a *learning progression* component, a *tasks and items* component, and an *interpretation* component. The *learning progression* component represents a period during which students are expected to learn knowledge and develop skills within a subject domain. The *tasks and items* component refers to the assessment tasks/tools that are designed and used in order to assess knowledge and skills attained by students within a specified learning progression. The *interpretation* component refers to the scores used to evaluate students’ progress. These scores are obtained from analyzing student responses related to the given *tasks and items*.

Besides the learning progression framework and the assessment triangle framework, the BEAR system framework (Kennedy, 2005) is another example of an assessment design framework used for designing assessments. The BEAR system framework, like the learning progression framework, is also informed by the assessment triangle. The BEAR system framework has four components, namely the *construct map* component, the *items design* component, the *outcome space* component, and the *measurement model* component. The *construct map* component encompasses the knowledge and skills that students portray at different levels of understanding. The *items* *design* component refers to the assessments that are designed and used to assess students' knowledge at various levels of understanding. The *outcome space* component, on the other hand, refers to the different levels of student understanding revealed by analyzing students' responses from the assessment items. The *measurement model* component describes how inferences can be made from student responses in order to ensure consistency "across multiple instruments."

The assessment frameworks described above have three common features: (i) they address the importance of ensuring that the assessment addresses the targeted learning outcomes; (ii) they emphasize the importance of ensuring that the assessment probes for students' knowledge and skills attained within a subject domain; (ii) and they highlight the importance of knowing how to analyze and interpret student responses so as to gauge their level of understanding. When using any one of these frameworks as a guide to design an assessment, it is therefore important to make sure that all the components of the frameworks "are in synchrony" so as to design effective assessments. Although the three frameworks described above are useful for the design of assessments, they are too abstract for the instructors who are not familiar with education related terminology/education research. Therefore, I decided to design a simple, step-by-step assessment model (see Chapter 6; Goal 3) that can be used by educators in order to design effective assessments. This assessment model is not abstract, it provides instructors step-by-step instructions regarding how to design and qualitatively check the validity of the designed assessment.

CHAPTER 3: METHODS

In order to address the research questions pertaining to Goals 1, 2 and 3, presented in Chapter 1, this study was divided in to three mini-studies to be discussed in Chapters 4, 5 and 6. Since different data collection methods were used for each mini-study, each method will be discussed in connection with the relevant mini-study. This chapter discusses the general data collection and data analysis methods that were used across the three mini-studies.

3.1 Researcher Context and Role in the Study

Prior to conducting this study, I enrolled in several qualitative methods classes (e.g. EDPS 53300 *Introduction to Educational Research I: Methodology*, EDCI 61500 *Qualitative Research Methods in Education* and EDCI 61600 *Advanced Qualitative Research Methods in Education*) where I was introduced to and practiced skills and knowledge necessary for conducting qualitative research. Such knowledge and skills include, for example, conducting interviews and analyzing qualitative data. Thus mentioned, this provided me with the skills and knowledge required to conduct this study.

I have been a graduate teaching assistant for various general chemistry courses (e.g. CHM 11100 *General Chemistry*,11500 *General Chemistry* & 11600 *General Chemistry*) since Fall 2011. These courses, specifically CHM 11500 and 11600, are designed for engineering majors and life science majors such as biology majors. As a teaching assistant, I was exposed to the curriculum used in these courses, including the content that was taught, how it was taught, and the emphasis that was made when the course material was taught. Since I was directly involved in the collection, analysis, and interpretation of data regarding the chemistry concepts and representations that biology instructors consider to be important for the biology courses that they teach, I acknowledge that my background as a chemistry graduate teaching assistant affected my interpretation of the data. However, in order to ensure that the interpretation of data was not biased, I asked two other science education researchers to review and critique my analysis and interpretation of the data, in a peer debriefing process as described in section 4.4.2 (Creswell, 2009; Lincoln & Guba, 1989)

3.2 Research Context

The research study was conducted at a research intensive university in the Midwest of the United States where chemistry faculty are revising the introductory chemistry and biochemistry curricula in order to better prepare biology students to tackle the challenges of modern biology. At this university, the programs of biological science majors are intended to provide excellent preparation for professional school (medicine, veterinary medicine, dentistry) or careers in academic or industrial research. Because fields in biology and chemistry overlap, it is important to consider the sequence of courses provided for biology students in the context of this study. The undergraduate biology courses taught by participants in this study require students to take a two-year plus one semester sequence of biology lab and lecture courses that cover biodiversity, ecology, evolution, development, structure, and function of organisms, cell structure and function, genetics, molecular biology, ecology and evolution plus a more specialized intermediate biology course which opens a pathway to upper division elective courses for either a general Biology degree or a specialization in one of these areas: Biochemistry; cell, molecular, and developmental biology; health and disease; ecology, evolution, and environmental biology; microbiology; biology education; genetics; or neurobiology and physiology. As they complete their lower division coursework, biology majors at this university also take courses taught by faculty members in the chemistry department. Most students now opt to complete a recently implemented accelerated two-year chemistry course sequence that consists of one semester of general chemistry followed by two semesters of organic chemistry and one semester of biochemistry.

3.3 Motivation for Using Qualitative Research Methods

Qualitative research can make use of a realistic approach so as to understand phenomena in their original settings and to obtain “in-depth information” about phenomena under study (Creswell, 2003; Gay & Airasian, 2003; Hoepfl, 1997). This was useful in the current study because biology instructors were expected to provide in-depth information regarding the acid-base knowledge they consider relevant to the biology courses they teach and the ways they expect students to reason with that knowledge. As noted by Gay and Airasian (2003), three main types of data are collected in qualitative research: i) verbal data in the form of interviews, ii) direct observations, and iii) written documents. Likewise, in the current study data collected were in the form of (i) interview notes/transcriptions; and (ii) written documents from biology instructors (Chapter 4). Furthermore, in a qualitative research approach, the researcher acts as a "human instrument" (Hoepfl, 1997, p. 49) in the collection and analysis of data. Thus it is likely that the researcher's beliefs may influence the findings of the study (Gay & Airasian, 2003; Hoepfl, 1997). Interviews in qualitative research mainly use open-ended questions, which are of great importance because participants are given the freedom to "say their minds" (Hoepfl, 1997). This approach aids the researcher to discover the nature of participants' true knowledge. For these reasons, open-ended questions were used in the present study. I wanted to uncover biology instructors' views regarding the acid-base knowledge that is of relevance to the courses they teach.

3.4 Theoretical Framework

According to Bodner (2007), theoretical frameworks "provide the assumption that guide the researcher, help the researcher choose appropriate questions for a given study, direct the researcher to choose appropriate questions for a given study, and direct the researcher toward data collection methods that are appropriate for the study" (p.11).

We identified the Concepts-Reasoning-Representational Mode (CRM) model of Schönborn and Anderson (2009) as an appropriate framework for this study because the model framed my thinking with respect to: (i) the concepts, representations and ways of reasoning that I aimed to identify by addressing Goals 1 and 2 noted in Chapter 1, and (ii) the development and validation of an assessment model that I aimed to design by addressing Goal 3 noted in Chapter 1. The CRM model has been fruitfully employed to inform the coding of data as described in Anderson et al. (2013) and to guide the design of an original assessment in the context of a cutting-edge research problem (Dasgupta, Anderson, & Pelaez, 2016).

The CRM model is composed of several factors including: (i) the conceptual factor (**C**) which, relates to students' prior conceptual knowledge that is relevant to a particular representation; (ii) the mode factor (**M**) which relates to the nature of the representation; and (iii) the reasoning factor (**R**) which includes reasoning abilities required for both retrieving and applying the appropriate conceptual knowledge (**R-C**) and for making sense of the representation (**R-M**). All factors are interdependent because prior conceptual knowledge is required in order to make sense (**R-C**) of the presented representation and its graphical features (**R-M**). Moreover, a particular representation is meant to portray scientifically correct knowledge (**C-M**). Previous research has shown that the interpretation of the representation is successful if the students engage all factors of the model such that prior conceptual knowledge is used to make sense of the representation and its graphical features (**C-R-M**) (Schönborn & Anderson, 2009).

In addition to the developed CRM model, Anderson et al. (2013), Anderson and Schönborn (2008) and Schönborn and Anderson (2010) compiled a list of cognitive skills, specifically reasoning and visual skills, employed by experts when reasoning with scientific concepts and visual representations. The cognitive skills were further classified based on the CRM model as **R-C** or **R-M** as shown below. It is important to point out that the cognitive skills, specifically the reasoning skills (**R-C**), are related to those used in the cognitive domain of Bloom's revised taxonomy (Anderson et al., 2001).

According to Schönborn and Anderson (2008), reasoning with concepts (**R-C** in CRM) means having the ability to:

I. Memorize knowledge of a concept in a mindful manner (R1)
II. Integrate knowledge of a concept with that of other related concepts so as to develop sound explanatory frameworks (R2)
III. Transfer and apply knowledge of a concept to understand and solve problems (R3)
IV. Reason analogically about a concept (R4)
V. Reason locally and globally about a concept (R5)
VI. Reason algorithmically about a concept (R6)
VII. Critically analyze or evaluate a concept (R7)
VIII. Think metacognitively about a concept (R8)

According to Schönborn and Anderson (2008), reasoning with representations (**R-M** in CRM) means having the ability to:

I. Decode the symbolic language composing a visual representation (V1)
II. Evaluate limitations and quality of a visual representation (V2)
III. Interpret and use a visual representation to solve a problem (V3)
IV. Spatially manipulate a visual representation to interpret and explain a concept (V4)
V. Construct a visual presentation to explain a concept or solve a problem (V5)

VI. Translate horizontally across multiple visual presentations of a concept (V6)

VII. Translate vertically between visual presentations that depict various levels of organization and complexity (V7)

VIII. Visualize orders of magnitude, relative size and scale (V8)

IX. Interpret the temporal resolutions of visual representations considering what came before and will come next (V9)

In the present study, the CRM model helped shape the design of the three-stage process in terms of the questions asked at each stage (Goal 1, see Chapter 4). The questions asked required the biology instructors to provide the chemistry and biochemistry concepts (**C** in CRM) and representations (**R** in CRM) they considered to be relevant to the biology courses they taught. I also asked the instructors to state how they expected their students to reason with the concepts (**R-C** in CRM) and representations (**R-M** in CRM). The reasoning and visual skills shown above became helpful specifically in the categorization of the statements that stipulated how the instructors expected the students to reason with the chemistry and biochemistry concepts and representations. The CRM model was also useful because it helped guide the development of the interview questions used to identify the acid-base knowledge that the biology instructors considered to be important for the courses they taught (Goal 2, see chapter 5). Finally, the CRM model was important in the present study because it helped guide the design of an assessment model that assesses students' understanding and ways of reasoning with concepts (**R-C**) and representations (**R-M**) (Goal 3, see Chapter 6).

3.5 Participants and Sampling Strategy

Although the participants in this study were all biology instructors, not all of them participated in the same mini-studies. Therefore, the description of the biology instructors who participated in each mini-study to address Goals 1, 2 and 3 has been provided in the relevant Chapters 4, 5 and 6 respectively. The sampling strategy used for selecting biology instructors who participated in each study was the same.

Purposeful sampling (Patton, 2002), rather than random sampling, was used in this study for two reasons. First, purposeful sampling is mainly used in qualitative inquiry and since only qualitative methods were used in this study, this sampling technique became highly relevant for this study (Patton, 2002). Second, purposeful sampling aims at selecting "information rich cases" that provide in-depth information addressing the research questions (Patton, 2002). Purposeful sampling was useful for this study because I wanted to make sure that I selected participants who would provide in-depth information addressing the research questions stated in Chapter 1. Given the goals of this study, I purposefully selected biology instructors who have an advanced degree (either a Masters or Ph.D.) in biology and have worked and taught at the institution under study for at least three years.

3.6 Ethical Considerations

Ethical clearance to perform this study was given by Purdue's Institutional Review Board, (Protocol number 1408015145). A copy of the approved Institutional Review Board document is provided in Appendix A. Before faculty participated in the study, I sent an email to the biology instructors. In the email, the instructors were informed of the aims of the study and the fact that their participation was voluntary and that they were free to leave the study anytime they were no longer interested in participating. Though the faculty were asked to provide the name(s) of the biology courses they taught, the course names were not explicitly disclosed when reporting the results/data. Instead, where appropriate, categories such as "lower-and-upper division biology courses" were used. Furthermore, when reporting data collected from the interviews, pseudonyms were used instead of using the biology instructors' real names. This was done in order to protect their identity.

3.7 Data Collection

In this section, I discuss the general overview of the methods used and the reasons why they were used.

3.7.1 Overview of the Methods Used to Address Goal 1 (Chapter 4)

In order to address Goal 1, a process informed by the Delphi method (Dalkey, 1969) was used to survey biology instructors for the biochemistry and chemistry concepts (**C**) that they consider most relevant for the biology courses they teach and ways in which they expected the students to use the concepts (**R-C**).

The Delphi method was developed at the Rand Corporation in the early 1950s (Delbecq, Van de Ven & Gustafson, 1975; Helmer, 1966; Judd, 1972). Since then, this method has been adopted and used in areas such as management studies (e.g., Grisham, 2009), health sciences (e.g. Green, Jones, Hughes, & Williams, 1999; Ludwig & Starr, 2005), science education (e.g. Alake-Tuenter, Biemans, Tobi, & Mulder, 2013; Koksal & Cimen, 2008), biochemistry and engineering education (Degerman & Tibell, 2012; Rossouw, Hacker, & Vries, 2010; Streveler, Olds, Miller, & Nelson, 2003), and many more disciplines. The Delphi method is normally used in situations that require a consensus from experts about the topic under research (Dalkey, 1969; Delbecq et al., 1975; Helmer, 1966; Judd, 1972). This method does not require face-to-face contact; hence data is mainly collected via written responses.

Experts who participate in the Delphi study remain anonymous, which is an advantage because they can communicate their ideas freely and effectively without feeling pressured to support ideas posed by other influential or highly respected experts (Dalkey, 1969; Judd, 1972). However, the number of experts who should be involved in a Delphi study is often debated. Cochran (1983), as cited in Osborne et al. (2003, p.698) argued that the number of experts has to be more than ten in order to increase reliability and validity of the results. Ludwig and Starr (2005), however, stated that the reliability and validity of Delphi results do not depend on the number of experts involved in a Delphi study; instead, they depend on the knowledge of the experts. For this reason, Ludwig and Starr (2005) argued that the number of experts in a Delphi study can be as small as five. Delbecq and colleagues (1975) have argued that the number of experts in a Delphi should not exceed 30, specifically in instances where a homogenous group of experts is used because not many new ideas are generated if a homogenous group of experts is involved in a Delphi study (Delbecq et al., 1975).

The Delphi method usually involves a series of two to four iterative rounds, combined with anonymous controlled feedback (Dalkey, 1969; Green et al., 1999; Green, 2014; Grisham, 2009; Judd, 1972). The questions asked in the first round are usually open-ended to allow experts to generate as many important ideas as possible without feeling restricted (Fletcher & Marchildon, 2014). Questions in subsequent rounds, however, are often more restrictive and close-ended (Cafiso, Di Graziano & Pappalardo, 2013; Green et al., 1999; Linstone & Turoff, 2002). The total number of rounds in a Delphi study is determined by how slow or how fast the participants reach an agreement. Since there are no universal features or guidelines that indicate when an agreement is reached, researchers use various items to evaluate if an agreement has been reached or not such as using (i) scales and setting a specific percentage level; (ii) standard deviation, and (iii) indices such as Cohen's kappa (Meijering, Kampen, & Tobi, 2013).

In the present study, the Delphi method was used to obtain biology instructors' views and opinions regarding the chemistry and biochemistry concepts, and ways of reasoning important to the courses they teach. Since the process involved acquiring biology instructors' opinions, I wanted to ensure that participation was anonymous so that the instructors could feel free to give their opinions without being pressured to support ideas/opinions of more prominent instructors. Details of how the Delphi method was used to inform the design of the three step process are provided in Chapter 4.

Besides the Delphi method, an online qualitative survey (Appendix D) was used to further validate and investigate the nature and use of chemistry and biochemistry representations that will be discussed in Chapter 4. Qualitative surveys are mainly aimed at investigating the prevalence of a phenomena being studied in a population (Jansen, 2010). This type of a survey does not "count the number of people with the same characteristic but it establishes the meaningful variation within that population," (Jansen, 2010, p.2). In the current study, a qualitative survey was used because my goal was to validate and learn more about the various types of biochemistry and chemistry visual representations that are important for biology courses.

3.7.2 Overview of the Methods Used to Address Goal 2 (Chapter 5)

A standardized open-ended interview approach was used (Patton, 2002), which allows the interviewer to ask the interviewees exactly the same questions, in the same order during the interview. This is an advantage specifically in cases whereby the interviewer's goal is to: (i) make comparisons between responses, and (ii) conduct focused interviews so as to ensure that "interviewee time is used efficiently" (Patton, 2002 pg. 346). In the current study, the standardized open-ended interview approach became relevant because I wanted to compare biology instructors' responses regarding the type of acid-base knowledge and ways of reasoning that are relevant for the different courses they teach. Furthermore, since instructors are always busy I wanted to use their valuable time efficiently, hence, designing focused interview questions became the main priority. In this study, although structured open-ended interview questions (Appendix E) were asked during the interviews, probes and follow up semi-structured questions (Gay & Airasian, 2003) were also used in order to obtain more in depth explanations to a response (Gay & Airasian, 2003). Combining the structured and semi-structured approaches allowed me to collect data that could be tabulated and explained as shown in tables 5.1 and 5.2 in the results section (Gay and Airasian, 2003).

Prior to beginning the interviews, I established rapport with the participants by introducing myself to the interviewee(s); and explaining the goals of the interview (Gay

& Airasian, 2003; Gill, Stewart, Treasure, & Chadwick, 2008). During the interviews, I maintained: (i) close eye contact with the interviewees; (ii) a neutral body language by nodding and smiling and; (iii) showed interest in the interviewees' responses (Gill et al., 2008). Since the standardized, open-ended approach was employed, all the participants were asked the same questions about the acid-base concepts that had been shown, in the Delphi study, to be important for the biology courses they teach. At the end of the interviews, I thanked the participants for taking part in the study.

Interviews are at risk of invalidity and unreliability because in some cases the interviewer might unintentionally ask leading questions that could distort the results. Recognizing this, I ensured, where possible, that the manner in which I asked questions did not lead the biology faculty to the responses I was expecting. Furthermore, validity of interviews can also be threatened by observer bias, in order to minimize this, I tried, to maintain neutrality during the interviews, transcription of the interview responses, analysis and interpretation of data (Gay & Airasian, 2003; Patton, 2002).

3.7. 3 Overview of the Methods used to Address Goal 3 (Chapter 6)

A modeling framework developed by Justi and Gilbert (2002) guided the development process of the assessment model. This framework has successfully been used in science education research to guide the development and validation of models; for example, Schönborn and Anderson (2009) used this framework to guide the development and validation of the CRM model, whereas Trujillo, Anderson, and Pelaez (2015) used this framework to inform the development and validation of the MACH model. The framework portrays modelling as a non-linear process composed of four stages. These stages include *purpose*, that is, the purpose for which the model is being developed; *expression of the mental model*, that is, conveying initial thoughts about the model as a mental model and deciding whether to express the mental model visually, mathematically, verbally or as written material. Expression of the mental model is followed by using *thought experiments* in order to test if the model fulfils the stated purpose. This is followed by *evaluating the scope and limitations* of the model which can lead to either acceptance or rejection of the model and recommencement of the modeling process at any of the earlier steps (hence the non-linear nature of the process).

In this study, the *purpose* was to model the crucial stages/steps that are important to consider when designing and validating assessments. This was then followed by developing an *initial mental model* based on the CRM model, other literature and the assessment and validation guidelines published by Anderson and Rogan (2010). Once developed, the mental model was *expressed visually*. This was followed by using *thought experimentation* conducted in the 'mind's eye' in order to evaluate if the model fulfilled the stated purpose. Once the predictions made about the mental model appeared successful, empirical evidence was obtained by designing an organic chemistry assessment using the proposed assessment model to be discussed in Chapter 6. This was done in order to check if the model fulfilled the intended purpose.

This was followed by evaluating the scope and limitations of the model by analyzing student responses from the assessment. Analysis of the responses revealed that the model was appropriate for designing an assessment that revealed students' conceptual understanding and their reasoning abilities. However, the assessment did not reveal the actual reasoning and visual skills (see section 3.4) that the students had or did not have. Table 3.1 below shows a summary of the four stages of the modeling framework of Justi and Gilbert (2002), how they were implemented in the current study, and the research questions addressed at each stage.

Table 3.1: The Four Stages of the Model of a Modelling Framework (Justi & Gilbert, 2002) and Their Implementation in the Current Study

Stages	Implementation of the stages in this study	Research Questions addressed
1. Purpose of developing a model	Purpose is to model stages to consider when developing and validating assessments	RQ-7
2. Express mental model visually, verbally, mathematically or as written material	Development of the initial mental model was informed by literature; specifically, the CRM Model and the assessment and validation guidelines by Anderson and Rogan (2010). This model was expressed visually (See Fig. 6.1)	RQ-7
3. Use empirical evidence to test if the model fulfils the purpose	An organic chemistry assessment was designed and validated as per the proposed stages/steps shown in the model. This was done in order to check if the model was valid for being used as a guide when designing assessment tasks.	RQ-8
4. Evaluate the scope and limitations of the model	The scope and limitations of the developed model were evaluated by analyzing student responses from the assessment.	RQ-8

3.8 Data Analysis

In the present study, I used open coding to analyze transcribed interviews of biology instructors' statements so as to learn how they expected the students to reason with the chemistry and biochemistry concepts and representations (Strauss & Corbin, 1998). During the open coding process, "the data are broken down into discrete parts, closely examined and compared for similarities and differences," (Strauss & Corbin, 1998, p. 102). As data is examined and read, the researcher assigns brief labels to excerpts of data that help address the questions being studied. The labels are referred to as codes and can either come directly from the data (in vivo codes) (Saldana, 2009; Strauss & Corbin, 1998) or from the researcher's mind (constructed codes). It is important to point out that during the analysis, as the researcher constantly compares codes with each other and their supporting data, the researcher might decide to link some codes (Glaser, 1992; Strauss & Corbin, 1998). Furthermore, in order to reduce the number of codes developed, the researcher organizes them into larger categories. A detailed description of how I employed open coding in this study is provided in Chapters 4 and 5.

3. 9 Trustworthiness in Qualitative Research

Striving for validity is of great importance in any qualitative research (Golafshani, 2003). Since the study employed qualitative data collection and data analysis methods, striving for validity became my main goal. Therefore, in order to increase validity of the results, I acknowledged my role as a researcher, explained why I am qualified to carry out the current research and also acknowledged the bias I brought into this study.

Furthermore, during the analysis of data, I engaged in peer debriefing (Creswell, 2009; Lincoln & Guba, 1989), that is, I constantly asked my lab colleagues to read through the codes I had developed and the supporting data in order to check if the developed codes were a good description of the supporting data. These discussions led to the refinement of some codes. As will be described in Chapter 4, I employed member checking (Carlson, 2010; Creswell, 2009; Lincoln & Guba, 1989) in order to ask the biology instructors to check if their ideas had been represented authentically.

CHAPTER 4: THE DESIGN AND TESTING OF A THREE-STAGE PROCESS THAT CAN BE USED FOR COLLECTING CURRICULUM RELATED DATA

4.1 Introduction and Research Questions

As stated in Chapter 1, various authors and sponsored projects have exhaustively identified the key chemistry and biochemistry concepts and competencies important for teaching and learning of life sciences (e.g. AAMC-HHMI, 2009; Loertscher et al., 2014; Rowland et al., 2011; Tansey et al., 2013; White et al., 2013; Wright et al., 2013). The identified concepts and competencies are meant to be used as "a framework for initiating conversations about curricular evaluation and revision within biology departments and for catalyzing cross-departmental discussions about interdisciplinary programming," (Brewer & Smith, 2011, p. 17). The identification of the concepts and competencies was done through meetings and workshops. There, however, needs to be a simple step-by-step process that can be used by instructors at any institution in order to collect data that can service as the basis of curriculum related discussions. This is significant because when performing curriculum development at a particular institution with its own unique context, it is obviously additionally important to identify the specific content needs of that context. In the present study, I decided to develop and test a simple three-stage process that could be used by instructors at any institution in order to collect data to initiate curriculum discussions regarding the concepts and competencies to include in the curriculum. In this way, curriculum discussions would be directly informed by empirical data from the same context. What people consider to be important at one institution may differ from what is deemed most important at another institution. Therefore, in order to address the goal of this study, I decided to collect data from biology instructors at Purdue university regarding the chemistry and biochemistry concepts and representations they consider to be important for the courses they teach. The following research questions were addressed:

- Which biochemistry and chemistry concepts do the biology instructors at a Midwestern university consider relevant to the courses they teach? (RQ-1),
- How do these biology instructors expect students to use the identified concepts in the courses they teach? (RQ-2).
- Which biochemistry and chemistry representations do the biology instructors at a Midwestern university consider relevant to the courses they teach? (RQ-3),
- How do these biology instructors expect students to use these representations in the courses they teach? (RQ-4).

I decided to ask biology instructors about the chemistry and biochemistry representations as well as ways of reasoning about representations because literature contains limited studies in these areas. Furthermore, although it is apparent that representations are indistinguishable from their related concepts as shown in numerous textbooks, I found it important to ask the biology instructors to identify the biochemistry and chemistry representations they consider to be relevant to the courses they teach. The latter became important because not all instructors at the present institution use representations from textbooks; instead, some use representations from articles.

4.2 Theoretical Framework

I choose the Concepts-Reasoning-Representational Mode (CRM) model of Schönborn and Anderson (2009) as an appropriate framework for this study because the model helped frame my thinking with respect to the concepts, representations and ways of reasoning that were going to be identified by addressing the stated research questions. As discussed in Chapter 3, the CRM model has three interdependent factors: the conceptual factor (**C**); the reasoning factor (**R**); and the mode factor (**M**). In the present study this framework guided my focus on key concepts (**C**; RQ-1); representations (**M**; RQ-3); and the way the concepts and representations are respectively used for reasoning (**R-C** and **R-M**; RQ-2 and RQ-4). This allowed me to detect **R-C** and **R-M** type abilities that instructors expected students to develop when using concepts and representations to explain and solve problems in biology. In addition, by referring to the various specific cognitive and visual skills documented in previous studies (Anderson & Schönborn, 2008; Anderson et al., 2013; Schönborn & Anderson, 2010) I was able to identify specific reasoning abilities students should use when working with chemistry and biochemistry concepts and representations in their biology class.

4.3 Methods

A process informed by the Delphi method (Dalkey, 1969) and the CRM model (Schönborn & Anderson, 2009) was used to survey biology instructors for the biochemistry and chemistry concepts (**C**) that they consider most relevant for the biology courses they teach and typical examples of test questions illustrating how they expect students to use the concepts (**R-C**). The Delphi method is a group process that is normally used in situations that require opinions and consensus or divergence from selected experts about the topic being studied (Dalkey, 1969; Helmer, 1966). This method usually involves a series of two to four iterative rounds, combined with anonymous, controlled feedback (Dalkey, 1969; Judd, 1972). In the present study since consensus was reached after only two rounds no further iterations of the process were performed. The questions asked in round one were open-ended to allow experts to generate as many important ideas as possible without feeling restricted (Dalkey, 1969). Questions asked in round two were close-ended; hence they were more restrictive (Linstone & Turoff, 2002). Biology instructors who took part in the study remained anonymous: this was an advantage because they could communicate their ideas freely and effectively without feeling pressured to support ideas posed by other influential or highly respected expert biology instructors (Dalkey, 1969; Degerman & Tibell, 2012; Delbecq et al., 1975).

4.3.1 Selection of Biology Experts

Researchers define the word expert in different ways, for instance, Grisham (2009, p. 11) defines an expert as “a person that has at least 20 years of practical experience working in an international/multicultural environment in any industry; or a person that has an advanced degree in leadership or cross-cultural studies with over 20 years of research, teaching, publication experience; or a combination of the two.” In this study, an expert is defined as anyone who is competent in biology, holds an advanced degree in biology (either Masters or Ph.D.), and has taught biology course(s) at a major research university in the Midwest of the United States for at least three years. Biology instructors were invited via email, which resulted in twenty expert instructors volunteering to participate in round one, of which seven participated in round two. Although the number of experts decreased in round 2, more experts were not recruited because, as stated by Ludwig and Starr (2005), the validity and reliability of Delphi results does not depend on the number of participants. Instead, it depends on the expertise of the participants. Furthermore, more experts were not recruited because, according to Delbecq and colleagues (1975), homogenous groups of experts (biology experts in this case) tend to provide similar ideas. It is important to point out that in this study, the words “biology expert” and “biology instructor” are used interchangeably.

4.3.2 Questionnaire 1: Exploration Phase Informed by the Delphi Method

In round one, an open-ended Questionnaire 1 (Appendix B) was given to expert biology instructors to identify up to 10 biochemistry and chemistry concepts (**C**) they consider to be important for the biology course(s) they teach (RQ-1). The instructors were also asked to provide examples of their exam questions that require students to use one or more of these "important" biochemistry or chemistry concepts.

The concepts provided by the biology instructors were classified into categories based on similarity and relevancy. The concepts were classified into 14 categories and then, through peer debriefing, they were validated by six other researchers with specialties in biochemistry, biology, chemistry and education. The 14 categories were used to inform the design of questionnaire 2 (Appendix C) that was used in the confirmation stage described in section 4.3.3. It is important to point out that as shown in Table 4.2, category 14, the instructors also provided examples of representations they considered to be relevant to the biology courses they taught. The representations were classified into four categories based on similarity and relevancy. These four categories, particulate models, graphs, chemical equations, and mathematical equations, were subsequently used to inform the design of a representations survey questionnaire (Questionnaire 3).

4.3.3 Confirmation Phase Informed by the Delphi Method

Questionnaire 2 (Appendix C) asked expert biology instructors to rate the level of importance of the biochemistry and chemistry concepts that had been provided as responses to Questionnaire 1. Although a 5-point Likert scale was used, the number of ratings for 1 and 2 on the scale were added to give a total percentage of respondents who deemed that item unimportant. Similarly, the number of ratings for 4 and 5 were summed to give a total percentage of respondents who deemed an item to be important. The "undecided" ratings were not changed. Descriptive statistics in the form of percentages were used to analyze the Likert scale data as "important", "undecided" or "not important" to summarize responses from the expert biology instructors who participated in the survey. The latter was done because the aim was to summarize the experts' responses and not to use their responses as a representative sample for a population.

Questionnaire 2 also asked the experts to specify how they expected the students to reason with the concepts they rated as being important for the courses they taught. Open coding (Strauss & Corbin, 1998) was used to analyze the experts' responses that stipulated how they expected students to reason with/use the biochemistry and chemistry concepts identified as important for the biology courses they taught. During the open coding process (Strauss & Corbin, 1998), I read each response line by line, and as I read, I underlined and coded each line that informed me how the instructors expected the students to reason with the chemistry and biochemistry concepts they rated as important for the courses they taught. I used the code "reasoning with the concepts (**R-C**)" to label the lines that informed me how students were expected to reason with the concepts. After I finished analyzing the responses, I pulled together all the statements that informed me how the instructors expected the students to reason with the concepts. I re-analyzed these statements using open coding. This analysis produced themes, which through constant comparison, I realized that they repeated across the 14 categories in Table 4.2. therefore, I decided to condense the 14 categories into six themes (see Results section) which better aligned with the themes from the open coding analysis.

The Likert agreement level was measured by calculating the percentage of experts who rated each concept as either important or not important. I decided to stop this study after round 2 because most of the concepts were confirmed to be either important or not important by 50% or more of the expert biology instructors. Once the data from the exploration stage and the confirmation stage were analyzed, member checking (Carlson, 2010; Creswell, 2009; Lincoln & Guba, 1989) was conducted by interview with respondents. Member checking was done on the data compiled from Questionnaire 2. This was done in order to establish the authenticity of the analyzed data. The biology instructors verified that their ideas had been reported correctly.

4.3.4 Questionnaire 3: Online Qualtrics Survey for Biochemistry and Chemistry Representations of Importance to Biology Courses.

An open-ended, online qualitative survey (Appendix D) was developed to further investigate the nature and use of chemistry and biochemistry representations in biology courses for this study. Open ended questions were used because they allow the participants to speak their minds without being forced to think in a particular way (Gay & Airasian, 2003). A web based survey was used because (i) it is cheap as no paper or pen is used and (ii) it is easy to deliver (Fleming et al., 2013; Kwak & Radler, 2002). To increase the response rate (Mcclelland, 1994), I designed a simple survey that required approximately ten minutes to complete.

The questions required instructors to (i) state the various biochemistry and chemistry representations (**M)** that are relevant to the biology courses they teach (RQ-3), and (ii) explain how they expect students to reason with the identified representations (**R-M**) (RQ-4). To identify a comprehensive representation of biology faculty to participate in the survey, all the biology courses that students (biology majors) must take were identified, and then the biology faculty who had taught the identified biology courses in the previous three years were invited to participate. Once developed, the content validity of the questions was checked (Cohen, Manion, & Morrison, 2000). This was achieved by giving the survey to biochemistry, biology and chemistry PhD students. These students were asked to check if the language used was clear and appropriate. In addition to content validity, face validity was checked: that is, at "face value" the survey questions had to appear to be addressing RQ-3 and RQ-4 (Cohen et al., 2000). Once validity was checked, the link to the questionnaire was emailed to the participants.

Deductive analysis was used to categorize representations. During deductive analysis, the four categories of representation, *graphs*, *particulate models*, *mathematical equations* and *chemical equations*, were used as a categorization matrix which was, in turn, used to classify the representations from the data supplied in response to Questionnaire 3. Table 1 summarizes the steps that were employed to address the four research questions posed in this study. This table also shows how the CRM model informed the collection and analysis of the data. As shown in table 1, data collected from Exploration Phase was comprised of concepts (**C**) and representations (**M**). These concepts and representations were further grouped into categories that were used in the Confirmation Phase of the study. The importance of the concepts and representations was rated and specifications of how students are expected to reason with the concepts (**R-C**) and representations (**R-M**) were provided. This was followed by interpretation of the data.

Table 4.1: Summary of the Three-Stage Process used to Collect Data Regarding the Chemistry and Biochemistry Concepts the Biology Instructors Consider to be Important for the Courses They Teach.

Stages	How to use the CRM Model to guide and inform data analysis		
	C/R-C	**M/R-M**	Instrument or Examples
Explore: What would faculty like to assume that students know when they enter each biology course at this institution?	Compile an organized list of the most important concepts **(C)** provided by faculty in response to Questionnaire 1	From sample exam questions, list biochemistry and chemistry representations **(M)** that are relevant to biology courses at this institution.	Questionnaire 1 (Appendix B)
Group concepts and representations into themes	Concepts grouped into subject matter categories	Representations grouped into different types	Table 4.2 Table 4.3
Confirm**:** How do faculty rate the level of importance of each concept and representation? Give examples to specify what students are expected to do with that knowledge.	Calculate the frequency of respondents who consider each listed biochemistry or chemistry concept to be important or not important. Compile a list of how students are expected to use/reason with the important concepts (**R-C**)	Calculate the frequency of respondents who consider each listed biochemistry or chemistry representation to be important or not important. Compile a list of how students are expected to use/reason with the important representations (**R-M**)	Questionnaire 2 (Appendix C) Table 4.2
Illustrate: Which concepts are important and how are students expected to represent and use them?	Show how students are expected to use their knowledge by considering both the concepts and the representations typically used by students to answer sample exam questions as well as quotes and other examples provided by faculty who participated in each round of the study.		Tables 4.3 and 4.4, Exam questions, e.g. figures 1-8 Quotes from instructors: Questionnaire C and D

4.4 Results and Discussion

For all three rounds of data collection outlined in table 4.1, respondents were roughly representative of faculty members who teach biology at the current institution, although there is some evidence of self-selection since no one provided any information about upper division courses in ecology or evolution. Biology instructors were invited via email, which resulted in twenty expert instructors volunteering to participate in the Exploration Phase. These professors who responded to Questionnaire 1 (Appendix B) provided exam questions from 11 different courses. In response to Questionnaire 2 (Appendix C), seven biology professors provided information about eight different courses. In the final round, 13 biology professors who responded to an online Qualtrics Survey (Appendix D) provided information about 23 biology courses. Although the methods and timing employed were in favor of a high response rate, the response rate at each round varied due to a number of reasons. Firstly, some biology instructors pointed out that biochemistry and chemistry concepts, and the related representations, were not at all relevant to their specific biology course, and thus they did not participate in the survey. Secondly, some participants were at one time unavailable due to illness, sabbatical leave, an administrative assignment, or leaving their job. Thirdly, some biology instructors' working schedule was so hectic and busy that they were sometimes not able to participate, thus, for a variety of reasons, some did not provide responses for all rounds of this study.

As further evidence that a comprehensive representation of biology faculty participated and to further characterize the participants, the textbooks required by respondents for biology students at the current institution were identified. Those who participated in all three rounds used Alberts et al. (2013) *Essential Cell Biology*, Nicholls et al. (2012) *From Neuron to Brain*, Sadava et al. (2008) *Life: The Science of Biology*, and Sun (2014) *Introduction to Microbiology*. Participants who responded to the first and third but not the second stage required students to purchase Raven et al. (2008) *Biology* and Tortora & Derrickson (2014) *Principles of Anatomy and Physiology*. Participants who responded to the first and second but not the third round required students to use the Urry et al. (2012) *Campbell Biology in Focus*. Participants who required students to purchase Klug et al. (2014) *Concepts of Genetics* and Lodish et al. (2007) *Molecular Cell Biology* responded only to the first and third stage of the study respectively. Faculty members sometimes did not require students to purchase textbooks for upper division courses.

4.4.1 RQ-1: Biochemistry and Chemistry Concepts Important to Biology Courses (**C**)

In addressing RQ-1 and in response to round 1 of the Delphi method in which instructors' listed up to ten most important concepts of relevance to their courses, a total of 100 concepts were provided by the expert biology instructors. This number was decreased to 74 by merging descriptions of similar concepts. The 74 concepts were then grouped into 14 major categories (Table 4.2) based on similarity and relevance, and used to prepare Questionnaire 2 in which biology instructors were asked to rate the level of importance of each concept to the particular courses they teach. The findings are presented in Table 4.2.

Since instructors were restricted to a maximum of 10 concepts, it is important to note that the 74 listed concepts (Table 4.2) are not meant to provide a complete list of all the concepts the respondents considered key to mastering their courses. Clearly, there are many other concepts taught in chemistry and biochemistry courses that are necessary for biology understanding, and which have been cited in textbooks and published in comprehensive studies in the literature (e.g. Tansey et al., 2013; Wright et al., 2013). However, the importance assigned to these specific 74 concepts by biology instructors suggests that introductory chemistry and biochemistry courses at the current institution should especially focus on them and their significance and application to biological examples.

Table 4.2: Frequency of Chemistry and Biochemistry Concepts from the Exploration Stage Being Rated in the Confirmation Stage as Being Important or not Important to Biology Courses They Teach

Exploration Stage (n=20 participants)	Confirmation Stage (in percent of courses)		
	Frequency of ratings of the level of importance for each concept (n = 8)		
	1 not important	2 undecided	3 important
1. Properties of Water			
heat capacity	38	50	13
cohesion	25	25	50
surface tension	25	13	63
hydrophilicity	0	0	88
hydrophobicity	0	0	88
2. Chemical Bonds			
coulombic interactions	13	38	50
dipole interactions, dipole-dipole forces	0	25	75
ester linkages	0	25	75

Table 4.2, continued

Exploration Stage (n=20 participants)	Confirmation Stage (in percent of courses)		
	Frequency of ratings of the level of importance for each concept (n = 8)		
	1 not important	2 undecided	3 important
hydrogen bonding	0	13	88
ionic bonding	0	0	100
non-covalent bonds	0	0	100
polar & non-polar [properties of amino acid side-chains]	0	0	100
3. Chemical Reactions			
nucleophilic substitution reactions	25	50	25
redox reactions	0	25	75
anabolic and catabolic reactions	0	50	75
hydrolysis reactions	0	13	88
4. Chemical Equilibrium			
Nernst equation	0	13	75
Le Chatelier's principle	13	0	75
5. Enzymes			
enzyme kinetics	13	25	63
activation energy	0	25	75
role of inhibitors	0	0	100
property & function of enzymes	0	0	100
substrate binding	0	0	100
signal transduction	0	0	100
6. Macromolecules			
lipids	0	0	100
amphipathic molecules	0	25	75
proteins	0	0	100
amino acids	0	0	100
function of proteins	0	0	100
protein structure	0	0	100
carbohydrates	0	13	100
nucleic acids	0	13	100

Table 4.2, continued

Exploration Stage (n=20 participants)	Confirmation Stage (in percent of courses)		
	Frequency of ratings of the level of importance for each concept (n = 8)		
	1 not important	2 undecided	3 important
7. Cellular Processes			
tricarboxylic acid cycle (TCA)	13	25	63
electron transport chain	13	25	63
fermentation	25	13	63
glycolysis	13	13	75
regulation of cell processes	0	0	100
8. Thermodynamics			
enthalpy	0	13	75
entropy	0	13	88
Gibbs Free Energy	0	13	88
osmotic pressure	0	13	88
osmosis	0	13	100
diffusion	0	0	100
potential energy	0	0	100
ATP structure & hydrolysis	0	0	100
9. Analytical Techniques			
UV Vis Spectroscopy	63	25	13
chromatography	50	25	25
X-ray crystallography	38	13	50
microscopy	0	0	88
10. Gas Laws			
Henry’s Law of gas solubility	50	13	38
Dalton’s Law of partial pressure	50	13	38
STP	50	13	38
11. Atomic Theory & Structure			
VSEPR	38	38	13
atomic orbitals	63	0	25
structure of the atom	38	13	50
electronegativity	13	13	63
cation(s) and anion(s)	13	0	88
charged particle interactions	13	0	88

Table 4.2, continued

Exploration Stage (n=20 participants)	Confirmation Stage (in percent of courses)		
	Frequency of ratings of the level of importance for each concept (n = 8)		
	1 not important	2 undecided	3 important
12. Solutions and Mixtures			
colloids	50	25	25
Beer Lambert Law	25	38	38
suspension	38	38	50
solutions	13	0	75
molarity calculations	13	0	88
13. Acids & Bases			
Lewis acids & bases	63	13	13
acid dissociation Ka & pKa	13	63	25
Brønsted acids & bases	50	13	25
Henderson-Hasselbalch	13	25	50
acid and base strength	13	13	63
pH	0	0	100
buffers	0	0	100
14. Visual Representations			
math equations (e.g. Henderson-Hasselbalch, enzyme kinetics)	13	25	63
structures of organic molecules	0	13	88
space filling models, ribbons and wireframes (e.g. amino acids, proteins and phospholipids)	0	0	100
graphs (e.g. enzyme kinetics and solubility graphs)	0	0	100

Regarding the rating of importance (Questionnaire 2; Appendix C) of each concept shown in Table 4.2, the data shows very little consensus that any of the listed concepts are not important to biology. In fact, only UV Vis Spectroscopy, atomic orbitals, and Lewis acids and bases were rated as not important to their biology courses by more than half of the expert biology instructors. Furthermore, all 74 concepts were considered important by at least one instructor for at least one biology course. When some biology instructors were questioned during member checking interviews, they indicated that they rated some concepts as “undecided” because knowledge of those concepts was important but not directly required for understanding the biology course(s) they taught.

As discussed in greater detail later in this paper, visual representations (Group 14) were highly rated by almost all instructors, reflecting the modern acceptance that science is a visual subject in which learning and research is considerably facilitated by the use of representations (e.g. Schönborn & Anderson, 2010; Tsui & Treagust, 2013). Indeed, the fact that visual representations were rated as important by the majority of the instructors substantiates the fact that they are essential for knowledge construction (e.g. Peña & Quílez, 2001; Treagust et al., 2002) and for promoting conceptual understanding and visualization of abstract phenomena (e.g. Kozma, 2000; Schönborn & Anderson, 2010).

The extensive nature of the 74 listed concepts, begs the question of how well all of this material can be covered in the two years of chemistry and biochemistry typically required for biology students at the current institution. This suggests the need to discuss the extent of coverage of each topic and the possibility of rationalization of certain areas to minimize repetition so that other areas can be covered in greater depth. For example, those topics in general- and organic chemistry textbooks, that do not appear on the list in Table 4.2, could be considered less important to biology students and dropped from chemistry courses for life science students, or more effort made to help biology faculty and students grasp their importance. Another key consideration could be how the curriculum for biology students could be modified to facilitate students’ logical construction of knowledge of concepts to enhance vertical progression between courses starting with the basics in chemistry and progressing to higher levels of understanding in biochemistry before their application in biology.

In summary, these findings suggest a strong need to consider molecules and reactions in a biological context when students learn how molecules interact with each other. For example, biology students need to understand how, the pH of an aqueous cellular environment, which may be partially organic in nature, impacts molecular interactions. These sorts of considerations are crucial for an understanding of how chemistry and biochemistry applies to living organisms.

4.4.2 RQ-2: How do Biology Instructors Expect Students to Use Their Knowledge of Biochemistry and Chemistry Concepts in Their Various Biology Courses? (**R-C**)

As per RQ-2 and the theoretical framework, the CRM model, I felt it was important to not only establish what concepts (**C**) biology instructors consider important to biology students but also how students are expected to use/reason with the concepts (**R-C**). To address this question I used Questionnaires 1 and 2 to respectively collect two types of data from the biology instructors: 1) Quotations from instructors, about what they expected students to do with their knowledge of each topic or concept in their biology courses (Questionnaire 2); and, 2) Examples of test questions from their courses that, in their view, require students to use their knowledge of each topic or concept in order to give a sound answer (Questionnaire 1). In this section I use selected examples of questions and quotations to address RQ-2. To facilitate the clarity of the discussion I also group the 14 categories (Table 4.2) into six common, overlapping themes.

4.4.2.1 Theme 1: Properties of Water, Chemical Bonds and Biomolecular Structure and Function

Extensive scientific research (e.g. Bertoluzza, Fagnanoa, Morellib, Tintia, & Tosic, 1993; Wiggins, 1990) has demonstrated the universal role that water plays as a medium within, and outside cells by virtue of its properties relating to solubility, hydrophilicity and hydrophobicity. Thus, as suggested by the following selected quotes, biology instructors expect students to be able to use their knowledge of properties such as hydrophobicity and hydrophilicity to explain how water has a strong influence on the structure and function of biomolecules, including bio membranes (**R-C**).

> *"Needed for understanding behavior of DNA in solution which we discuss as background to DNA hybridization."*
>
> *"Why chemicals & molecules exhibit these properties and importance in context of biological membranes."*
>
> *"Apply to understand molecular partitioning and i/o in cell."*

The properties of water, in turn, strongly influence the non-covalent interactions that determine macromolecular folding and structure, and the specificity of binding interactions with other molecules involved in multiple cellular functions. It is not surprising, therefore, that biology instructors would like students to be able to apply their knowledge of the role non-covalent interactions like H-bonds, ionic bonds, dipole-dipole and coulombic interactions, and van der Waal's forces to understanding of macromolecular and membrane structure, behavior and function. In this regard, the following quotes from the biology instructors illustrate what the faculty wrote when they were asked what they expected students to do with their knowledge of non-covalent bonds in general to explain the structure and function of biomolecules.

> *"Things that hold biological molecules together in cell structures. Reversibility of non-covalent interactions. Protein tertiary structure."*
>
> *"Understand these interactions among macromolecules in the cell."*
>
> *"These are the mainstay of biomolecule interaction. H-bonds & van der Waals especially."*

Taken together, even though the quotes are about what students should know and not how they would use their knowledge, the data from biology instructors presented above and in Table 4.2 suggest that the basic concepts of this topic are of significance to biology in learning about the structure and function of biomolecules in living systems. The need to apply this conceptual knowledge to understand and solve problems (**R-C**) to do with biomolecules is supported by the following example (Fig. 4.1) of how instructors expected their students to use such basic concepts for assessments in their biology courses.

The question in Fig. 4.1 concurs with the above quotes in that it illustrates how the instructors expected the students to use their understanding of hydrophobicity, hydrophilicity and non-covalent interactions such as hydrogen-bonding and ionic bonds to relate biomolecular structure to function. The example of an answer in Fig. 4.1 is a typical response provided by one of three participants who were recruited to pilot this question. Typical of the nature of open-ended questions the three participants provided different but scientifically feasible answers, which included the use of common concepts.

These concepts included knowledge of: different types of amino acids; non-covalent interactions such as hydrogen bonding, hydrophobic and hydrophilic interactions; charged and uncharged amino acids; and protein conformation. Overall, this question is a transfer-, application type question (**R-C**; Anderson et al., 2013) in that it requires students to transfer and apply their understanding of the above mentioned concepts in order to explain how they contribute to protein structure, function and flexibility.

Figure 1

Give a specific example of how primary structure influences the shape and therefore the function of a protein. (The amino acid structures are on the back page of the exam). Then give a specific example of how protein function depends on the protein being flexible and able to move.

Example of a typical answer

Primary structure influences a protein's shape because the different amino acids will have different non-covalent interactions with each other and their environment. For example, a potassium ion channel protein has lots of hydrophobic amino acids in the part of the protein that is embedded in the cell membrane; these amino acids interact with the lipids in the membrane. There are hydrophilic amino acids in the parts of the protein that stick out on either side of the membrane, interacting with water molecules in the aqueous environment inside and outside of the cell. In the interior of the protein, there are negatively charged amino acids that can interact with the positively charged potassium ion to allow it to move through the protein, crossing the membrane.

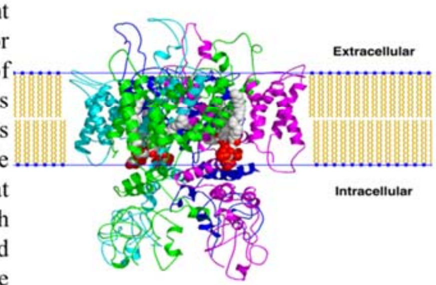


Figure 4.1: An Example of a Question for a Theme 1 (Properties of Water, Chemical Bonds and Biomolecular Structure and Function) from a Lower Division Second Year Biology Course.

In order to successfully answer this question, I assume that students are expected to remember knowledge (**R-C**) about different types of amino acids, hydrophobic and hydrophilic interactions, hydrogen bonding, and how the charges of different types of amino acids determine the structure, function and flexibility of proteins. Furthermore, I assume that students are expected to use a specific example of a protein, such as the potassium ion channel, to integrate (**R-C**) and explain how different types of amino acid side chain properties and non-covalent interactions determine the shape and function of proteins such as a potassium channel. Moreover, I assume that students are expected to transfer and apply knowledge (**R-C**) about the characteristics of the different types of amino acid side chains and the formation of non-covalent interactions in order to explain how they influence the function, shape and flexibility of proteins like, for instance, a potassium ion channel.

4.4.2.2 Theme 2: (Bio)Chemical Reactions, Enzymes, Cellular Processes and Their Regulation

Instructors considered it important for students to learn how to apply (**R-C**) their knowledge (**C**) of key (bio)chemical reactions, enzymes and cellular processes to understanding and solving problems (**R-C**) to do with various biological systems and their regulation in cells. Of the basic chemical reactions, instructors particularly favored redox and hydrolysis reactions as these play major roles in cells in energy generation but also need to be understood in the context of laboratory work. The instructors provided the following specifications regarding how students should reason with concepts (**R-C**) related to redox reactions and metabolism.

> "*They need to know what in a microbiological media can serve as reductant/ oxidant/ e- source/sink for metabolism.*"

"Energy generation –what drives biochem. Rxns [reactions]"

Biology instructors see knowledge of basic chemical reactions and enzyme function coming together, not down to the organic mechanism level, but at the anabolic and catabolic level of metabolism and how the different cellular processes impact regulation of systems at the organism level. This is apparent from the following selected quotes:

"Talk about lac operon catabolite – I assume they know about catabolic reactions."

"A major part [of my course] is a discussion of how bacteria obtain energy from catabolic reactions."

These expectations by instructors regarding what they wish students to know, are further supported by the following example (Fig. 4.2) of a test question that shows how that knowledge should be used, according to responses to Questionnaire 1. This question is probing students' understanding of concepts such as dosing regimen, rate of drug clearance, poor, normal and ultrafast metabolizers and thermodynamic and kinetic factors affecting drug metabolism. To successfully answer this question, students are expected to remember (**R-C**) knowledge associated with these concepts, and to transfer and apply (**R-C**) their knowledge of metabolism to explain the difference between poor, normal and ultrafast metabolizers regarding the rate at which they metabolize and clear drugs. Moreover, students are expected to know the local and system effects (**R-C**) of being a poor, normal and an ultrafast metabolizer, that is, they are expected to explain how, for example, differences in the CYP2D6 gene affect the pharmacokinetics of patients and thus their dosing regimen. Furthermore, students are expected to be able to evaluate (**R-C**) how and why dosing regimen is different for poor, normal and ultrafast metabolizers.

Figure 2

Predict what will happen with a dosing regimen if a person is a poor metabolizer; a normal metabolizer; and an ultrafast metabolizer of a drug

Example of a typical answer

If a person is a poor metabolizer, they will metabolize the drug more slowly, so a higher concentration will build up in their body. Therefore, they should be given doses with longer time interval between so that they don't have too high of a concentration of the drug in their body. If they are given the next dose of a drug before the previous dose has been metabolized, more of the drug will accumulate, which could have a negative effect. For a person who is an ultrafast metabolizer, they metabolize the drug much faster than normal, so they must be given doses at shorter time intervals in order to maintain the appropriate concentration of the drug in their body and for that drug to have an effect. If the time between doses is too long, there will not be enough of the drug in their bloodstream to have the intended effect because it will all have broken down. A person who is a normal metabolizer would fall somewhere in between these two extremes. Given the drug at appropriate intervals, it will have broken down before the next dose is given, maintaining a proper concentration in the body to have the intended effect.

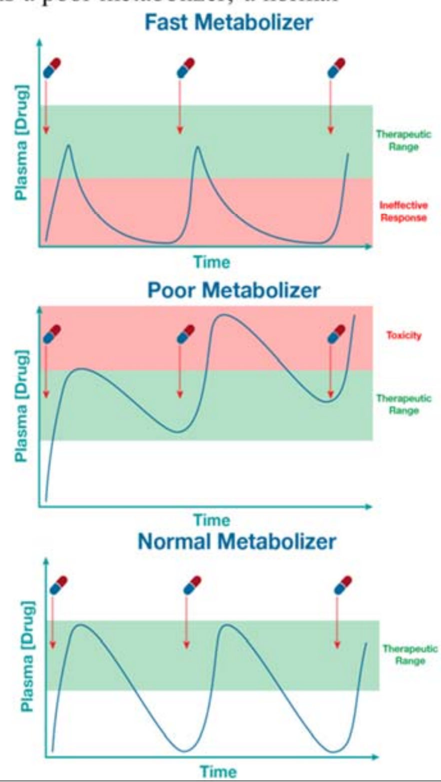


Figure 4.2: An Example of a Question for a Theme 2 ((Bio)chemical Reactions, Enzymes, Cellular Processes and Their Regulation) from an Upper Division Biology Course

4.4.2.3 Theme 3: Thermodynamics Including Chemical Equilibrium, ATP and Membrane Transport

An understanding of enzymatic reactions and metabolic processes is incomplete without the ability to apply knowledge of thermodynamics to answer important questions like: why does a metabolic reaction or pathway proceed in a particular direction and how does pathway efficiency contribute to thermoregulation? Thus biology instructors placed great emphasis on understanding the laws of thermodynamics to be able to predict the behavior of reactions, processes, pathways and even metabolic systems. Examples of quotes indicating what students need to be able to do with thermodynamic knowledge in general included the following:

"Predict equilibrium status of enzymatic reactions."

"What molecules can serve as an energy source."

"Membrane potential as a regulatory function-> photoreceptor and muscle function."

"Apply these in thinking about non-eq systems."

The above expectations on how students are expected to use their knowledge are supported by the following example of an exam question (Fig. 4.3) provided in response to Questionnaire 1.

The above question is testing students' understanding of concepts such as K_{eq}, ΔG°, spontaneity, and thermodynamically favorable and unfavorable reactions. This question shows that the instructor expects students to have the ability to apply knowledge (**R-C**) of thermodynamics to explain why a metabolic reaction or pathway proceeds in a particular direction. Therefore, in order to successfully answer this question, students are expected to remember, transfer and apply (**R-C**) knowledge related to the stated concepts; critically analyze the given experimental information in order to know the values to use to calculate K_{eq}, ΔG°; use the appropriate equations to calculate K_{eq}, ΔG°; and use the calculated values to predict if the reaction is spontaneous or not. Interestingly, although this question was supplied by a biology instructor, the key influence of cellular concentrations of intermediates on the spontaneity of such reactions is ignored in favor of standard conditions of temperature and (1M) concentration which would never exist in a cell because of obvious toxicity. This suggests that even biologists may revert to a chemist's treatment of metabolic reactions. Once again, on the basis of the above, it is evident that expert biology instructors consider low order reasoning skills (**R-C**) such as the mindful memorization of concepts, integration of related concepts (**R-C**) and high order reasoning skills such as the ability to transfer and apply knowledge of concepts; and the ability to reason algorithmically (**R-C**), to be important for biology courses.

Figure 3

You are studying the enzymatic reaction that drives the third step in glycolysis, the one catalyzed by phosphofructokinase (PFK):
fructose-6-phosphate + ATP ⇌ fructose-1,6 diphosphate + ADP
In an eppendorf tube, you start the reaction with a small amount of the enzyme PFK and your favorite concentrations of reactants and let it run to equilibrium. You then determine that the concentrations at equilibrium of each component are as follows:
[fructose 6-phosphate] = 1 mM [ATP] = 10 mM
[fructose 1,6-diphosphate] = 100 mM [ADP] = 100 mM

A) Calculate the K_{eq} for this reaction:
Answer:
K_{eq} = [Fr 1,6-diP][ADP]/ [Fr 6-P][ATP] = $(10^{-1}\ M)(10^{-1}\ M)/\ (10^{-3}\ M)(10^{-2}\ M) = 10^{-2}/10^{-5} = 10^{3}$

B) Calculate the ΔG° for this reaction
Answer:
At equilibrium,
$\Delta G^{\circ} = -RT \ln (K_{eq})$
$= -5.7$ kJ/mol · log (K_{eq})
$= -5.7$ kJ/mol · log (10^{3})
$= -5.7$ kJ/mol · 3
= -17.1 kJ/mol

C) Will this reaction run spontaneously under standard conditions, from left to right, as written? ANSWER YES or NO, and in a sentence, EXPLAIN how you can tell:
Answer:
YES. We can tell it is spontaneous because the standard Gibbs free energy change (ΔG°) is <0. (or, the K_{eq} is >> 1).

D) The phosphorylation of fructose 6-phosphate is very unfavorable:
Fructose 6-phosphate + P_i ⇌ fructose 1,6- diphosphate
$\Delta G^{\circ} = +15$kJ/mole
In a sentence or two, EXPLAIN: how is phosphofructokinase able to carry out this reaction in the cell?
Answer:
The enzyme carries out a COUPLED REACTION, in which the favorable hydrolysis of ATP is coupled to the unfavorable phosphorylation of fructose 6-P. The overall, or net, reaction is favorable, as determined by the sum of ΔG° for the two reactions.

Figure 4.3: An Example of a Question for a Theme 3 (Thermodynamics Including Chemical Equilibrium, ATP and Membrane Transport) from a Lower Division Second Year Biology Course

4.4.2.4 Theme 4: Acids and Bases

Nearly all biology instructors expected students to be able to transfer and apply their knowledge of acid-base concepts, such as pH and buffers, to explain how they affect the structure and functional behavior of proteins at the molecular level while also playing a buffering role at the physiological level. Acid-base considerations are also considered key to laboratory practice. This expectation is evident by the following quotes about the use of acids and bases:

“Understand biological acids & bases, function[al] groups on proteins & nucleic acids.”

“We discuss pH, students need to understand what pH is. We especially focus on alkaline pH denaturing DNA. And focus on specifics of Southern blot and plasmid isolation via alkaline lysis methods.”

“Basics of buffering- implications of variation- protein structure function.”

How instructors, expect students to use their knowledge of acid-base, is further supported by the following example of an exam question (Fig. 4.4). The question in Fig. 4.4 below corresponds to some quotes given by the participants regarding how they expect students to use their understanding of pH. Interestingly, once again as in the case of the exam question in Fig. 4.3, students were not specifically asked to identify which ionic species predominates under cellular pH conditions, something of obvious importance to biology. The question in Fig. 4.4 covers both theme one (T1) and theme four (T4): that is, the question addresses biomolecular structure and function (T1) and acids and bases (T4). Based on the above question, students are expected to be familiar with knowledge associated with concepts such as hydrogen bonds and their formation; characteristics of the R-groups of the given amino acids (H, G, E); peptide bonds and how they are formed; and the effect of pH and pK_a on the charge of the given amino acids (H, G, E). For this question, students are expected to remember knowledge relevant to the stated concepts; and integrate, transfer and apply understanding of these concepts (**R-C**) in order to be able to draw the tripeptide (H-G-E), identify the hydrogens that will participate in hydrogen bonding and determine the charge of the tripeptide at the given pH values. On the basis of the above, it is evident that the expert biology instructors expect students to have attained reasoning skills (**R-C**) such as the mindful memorization of concepts like hydrogen bonds and charge; integration of related concepts; and transfer and application of knowledge about pH and ionization.

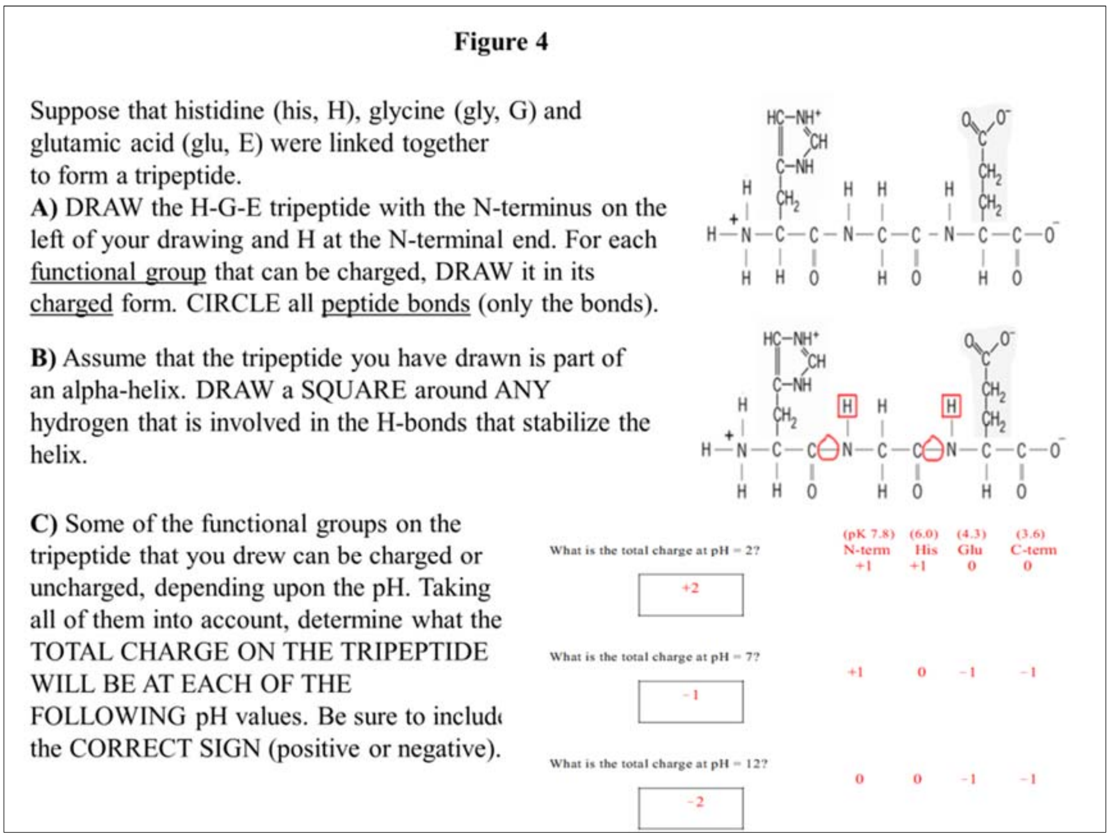


Figure 4.4: An Example of a Question for a Theme 1(Properties of Water, Chemical Bonds and Biomolecular Structure and Function) and Theme 4 (Acids and Bases) from a Lower Division Second Year Biology Course

4.4.2.5 Theme 5: Solutions, Mixtures and Analytical Techniques

Based on the instructors' Likert scale ratings, concepts such as molar concentration, Beer-Lambert Law and solutions were selected to be important for biology courses. Some instructors showed that students needed to understand only basic information related to the stated concepts, whereas other instructors showed that students needed to be able to use the Beer-Lambert law for calculations related to spectrophotometry. The following quotes show what the instructors wrote when they were asked how they expect students to make use of these concepts:

"Concentration of ions and other molecules in cells."

"Calculations-Spectrophotometry."

These quotes show what students should know, but to see how students would be expected to use that knowledge, examples of exam questions instructors provided illustrate how they expect students to use their knowledge of solutions and mixtures. Fig. 4.5 below shows an example of an exam question supplied by an instructor. The question in Fig. 4.5 addresses both theme three (T3) and theme five (T5), that is, the question covers thermodynamics and equilibrium (T3) in addition to solutions, mixtures and analytical techniques (T5). Furthermore, this question requires students to apply (**R-C**) their understanding of membrane potential to an experimental setting. What is even more interesting about this question is the fact that students need to be familiar with concentration units and know how to convert from one unit (mM) to the next unit (M). The above question is testing students' understanding of concepts such as equilibrium potential, membrane potential, Gibb's free energy, Nernst equation, conversion factors between the units of molarity, energetics of ion transport via the membrane and the Na/glucose symporter.

Figure 5

You are studying the membrane properties of human fibroblasts growing in a culture dish in artificial medium. So far, you have determined that it has a V_m = -70mV, and the following solute concentrations:

Solute	***[Intracellular]***	***[Extracellular] (culture medium)***
glucose	200 mM	200 mM
Ca^{++}	10^{-8}M	10^{-2}M
Na^{+}	20 mM	20 mM
K^{+}	150 mM	1.5mM

A) Calculate the equilibrium potential (V_X) for EACH of the IONS.

Answer

At equilibrium, V_X = 59mV/z x log ($[X]_{out}$/ $[X]_{in}$)

V_{Ca} = 59mV/2 x log (10^{-2}M/ 10^{-8}M)

= 59mV/2 x log (10^{-6})

= **+177mV**

V_{Na} = 59mV × log (20mM / 20mM)

= 59mV × log (1)

= **0 mV**

V_K = 59mV × log (1.5mM / 150mM)

= 59mV × log (10^{-2})

= **-118 Mv**

B) Calculate the ΔG for the gradient of EACH ION.

Answer;

For a charged molecule X: ΔG = zF(V_m – V_X),

where F = 10 kJ/V · mole

$ΔG_{ca}$ = (2)(10^2 kJ/V· mole)(-0.070V - 0.177V)

= 2 x10^2 kJ/V· mole (-0.247V)

= **-49.4 kJ/mole**

$ΔG_{Na}$ = 10^2 kJ/V· mole (-0.070V - 0V)

= 10^2 kJ/V· mole (-0.070)

= **-7.0 kJ/mole**

$ΔG_K$ = 10^2 kJ/V· mole (-0.070V - (-0.118V))

= 10 kJ/V· mole (+0.048V)

= **+4.8 kJ/mole**

C) Calculate the ΔG for the glucose gradient.

Answer:

For any solute, charged or uncharged:

ΔG = 5.7 kJ/mole × log ($[X]_{in}$ /$[X]_{out}$) + zFV_m

(For gluc, z = 0, so zFV_m = 0)

so: ΔG = 5.7 kJ/mole × log ($[gluc]_{in}$ /$[gluc]_{out}$)

= 5.7 kJ/mole × log (200mM/200μM)

= 5.7 kJ/mole × log (10^3)

= **+17.1 kJ/mole**

D) Under these culture conditions, you find that the Na/glucose symporter in your cells will NOT function efficiently. Based on your calculations, what is the reason for this? EXPLAIN in a sentence or two.

Answer: -2$ΔG_{Na}$ is NOT > $ΔG_{glucose}$. So the magnitude of $ΔG_{Na}$ is not adequate to transport glucose even though the symporter uses the movement of two moles of Na^+ per mole of glucose.

[-2$ΔG_{Na}$ glucose = -2 x -7.0 kJ/mole = 14 kJ; $ΔG_{glucose}$ = 17.1 kJ/mole]

E) Given that these cells are growing in culture, what simple CHANGE could you make that would cause the Na/glucose symporter to transport glucose into the cell efficiently?

Answer: Increase the [Na] in the culture medium until the $[Na]_{out}$ / $[Na]_{in}$ is large enough to give the necessary $ΔG_{Na.}$ [Even a 10-fold difference would do nicely: then V_{Na} would = 59mV, and $ΔG_{Na}$ would = -12.9 kJ/mole, so 2$ΔG_{Na}$ (-25.8 kJ/mole) would be more than adequate]

Figure 4.5: An Example of a Question for a Theme 3 (Thermodynamics Including Chemical Equilibrium, ATP and Membrane Transport) and Theme 5 (Solutions, Mixtures and Analytical Techniques) from a Lower Division Second Year Biology Course

In this question, students are expected to remember knowledge relevant to the stated concepts; integrate knowledge of these concepts with other related concepts in order to know the values to use, from the experimental information, to calculate the equilibrium potential and Gibb’s free energy for each ion. The students are also expected to use appropriate equations in order to calculate the equilibrium potential and Gibb’s free energy for each ion. Furthermore, students are expected to transfer and apply knowledge (**R-C**) related to the stated concepts so as to explain why the Na/glucose symporter will not work under the described conditions and to suggest how the symporter could be changed. Students are also expected to be able to analyze the given experimental information so as to solve a problem about the transport of glucose into a cell using their knowledge of the values needed to calculate equilibrium potential and Gibb's free energy.

4.4.2.6 Theme 6: Atomic Theory and Structure and Gas Laws

These atomic theory and gas law topics were grouped together because of their basic chemistry nature and importance in underpinning much of biology understanding. Although nearly all the atomic theory concepts were shown to be important for biology courses, most instructors showed how they expect students to use concepts with examples of ions. According to the instructors' specifications, it is clear that the instructors expect students to know the biological importance of cations and anions. The instructors provided the following quotations when they were asked how they expect students to make use of these concepts:

"Discuss DNA as a polyanion & discuss counterions."

"Membrane potential, ion transport."

To illustrate how students might be expected to use this knowledge consider a question that probes students' understanding of atomic theory and structure and gas laws shown in Fig. 4.6 below. The question in Fig. 4.6 below is testing students' understanding of Le Chatelier's principle, bicarbonate/carbonic acid buffering and partial pressure. In order to answer the question correctly, students are expected to remember knowledge associated with the stated concepts. They are expected to know the relationship between the gas law and acid-base concepts (integrate) and also be able to transfer and apply knowledge of these concepts in order to state the consequences of not breathing for 90 seconds.

Figure 6

If a person stops breathing for about 90 sec, what would happen?

A. P_{CO2} would decrease, P_{O2} will decrease, pH will decrease and HCO^{-}_{3} will increase
B. P_{CO2} would increase, P_{O2} will decrease, pH will decrease and HCO^{-}_{3} will increase
C. P_{CO2} would increase, P_{O2} will decrease, pH will increase and HCO^{-}_{3} will increase
D. P_{CO2} would decrease, P_{O2} will decrease, pH will decrease and HCO^{-}_{3} will decrease
E. P_{CO2} would decrease, P_{O2} will decrease, pH will increase and HCO^{-}_{3} will increase

Answer:
B. P_{CO2} would increase, P_{O2} will decrease, pH will decrease and HCO^{-}_{3} will increase

Figure 4.6: An Example of a Question for a Theme 4 (Acids and Bases) and Theme 6 (Atomic Theory and Structure and Gas Laws) from a Lower Division First Year Biology Course

In conclusion, and generally speaking, the instructor responses and the exam questions revealed that students are expected to know the importance of biochemistry/chemistry knowledge to biological systems. Furthermore, it appears that the instructors expect the students to have attained a meaningful understanding of the biochemistry/chemistry concepts. This is due to the fact that the exam questions did not only probe students' ability to mindfully memorize concepts. Instead, they probed for students' ability to integrate, transfer, apply and analyze knowledge of biochemistry/chemistry concepts to solve problems and explain biological phenomena (**R-C**). Transfer has been defined by Mayer and Wittrock (1996) as the ability to use or apply knowledge of a concept to solve new problems, answer new questions, or facilitate learning of new subject matter. Indeed, according to the revised Bloom's taxonomy

(Anderson et al., 2001), Anderson et al. (2013), Anderson and Schönborn (2008), Mayer (2002), Schönborn and Bögeholz (2009), transfer, application and analysis/evaluation are among the most important reasoning skills (**R-C**) students ought to have in order to construct a good and meaningful understanding of concepts. Thus mentioned, it is important that biochemistry and chemistry courses designed for life science students, specifically biology students, equip students by giving opportunities to practice both low and high order reasoning skills.

4.4.3 RQ-3: Representations Important to Biology Students (**M**)

Analysis of the data from Questionnaire 1 revealed that biology instructors at the current institution under study use various representations in their courses. The representations were assigned to four categories, namely, particulate models, chemical equations, graphs, and mathematical equations. The importance of these categories was confirmed in instructor responses to Questionnaire 2. I therefore decided to further investigate these four representation categories through the design of a Qualtrics survey (Questionnaire 3). This survey asked instructors to elaborate on the different types of representations (**M**) they use within each category and how they expect students to use (**R-M**) such representations. As shown in Table 4.3, various types of biochemistry and chemistry representations were considered by the instructors to be important for the biology courses under study. This suggests that more time has to be spent teaching these representations and ensuring that students understand the importance of these representations to depicting abstract phenomena. It is not surprising that a large number of representations were shown to be important for biology courses. This is because, according to Schönborn and Bögeholz (2009), representations are "carriers of biological information" (p.935). The representations listed in Table 4.3, above, are related to most of the concepts that were reported in the Confirmation Phase of the study as relevant for biology courses.

Table 4.3: Examples of the Types of Chemistry and Biochemistry Representations the Instructors Regard as Being Relevant to the Biology Courses They Teach.

Types of Representation (M)	
Particulate Models	
Proteins, 3D protein structure	Signal transduction
DNA and RNA structures	Space filling models
Lipid membrane	beta sheet and alpha helix
Chemical Equations	
Acid-base equilibrium reactions	Enzymes, like glycolytic enzymes
Components of respiration and photosynthesis	Autoionization of water
Oxidation	Illustrations of Le-Chatelier's Principle
$H_2O + CO_2 \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+$	Equilibrium reaction of CO_2 and HCO_3^-
Calculation of H+ production in the body	
Graphs	
Michaelis-Menten enzyme kinetics	Hyperchromatic shift and re-association kinetics
Maxwell-Boltzmann distribution	Titration curves where x axis is volume of titrant and y-axis is the pH
Activation energy (delta-G vs. reaction completion)	Absorption spectra where x-axis is wavelength and the y-axis is the absorbance
Cooperativity (bound substrate vs. substrate concentration)	Calibration plot where x-axis is the concentration and y-axis is the absorbance
Graphs	
The absorbance spectra for the two forms of the phytochrome molecule. A graph shows the fraction of the light that is absorbed (y-axis) by a suspension of the molecules as a function of the wavelength of the light (x axis)	Oxygen hemoglobin dissociation curve. X axis partial pressure of oxygen. Y axis percent saturation of hemoglobin (Hb-O2 equilibrium curve)

Table 4.3, continued

Types of Representation (M)	
Mathematical Equations	
Nernst equation	Ideal Gas Law
Gibbs free energy equation	Fick's Law
Michaelis-Menten equation	Diffusion equations for 1, 2, and 3 dimensions
Reaction rate constants	Henderson Hasselbalch
Boyles Law	Calculation of pH ($pH=-log[H^+]$)
Poiseuille equation	$K_w = K_a.K_b$

4.4.4 RQ-4: How Do Biology Instructors Expect Students to Use Biochemistry and Chemistry Representations? (**R**-**M**)

4.4.4.1 Particulate Models

Given that modern biology is a strongly visual subject (Tsui & Treagust, 2013), it was not surprising that the biology instructors in this study considered that particulate models are key to the success of their courses. They supported this opinion by providing a range of examples of how they expect students to be able to use such representations (**R**-**M**). This allowed us to not only classify examples as **R**-**M**-type activities, but to suggest what specific visual skills the student would need to use to perform such activities (Anderson et al., 2013; Schönborn & Anderson, 2010), as discussed below.

Biology instructors suggested a range of ways they might ask students to use particulate models. For example, there was a strong emphasis on using models of macromolecules "To explain protein structure-function relationships," or to "Identify structures and functional groups." Related to this, one instructor stated, "I expect the students to know the general features of DNA and RNA structures, including strand polarity, base and sugar composition, and base-pairings.” Thus, instructors expect students to be able to use particulate models to explain, identify and know- all important visual skills (**R-M**) as defined previously (Anderson et al., 2001; Anderson et al., 2013; Schönborn & Anderson, 2010).

Instructors also emphasized the importance of their students being able to draw (**R-M**) (Anderson et al., 2013; Quillin & Thomas, 2015) or modify diagrams to explain and solve problems. This is evident by the following three examples of quotes:

> *“We only use sketches on the exams, not 3-D models. For example, I may ask students to modify a structure (mutation) and then explain how the modification would affect the function of the structure.”*
>
> *“Memorization of the complete structure of a molecule like phosphatidylcholine is not required, but students should be able to draw the structure of a phospholipid if given the structures of the fatty acids and the polar group. Know the structure of glycerol and how the ester linkages are formed.”*

In order to fully perform tasks with 2D and 3D particulate models and drawings, students always need to be able to transfer their knowledge (**R-C**) from the relevant content domain; to interpret (**R-M**) the representation, they need to decode (**R-M**) the symbolism in the representations (Anderson et al., 2013); spatially rotate (**R-M**) the model to perceive 3D structure; and evaluate the limitations (**R-M**) of the models to establish what they do/do not represent of the ‘real’ structure (Schönborn & Anderson, 2010). All these skills are necessary for working with representations and thus should be taught by giving students multiple experiences at working with representations. Some of the above quotes are supported by Fig. 4.7, an exam question that was provided by an instructor in response to Questionnaire 1.

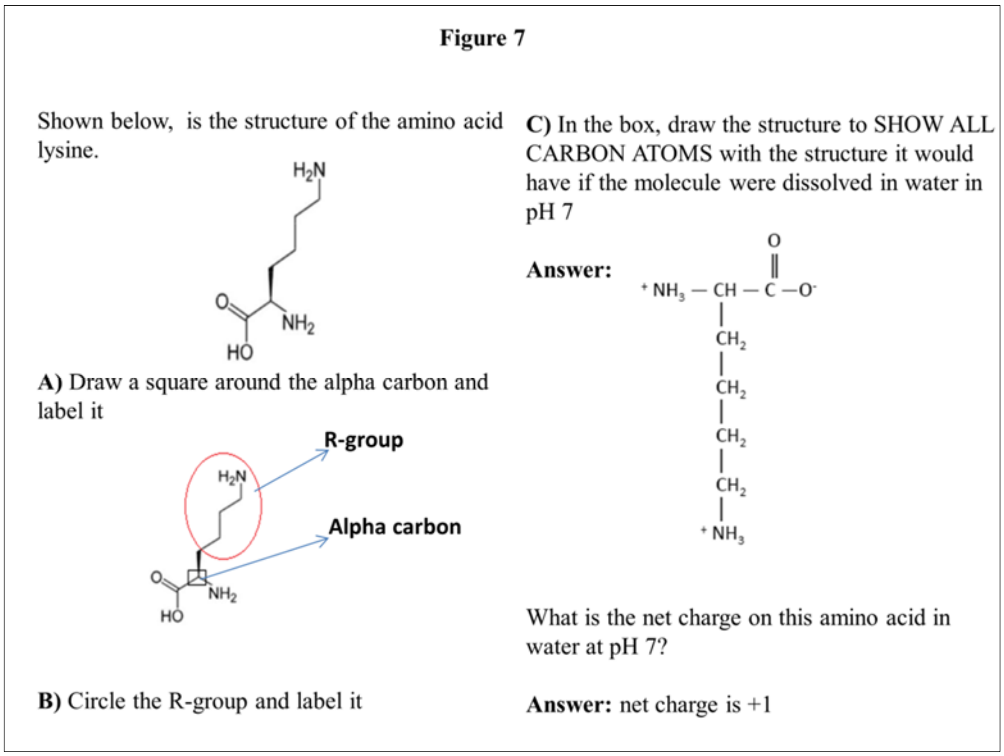


Figure 4.7: An Example of a Question Probing for Students' Ability to Interpret and Use Molecular Models in a Lower Division First Year Biology Course

Regarding this question, students need to remember, integrate, transfer and apply relevant knowledge in order to successfully answer the question. However, since a particulate model of a lysine residue is provided in the question, students need to also reason with the representation (**R-M**). That is, they need to decode the representation by identifying the symbolism depicting the R-group, the alpha carbon, the amine group and the carboxylic acid group. Furthermore, students are expected to know how to construct a lysine residue that shows the appropriate charge for this amino acid at pH 7. They may have memorized the ionic charges for lysine or they might have solved this problem based on the relative pK_a values of the titratable groups of lysine. Similar to this question, in Fig. 4.4, students were asked to draw a tripeptide (H-G-E), also decoding the structure to identify the functional groups, including the N-terminus and the atoms involved in peptide bond formation. Furthermore, students were expected to be able to translate vertically (**R-M**) between the tripeptide and the alpha helix structure (Fig. 4.4, part B) in order to predict and identify the hydrogens that will be involved in hydrogen bonding to stabilize the alpha helix.

Overall, based on these questions and the instructor quotes provided above, it could be deduced that interpretation of diagrams and construction/drawing of diagrams (**R-M**) is important to the biology courses taught by the participating instructors. Drawing is an important part of biology (Betz & Dempsey, 2015; Quillin & Thomas, 2015) and other scholars report it has positive benefits towards student learning (Bell, 2014; Dikmenli, 2010; Lerner, 2007). For instance, drawing promotes thinking, communication, visualization, interpretation of results (Quillin & Thomas, 2015; Van Meter & Garner, 2005) and can be used as a tool for revealing students' misconceptions in a specified discipline such as biology (Dikmenli, 2010; Köse, 2008; Quillin & Thomas, 2015).

4.4.4.2 Graphs

Graphs are used extensively in biology for a wide range of purposes including to process and visualize data in biological experimentation, or to represent research outcomes and knowledge in the literature, including textbooks. Some instructors were more general while others were specific about the use of graphs in their biology course. In the case of general usage of graphs, some instructors made statements like the following:

"I expect them to know the importance of the graph. They should know what the graphs help us obtain. They should know the relationship between the y and x axis."

"[....] I expect they will be able to look at the graph and interpret how the dependent variable changes as the independent variable is altered during an experiment (i.e. to interpret the graph) [....]"

"Understand how dependent variables change with changes in independent variables. Compare responses in two difference conditions or states (e.g. proteins with slightly different function as a consequence of amino acid differences....) and the implications for function."

The majority of instructors cited specific examples of how they expect students to use the graphs. This is supported by the following quotes:

"Determine kinetic parameters for enzyme activity; identify optima or activity timing."

"I expect the students to be able to use a hyperchromatic shift graph to compare the base composition of two DNA species. In addition, I expect the students to be able to use a

reassociation kinetics graph to compare the size and complexity of genomes from two different species."

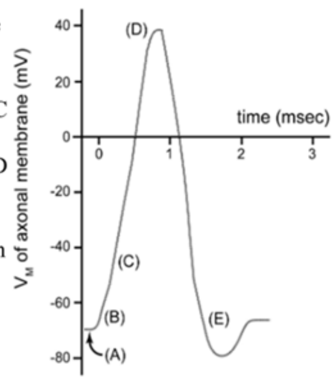
"Use the graphs to calculate say the chloride excretion rate between hydrated and dehydrated individuals."

"Relate the absorbance spectra for the two forms of the phytochrome molecule (Cis and Trans isomers), and… relate the form of the molecule to the absorbance spectrum and how the form impacts the biological activity of phytochrome molecules."

Based on the above expectations, it can be deduced that instructors expect students to know what the provided graphs represent and be able to interpret the graphs. These expectations were also portrayed in Fig. 4.8 with the exam question that an instructor provided in Questionnaire 1.

Figure 8

When you depolarise the neuron in the previous problem to its threshold V_m, it has a characteristic action potential, shown here in a plot of V_m vs time. As you know, V_m changes with a time course that is determined by specific events associated with the membrane. Refer to the plot and answer the questions below:



A) What causes the changes in V_m that occurs between points C and D on the plot?
B) What causes the changes in V_m that occurs between points D and E on the plot?
C) What has to occur to change V_m from point A to C?
D) What property of axonal membrane proteins PREVENTS an action potential that is being propagated along an axon toward the synapse from CHANGING DIRECTION?

Answers:

A) Voltage gate Na channels are open and Na^+ flows into the cell
B) Voltage gated K channels are open and K^+ flows out of the cell. The Na channels have closed.
C) The membrane must be polarized past the threshold for opening the voltage gated ion channels
D) The voltage gate ion channels have a refractory period: once opened in response to a threshold depolarization, they quickly close and cannot be opened again for a few msec.

Figure 4.8: An Example of a Question Probing Students' Ability to Interpret and use a Graph in a Second Year Lower Division Biology Course

In order to successfully answer this question, students are expected to remember, transfer and apply knowledge related to an action potential. Furthermore, since a graph is provided, students have to be able to interpret the graph (**R-M**). However, in order to successfully interpret the graph, students have to decode the symbolism (**R-M**) of the graph to explain what points A to E represent. They also have to be able to identify the limitations (**R-M**) of the graph in terms of what the graph is, and is not showing about an action potential. For example, to answer this question, students would need to remember that the membrane prevents flow of ions into and out of the cell unless an ion channel opens to allow flow into or out of the cell, based on the electrochemical gradient for that particular ion. Thus the results suggest that in courses taught by the participating instructors, students must interpret a graph by relating what was happening in the graph to their biological knowledge.

4.4.4.3 Chemical Equations

As shown in Table 4.3, examples of chemical equations considered by instructors to be relevant to the biology courses at the institution under study include those pertaining to oxidation reactions and acid-base equilibrium such as reversible carbonic acid/bicarbonate reactions. Instructors also specified how they expect students to use some of the listed chemical equations. Examples of the instructors' expectations are shown below:

"Body fluids contain buffering substances including proteins and bicarbonate ions. Buffers absorb protons (H^+ ions) to neutralize acids. The major buffer in the blood is bicarbonate ions (HCO_3^-) that are formed from the dissociation of carbonic acid, which in turn is formed by the hydration of CO_2 according to the equilibrium reaction. How do bicarbonate ions (HCO_3^-) stabilize the blood pH?"

"I never have students just memorize equations. These are so easy to look up nowadays that there is not much point. I have students go to a website like KEGG or BioCyc and interpret metabolic flux through a pathway either in different bacteria (comparative metabolomics) or in cases of mutation, either spontaneous or designed."

"They should know how to use the equations to correctly answer the questions."

When looking at these quotes, one can deduce that the instructors are expecting students to have attained abilities that will enable them to correctly use various equations.

Based on the above quotes, the major skill that is emphasized is the ability to interpret and use the equations to solve problems (**R-M**). Thus it is important that chemistry/biochemistry courses intended for biology students should equip students with this skill.

4.4.4.4 Mathematical Equations

As shown in Table 4.3, many different mathematical equations were also listed as being important for biology courses. Examples include the Nernst, Henderson Hasselbalch and Michaelis Menten equations, and equations relating to Gibbs free energy and Fick's and Boyle's Law. Instructors provided the following expectations regarding how students should use these equations:

"[…] I have them use an equation to solve a problem that requires a calculated answer, and occasionally to model data mathematically […]"

"E.g. Fick's Law of Diffusion.... use it conceptually to understand physiological adaptations of different animals to maximize flux. Think about trade-offs for optimizing one parameter in the equation."

"If a cell has a total cytosolic solute concentration of 500 mM and the total solute concentration of the extracellular medium is 200 mM, what will be the turgor (hydrostatic) pressure of the cell if water is at equilibrium across the cell membrane? Use RT = 2.5 L MPa/mol as a conversion factor."

"The movement of substances (the flux) can often be described by an equation of the form Flux = Constant times Driving Force, where the constant is determined by the properties of the substance and the pathway through which it is moving. Fick's Law was given as

an example of this kind of equation. What aspect of Fick's Law is dependent on aquaporins in the membrane and how would changing the number of membrane aquaporins affect flux across the membrane?"

"Pretty simple stuff here--no calculus. But, they need to know how to use arithmetic and algebraic equations to solve problems."

The exam questions provided by the instructors in Questionnaire 1 support the expectations stated above. Examples of exam questions provided in Fig. 4.3 and Fig. 4.5 illustrate how instructors expect students to use mathematical equations to solve (**R-M**) biological problems. Therefore, to successfully answer these questions, students are expected to remember, integrate, transfer and apply knowledge (**R-C**) relevant to the problem to be solved. Furthermore, for each of these questions, students are also expected to firstly, know the relevant equations to use for calculating K_{eq}, ΔG° and the equilibrium potential. Secondly, students need to interpret these equations so that they know what each equation represents. However, in order to successfully interpret the equations, students need to decode the symbolism of the equations, that is, they need to know what each symbol represents so that they could know the relevant experimental values to use for calculating K_{eq}, ΔG° and the equilibrium potential. Once again, it appears that interpretation of equations is very crucial in the biology courses taught by the participating instructors. Therefore, it is important that students are trained how to interpret mathematical equations so that they are able to successfully use them to solve biological problems.

Since some of the exam questions (Fig. 4.1-4.8) provided in the Exploration Phase of the study include the use of representations, I found it important to determine if the representations used in the exam questions are comparable to those identified as being relevant to biology courses (Table 4.3). Table 4.4 shows the various types of representations from Table 4.3 that appear in the exam questions. The data shows that each exam question covered one or more representations. Furthermore, some of the exam questions covered the same types of representation (Fig. 4.1 and 4.4, for example) while others covered different ones (such as Fig. 4.2, 4.6, and 4.8). Collectively, though, the eight selected exam questions covered a broad range of the identified representations. This confirms the importance of the identified types of representation for the teaching of biology at the present institution.

Table 4.4: Representations Supplied or Typically used by Students to Answer the Questions in Fig. 4.1-4.8

Type of Representation (**M**)	Figures representing examples in response to exam questions provided by the participants.							
	Fig. 4.1 (T_1)	Fig. 4.2 (T_2)	Fig. 4.3 (T_3)	Fig. 4.4 (T_1 & T_4)	Fig. 4.5 (T_3 & T_5)	Fig. 4.6 (T_4 & T_6)	Fig. 4.7	Fig. 4.8
Particulate Models								
3D protein structure	x	-						
Protein structure				X			x	
Alpha helix	x			X				
Beta sheets	x							
Space filling models	x	-		X				
Amino acids	x	-		X			x	
Graphs								
Action potential showing voltage vs time plots		-						x
Titration curves where x axis is volume of titrant and y-axis is the pH		-		X			x	
Drug dosage graphs where x axis is time and y axis is concentration of drug in blood		x						
Chemical Equations								
$H_2O + CO_2 \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+$		-				x		
Equilibrium reaction of CO_2 and HCO_3^-		-				x		
Equilibrium equation: K_{eq} = [product]/[substrate]		-	x					
Metabolic pathway reactions in glycolysis		-	x					
Titration equilibrium equations		-		X			x	
Mathematical Equations								
Nernst equation		-			x			
Gibbs free energy equation		-	x		x			

Table 4.4, continued

Type of Representation (**M**)	Figures representing examples in response to exam questions provided by the participants.							
	Fig. 4.1 (T_1)	Fig. 4.2 (T_2)	Fig. 4.3 (T_3)	Fig. 4.4 (T_1 & T_4)	Fig. 4.5 (T_3 & T_5)	Fig. 4.6 (T_4 & T_6)	Fig. 4.7	Fig. 4.8
Molarity and dilution calculations		-			x			
Henderson Hasselbalch		-				x		
Gas Laws		-				x		

4.5 Conclusions and Implications

Regarding the rating of importance (Questionnaire 2; Appendix C) of each concept shown in Table 4.1, the data shows very little consensus that any of the listed concepts are not important to biology. In fact, only UV Vis Spectroscopy, atomic orbitals, and Lewis acids and bases were rated as not important to their biology courses by more than half of the expert biology instructors. Furthermore, all 74 concepts were considered important by at least one instructor for at least one biology course. This is not surprising given the foundational nature of the concepts. Regarding the undecided rating of concepts, this could suggest that either the concepts are unimportant or are so intricate to biology knowledge that biologists do not realize that they are being guided by such concepts in their understanding of biology. Indeed, when some biology instructors were questioned about this during member checking interviews, they indicated that they rated some concepts as “undecided” because knowledge of those concepts was important but not directly required for understanding the biology course(s) they taught. The majority of the 74 listed concepts are among those included in the undergraduate biology curriculum proposed by the National Research Council (2003) as well as those identified in the ASBMB study of Voet et al. (2003). It is important to point out that the list of the representations shown in Table 4.3 adds new knowledge to the current undergraduate biology curriculum research because at the point of writing this dissertation, there were no studies that had reported the biochemistry and chemistry representations that biology instructors consider to be important for the biology courses they teach.

As shown in Table 4.1, with the exception of colloids and the Beer Lambert law, there was a high degree of consensus about the need to teach about solutions (Concept Group 12), including molarity calculations and suspensions. The same high rating applied for cohesion and surface tension (Group 1). The importance of both intermolecular interactions as well as chemistry of solutions is reinforced by the importance assigned to properties such as hydrophobicity and hydrophilicity as well as cohesion and surface tension (Group 1). Clearly all these play crucial roles in determining cellular environments, the structure and function of biomembranes, macromolecules and countless other cellular and extra-cellular processes.

Chemical reactions (Group 3) such as redox, hydrolysis and general catabolic and anabolic processes were rated important for most biology courses, whereas reactions like nucleophilic substitutions were rated less important. This finding, together with the high percentage of undecided responses for this topic, suggests that organic chemistry courses need to place great emphasis on the usefulness of such organic mechanisms for biological understanding. As expected, most biology instructors believe that topics like chemical equilibrium (Group 4), enzymes (Group 5), macromolecules (Group 6), cellular processes (Group 7), and thermodynamics (Group 8) are indispensable to the learning of biology. Furthermore, topics that include acid-base concepts (Group 13) are pervasive, appearing in multiple categories in Table 4.1, including equations, reactions, solubility, concentration of solutions, and pH. This is not surprising given the central role that acid-base chemistry plays in our understanding of biological systems (Haudek et al., 2012). Interestingly, Lewis and Brønsted acid-base models are deemed unimportant by the majority of instructors. This is surprising given the fact that the Brønsted-Lowry model is extensively used in acid-base physiology (Story, 2004) because "in the 1950s clinical chemists combined the Henderson-Hasselbalch equation and the Brønsted-Lowry definition of an acid to produce the current bicarbonate ion-centered approach to metabolic acid–base disorders," (Story, 2004).

There was less consensus as fewer instructors considered topics like heat capacity, UV-Vis spectroscopy, VSEPR, and atomic orbitals as important, which indicates they are important to some but not all courses in the biology program. Of the listed analytical techniques (Group 9), only microscopy and, to a lesser extent, x-ray crystallography were rated as important by most instructors, whereas surprisingly fewer instructors agreed on the importance of popular techniques like chromatography and UV/Vis spectroscopy. This could be in line with changing trends in modern biology towards techniques like ultrafiltration for sample cleanup and automated "black box" chromatography for analysis rather than the older chromatography methods. Also, these days more use is made of fluorescent probes rather than UV-Vis detection and analysis systems. Not surprisingly, the various gas laws (Group 10) were not rated highly, probably because such laws are mainly only important to areas of biology like physiology.

As stated in Chapter 1, the NRC (2003; Brewer & Smith, 2011) and AAMC-HHMI (2009) called for reform in biology undergraduate education. In particular, the NRC (2003) stipulated the importance of integrating biology with physical sciences and mathematics in order to help biology majors to understand the interdisciplinary nature biology. In order to design integrated curricula, instructors ought to identify the concepts and competencies that need to be included in the curricula. Instead of holding meetings or workshops, the three-stage process discussed in this study can be used by instructors at any university in order to collect data that can be used to initiate curriculum related discussions.

The results of this study have provided key information from biology instructors at large research university about the chemistry and biochemistry concepts they think biology students should know for their biology course. For data on representations and related ways of reasoning with such concepts and representations it was useful to look at exam questions that revealed how instructors believe students should use the chemistry and biochemistry knowledge they see as important for their biology courses. This in-house data could be used directly and synergistically with published information from other national studies (e.g. Tansey et al., 2013; Voet et al., 2003; White et al., 2013; Wright et al., 2013) to inform curricular discussions at the current institution. Such findings, however, should be used with caution by other institutions in which the educational and student context may be very different. Instead I advocate that the process deployed in this study (Table 4.1) could be used at other institutions to yield local data about their own biology program and any related curricular issues which could, in turn, motivate curriculum discussions between stakeholders at that institution. The methods used in this study suggest the following potentially useful advice for practitioners (in no order of importance), both at the institution under study and other institutions:

- A sound grounding in basic chemistry and biochemistry is indispensable to the education of biology students.
- Such grounding should include a strong focus on equipping students with the necessary cognitive skills to enable them to use or reason with concepts (**R-C**)

and related representations (**R-M**) to solve problems, rather than just memorization of information.

- Results in Tables 4.2 and 4.3 could inform ways teaching about biochemistry and chemistry concepts might be linked to their biological importance, so that students can more readily integrate, transfer and apply such knowledge to their future biology studies. Concurrently, these findings might help biology instructors know when to cue their students to link (transfer; **R-C**) to what they learn in chemistry and biochemistry in order to reinforce the application of such concepts.
- Although the 74 concepts listed as important by biology instructors do not provide a complete list of the basic chemistry and biochemistry concepts required to master biology, they do provide a basis for discussion about the curriculum in the specific context of the current institution. These concepts may also provide a starting point for discussion and comparison by instructors at other institutions.
- The extensive nature of the 74 listed concepts begs the question of how well all of this material can be covered in the two years of chemistry and biochemistry typically required for biology students at the current institution. This suggests
- The need to rationalize the scope and sequence of topics and to minimize any repetition.
- There is clearly a need to discuss how the concepts and representations fit into an integrated curriculum where biology, biochemistry and chemistry material

is sequenced to meet the needs of all stakeholders. Development of such a curriculum would help in the development of biologists who have the ability to see the interconnectedness of biology, biochemistry and chemistry.

Although, the sample size of this study, being highly dependent on (very busy) faculty volunteers, was rather small, the sample was representative of the majority of instructors responsible for undergraduate biology at the current institution. Thus the findings are generalizable to the needs of this single institution and, where necessary, could be used to stimulate curricular discussion between chemistry, biochemistry and biology instructors. More research is required to establish the various education levels at which the identified concepts and representations could be taught. This is important because it will help in the development of curricula that address each concept and representation at an appropriate level so as to promote sound construction of knowledge and logical progression and knowledge transfer. Furthermore, it would be interesting to find out how the results would turn out if professional biologists, chemistry and biochemistry instructors would also be invited to participate in this study.

In summary, this study highlights the value of a simple three-step process (Table 4.1) for surveying biology instructors about the prior knowledge they expect their students to have acquired from chemistry and biochemistry courses so that curricular decisions can be empirically-based and designed to ensure the logical and sound construction of knowledge as the students progress from freshman to more senior years of study. These studies will enable chemistry, biology and biochemistry instructors at the current institution to explore whether curriculum discussions are desirable and, if so, whether they could lead to a mutually beneficial process and an improved integrated undergraduate curriculum for biology students. This in turn, could have an important impact on how well such students are prepared for later challenges including graduate studies in biology.

CHAPTER 5: HOW IS ACID-BASE KNOLWEGDE USED BY INSTRUCTORS IN DIFFERENT BIOLOGY COURSES?

5.1 Motivation, Rationale and Research Questions

As shown in Chapter 4, a wide range of chemistry and biochemistry concepts and representations are considered by instructors to be important for their different biology courses. This posed the question, how do instructors specifically use each of these concepts and representations in the teaching of their courses. Since addressing this question for all the concepts and representations presented in Chapter 4 would be beyond the scope of this course, in the interests of brevity, I decided to narrow my focus to a single topic namely acid-base.

I was motivated to study acid-base because, as discussed in Chapter 4, instructors considered this topic to be one of the most important for the teaching and learning of their various courses that focus on a range of biology sub-disciplines. Indeed, acid-base concepts are both cross-cutting, in that they are important across a wide range of topics and disciplines (Haudek et al., 2012; Rhodes, 2006), and they serve as threshold concepts (Talanquer, 2015) for the learning of higher-level concepts such as the impact of buffers on the concepts of molecular structure and enzyme activity (Orgill & Sutherland, 2008). In this regard, and of great significance to the present study, I was also interested in focusing on acid-base because of its crucial importance for understanding biological processes and systems (Haudek et al., 2012; Rhodes, 2006; Roche, 2007; Orgill & Sutherland, 2008).

In biology, very limited studies have been done regarding the acid-base content that is important for biology courses (e.g. Haudek et al., 2012; Rhodes, 2006; Modell et al., 2015). Therefore, there is a need to find out from the biology instructors, the specific acid-base content they consider to be important for the biology courses they teach. The latter is important because acid-base chemistry is very broad, meaning that what chemists and biochemists consider to be important may not be relevant to biology courses.

One important aspect to remember is that like many other sciences, concepts of acid-base chemistry are "structured by mathematical representations used to better describe or explain scientific phenomena or knowledge" (Park & Choi, 2012). For instance, concepts such as ionization, neutralization, solubility, equilibrium, mathematical aspects of pH usually expressed in terms of logarithms and the importance of logarithmic scales are crucial for understanding the concept of pH (Park & Choi, 2010). Furthermore, students are also expected to comprehend mathematical aspects of pH usually expressed in terms of logarithms and logarithmic scales as pH= -log $[H^+]$ (Park & Choi, 2010). Based on Park and Choi (2012), mathematical representations/equations such as the latter aid students to better understand scientific concepts such as pH. Moreover, Watters and Watters (2006) reported that some of the content that is important for understanding the concept of pH included knowledge of the properties of acids and bases, dissociation constants and "the meaning of "minus" log [in pH= -log$[H^+]$ and the notion of concentration as a proportion and to be able to work from a pH measure (e.g. pH 4.5) to a concentration of hydrogen ions expressed in exponential terms (e.g. 3.16 x 10^{-5} moles/liter) and from a concentration given in exponential terms to a pH representation," (p. 278). Thus, since mathematical representations are important for acid-base chemistry, I decided to ask the biology instructors to identify the acid-base representations that they use in their courses.

Various education researchers have reported that acid-base theory is an important topic because it is a fundamental theory that is encompassed within various chemistry topics such as the nature of inorganic oxides of metals and non-metals, phenols and carboxylic acids (Halstead, 2009); and it is the basic theory upon which explanations of cellular processes such as homeostasis are built (Story, 2004). Whereas a number of studies have concentrated on acid-base chemistry in the context of biochemistry and chemistry, only limited studies have focused on such studies in the context of biology, despite its importance in this area of science. Studies done in biochemistry and chemistry have concentrated on students' acid-base difficulties (e.g. Cartrette & Mayo, 2011; Kousathana et al., 2005; Muchtar, 2012; Orgill & Sutherland, 2008; Sheppard, 2006; Watters & Watters, 2006); and developing teaching strategies in order to help remediate such difficulties (e.g. Demircioğlu, Ayas, & Demircioğlu, 2005; Nakhleh & Krajcik, 1994).

To investigate how instructors use acid-base concepts and representations in the teaching of their biology courses, I decided to use clinical interviews. Thus, for example, when instructors said pH and pK_a are important for their course, I was interested in probing how they use such concepts and related representations to teach the biology in their particular courses and, therefore, how they expect their students to use them. Towards this end, I addressed the following research questions:

- How is knowledge of acid-base concepts and ways of reasoning about such concepts used by instructors in their particular biology courses? (RQ-5)
- How are visual representations and ways of reasoning with acid-base representations used by instructors' in their particular biology courses? (RQ-6)

5.2 Theoretical Framework

The goal of this study was to identify the specific acid-base content, the related acid-base representations and ways students are expected to reason with the concepts and representations. Therefore, I selected the CRM model (Schönborn & Anderson, 2009; Anderson et al., 2013) to be the theoretical framework for this study. I found the CRM model (see described in detail in Chapter 3) to be an appropriate framework for this study because the model framed my thinking with respect to concepts, representations and ways of reasoning that I aimed to identify by addressing the stated research questions. In the present study this framework guided my focus on the specific acid-base knowledge (**C**; RQ-5); acid-base representations (**M**; RQ-6); and ways in which students are expected to reason with the knowledge (**R-C;** RQ-5) and the representations (**R-M**; RQ-6). Furthermore, by referring to the various specific reasoning (**R-C**) and visual skills (**R-M**) documented in previous studies (Anderson et al., 2013; Anderson & Schönborn, 2008; Schonborn & Anderson, 2010; Schönborn & Anderson, 2009). I was able to identify specific reasoning abilities students are expected to use when working with chemistry and biochemistry acid-base concepts and representations in biology courses..

5.3 Methods

5.3.1 Participants

To obtain volunteers for interview, I visited six biology instructors who had participated in the Exploration and Confirmation Phases (Chapter 4; Table 4.1) and the Qualtrics representations survey and who had indicated that acid-base chemistry is relevant to the biology courses they taught. I briefly informed the instructors about the goals of conducting the interviews and asked them if they had time to participate. Out of the four who agreed to participate, one participant, Dr. T.I., indicated that although he wanted to participate in the interviews, he would not have time for a formal face-to-face interview. For this reason, he was interviewed via email. In addition, two of the four participants, Dr. Luda and Dr. Drake, stated that they would prefer to have the interview questions ahead of the actual interview date so that they could be better prepared.

The four participants taught biology courses at different educational levels: one participant, Dr. Nelly, taught a 100-level biology course; two of the participants, Dr. T.I. and Dr. Luda each taught a different 200-level biology course; and Dr. Drake taught a 400-level biology course. According to the course descriptions provided online at https://www.bio.purdue.edu/Academic/undergrad/coursedesc.php, the university's biological sciences website, the biology course taught by Dr. Nelly "…introduces embryonic development and examines the functioning of physiological systems of both plants and animals. The underlying cellular and molecular basis for these processes will be emphasized. In particular, the transport of molecules and small ions through biological membranes will be studied. This will require an understanding of membrane structure, diffusion, electrical potentials and other physical and chemical principles." Dr. T.I., on the other hand, taught an introductory microbiology course intended for biology majors: this course "…covers the following topics: biochemistry; microscopy; bacterial physiology; growth and metabolism; growth control; genetics and its modern applications; immunology; pathogenesis, including specific microorganisms of medical importance; agricultural and environmental microbiology; and food microbiology." After completing this course, students will "…have the background in microbiology necessary for further study in medicine or allied health sciences, microbial ecology, antimicrobial pharmacology and related disciplines." The biology course taught by Dr. Luda "…introduces students to cell biology through 3 over-arching themes: First, the shape and organization of molecules, organelles, and cells underlie their function. Second, cellular organization and function require energy, and cells are in part energy-transducing machines. Third, the cell is constantly changing-- its shape, activity, and molecular composition are dynamic and transient. Cell biology builds on a foundation of math, chemistry and physics, thus, the course begins by discussing the structure and function of macromolecules and the most relevant principles of chemistry, kinetics, and thermodynamics." Lastly, Dr. Drake taught a biology course that "…covers key aspects in molecular, cellular, and developmental neurobiology. Topics include cell biology of neurons and glial cells, electrophysiological properties of neurons, electrical and chemical signaling between neurons, synaptic integration and plasticity, development and regeneration of the nervous system, nervous system diseases. A basic knowledge of cell biology and protein structure and function is strongly recommended."

5.3.2 Description and Validation of the Interviews

The four participants took part in the Exploration stage and the Confirmation stage (Chapter 4; Table 4.1). Some of the participants rated all the five concepts, shown in Tables 5. 1 and 5.2, as important for the courses they taught, whereas some participants selected only four of the five concepts. As described in Chapter 3 (section 3.7.2), the standardized open-ended interview approach was used (Patton, 2002; Gay & Airasian, 2003). The interviews were audio recorded and were not longer than 30 minutes. The interviews were transcribed verbatim and included recording (in square brackets) of any motions or expressions such as pauses, signs, hesitations and giggles. Open coding (Strauss & Corbin, 1998) and the CRM model (Anderson et al., 2013; Schönborn & Anderson, 2009) informed the analysis of the transcribed interview data. Data was analyzed as described below.

5.3.2.1 Data Analysis Informed by the CRM Model

Before analyzing the data, I decided to break each of the two research questions into two sub questions. I did this so as to ensure that I addressed each important aspect of the research questions. RQ-5 and RQ-6 have two important aspects, namely, (i) knowledge of acid-base concepts and representations used in the instructors' biology courses and (ii) ways of reasoning about the concepts and representations. During the open coding process (Strauss & Corbin, 1998), I read each transcript line by line, and as I read, I underlined and coded each line that informed me how the instructors expected the students to reason with the acid-base concepts and representations. I used the code “reasoning with the concepts (**R-C**)” to label the lines that informed me how students were expected to reason with the concepts. Furthermore, I used the code “reasoning with representations (**R-M**)” to label the lines that informed me how students were expected to reason with the representations. After I finished analyzing all the four transcripts, I pulled together all the sentences that had similar codes, that is, I pulled together all the sentences that had the **R-C** code and all the sentences that had the **R-M** code. All in all, I ended up having only two codes namely, reasoning with concepts (**R-C**) and reasoning with representations (**R-M**). Besides using open coding to identify ways in which the instructors expected the students to reason with the concepts and representations, I also used open coding to identify the knowledge of acid-base concepts and representations used in the instructors’ biology courses. Therefore, during the open coding process, I read and coded the transcripts line by line. I used the code “conceptual knowledge (**C**)” to label lines that informed me about the acid-base content that the instructors considered to be important for the teaching of certain biology topics in their courses. Furthermore, I used the code “representations” (**R**) to label the lines that informed me about the acid-base representations that the instructors considered important for the teaching of certain biology topics in their courses.

5.4 Results and Discussion

5.4.1 How is Knowledge of Acid-Base Concepts, and Ways of Reasoning About Such Concepts, Used by Instructors in Their Particular Biology Courses? (RQ-5)

Table 5.1 shows a summary of the acid-base concepts that are relevant to the biology courses taught by the four instructors who participated in the interviews and how they use/reason with them (**R-C**) to teach biology. Overall, although the instructors indicated in the Exploration and Confirmations stages that knowledge of acid-base concepts are important for biology students, the data presented in Table 5.1 shows that they use such concepts in a range of different ways to teach their different courses. In my view, all these different ways could be used by chemists and biochemists instructors to inform the design of teaching and learning activities that are more relevant to the needs of the biology students. For example, when looking at the concept of acid-base strength (Table 5.1), Dr. T.I. stated that knowing "which acids are strong and which acids are weak" is important for the courses he teaches. In addition, Dr. Drake indicated that thinking about acid-base strength in terms of the charge of amino acids and proteins is important for the biology course he teaches. Furthermore, Dr. Luda indicated that weak ~~or strong~~ acids or bases are much more important to the biology he teaches than strong acids and bases, while Dr. Nelly, stated that knowledge that something like hydrochloric acid has complete dissociation is important for the courses she teaches. Thus, all these different ways of using the concept of acid-base strength could inform teaching and

Table 5.1: Acid-Base Concepts **(C)** and How They are Used **(R-C)** by Instructors to Teach their Various Courses (Red Color-Declarative Knowledge; Orange Color- Procedural Knowledge)

Concepts	What knowledge about the identified acid-base concepts (**C**) is used (**R-C**) by the instructors to teach their biology courses? (Quotes from the interviews).			
	Dr. Wade T.I	Dr. Sean Drake	Dr. Hall Luda	Dr. Nicky Nelly
Acid-base strength	• Know which acids are strong and which are weak acids • Understanding of how to use pK_a to calculate the acidity of a solution made from a weak acid/base.	• Amino acids are parts of proteins and how their charge is being affected by pH: we have the acidic and basic amino acids, the neutral amino acids and depending on the pH, they are charged and not charged, they are neutral.	• Acid-base strength, we don't talk about that much because in biology everything is a weak acid or base.	• Know that something like hydrochloric acid has almost complete dissociation [figure below]. $HCl \rightarrow H^+ + Cl^-$ Figure 1: Dissociation of HCl
Buffers	• Calculating how many grams of a conjugate acid/base to use for preparing a solution of predetermined pH[Henderson Hasselbalch equation] when preparing biological buffers • Understanding how a zwitterionic buffer[like amino acids] works is also important	• Need to understand that cells need to be in certain pH environment that is buffered • Concept that individual parts of the cells or organelles have distinct pH • Protein interactions. One protein binding another protein is pH dependent. • Probes of fluorescent dyes are pH dependent.	• Uhmm, buffers we don't talk about them that much	• So, if you have something like this [fig.1] you are not going to have that buffering capacity, it's just the acid is there until it's pumped away. But if on the other hand, you have something like carbonic acid, and if $H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$ you take something like this and then you pump those protons out of the cell, then more bicarbonate is going to dissociate and replace those bicarbonate ions

Table 5.1, continued

Concepts	What knowledge about the identified acid-base concepts (**C**) is used (**R-C**) by the instructors to teach their biology courses? (Quotes from the interviews).			
	Dr. Wade T.I	Dr. Sean Drake	Dr. Hall Luda	Dr. Nicky Nelly
pH	• Everything about pH is important • How to calculate pH of a solution • Understanding how pH is measured, both electrically & with pH-sensitive dyes • Acid-base titration curves • Understanding how pH affects chemical reactions [e.g. different products favored at different pH] • Effect of temperature on measured pH	• Need to understand that cells need to be in certain pH environment that is buffered • Concept that individual parts of the cells or organelles have distinct pH • Protein interactions [. ..] one protein binding another protein is pH dependent. • Probes of fluorescent dyes are pH dependent	• Understand that (pH) it's a negative logarithmic relationship to concentration (pH= -log[H^+]) • pH of the environment has a powerful effect on the charges and, therefore, the interactions of molecules • Understanding that because biomolecules have functional groups whose charge changes with pH, understanding how biomolecules function and how they interact with each other is critically dependent on knowing the pH, knowing the isoelectric points.	• Know that if the pH in the body is 7.4, that represents a particular hydrogen ion concentration and that pH could change with different chemical substances in $H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$ the environment • Know that if you start breathing and retain the carbon dioxide in your body […] the carbon-dioxide is going to react with water and that what you have here [figure below] is carbonic acid and that this acid, added to the plasma is going to actually lower the pH because the pH is the negative log of the hydrogen ion concentration. So this would then lower body pH.

Table 5.1, continued

Concepts	What knowledge about the identified acid-base concepts (**C**) is used (**R-C**) by the instructors to teach their biology courses? (Quotes from the interviews).			
	Dr. Wade T.I	Dr. Sean Drake	Dr. Hall Luda	Dr. Nicky Nelly
Henderson Hasselbalch	-	-	• That's in the back of my lecture notes; I assume that they did that in high school. • We do not explicitly deal with the Henderson Hasselbalch, I give them a supplement just in case they haven't done it while in high school	• Understand the Henderson Hasselbalch as being an equation that relates three things, that is basically the bicarbonate concentration, the hydrogen ion concentration, and the pH

learning activities and problem sets used in the various chemistry and biochemistry courses taken by the biology students.

Regarding the concept of pH, although Dr. Luda, Dr. Drake and Dr. Nelly consider the biological importance of pH to be essential for the biology courses they teach, the context in which the biological importance of pH needs addressing is different. For Dr. Drake, the importance of pH has to be emphasized in amino acid charge; for Dr. Luda, the importance of pH has to be stressed in cell function whereas for Dr. Nelly, the importance of pH has to be highlighted in blood acidosis. Whereas Dr. Luda, Dr. Drake and Dr. Nelly consider the biological importance of pH to be important for the biology courses they teach, Dr. T.I. emphasized the importance of knowing how to calculate the pH of a solution.

Once again, I argue that the multiple ways discussed above that the instructors use pH could inform different teaching and learning tasks in chemistry and biochemistry courses. In addition, it is my contention that the same reasoning could be applied to all the concepts and ways of reasoning with concepts presented in Table 5.1. Furthermore, the examples presented here are not intended to be representative because there are clearly other examples of different ways in which a concept, such as the concept of pH, is used to teach about biology. For example, in a *Molecular Cell Biology* textbook, Lodish et. al., (2000) have emphasized the importance of pH in the stomach, membrane transport, and endocytosis.

When looking more deeply into the data, one can see that the instructors want their students to have both declarative and procedural knowledge. Declarative knowledge is referred to as factual knowledge or “knowing what” whereas procedural knowledge involves "knowing how" (Lawson, 2001; Odom & Kelly, 2001). The data shown in Table 5.1 indicates that both declarative and procedural knowledge are important for the biology courses taught by these four instructors. Examples of declarative knowledge (RED COLOR in Table 5.1) include "*Know[ing] which acids are strong and which are weak acids*" [Dr. T.I.] and "[…] *know[ing] that something like hydrochloric acid has almost complete dissociation*" [Dr. Nelly]. Examples of procedural knowledge (ORANGE COLOR in Table 5.1) include "[…] *understanding how biomolecules function and how they interact with each other[..]*" [Dr. Luda] and "[…] *understanding how pH is measured, both electrically & with pH-sensitive dyes*" [Dr. T.I.]. The fact that the instructors consider both declarative and procedural knowledge important for their biology courses implies that they expect their students to have both factual knowledge about the stated acid-base concepts (declarative knowledge), as well as being able to reason with the acid-base knowledge (**R-C**) to explain how biological processes or how instruments work (procedural knowledge). The importance of declarative and procedural knowledge for learning biology has been supported by other scholars such as Mthethwa-Kunene, Onwu and de Villiers (2015) and Odom and Kelly (2001).

The fact that the instructors expect their students to be able to reason with the stated acid-base concepts (**R-C**) is further supported by the following quotes, which suggest that the ability to mindfully memorize knowledge of concepts such as pK_a, K_a and acid-base strength is insufficient. In addition, as described by Anderson and Schönborn (2008), they are also expected to be able to i) reason algorithmically about K_a and pK_a in order to solve problems; and ii) explain why, for example, an acid is either strong or weak. In support of this, the instructors provided the following quotes:

"*Understanding of how to use pK_a to calculate the acidity of a solution made from a weak acid/base.*" Dr. T.I.

"[..] K_a and pK_a just because I want them to be able to quantify the things they are talking about." Dr. Luda

"Be able to explain why an acid is strong or weak." Dr. T.I.

Furthermore, Dr. Nelly and Dr. Luda want their students to not only know what pH is, but they expect them to be able to transfer, apply and integrate knowledge of pH (**R-C**; see Anderson & Schönborn, 2008) with other related concepts in order to provide sound biological explanations. The latter is supported by the fact that Dr. Nelly expects students to be able to "*think through*" connections between asthma, gas exchange and blood acidosis whereas Dr. Luda expects students to "*think about*" connections between pH, structure and interactions of molecules. These instructors provided the following quotes:

"*I would expect my students to be able to think through if I stop breathing or if my airways are constricted or if I have asthma and don't have efficient gas exchange that I could get acidosis in the blood*." (Dr. Nelly)

"[..] *to be able to think through that some types of combinations of chemicals which are a strong acid could easily get pumped away and give the cell strong ability to drop the pH quickly, whereas other types which have a buffering capacity to pump the proton away and they are immediately replaced because there is more dissociation*." (Dr. Nelly)

"*So, I ask them to think about pH with respect to the structure and interactions of molecules*." (Dr. Luda).

According to Schönborn and Bögeholz (2009), transfer of knowledge in biology can occur either horizontally or vertically. Horizontal knowledge transfer occurs when knowledge from one situation is applied to another situation "at the same level of biological organization." On the other hand, vertical knowledge transfer occurs when knowledge is applied "to different levels of biological organization." When looking at the above quotes, it is evident that Dr. Nelly and Dr. Luda expect students to have the ability to transfer knowledge horizontally, that is apply knowledge about pH to "*structure and interactions of molecules*" and apply knowledge about pH "*to blood acidosis.*" The importance of horizontal and vertical knowledge transfer in learning and researching biology was emphasized in the study conducted by Schönborn and Bögeholz (2009).

The fact that Dr. Nelly, Dr. T.I. and Dr. Luda expect their students to have the ability to: i) mindfully memorize knowledge about the stated acid-base information; ii) transfer, apply and integrate these knowledge with other related concepts in order to develop sound explanatory frameworks; and iii) reason algorithmically about these concepts, suggests that these instructors want their students to have a deep and meaningful understanding about the importance of the stated acid-base information to biological systems. The latter is due to the fact that these reasoning skills are some of the most important skills students ought to have in order to construct a good and meaningful understanding of concepts (Anderson et al., 2001; Mayer, 2002; Schönborn & Anderson, 2008; Schönborn & Bögeholz, 2009).

Whereas the biology instructors think of acid-base strength in terms of either knowledge of strong and weak acids, or charge of amino acids and proteins, chemistry instructors such as McClary and Talanquer (2011) express the concept of acid-base strength in terms of the three acid-base models. According to these workers, in the Arrhenius model, acid strength encompasses "the extent to which a certain amount of acid dissociates or reacts with water to produce H^+ ions," whereas in the Brønsted model, acid strength is given by the "ratio of the forward to the backward reaction rates" (p. 398). Furthermore, in the Lewis model, acid strength "depends on the chemical nature of the Lewis acid, the solvent and products of the acid-base reaction," (p.399). The fact that biologists and chemists think of acid-base strength in different ways substantiates the importance of holding curriculum-related discussions to decide what to include in the curriculum, specifically if the curriculum to be designed involves stakeholders from different disciplines.

Regarding the concept of pH, the instructors contextualized their explanations to show how the biological importance of pH was essential for the courses they teach. The idea of instructors or experts contextualizing their explanations to portray the importance of a biological phenomenon is one of the themes that Trujillo and colleagues (2015) described in the MACH model, the model that illustrates how biology experts explain molecular and cellular mechanisms. Besides the biological importance of pH, instructors such as Dr. T.I. and Dr. Luda consider knowing how to calculate the pH of a solution to be important for their biology courses. One important aspect that Watters and Watters (2006) pointed out was the fact that in order to know how to calculate the pH of a solution students need to understand how to use logarithms since pH is given by the negative negative logarithm of the concentration of hydrogen ions. Interestingly, Dr. Luda also pointed out that “understand that (pH) it’s a negative logarithmic relationship to concentration (pH= $-\log[H^+]$),” was important for the biology courses that he taught. Furthermore, Dr. Drake and Dr. Nelly reported that knowledge of the biological importance of buffers is important for the biology courses they taught. The latter is in line with what was reported by Orgill and Sutherland (2008).

When looking at the data presented in table 5.1, it is evident that each of the four instructors added different information about the importance of acid-base concepts. The fact that the instructors provided different information about the same acid-base concepts points out the importance of not only asking for a list of concepts from instructors when deciding what to include in the curriculum, specifically an integrated curriculum. Instead, it is essential to ask the instructors to specify how they use such concepts to teach biology and thereby enhance student understanding. Indeed, these findings support what Meredith and Redish (2013) discovered during their curriculum discussion meetings, and that is, although the biologists considered the same physics concepts to be relevant to their courses, the knowledge about the concepts and how they are used to teach biology varied between biologists.

5.4.2 How are Visual Representations and Ways of Reasoning with Acid-Base Representations Used by Instructors in Their Particular Biology Courses? (RQ-6)

The participants also provided examples of representations (Table 5.2) that are relevant to the acid-base knowledge they consider important for the biology courses they teach. As for the concepts (Table 5.1), each instructor added information about the types of representations considered important. For example, Dr. Nelly uses chemical equations such as bicarbonate/carbonic acid buffer equations, mathematical equations such as the Henderson-Hasselbalch equation and graphic diagrams such as the nomogram to teach her biology course. In contrast, Dr. Luda gets students to make drawings (either a table or a graph) to show ionization of titratable amino acid functional groups, while Dr. T.I. makes use of titration curves and the Henderson Hasselbalch equation to teach part of his course. Interestingly, Dr. T.I expects students to know how to use the equations for performing calculations whereas Dr. Nelly expects students to understand the concepts associated with the equations, and thus the meaning behind the equation(s). Clearly all these different uses of ERs are important for teaching biology and thus could be used to inform different teaching and learning tasks in chemistry and biochemistry courses that would help students appreciate the relevance of such subjects to biology.

Besides giving examples of representations (**M**) that they use to teach their courses, Dr. Nelly and Dr. Luda also specified how they expect the students to reason with the representations (**R-M;** see Schönborn and Anderson, 2010). Dr. Luda indicated that he expects students to be able to predict the overall charge of an amino acid by looking at the R-group at different pH values. Dr. Nelly, on the other hand, stipulated that she expects students to be able to use equations showing the dissociation of weak and

Table 5.2**:** Acid-Base Representations **(M)** and How They are Used **(R-M)** by Instructors to Teach their Various Courses

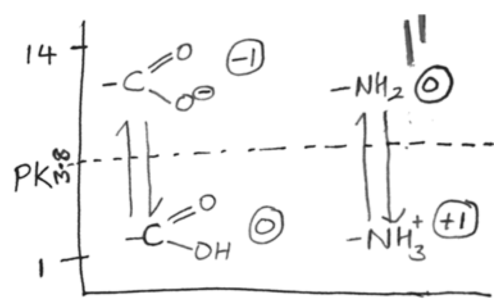
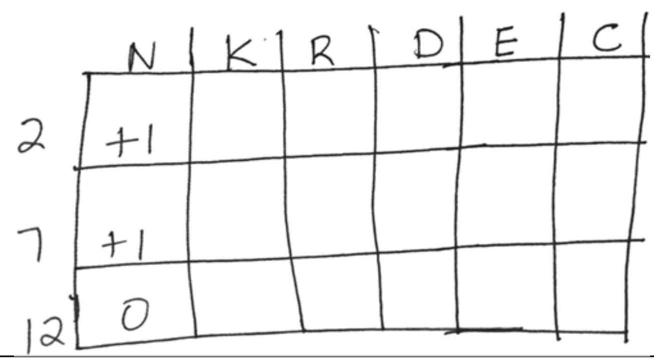
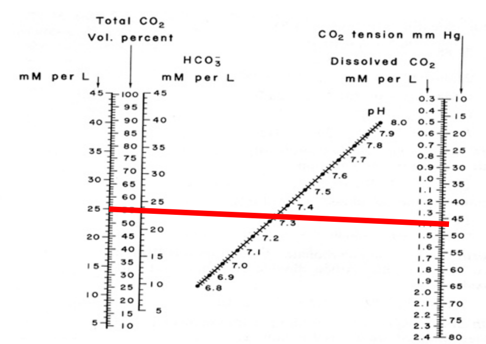
Concepts	What acid –base visual representations(**M**), are used (**R-M**) by the instructors to teach their biology courses? What do students need to know about each visual representation?
	Dr. Wade T.I
Acid-base strength	“Using pK_a to calculate pH of a solution containing a weak acid or base.”
Buffers	“Titration curves, Henderson Hasselbalch. Calculating how many grams of a conjugate acid/base to use for preparing a solution of predetermined pH (Henderson Hasselbalch equation) is very important when preparing biological buffers.”
pH	“pH and conductivity correlation to understand how a pH meter works.”
Concepts	Dr. Hall Luda
Acid-base strength	“[…] I have them look K_a and pK_a […] I want them to [..] quantify the things they are talking about.”
pH	Use a table or graph to determine the charge of functional groups or amino acids at a particular pH.  
Concepts	Dr. Sean Drake
Acid-base strength	“I don’t go over amino acids structures because that’s ahh, I don’t have time for that and basically, I expect that they have learned the different types of amino acids in protein.”
pH & Buffers	“The second question about graphs and equations is really that’s not that important for me, I really don’t need to use the, any of the typical equations for pH or pK_a and so on in what I teach in these courses.” “In terms of chemical reactions, in terms of equations, ahh, calculations, really they don’t need to do for that concept (buffers).”

Table 5.2, continued

Concepts	What acid –base visual representations(**M**), are used (**R-M**) by the instructors to teach their biology courses? What do students need to know about each visual representation?
Concepts	Dr. Nicky Nelly
Acid-base strength & buffers	"Know that something like hydrochloric acid has almost complete dissociation: $HCl \rightarrow H^+ + Cl^-$ "[…] if you have something like this [fig.1 above] you are not going to have that buffering capacity, it's just the acid is there until it's pumped away. But if on the other hand you have something like carbonic acid, and if you take something like this $H_2CO_3 \leftrightarrow H^+ + HCO_3^-$ and then you pump those protons out of the cell, then more bicarbonate is going to dissociate and replace those bicarbonate ions [$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$][..]"
pH	"[..] know that if the pH of the body is 7.4, that represents a particular hydrogen ion concentration [pH= -log[H^+]."
Henderson Hasselbalch	"[…] understand the Henderson Hasselbalch as being an equation that relates three things, and that's basically the bicarbonate concentration, the hydrogen ion concentration and the pH." "[…] I provide the nomogram[..] and what they really need to understand is that there is a relationship between the three things [..], could be carbon dioxide or bicarbonate with the pKa of carbonic acid." Nomogram:  Thus most of the CO_2 (about 85%) is carried as bicarbonate in the blood Total CO_2 = dissolved + bicarbonate

strong acids to explain how cells resist changes in pH. This is supported by the following quotes:

> *"[…] we talk about the pK_a of R-groups, and in a sense we are talking about the isoelectric point of proteins, I do want them to understand umm, how to think about what the charge would [be] [of] let's say peptide or small protein, based on looking at the R-groups at a particular pH […]."* Dr. Luda

> *"So if you basically have something like this [$HCl \rightarrow H^+ + Cl^-$] its, you are not going to have that buffering capacity, it's just the acid is there until its pumped away right? But if on the other hand you have something like carbonic acid, and if you take something like this [$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$] and then you pump those protons out of the cell, then more bicarbonate is going to dissociate and replace those bicarbonate ions, and so to be able to think through that some types of combinations of chemicals which are a strong acid could easily get pumped away and give the cell strong ability to drop the pH quickly, whereas other types which have a buffering capacity to pump the proton away and they are immediately replaced because there is more dissociation, it's a kind of reasoning that I expect to see my students capable of doing and they have real trouble with that."* Dr. Nelly

The above quotes show that Dr. Luda and Dr. Nelly want their students to have the ability to interpret and use representations (**R-M**) such as amino acid structures and the carbonic acid equation to explain how, for example, cells maintain resistance to pH. The fact that Dr. Luda and Dr. Nelly consider the ability to reason with representations to be important for the biology courses they teach is further supported by the instructors indicating that calculations and memorization of equations and biochemical structures alone are not important. Instead, reasoning with the representations is important for the courses they teach. The following quotes were provided by Dr. Luda and Dr. Nelly:

> *"[…] well, I don't ask them to memorize a lot of biochemical structures, but I do expect them to umm, understand, be able to draw the key functional groups of proteins/ amino acids and nucleic acids and also fatty acids that can be charged or uncharged depending on the pH and to be able to draw them in the charged and uncharged form."* Dr. Luda
>
> "[…] the Henderson Hasselbalch, I have to be uhh, frank, I don't [do not] actually remember it myself, so *I don't [do not] actually think that my students should have to memorize something that I actually don't [do not] remember. […] I provide the equation and I provide the nomogram and all they have to do is basically be able to reason through […]."* Dr. Nelly

Dr. Luda further indicated that drawing is important for the biology courses he teaches as it helps students visualize the effect(s) of pH on the charge of functional groups and proteins. Dr. Luda provided the following quote to support this contention:

> *"I do expect them to umm, understand, be able to draw the key functional groups of proteins/amino acids and nucleic acids and fatty acids that can be charged or uncharged depending on pH and to be able to draw them in the charged and uncharged form. […] I want you to be able to draw the way it would really be at*

pH 7 which is always with the amino group with a positive charge and the acidic group with the negative charge. […] this is just a way I find that it helps some of them to visualize it."

The fact that Dr. Luda wants biology students to be able to draw suggests that he expects them to have the ability to construct representations (see Schönborn & Anderson, 2010) to explain or solve biological problems such as determining the overall charge of amino acids and proteins. Indeed, the fact that Dr. Luda considers drawing as an important part of learning about the effect of pH on the charge of amino acids supports other studies that have stated that drawing is an important part of biology (Dempsey & Betz, 2015; Quillin & Thomas, 2015). Others report positive benefits towards student learning (Bell, 2013; Dikmenli, 2010; Lerner, 2007). For instance, drawing promotes thinking, communication, visualization, interpretation of results (Quillin & Thomas, 2015; Van Meter & Garner, 2005) and can be used as a tool for revealing students' misconceptions in a specified discipline such as biology (Dikmenli, 2010; Köse, 2008; Quillin & Thomas, 2015).

Several other publications have supported the importance of using representations for the teaching and learning of biology (See, for example, Tsui & Treagust, 2013; Schönborn & Bögeholz, 2013; Roth & Pozzer- Ardenghi, 2013; Eilam, 2013). According to Tsui and Treagust (2013), this is because learning biological knowledge is more complex because it involves "hierarchically organized levels of nested but different biological entities. That is, cells are nested within tissues, which are in turn nested within organs and then within the next level systems, organisms, populations, communities, ecosystems and up to the top level of the biosphere" (p. 8). Clearly, representations of this hierarchy are important for the teaching and learning of biology.

5.5 Summary and Implications

The following research questions were addressed: 1) How is knowledge of concepts and ways of reasoning about acid-base used by instructors in their particular biology courses? (RQ-5) and 2) How are visual representations and ways of reasoning with acid-base representations used by instructors' in their particular biology courses? (RQ-6). The findings described above suggest that using interviews was an effective method for addressing the stated research questions. In general, it appears that the experts want biology students to not only understand the basic information about the stated acid-base concepts and representations, but also acquire the ability to reason with the concepts (**R-C**) and representations (**R-M**) in order to construct sound biological explanations. The fact that the experts want students to be able to reason with the biochemistry and chemistry concepts and representations in biology courses is important because it will help students realize the connections that exist between these disciplines.

Both declarative knowledge and procedural knowledge appear to be important for the biology courses taught by the participants. Based on this, therefore, it is important to promote the acquisition of both declarative knowledge and procedural knowledge because it can be useful for learning biology. This can be achieved by exposing students to learning environments that will train them to use both declarative knowledge and procedural knowledge when solving problems, explaining biological problems, and using laboratory equipment. Such learning environments may include using formative assessments that involve asking students to use concept maps. Concept maps have been shown to help in developing students' use of declarative and procedural knowledge.

Biology experts want biology students to draw and visualize, for example, the effect of pH on the charge of proteins. This finding supports other studies that have stated that drawing is an important part of biology (Dempsey & Betz, 2001: Quillin & Thomas, 2015), and, though no evidence for this possibility is presented here, others report it has positive benefits towards student learning (Bell, 2013: Lerner, 2007: Dikmeli, 2010).

In conclusion, it is important to consider how students will use their knowledge of acids and bases when ensuring that biochemistry and chemistry courses designed for life sciences, specifically biology majors, equip students with appropriate abilities to reason with concepts (**R-C**) and representations (**R-M**). Effective learning of relevant knowledge of acids and bases in biochemistry and chemistry can be achieved by exposing students to teaching practices, learning activities, problem sets and formative assessments that will assist students to attain such skills that are indispensable to explaining biological phenomena and solving biological problems. In so doing, a major recommendation from this study is that chemistry and biochemistry instructors consider using feedback, like that presented in this chapter, to inform the design of teaching and learning activities and problem sets that will help students better understand the relevance of the chemistry to the biology they learn.

CHAPTER 6: A MODEL FOR THE DESIGN AND QUALITATIVE VALIDATION OF ACID-BASE ASSESSMENT IN ORGANIC CHEMISTRY

6.1 Introduction and Research Questions

As discussed in Chapters 1 and 2, major organizations (Association of American Medical Colleges-Howard Hughes Medical Institute, 2009; Bell, 2010; Brewer & Smith, 2011; NRC, 2003) have pointed out the need to design science curricula that will help students become aware of the interdisciplinary nature of science disciplines, and develop reasoning and visual skills that will help them integrate knowledge from various disciplines when explaining scientific phenomena. Besides identifying the concepts and competencies to include in any newly reformed science curriculum, recent reports published by these organizations also stipulated the need to design assessment tasks that will assess student understanding of science concepts (Association of American Medical Colleges-Howard Hughes Medical Institute, 2009; Bell, 2010; NRC, 2001, 2003). Others have given a number of reasons why assessment tasks are considered important in education: first, assessments formatively promote learning during a course. This is because, the more students are assessed, the more they have to review their course materials in order to prepare for tests/exams (Anderson, 2007; Briggs et al., 2015; Pellegrino, 2014). Second, assessments, when used frequently, can be important for monitoring students' progress during the course (Anderson, 2007). Third, in addition to summatively assessing students' sound and unsound understanding, assessments can be used for assessing students' cognitive skills (Kane & Bejar, 2014; Masters, 2013).

The idea of assessing cognitive skills was the focus of studies by Anderson and co-workers in the context of biochemistry who published various papers that emphasized the importance of developing and assessing students' multifaceted conceptual understanding (Anderson & Schönborn, 2008; Schönborn & Anderson, 2008) and their related visual literacy (Schönborn & Anderson, 2006, 2010). More specifically, various ways experts reason with concepts and visual representations were identified. Previous investigations demonstrated how such ways of reasoning can be developed (formatively) and assessed summatively in students (Anderson, 2009; Anderson et al., 2013; Schönborn & Mnguni et al., 2009; Schönborn et al., 2002, 2003). In the present study, the knowledge acquired from the above and other papers was used to inform what types of student knowledge that could be assessed and, therefore, how such assessment should be designed (Anderson, 2007).

As discussed in Chapter 2, the design of assessment instruments has been informed by various guidelines, models/systems and frameworks (Anderson & Rogan, 2010; Anderson et al., 2013; Briggs et al., 2015; Kennedy, 2005; NRC, 2001, 2003; Pellegrino, 2014). Despite this, there is general consensus that most assessments are poorly written , not valid and reliable, and not informed by learning objectives and the desired learning outcomes and thus do not measure students' achievement of each learning objective (DeBoer et al., 2008). It is essential to design assessments that are aligned with learning objectives because these will inform instructors whether or not students have attained the desired learning outcomes (Anderson, 2007; Herman, 2010; NRC, 2001, 2003; Pellegrino, 2014). Checking the quality of an assessment is crucial because it will inform instructors whether or not the assessment is a reliable and valid measure of students' conceptual understanding (Anderson & Rogan, 2010; DeBoer et al., 2008; Herman, 2010; NRC, 2001; Pellegrino, 2014). In this study, reliability of an assessment refers to the "degree to which it consistently measures" what it is intended to measure (Gay & Airasian, 2003, p.141) whereas validity of an assessment refers to whether or not an assessment is assessing what it is intended to assess (Gay & Airasian, 2003). Therefore, there is a need to develop a model that will aid in designing assessments that focus on reasoning with concepts and representations, and has a unique way of qualitatively validating the assessments by comparing experts' expectations of what the assessment will assess versus what outcomes students actually show. Validation of assessments is important as it can lead to changes in either the assessment task or in the learning objectives so that the assessment is confirmed to be measuring what the expert claims/expects it will.

In response to all the above concerns, I decided to develop a simple five-step model that instructors could use as a guide for designing, evaluating and validating assessments that would probe students' deep understanding and reasoning about biochemistry concepts and representations. Towards achieving this goal, I addressed the following research questions and used the phenomenon of acid-base in the context of a pharmacy course in organic chemistry to test the model:

i) What is an appropriate model for designing and validating assessment tasks? (RQ-7).

ii) Do acid-base assessments designed by an organic chemistry instructor support the validity of this model? (RQ-8).

The design of the assessment model was informed by the literature discussed above and more specifically the CRM model developed by Schönborn and Anderson (2009) and assessment guidelines developed by Anderson and Rogan (2010) and Anderson et al. (2013).

6.2 Theoretical Framework

The CRM model (Schönborn & Anderson 2009) was selected as an appropriated theoretical framework for the current study. As discussed in Chapter 3, the CRM model has three interdependent factors, namely, the conceptual (**C**) factor, the reasoning factor (**R**) and the mode (**M**) factor. In the current study, this model helped frame the design of an assessment model that would aid instructors to develop assessment tasks that i) address the targeted learning objectives (Fig. 6.1: label 3); ii) probe for students' conceptual understanding of the targeted concepts (**C)** (Fig. 6.1: label 1) and representations (**M**) (Fig. 6.1: label 2); and iii) probe for students' ability to reason with concepts (**R-C**) and representations (**R-M**). By comparing expert opinion of the purpose of the designed assessment in terms of these factors with what the students actually showed in their responses, it would be possible to qualitatively validate the assessments (Fig. 6.1: label 4b & 4c). Furthermore, by aligning the learning objectives with the designed assessment (Fig. 6.1: label 4a), it would be possible to determine if the assessment assesses the targeted concepts (**C**), representations (**R**), and ways of reasoning about the concepts (**R-C**) and representations (**R-M**).

6.3 Methods

6.3.1 The Assessment Model (RQ-7): Description of the Development of the Initial Assessment Design and Validation Model

A modeling framework developed by Justi and Gilbert (2002) guided the development and validation processes of my assessment model (see Chapter 3). As described in Chapter 3, the development of the initial mental model was informed by the assessment design and validation guidelines of Anderson and Rogan (2010). The guidelines (Appendix F), informed by the CRM model, were adapted in order to develop the assessment design and validation model shown in Fig. 6.1. According to the Anderson and Rogan (2010) assessment guidelines, when designing or evaluating an assessment, it is essential to ensure that the assessment assesses relevant concepts (identified in Fig 6.1; label 1) and the related ways of reasoning with such concepts (**R-C**). For example, some of the reasoning skills that can be assessed include the ability to memorize knowledge of a concept in a mindful manner, and the ability to integrate knowledge of a concept with that of other related concepts so as to develop sound explanatory framework. This can be achieved by checking if the assessment questions align with the targeted concepts and cognitive skills. If representations (identified in Fig 6.1; label 2) are included in the assessment, it is important to ensure that they are not

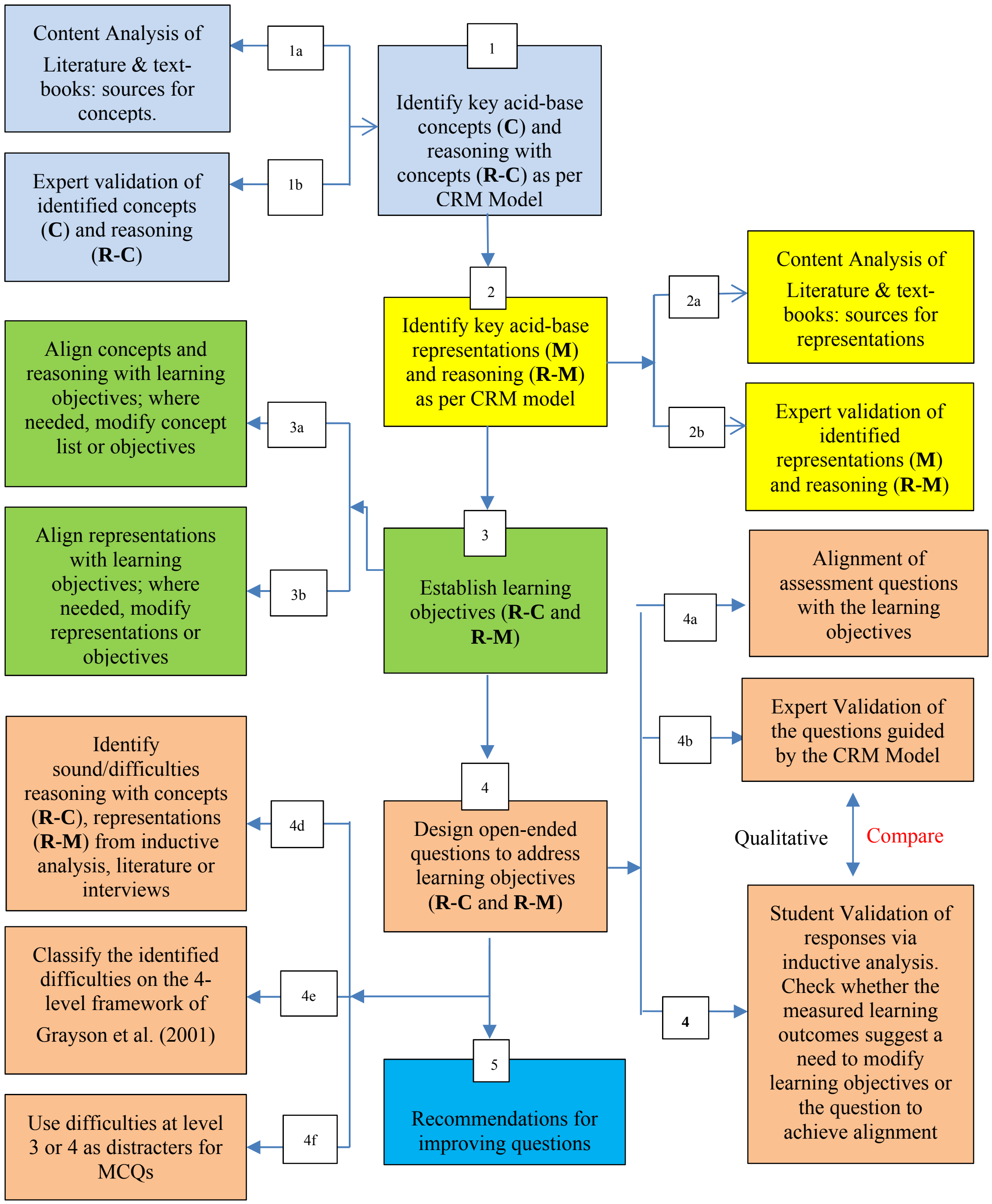


Figure. 6.1: Assessment Design and Qualitative Validation Model

complex and will be understood by the students. Furthermore, it is important to ensure that the assessment requires students to reason with the representation (**R-M**), like for example, the assessment could assess students' ability to decode the symbolic language composing a visual representation, and evaluate limitations and quality of a visual representation. It is important to ensure that the assessment measures the targeted learning objectives (Fig. 6.1; label 3) and the desired learning outcomes. This can be achieved by checking if the assessment questions align with the learning objectives (Fig 6.1; label 3c) and the desired learning outcomes achieved by the students. The quality of the assessment can be checked qualitatively via, for instance, checking the instructors' answers (Fig. 6.1; label 4b) to see how they are expecting the students to answer the questions, and also analyzing student responses (Fig. 6.1; label 4c) to see how they answered the questions. Qualitative analysis of student data is important as it reveals: (i) any existing conceptual difficulties (Fig. 6.1; label 4d), (ii) if the assessment measured the targeted content/concepts/learning objectives; and (iii) if either the assessment questions or the learning objectives have to be modified (Fig. 6.1; label 5).

6.4 Validation of the Model (RQ-8)

6.4.1 Identification and Validation of Key Acid-Base Concepts and Representations (Fig. 6.1: label 1a and 2a)

Prior to designing the assessment guided by the model (Fig. 6.1), I conducted qualitative content analysis (Hsieh & Shannon, 2005) in order to identify key concepts, representations and related ways of reasoning (**R-C** and **R-M**) (Fig. 6.1: 1a and 2a) to do with acid-base. According to Hsieh and Shannon (2005) qualitative content analysis includes three approaches, namely, *conventional, directed and summative*. Although the three approaches are mainly used for analyzing text in order to understand the phenomena under study, they differ in terms of the coding schemes used and origins of the codes. In *conventional* content analysis, an inductive analysis approach is employed; hence the codes used originate from the data. In contrast, in *directed* content analysis a deductive approach is used, thus the codes applied originate from other similar studies. On the other hand, *summative* content analysis involves counting the occurrence of words, phrases or visuals within paragraphs of the given data. This is followed by the inductive interpretation of the underlying context of the identified words. In the present study, convectional content analysis was used to analyze the organic chemistry textbook used in the Medicinal Chemistry and Molecular Pharmacology course (MCMP 204). MCMP 204 is an organic chemistry course that focuses on “a study of the compounds of carbon on a functional group basis, with particular emphasis on those organic compounds of pharmaceutical and physiological importance; micro laboratory experiments involving the methods of purification, reactions, and synthesis of organic compounds,”(https://www.pharmacy.purdue.edu/future-students/programs/bs-pharmaceutical-sciences/curriculum). The fifth edition of the Organic Chemistry textbook written by Marc G. Loudon was used in MCMP 204 course.

Open coding was used for analyzing the textbook. Since the aim was to identify key acid-base concepts and representations, only the acid-base chapter was analyzed (Chapter 3 in the textbook). Each sub-section of the chapter was classified as a category. Therefore, during analysis, each sub-section was read line by line with the aim of identifying words, phrases or representations that best describe the sub-section. These words, phrases or representations were highlighted and thus considered as the key concepts or representations. After analyzing chapter 3 of the organic chemistry textbook, a list of the identified concepts and representations was compiled. This list was shown to the instructor of the course, and he was asked to validate (Fig. 6.1: 1b & 2b) the results by i) identifying, from the list, the concepts and representations he considered to be important for understanding the acid-base topic; ii) identifying the concepts and representations that were not important; and iii) adding any concepts and representations that were not on the list but were important for understanding the acid-base topic. The compiled list was modified as per the instructor’s answers to the latter three questions.

6.4.2 Establishing Learning Objectives, Designing and Validating Assessment Questions

Once the key acid-base concepts and representations were identified, I asked the instructor of the course to provide a list of the learning objectives (Fig. 6.1: label 3) for the acid-base section (Appendix G). The identified concepts, representations and ways of reasoning were aligned to the learning objectives (Fig. 6.1: label 3a & 3b) in order to check if the objectives addressed these or whether the learning objectives needed to be modified. This was followed by designing open-ended questions that addressed the learning objectives (Fig. 6.1: label 4) and therefore, the key acid-base concepts, representations and ways of reasoning. Once designed, the assessment was subjected to expert and student validation (Fig. 6.1: label 4b & 4c). Criteria used for expert validation (Table 6.3) was informed by the CRM model (Schönborn & Anderson 2009) and the assessment guidelines (Appendix F) developed by Anderson and Rogan (2010). In order to verify that the designed assessment really probed for the targeted key acid-base concepts and representations, students' responses were analyzed in order to check for the concepts and representations and ways of reasoning they had included in their answers (Fig. 6.1: label 4c). These were compared to the concepts, representations and ways of reasoning included in the instructor's answers (Fig. 6.1: label 4b) provided in Appendix H. This was followed by analyzing students' responses to check for the presence of sound responses and conceptual, reasoning and visual difficulties (Fig. 6.1: label 4d). The identified students' difficulties were classified on the four-level framework (Fig. 6.1: label 4e) developed by (Grayson, Anderson, & Crossley, 2001). Recommendations for how the the assessments could be improved to enhance their validity were also made (Fig. 6.1: label 5).

6.4.2.1 Analysis of Student Responses

As described above, once the assessment has been designed, it is subjected to expert versus student validation in order to check if, for each question, the students used the same concepts as the ones used by the instructor. In order to check if the students' responses had the same concepts as those included in the instructor's answers, I read through each of the 230 student responses in order to check for the concepts used. I realized that the responses portrayed different characteristics. That is, there were responses that included the same concepts as those included in the instructor's answers, and there were responses that did not include the same concepts as those used in the instructors' answers. Therefore, I divided the responses into two groups: Group 1, the responses that had similar concepts as those included in the instructor's answers and; Group 2, the responses that did not have the same concepts as those used in the instructor's answers. I further read through the responses in Group 1 and I discovered that some of the responses in this group were correct whereas some were not correct. Therefore, I grouped the responses in Group 1 into two sub-groups: Group 1a, the responses that were correct and included the same concepts as those used in the instructor's answers. and Group 1b, the responses that were incorrect and included the same concepts as those used in the instructor's answers. Since the responses in Groups 1a, 1b and 2 portrayed similar characteristics, I selected one representative from each group, for each assessment question, in order to demonstrate expert versus student validation of the assessment questions (see Tables 6.5 and 6.6).

Students' responses were also analyzed for the presence of sound responses, and conceptual, reasoning and visual difficulties. I used open coding to analyze student responses. During open coding, I read students' responses line by line, and as I read, I underlined and coded each line that informed me if the response was correct or not. I used the code "sound response" to label the lines that showed sound responses, and I used the code "unsound response" to label the lines that showed unsound students responses.

Once the coding was complete, I compiled the sound responses and I also piled the unsound responses together. I further used open coding to analyze the unsound responses because I wanted to find out the types of difficulties that students had. As described in section 6.5.3, analysis of students' unsound responses yielded two major categories that showed the types of difficulties the students portrayed.

6.5 Results and Discussion

In order to address RQ-8, that is to validate the proposed assessment model (Fig. 6.1), I collected data at each stage of the model to guide the design of the acid-base assessment for MCMP 204 course. These data are presented and discussed in the sections that follow.

6.5.1 Stage 1 and 2: Identification and Validation of Key Acid-Base Concepts and Representations Relevant to MCMP 204 Course

Before designing the assessment, I identified the key acid-base concepts and representations relevant to MCMP 204 course by analyzing the acid-base chapter of the textbook as described above (see Section 6.4.1), and I had the list of concepts and representations validated by the instructor of the course. Table 6.1 below shows the concepts and representations that, according to the instructor of the course, are relevant to the MCMP 204 course. The identification of concepts and representations was important because I wanted to ensure that the assessments would indicate students' understanding of the acid-base concepts and representations that are relevant to the MCMP 204 course.

Table 6.1: Key Concepts and Representations rated Important for MCMP 204 Course by the Instructor

Acid-Base Concepts (**C**)			
Acids/acidity	Delocalization of electrons	Ionization	pK_a
Acid-base strength	Dissociation	Ions	Polar effect
Amphoteric compounds	Effect of resonance on free energy	K_a	Resonance double headed arrows
Arrhenius acid-base theory	Effect of resonance on pH	K_{eq}	Resonance
Atomic number	Effect of resonance on stability	K_W	Strong acids
Bases/basicity	Element effect	Lewis acid-base theory	Strong bases
Brønsted acid-base theory	Electronegativity	Moles	Water
Charge	Equilibrium	Nucleophile/electrophile /leaving group	Weak acids
Charge effect	H^+	OH^-	Weak bases
Concentration	Henderson Hasselbalch	Orbital theory	
Conjugate acid	H_3O^+	pH	
Conjugate base	Hybridization	pI	
Acids-base Representations (**M**)			
Arrhenius acid-base reactions	Equilibrium diagrams	Lewis acid-base reactions	Standard free energy of ionization (G^o_a= 2.3RTpk_a)
Brønsted acid-base reactions	General equilibrium constant equation (K_{eq}=[products/reactants]	Molecular structures of compounds	Standard free energy diagram that shows the effect of resonance on free energy
Curved arrow notations	Graph showing ionization of polyprotic acids	pH equation (pH= -log(H^+))	Zwitterion structure
Dissociation constant equation for acids (K_a= [H^+][A^-]/[HA])	Henderson-Hasselbalch Equation	pKa equation (pK_a=-logK_a)	
Equilibrium arrows	Ion product of water equation (K_w=[H^+][OH] =10^{-14} M^2 OR –logK_w=14	Resonance structures of acid compounds	
Equilibrium constant equation (K_{eq}= $10^{(pKa\ product-\ pKa\ reactant)}$)	Ionization reaction diagrams	Resonance double-headed arrows	

6.5.2 Stage 3: Establishing Learning Objectives and Aligning Concepts with the Learning Objectives

Once the key concepts and representations had been identified, I asked the instructor of the course to provide the learning objectives (Appendix G) for the acid-base topic. As shown in Table 6.2, the identified acid-base concepts and representations were aligned to the learning objectives (Fig. 6.1: label 3a). The latter was done so as to check if the learning objectives address all the concepts. On the basis of the alignment shown in Table 6.2, it is evident that most of the concepts are addressed by the learning objectives. There are, however, some concepts (e.g. atomic number, concentration, moles, shown in red color) and representations (e.g. ionization reactions, zwitterion structure, shown in blue color) that are not at all addressed by the learning objectives. This suggests that the learning objectives might be modified so as to include those concepts and representations that have not been addressed.

.

Table 6.2: Concepts and Representations aligned with the Learning Objectives derived by the instructor.

Acid-base Concepts	Learning Objectives																				
	A	B	C	D	d1	E	F	G	g1	g2	g3	g4	g5	H	h1	h2	h3	h4	h5	h6	I	J
Acids/acidity							x							x		x	x		x			
Acid-base strength			x																			
Arrhenius acid-base theory																						
Amphoteric compounds							x															
Atomic number																						
Bases/basicity							x							x								
Brønsted acid-base theory																						
Charge																x						
Charge effect																x						
Concentration																						
Conjugate acid			x															x				
Conjugate base			x															x				
Delocalization of electrons																		x				
Dissociation									x		x				x							
Effect of resonance on free energy																					x	
Effect of resonance on pH																		x				
Effect of resonance on stability																						
Element effect															x							
Electronegativity															x							
Equilibrium						x																
H^+																						
Henderson Hasselbalch								x														
H_3O^+																						
Hybridization																			x			
Ionization					x																	
Ions																						
K_a			x																			

Table 6.2, continued

Acid-base Concepts	Learning Objectives																					
	A	B	C	D	d1	E	F	G	g1	g2	g3	g4	g5	H	h1	h2	h3	h4	h5	h6	I	J
K_{eq}						x																
K_W																						
Lewis acid-base theory																						
Moles																						
Nucleophile/electrophile/leaving group		x																				
OH^-																						
Orbital theory																						
pH									x	x	x	x										
pI													x									
pK_a				x		x	x			x		x	x									x
Polar effect																	x					
Resonance																		x				
Strong acids			x																			
Strong bases			x																			
Water																						
Weak acids			x																			
Weak bases			x																			
Representations	A	B	C	D	d1	E	F	G	g1	g2	g3	g4	g5	H	h1	h2	h3	h4	h5	h6	I	J
Arrhenius acid-base reactions						x																
Brønsted acid-base reactions		x				x																
Curved arrow notations	x																					
Dissociation constant equation for acids ($K_a= [H^+][A^-]/[HA]$)																						
Equilibrium arrows						x																
Equilibrium constant equation ($K_{eq}= 10^{(pKa\ product-\ pKa\ reactant)}$)						x																
Equilibrium diagrams						x																
General equilibrium constant equation (K_{eq}=[products/Reactants]						x																

Table 6..2, continued

Acid-base Concepts	Learning Objectives																					
	A	B	C	D	d1	E	F	G	g1	g2	g3	g4	g5	H	h1	h2	h3	h4	h5	h6	I	J
Graph showing ionization of polyprotic acids										x												
Henderson-Hasselbalch Equation								x														
Ion product of water equation (K_w=[H^+][OH^-]=10^{-14} M^2 OR –logK_w=14																						
Ionization reaction diagrams																						
Lewis acid-base reactions																						
Molecular structures of compounds									x													
pH equation (pH= -log(H^+)											x											
pKa equation (pK_a=-logK_a)				x																		
Resonance double-headed arrows																		x				
Resonance structures of acid compounds																		x			x	
Standard free energy diagram that shows the effect of resonance on free energy				x																	x	
Standard free energy of ionization (G^o_a= 2.3RTpk_a)					x																	
Zwitterion structure																						

6.5.3 Stage 4: Design and Validation of an Assessment

As per the model in Fig. 6.1, label 3, I designed an open-ended assessment that addressed some, but not all the key acid-base concepts and representations shown in Table 6.1. The designed assessment was shown to the instructor of the course and was modified by the instructor. The assessment was modified because the instructor pointed out that some of the diagrams used were more biological and thus might confuse students; and the wording used in some of the questions was more biological in nature and thus might also confuse students. The final assessment, shown in Appendix H, had eight questions. However, the focus of this study was on assessment question eight. Question eight probed students' conceptual understanding of acid-base concepts and their ability to reason with concepts and representations. Once the assessment was finalized, only question eight was subjected to expert validation (Fig. 6.1: label 4b). As shown in Table 6.3, expert validation of the question included checking if the question is open ended or close ended (MCQs), if the question probes for conceptual understanding and the ability to reason with representations, and if the question probes for the targeted learning objectives. The reasoning (e.g. R1, R2 &R3) and visual (e.g. V1, V2 & V3) skills in table 6.3 are discussed in Chapter 3, section 3.4.

Table 6.3: Expert Validation of Assessment Questions (From Anderson and Rogan, 2010)

Question	A. Before Assessment: what is/are the questions probing?																										
		Probing for conceptual understanding?									Ability to reason with representations								Ability to reason about experiments					Ability to calculate & solve problems		Biological importance/relevance?	
		No	Yes	If yes, which Facets/reasoning skills are probed? (**R-C** in CRM model)							No	Yes	If yes, which Visual skills are probed?						No	Yes	If yes, which Experimental reasoning skills probed?			Yes	No	Yes	No
				R1	R2	R3	R4	R5	R6	R7			V1	V2	V3	V4	V5	V6			E1	E2	E3				
Quiz 8a			x	x	x	x						x	x		x	x	x		x						x	x	
Quiz 8b			x	x	x	x			x			x	x		x		x		x						x	x	
Quiz 8c			x	x	x	x						x				x			x						x	x	
Quiz 8d			x	x		x				x		x			x				x					x		x	
Quiz 8e			x	x	x	x			x			x	x		x				x						x	x	

I. Memorize knowledge of a concept in a mindful manner (R1). II. Integrate knowledge of a concept with that of other related concepts so as to develop sound explanatory frameworks (R2). III. Transfer and apply knowledge of a concept to understand and solve problems (R3). IV. Reason analogically about a concept (R4). V. Reason locally and globally about a concept (R5). VI. Reason algorithmically about a concept (R6). VII. Critically analyze or evaluate a concept (R7). VIII. Think metacognitively about a concept (R8). IX. Decode the symbolic language composing a visual representation (V1). X. Evaluate limitations and quality of a visual representation (V2). XI. Interpret and use a visual representation to solve a problem (V3). XII. Spatially manipulate a visual representation to interpret and explain a concept (V4). XIII. Construct a visual presentation to explain a concept or solve a problem (V5). Translate horizontally across multiple visual presentations of a concept (V6). XIV. Translate vertically between visual presentations that depict various levels of organization and complexity (V7). XV. Visualize orders of magnitude, relative size and scale (V8). XVI. Interpret the temporal resolutions of visual representations considering what came before and will come next (V9). XVII. Generate and analyze data (E1). XVIII. Identify independent and dependent variables (E2). XIX. Use positive and negative controls (E3)

Table 6.3, continued

Question	A. Before Assessment: type of questions designed																			
	Will the question be MCQs?						Will the questions be open-ended?				Are diagrams be included?						Is language clear		Questions address objectives?	
	No	Yes	If yes, what types of distracters are used?				No	Yes	If yes, are a range of scientifically correct answers allowed?		No	Yes	If yes ,				No	Yes		
													Is symbolism clear?		Diagram help answer quiz?				No	Yes
			Validated	Unpublished research	Teaching experience	Thumb -sucked			No	Yes			No	Yes	No	yes				
Quiz 8a	x							x		x		x		x		x		x		x
Quiz 8b	x							x		x		x		x		x		x		x
Quiz 8c	x							x	x			x		x		x		x		x
Quiz 8d	x							x	x			x		x		x		x		x
Quiz 8e	x							x		x		x		x		x		x	x	

Although the expert validation of question eight shown in Table 6.3 above indicates that most of the questions address the learning objectives, it does not not reveal the specific learning objectives addressed. To achieve the latter, the learning objectives were aligned with the questions (Fig. 6.1, label 4a) as shown in Table 6.4. Based on the information provided in Table 6.4, it is evident that question eight does not address the majority of the stated learning objectives. Furthermore, question eight addresses the same learning objectives, that is, question 8a and 8b both address learning objectives D, F, H, h4 and h5, whereas question 8c and 8d both address learning objectives g2. Since question eight does not address a wide range of the stated learning objectives, the next step would be to modify the questions (Fig. 6.1, label 5) in such a way that the questions address different learning objectives. However, in this case, as shown in Appendix H, the assessment had seven other questions besides question eight. It, is therefore possible that the other seven questions addressed the learning objectives that were not addressed by question eight.

Table 6.4: Assessment Questions Aligned to Learning Objectives

Questions	Learning Objectives																					
	A	B	C	D	d1	E	F	G	g1	g2	g3	g4	g5	H	h1	h2	h3	h4	h5	h6	I	J
8a			x	x			x					x		x				x	x			
8b			x	x			x					x		x				x	x			
8c										x		x										
8d								x		x												
8e																						

A. Define an *electron-pair displacement reaction* and its curved-arrow notation. B. Understand the terms *nucleophile, electrophile,* and *leaving group,* and how these are applied to Brønsted acid–base reactions. C. Understand how the strengths of acid and bases are expressed. *Key point:* K_a measures the strength of *both an acid and its conjugate base.* K_b values are unnecessary. D. Understand the relationship between pK_a and the standard free energy of dissociation. d1. Be able to represent the standard free energy of ionization graphically as an energy difference between two species. E. Understand how to estimate the equilibrium constant for a general acid–base reaction. *Key Point:* Calculating the K_{eq} for an acid–base reaction from the pK_a values of the two acids allows us to see whether a reaction at equilibrium lies to the right or left. While students can use an ICE table to calculate exact concentrations at equilibrium, this is not necessary to get a semi-quantitative idea of the position of equilibrium. F. Determine in specific cases whether an amphoteric compound is acting as an acid or a base, and which pK_a applies. G. Apply the Henderson–Hasselbalch equations in specific cases. g1. Be able to determine the fraction dissociation of a monoprotic acid at a given pH for biologically important molecules such as drugs. g2. Be able to determine, or at least describe with a sketch, the fractions of the different species of a diprotic acid as a function of pH, given its pK_a values. g3. Be able to calculate the pH of a solution as a function of fraction dissociation of an acid. g4. Understand the difference between pH of the solution and the pK_a of an acid. *Key point:* The pH is an experimental variable; the pK_a is a property of a compound that is not experimentally variable. g5. Define isoelectric point of an amino acid; calculate the isoelectric point given the relevant pK_a values. H. Understand and give examples of the effects of structure on acidity and basicity. h1. Understand the periodic trends in bond dissociation energies and electronegativities on acidity (the *element effect*). h2. Understand how a charge on the atom to which an acidic proton is bonded affects acidity (the *charge effect*). h3. Understand how substituents remote from the acidic group affect acidity (the *polar* or *inductive effect*). h4. Understand how resonance in a conjugate acid or base affects acidity or basicity (the *resonance effect*). h5. Understand how hybridization of the atom to which the acidic proton is attached affects acidity (*hybridization effect*). h6. Understand how the presence of an atom in an aromatic ring affects its basicity or acidity. I. Apply the reasoning used in Objective d1 to understand how energy differences in acids and bases result from the structural effects in Objectives h3, h4, and h5 and thus account for these effects on acidity. J. Learn a relatively small number of biologically important pKa values than can be used as a "baseline" for applying the trends implied by the effects of structure in Objective H.

Besides expert validation of the assessment questions, students' responses were analyzed in order to check if the assessment questions actually revealed what the instructor thought they assessed (Fig 6.1: 4b & 4c). I, therefore, analyzed student answers, whether correct or incorrect, in order to check if their answers had the same concepts as the expert/instructor's answers. Based on the information provided in Table 6.5, it is evident that the questions probed for some concepts but not others. For instance, student F-301's answer was correct and it included concepts such as hybridizations and basicity. These concepts were included in the instructor's answer. However, student F-301's answer for question 8a and 8b lacked concepts such as pH, conjugate base, conjugate acid and pK_a. These concepts were present in the expert's answer. Therefore, this shows that questions 8a and 8b explicitly probe for concepts such as hybridization and basicity. However, it is possible that these questions did not explicitly probe for concepts such as pH, pK_a, conjugate acid and conjugate base. This analysis provides important information for the instructor to modify questions 8a and 8b to ensure that they explicitly probe for the targeted concepts such as pH, pK_a, conjugate acid and conjugate base.

Table 6.5: Student Validation of the Assessment Questions

Key concepts important for MCMP204	Assessment Questions															
	8a & 8b				8c				8d				8e			
	EX	F-301	B-202	S-A	EX	F-301	B-202	S-A	EX	F-301	B-202	S-A	EX	F-301	B-202	S-A
Acids/acidity																
Acid-base strength																
Arrhenius acid-base theory																
Amphoteric compounds																
Atomic number																
Bases/basicity	X	Y	0	0												
Brønsted acid-base theory																
Charge																
Charge effect																
Concentration													X	Y	0	Y
Conjugate acid	X	0	0	0												
Conjugate base	X	0	0	0												
Delocalization of electrons																
Dissociation																
Effect of resonance on free energy																
Effect of resonance on pH																
Effect of resonance on stability	X	0	N	0												
Element effect																

Y: shows the existence of knowledge/concepts being probed where the answer is correct.
N: a good probe for the knowledge/concepts where the response shows lack of the correct knowledge.
0: no evidence – the probe has not elicited student difficulties or correct knowledge.
X: Experts' concepts
EX: expert
F-301, B-202, Stu A: students

Table 6.5, continued

Key concepts important for MCMP204	Assessment Questions															
	8a & 8b				8c				8d				8e			
	EX	F-301	B-202	S-A	EX	F-301	B-202	S-A	EX	F-301	B-202	S-A	EX	F-301	B-202	S-A
Electronegativity																
Equilibrium													X	0	0	0
H^+																
Henderson Hasselbalch									X	Y	N	Y				
H_3O^+																
Hybridization	X	Y	N	0												
Ionization					X	Y	Y	Y								
Ions																
K_a																
K_{eq}																
K_W																
Lewis acid-base theory																
Moles																
Nucleophile/electrophile/leaving group																
OH^-																
Orbital theory																
pH	X	0	0	0	X	Y	Y	Y	X	Y	N	Y	X	Y	0	0
pI																
pK_a	X	0	0	0	X	Y	Y	Y	X	Y	N	Y	X	Y	0	Y
Polar effect																
Resonance	X	0	0	0												
Strong acids																

Y: shows the existence of knowledge/concepts being probed where the answer is correct. N: a good probe for the knowledge/concepts where the response shows lack of the correct knowledge. **0:** no evidence – the probe has not elicited student difficulties or correct knowledge. X: Experts' concepts. EX: expert. F-301, B-202, Stu A: students

Table 6.5, continued

Key concepts important for MCMP204	Assessment Questions															
	8a & 8b				8c				8d				8e			
	EX	F-301	B-202	S-A	EX	F-301	B-202	S-A	EX	F-301	B-202	S-A	EX	F-301	B-202	S-A
Strong bases																
Water																
Weak acids																
Weak bases																

Y: shows the existence of knowledge/concepts being probed where the answer is correct. N: a good probe for the knowledge/concepts where the response shows lack of the correct knowledge.
0: no evidence – the probe has not elicited student difficulties or correct knowledge. X: Experts' concepts. EX: expert. F-301, B-202, Stu A: students

On the other hand, information provided in Table 6.6 below shows that questions 8c and 8d explicitly probed for students' ability to use representations such as the Henderson-Hasselbalch equation, ionization reactions and graphs showing ionization of polyprotic acids. The latter is due to the fact that the students' answers showed the same representations as those included in the expert's answers.

Table 6.6: Student Validation of Assessment Questions

Key acid-base representations important for MCMP204	Assessment Questions															
	8a & 8b				8c				8d				8e			
	EX	F-301	B-202	S-A	EX	F-301	B-202	S-A	EX	F-301	S-A	B-202	EX	F-301	S-A	B-202
Arrhenius acid-base reactions																
Brønsted acid-base reactions																
Curved arrow notations																
Dissociation constant equation for acids (K_a= $[H^+][A^-]/[HA]$)																
Equilibrium arrows																
Equilibrium constant equation (K_{eq}= $10^{(pKa\ product-\ pKa\ reactant)}$)																
Equilibrium diagrams																
General equilibrium constant equation (K_{eq}=[products/Reactants]																
Graph showing ionization of polyprotic acids					X	Y	Y	Y								
Henderson-Hasselbalch Equation									X	N	Y	N				
Ion product of water equation (K_w=$[H^+][OH^-]$=10^{-14} M^2 OR $-logK_w$=14																

Y: shows the existence of knowledge/concepts being probed where the answer is correct. N: a good probe for the knowledge/concepts where the response shows lack of the correct knowledge.
0: no evidence – the probe has not elicited student difficulties or correct knowledge. X: Experts' concepts. EX: expert. F-301, B-202, Stu A: students

Table 6.6 continued

Key acid-base representations important for MCMP204	Assessment Questions															
	8a & 8b				8c				8d				8e			
	EX	F-301	B-202	S-A	EX	F-301	B-202	S-A	EX	F-301	S-A	B-202	EX	F-301	S-A	B-202
Ionization reaction diagrams					X	Y	Y	Y								
Lewis acid-base reactions																
Molecular structures of compounds																
pH equation ($pH= -log(H^+)$)																
pKa equation ($pK_a=-logK_a$)																
Resonance double-headed arrows																
Resonance structures of acid compounds																
Standard free energy diagram that shows the effect of resonance on free energy																
Standard free energy of ionization ($G^o_a= 2.3RTpk_a$)																
Zwitterion structure																

Y: shows the existence of knowledge/concepts being probed where the answer is correct.

N: a good probe for the knowledge/concepts where the response shows lack of the correct knowledge.

0: no evidence – the probe has not elicited student difficulties or correct knowledge.

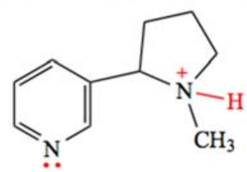
X: Experts' concepts

EX: expert

F-301, B-202, Stu A: students

One of the assessment questions (question 8a & 8b, Appendix H) provided the students with an organic structure of nicotine. As shown in Fig. 6.2 below, the students were expected to (i) draw a monocation of the nicotine structure; and (ii) explain how they knew where to put the proton.

(a) (3 pts) Draw the structure of *BH*. We have provided a partial structure to which you should add a proton, the appropriate charge, and any unshared pairs.



nicotine (form *BH* in the equilibrium above)

(b) (3 pts) Explain how you knew where to put the proton. *Do not exceed the allowed space.*

The hybridization effect lowers the basicity of the pyridine nitrogen (the one in the 6-membered ring). This means that the pK_a of its conjugate acid is lower. Consequently, the higher pK_a is associated with the conjugate acid of the other, more basic, nitrogen. As the pH is lowered, this is the first nitrogen to be protonated.

Figure 6.2: Question 8a and 8b of the Assessment Task. The Instructor's Answers are Shown in Red Color

Less than half, only 94 out of 230 students, provided the correct structure of the monocation of the nicotine. Furthermore, as shown below, some students provided sound explanations regarding how they knew where to put the proton.

Stu F301: *"The left nitrogen is sp^2 hybridized, making it more acidic, so it would rather donate a proton or accept an electron pair. The right nitrogen is more basic because it is sp^3 hybridized, so it would rather accept a proton or donate an electron* *pair. I put the proton on the right nitrogen because it is more basic and would rather accept a proton."*

Stu A75: *"The nitrogen on the benzene ring is* sp^2 *hybridized while the other is* sp^3 *hybridized. More S character means more acidic so less S character means more basic. The* sp^3 *nitrogen has less S character and is therefore, more basic."*

Further analysis of students' responses revealed some had conceptual and reasoning difficulties. The difficulties were classified into two major categories, namely, i) Category 1: protonation of nicotine; and ii) Category 2: inability to graphically represent the ionization of nicotine.

Category 1: Protonation of nicotine begins on the pyridine ring. This category included students who indicated that during the ionization of nicotine, the nitrogen on the pyridine ring will be protonated before the nitrogen on the methylpyrrolidine ring. This category consists of the three sub categories discussed below.

Sub Category 1: this sub category consists of students who indicated that during the ionization of nicotine, the nitrogen on the pyridine ring will be protonated first because it will form a resonance structure that will lead to the formation of a stable ion. The students provided the following responses to support their claim:

Stu D: *"[…] The proton went onto the nitrogen in the ring with double bonds because it will be able to delocalize the charge and create resonance structures, causing it to be more stable."*

Stu W: *"I put the proton where I did because the conj. acid (BH) will have stabilizing, resonance structures. [..]"*

Stu E: *"The double bonds in the left ring give more room for the charge to delocalize, giving it more resonance + making it more stable."*

Stu Z: *"This structure allows resonance in the ring where the H was added and therefore makes it more stable of the structures."*

As shown by the students' responses, the students in this sub-category thought the nitrogen in the pyridine ring will be protonated first because the presence of the proton will help in creating resonance which will stabilize the structure. The students seem to not realize or understand that the pyridine ring has resonance and the methylpyrroline does not have resonance. The presence of resonance increases acidity, hence the nitrogen in the pyridine ring is acidic. For this reason, the nitrogen in the pyridine ring will not be protonated first.

Sub Category 2: students in this category stated that the nitrogen in the pyridine ring will be protonated first because the proton added will make the nitrogen more stable. These students provided the following responses to support their claims:

Stu A: *"The proton goes to the N that is least stable. By adding a proton to the nitrogen on the left it stabilizes the structure".*

Stu B: *"[...] Nitrogen A[on pyridine ring] would be more stable when a proton was added to it than nitrogen B[on methypyrrolidine ring]."*

Stu C: *"[..] By adding a hydrogen to the less stable nitrogen on the left, it becomes more stable at higher pH."*

Stu O: *"You put the proton on the first nitrogen. By placing it on the nitrogen in the ring it helps stables [stabilize] the molecule [..]"*

The above responses suggest that the students thought adding the proton to the nitrogen on the pyridine ring will stabilize the nitrogen. The students seem to not understand that the nitrogen in the pyridine ring is more stable than the nitrogen in the methylpyrroline ring. This is because the nitrogen in the pyridine ring is sp^2 hybridized whereas the nitrogen in the methylpyrroline ring is sp^3.

Sub Category 3: this consists of students who claimed that the nitrogen on the pyridine ring gets protonated first during the ionization of nicotine. The latter, according to the students, is due to the fact that the nitrogen in the pyridine ring is less crowded. The following responses were provided by the students:

Stu P: *"The left nitrogen seemed less crowded. With less things going on over the left end, I figure the proton gets repelled less. So would rather bond there first."*

Stu Q: *"I knew where to put the proton because the nitrogen bonded to the CH_3 could not add another hydrogen because too many bonds would be on it. Therefore, I added it to the other nitrogen."*

Stu R: *"It is much easier to add the proton to the nitrogen on the left bec [because] it has one lone pair and no additional functional groups attached to it [...]."*

Stu V: *"The H^+ ion will go to the less crowded N initially."*

In general, the students that portrayed the difficulties that fall under category-1 seem to not understand that the nitrogen in the methylpyrrolidine ring will be protonated first because the methyl group pushes electrons towards the nitrogen group and the buildup of small negative charge around the nitrogen attracts the hydrogen ions. Secondly, the nitrogen in the methylpyrrolidine ring is sp^3 hybridized whereas the nitrogen in the pyridine ring is sp^2 hybridized. The more hybridized an atom is, the more basic it is, thus, the nitrogen in the methylpyrrolidine will be protonated first because it is more basic. Therefore, based on this and the responses provided by the students, it can be suggested that the students did not understand concepts such as the hybridization effect, resonance and its effect on acidity and basicity of an atom, ionization and pK_a acidity and basicity in relevance to organic bases. Furthermore, it can be suggested that the students lacked visual reasoning skills (**R-M**) such as the ability to decode the symbolism on nicotine structure and the ability to use the provided nicotine structure to identify the nitrogen that is more basic. Moreover, the students lacked reasoning skills (**R-C**) such as the ability to apply knowledge of the stated concepts, integrate knowledge of these concepts with that of other concepts in order to explain which nitrogen will be protonated first during the ionization of nicotine. The idea that stability determined acid strength was also discovered by McClary and Bretz (2012) who reported that organic chemistry students thought "p-methylphenol was more acidic than phenol because the methyl group destabilizes the conjugate base of p-methylphenol." The difficulties in sub-category 1 and 2 were therefore classified on level 2 of the four-level framework (Grayson et al., 2001).

Besides being asked to draw the monocation of nicotine, question 8c asked the students to sketch the fraction of each form of nicotine as a function of pH. The instructor provided the answer shown in Fig. 6.3 below.

(c) **(12 pts) Sketch (do not calculate) on the following set of axes the fraction of *B*, *BH*, and BH_2 as a function of pH. (There will be three superimposed curves.) On each curve label the corresponding form. On both axes, label the important reference points that were crucial in sketching your curves.**

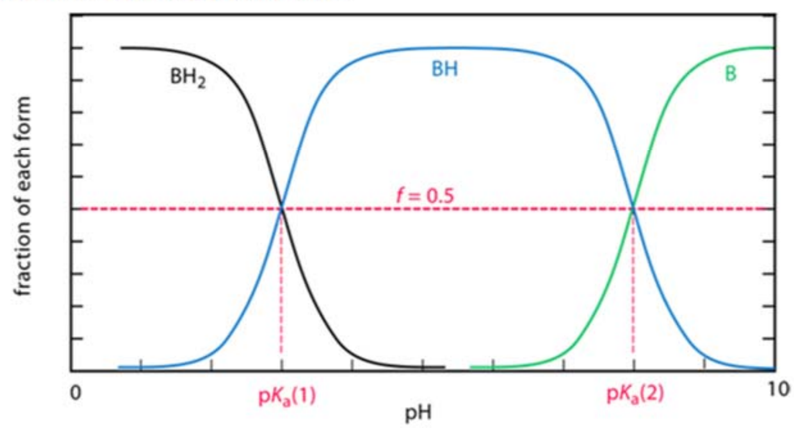
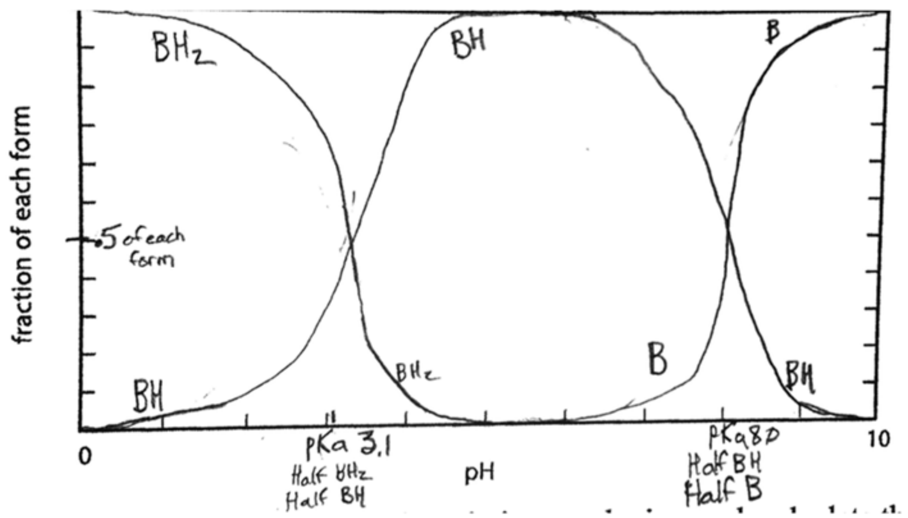


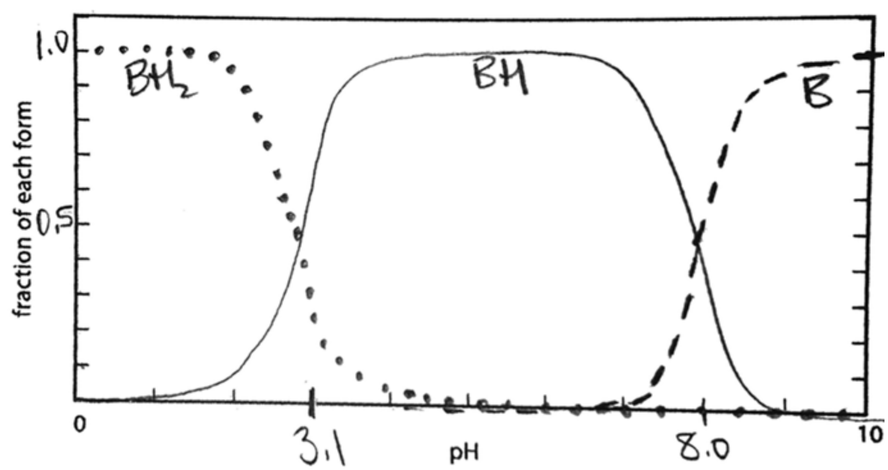
Figure 6.3: The Instructor's Answer to Question 8c

As shown below, some of the students were able to correctly draw the fraction of each nicotine form as a function of pH. The fact that some students were able to graphically represent conservation of matter with a constant total amount of nicotine as the fractional portion of a particular nicotine ion varies with pH further validates the assessment model shown in Fig. 6.1.

Stu A24



Stu D205



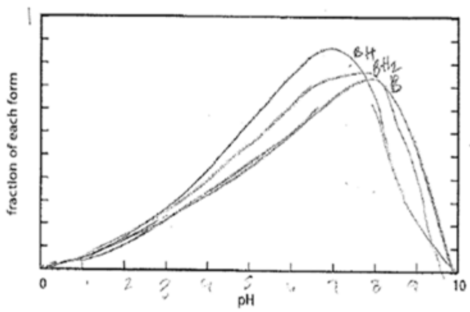
The fact that Stu A24 and Stu D205 were able to correctly represent the fraction of each form of nicotine as a function of pH implies that they understood that nicotine exists as a: (i) dication (BH_2) in acidic solutions (ii) neutral form (B) in basic solutions and; (iii) monocation (BH) in solutions that have intermediate pH. Stu A24 and Stu D205 seem to also understand that when pH is equal to pK_a, 50% of the two forms of nicotine exist in solution, hence as shown in their diagrams above, at pH 3.1 (equal to pK_a), 50% of both the dication (BH_2) and the monocation (BH) exist in solution, whereas at pH 8.0 (equal to pK_a) 50% of both the monocation (BH) and the neutral form (B) of nicotine exist in solution.

As stated, analysis of students' responses revealed that other students had conceptual and reasoning difficulties. The difficulties were classified into two major categories, Category 1: protonation of nicotine (discussed earlier) and; ii) Category 2: inability to graphically represent conservation of matter with a constant total amount of nicotine as the fractional portion of nicotine ions vary with pH.

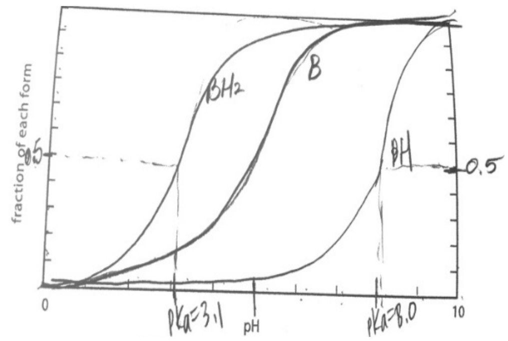
Category 2: Inability to graphically represent the fractional portion of various nicotine ions as a function of pH. This category included students who did not correctly, graphically represent the fraction of the three forms of nicotine as a function of pH. Graphs provided by the students ranged from being skewed to the right to having a central pH point where all the graphs converge. The students who provided skewed graphs seem to think that: (i) all the three forms of nicotine exist in solution at the same pH; (ii) the amount of all the three forms increases with increasing pH and; (iii) the amount of all the three forms either decreases after a certain basic pH (Stu A) or plateaus after a certain pH (Stu AB). Students who drew the graphs that converge at a central pH seem to think that the amounts of either two or three forms of nicotine increases till the two forms converge at a central pH after which the amounts of the forms of nicotine decreases.

Graphs skewed to the right:

Stu E:

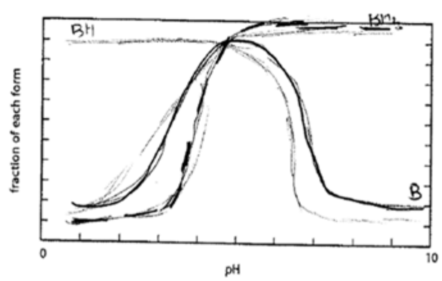


Stu AB:

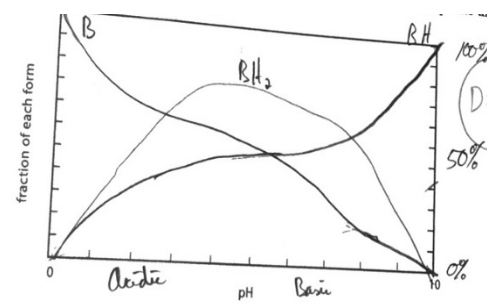


Graphs that converge at a central pH

Stu F:



Stu CD



The students that portrayed this difficulty seem to not understand that in highly acidic solutions, nicotine exists as a dication (BH_2); in highly basic solutions, nicotine exists as a neutral form (B); whereas in solutions that have intermediate pH, nicotine exists as a monocation (BH). Therefore, since the students did not understand which form of nicotine predominates in either acidic or basic pH, they were not able to graphically show the various forms of nicotine at various pH conditions. This therefore suggests that the students did not understand concepts such as ionization of nicotine, pH, pK_a and their relation to the ionization of nicotine. Based on the students' drawings, I suspect that the students lacked visual skills (**R-M**) such as the ability to construct a representation, or graph in this case, to solve a problem or show the fractional amounts of each form as a function of pH. Moreover, I suspect that the students lacked visual skills (**R-M**) such as the ability to translate horizontally between the various representations of nicotine in order to be able to graphically show the fractions of the three forms of nicotine as a function of pH. Therefore, interviews could be used in order to confirm that the students really lacked the aforementioned visual skills.

6.5.4 Step 5: Recommendations for Improving the Assessment

On the basis of the information collected from the steps shown in Fig. 6.1, the assessment shown in Appendix H can be improved as follows:

- In question 8c, in addition to asking the students to sketch the ionization of nicotine, the questions can be improved by asking the students to explain the graph they have drawn. This will help the instructor to have an idea of the thought processes that the students employed when drawing the graph.
- In question 8d, in addition to asking the students to calculate the fraction of the monocation of nicotine in blood, the students could also be asked to explain their calculations. By so doing, the instructor will have an idea of why the students decided to solve the problem the way they did.

6.6 Conclusion and Implications

The following research questions were addressed in this study: i) What is the appropriate model for designing and validating assessment tasks? (RQ-7); and (ii) Do acid-base assessments designed by an organic chemistry instructor support the validity of this model? (RQ-8). To gather the results presented in this study, the model of modelling framework by Justi and Gilbert (2002) was useful in guiding me to successfully design an assessment model that can be used for the development, evaluation and qualitative validation of an assessment. The results presented in this study suggest that using the organic chemistry acid-base assessments to validate the assessment design model (Fig. 6.1) was good because it revealed the strengths and weaknesses of the assessment design model. The strengths include the fact that the model helps instructors to design assessments that align concepts, representations and learning objectives. Furthermore, through expert validation, the instructors can evaluate their assessment questions in order to check the concepts, representations and learning objectives addressed by the assessment questions. Additionally, through student validation, the instructors can analyze student responses in order to check if the assessment really addresses what they think it is addressing. Analysis of student responses also informs the instructors about the difficulties that students have. The fact that the assessment design model shown in Fig. 6.1 includes a stage that guides instructors about how to validate assessments is an advantage because according to DeBoer and colleagues (2008), Kane and Bejar (2014), Herman (2010), Pellegrino (2014) and the NRC (2001) validation of assessments is important as it informs instructors about what the assessment items are testing. Besides the strengths of the model, the weaknesses include the fact that the assessment model may not be easy for instructors to implement and that its validity and usefulness in other disciplines and contexts remains to be confirmed.

In general, the assessment model in Fig. 6.1 shows the stages/steps that can be used by instructors when designing and validating assessments. It is important to point out that although in the current study the model was used to show how an assessment can be designed, the model can also be used to evaluate an assessment that has already been designed in order to assess if it addresses the targeted learning objectives; key concepts and representations; and reasoning and visual skills. Furthermore, it is essential to point out that assessment design is not a linear process, thus, when designing an assessment, an individual can decide to first identify learning objectives followed by identifying key concepts and representations. Although the model shows how assessments can be validated qualitatively, it is important to also use quantitative measures to validate an assessment. According to Kane and Bejar (2014), using quantitative measures to validate assessments is important specifically in terms of learning progressions or cognitive models because the scores can be used to "assign each student to a particular level in the progression," (p. 120). As a future step, the model can be improved by including a step or stage that shows how quantitative measures such as discrimination indices can be used to validate an assessment. Furthermore, the model can be improved by including a step that shows the design of MCQs using student difficulties (from analyzing student responses) as distractors. According to Anderson and Rogan (2010), distracters used in MCQs ought to be misconceptions documented in literature or identified during teaching because using senseless distracters might confuse students and thus lead to misconceptions.

One important aspect to point out is the fact that the assessment design model shown in Fig. 6.1 incorporates all the three components (*cognition*, *observation* and *interpretation*) of the assessment triangle (NRC, 2001). That is, the assessment design model aids instructors to design assessment tasks that address the content and skills of the subject domain (*cognition* and *observation* components). Furthermore, according to the model, instructors have to analyze students' responses in order to learn what they understand and what they do not understand (*interpretation* component). In addition to incorporating all the components of the assessment triangle proposed by the NRC (2001), the assessment model shown in Fig. 6.1 also guides instructors how they can qualitatively validate their assessments in order to ensure that they actually probing for what the instructors think they are probing.

Since the model has only been validated by using an assessment from a university in the Midwest of the USA, more studies need to be done in order to check if the model will be useful for designing assessments in other subject domains other than organic chemistry.

CHAPTER 7: CONCLUSIONS, IMPLICATIONS AND FUTURE WORK

7.1 Conclusions and Implications

The following goals were addressed in this study:

- Goal 1, to design and test a simple three-stage process for identifying the chemistry and biochemistry concepts, representations, and ways of reasoning important to biology courses.
- Goal 2, to investigate the specific acid-base content that the biology instructors consider to be important for their courses and how they expect students to use the acid-base knowledge.
- Goal 3, to design a model that instructors could use for the design, evaluation, and validation of assessments.

7.1.1 Goal 1: Design and Test a Simple Three-Stage Process for Identifying the Chemistry and Biochemistry Concepts, Representations, and Ways of Reasoning Important to Biology Courses.

In order to address this goal, I decided to explore the following research questions:

i) Which biochemistry and chemistry concepts do the biology instructors at a Midwestern university consider relevant to the courses they teach? (RQ-1).

ii) How do these biology instructors expect students to use the identified concepts in the courses they teach? (RQ-2).

iii) Which biochemistry and chemistry representations do the biology instructors at a Midwestern university consider relevant to the courses they teach? (RQ3).

iv) How do these biology instructors expect students to use the identified representations in the courses they teach? (RQ-4).

The results from these questions showed that there are 74 biochemistry and chemistry concepts that the participating biology instructors considered to be relevant for the biology courses they teach. Although the biology instructors selected these 74 concepts to be important for the courses they teach, there are still other biochemistry and chemistry concepts that have been published in literature and have been reported to be relevant for biology courses (e.g. Tansey et al., 2013; Wright et al., 2013). The fact that the participating biology instructors selected the 74 listed concepts to be relevant to the courses they teach suggests that introductory chemistry and biochemistry courses at the current institution should especially focus on them and their significance and application to biological examples. Regarding representations, the biology instructors provided various types of representations that they considered to be important for the courses they teach. The representations were classified into four categories, namely, graphs, particulate models, mathematical equations, and chemical equations. The fact that the instructors consider representations to be important for the biology courses they teach reflects the modern acceptance that science is a visual subject in which learning is facilitated by the use of representations (e.g. Schönborn & Anderson, 2010; Tsui & Treagust, 2013). The importance of representations for learning biology was also confirmed by Schönborn and Bögeholz (2009). Furthermore, the fact that the instructors considered these representations to be important for the courses they teach suggests that more time has to be spent teaching these representations and ensuring that students understand their biological importance. One important aspect to point out is the fact that the instructors expect the students to understand the biological importance of these 74 concepts and representations so that they are able to use them when explaining biological phenomena and solving problems.

In summary, using the three-step process helped survey biology instructors' views regarding the chemistry concepts and representations they consider to be relevant for the biology courses they teach. The data collected could be used to initiate curriculum-related discussions between the biology instructors and the chemistry/biochemistry instructors at the institution under study in order to decide the concepts to include or to teach in a chemistry/biochemistry course designed for life science students, specifically biology majors. Based on the findings, I believe that this 3-stage process is a piece of a missing puzzle between knowing what to include in a curriculum and how to initiate curriculum-based dissuasions to decide what to include in the curriculum. I also believe that this process will be useful at this institution and other institutions in order to collect data that can be used to launch curriculum discussions.

7.1.2 Goal 2: Investigate the Specific Acid-Base Content that the Biology Instructors Consider to Be Important for Their Courses and How They Expect the Students to Use the Acid-Base Knowledge.

In order to address this goal, I decided to explore the following research questions:

i) How is knowledge of concepts and ways of reasoning about acid-base used by instructors in their particular biology courses? (RQ-5)

ii) How are visual representations and ways of reasoning with acid-base representations used by instructors' in their particular biology courses? (RQ-6)

The results showed that although the four biology instructors indicated that acid-base concepts such as pH, acid-base strength, buffers, and the Henderson-Hasselbalch equation were important for the courses they taught, the content about these concepts that was relevant to each instructor's course was different. Furthermore, the one important aspect to emphasize is the fact that the instructors contextualized their explanations in order to portray the biological significance of the acid-base concepts to the courses they taught. Moreover, the instructors wanted their students to have both declarative and procedural knowledge. That is, the instructors wanted their students to not only know the factual knowledge related to the acid-base concepts, instead they also wanted them to be able to reason with the acid-base knowledge to explain how biological processes work. Therefore, it is important to promote the acquisition of both declarative knowledge and procedural knowledge because it can be useful for learning biology. This can be achieved via exposing students to learning environments that will train them to use both declarative knowledge and procedural knowledge when solving problems, and explaining biological problems. Such learning environments may include using formative assessments that involve asking students to use concept maps. Using concept maps has been shown to help in developing students' use of declarative and procedural knowledge (Mthethwa-Kunene et al., 2015).

7.1.3 Goal 3: Design a Model that Instructors Could Use for the Design, Evaluation and Validation of Assessments.

In order to address this goal, I decided to explore the following research questions:

i) What is an appropriate model for designing and validating assessment tasks? (RQ-7)

ii) Do acid-base assessments designed by an organic chemistry instructor support the validity of this model? (RQ-8)

The model of modelling framework by Justi and Gilbert (2002) helped guide the design of a model that instructors can use to design and validate assessments. The one feature that makes this assessment design model unique when compared to the currently used assessment design models (Briggs et al., 2015; Kennedy, 2005; NRC, 2001) is the fact that it guides instructors on how to qualitatively validate their assessments via comparing their expectations of what the assessment assesses versus the outcomes that students' responses actually show. Validation of assessments is important as it can lead to changes in either the assessment task or in the learning objectives so that the assessment assesses what the expert claims/expects it will.

In summary, the results discussed in this study will help advance the goals reported in the policy reports (AAMC-HHMI, 2009; Brewer & Smith, 2011; NRC, 2003) and discussed in Chapters 1 and 2 of this study. This is because, firstly, the three-stage process presented in Chapter 4 will enable instructors at any institution to collect data they can use to initiate discussions where they can decide what to include in the integrated curricula. Secondly, since in Chapter 1, I indicated that the faculty at the institution under study were in the process of developing a chemistry course for biology majors in response to the AAMC-HHMI (2009) call, the faculty could use the in-house data discussed in Chapter 5 with published information from other national studies (Tansey et al., 2013; Voet et al., 2003; White et al., 2013; Wright et al., 2013) to initiate curriculum related discussions where they can decide what to include in the chemistry course designed for biology majors. Thirdly, the data presented in Chapter 6 provides an assessment design model that instructors could use in order to design assessments that evaluate students' understanding of the targeted learning objectives. This, as discussed in Chapters 1 and 2, is one of the important aspects that the policy reports (AAMC-HHMI, 2009; Anderson, 2007; Brewer & Smith, 2011; Kennedy 2005; NRC, 2001, 2003) indicated had to be done when designing assessments. As discussed in Chapter 6, the strengths of the designed assessment model include the fact that it helps the instructors to: (i) design assessments that address the targeted concepts, representations and learning objectives; (ii) evaluate their assessment questions in order to check the concepts, representations and learning objectives addressed by the assessment questions; and (iii) analyze student responses in order to check if the assessment really addresses what they think it is addressing

7.2 Limitations of the Study

The limitations of this study include the following:

i) Although the three-step process used to identify biology instructors' views regarding the chemistry concepts and representations that are important for the biology courses they teach can be used by any instructor at any institution, the data collected is mainly relevant to curriculum change at the current study. The latter is due to the fact that there is a possibility that what the biology instructors in the current institution consider important for their courses may not be considered important by other biology instructors at other institutions.

ii) The fact that interview data was collected from a small sample size precludes generalizations of the findings to biology courses at other institutions. Therefore, more studies have to be done at other institutions in order to identify the acid-base knowledge that the biology instructors consider to be important for the courses they teach and the ways they expect their students to use the knowledge.

iii) Regarding the assessment design model, the validation of this model was done using an assessment that was designed for an organic chemistry course, therefore, more studies have to be done in order to investigate if the model will be useful for designing assessments in other subject domains.

iv) The fact that I only asked biology instructors regarding what they considered to be important for the biology courses they teach and did not ask professional biologists what they thought was important, is as a limitation for this study.

7.3 Potential Future Work

Based on findings of this study, the following questions could be a target for future work:

i) Will the three-step process used in this study be transferable to other institutions wanting to launch their own curriculum discussions around the needs of biology majors?

ii) To what extent are the findings at the current institution generalizable to other institutions and, if not, in what way do they differ across institutions?

iii) In what ways do the opinions expressed in this paper by biology instructors at the current institution concur or contrast with the opinions of chemistry and biochemistry instructors in terms of whether joint curriculum discussions could be valuable and productive?

iv) How does the above (iii) compare with bridging fields such as biochemistry?

LIST OF REFERENCES

LIST OF REFERENCES

Abdella BRJ. Walczak MM. Kandl KA. & Schwinefus JJ. (2011). Integrated Chemistry and Biology for First-Year College Students. *Journal of Chemical Education*, *88*(9), 1257–1263.

Aboulsoud SH. (2011). Formative versus Summative Assessment. *Education for Health*, *24*(2), 1- 651.

Ainsworth S. (2006). DeFT: A Conceptual Framework for Considering Learning with Multiple Representations. *Learning and Instruction*, *16*(3), 183–198.

Alake-Tuenter E. Biemans HJA. Tobi H. & Mulder M. (2013). Inquiry-based science teaching competence of primary school teachers: A Delphi study. *Teaching and Teacher Education*, *35*, 13–24.

Anderson TR. (2007). Bridging the Educational Research-Teaching Practice Gap. The Power of Assessment. *Biochemistry and Molecular Biology Education*, *35*(6), 471–477.

Anderson LW. Krathwohl DR. Airasian PW. Cruikshank KA. Mayer RE. Pintrich PR. Raths J. Wittrock CM. (2001). *A Taxonomy for Learning, Teaching and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives,* New York: Longman.

Anderson TR. & Rogan JM. (2010). Bridging the Educational Research-teaching Practice gap: Tools for Evaluating the Quality of Assessment Instruments. *Biochemistry and Molecular Biology Education*, *38*(1), 51–7.

Anderson TR. & Rogan JM. (2011). Bridging the educational research-teaching practice gap. Curriculum development, Part 1: Components of the curriculum and influences on the process of curriculum design. *Biochem Mol Biol Educ*, *39*: 68–76.

Anderson TR. & Schönborn KJ. (2008). Bridging the Educational Research-Teaching Practice Gap: Conceptual Understanding, Part 1: The Multifaceted Nature of Expert Knowledge. *Biochemistry and Molecular Biology Education*, *36*(4), 309–15.

Anderson TR. Schönborn KJ. du Plessis L. Gupthar A. Hull T (2013). Identifying and Developing Students' Ability to Reason with Concepts and Representations in Biology. In: Treagust DF, Tsui CY, editors. *Multiple Representations in Biological Education*, *vol. 7*. Dordrecht: Springer Netherlands; p. 19–38.

Association of American Medical Colleges and Howard Hughes Medical Institute. (2009). *Scientific Foundations for Future Physicians*, Washington, DC: HHMI.

Bell E. (2010). Promoting Concept-driven Teaching Strategies. *ASBMB Today, September*.Retrievedfromhttp://www.asbmb.org/asbmbtoday/asbmbtoday_article.aspx?id=9148

Bell JC. (2013). Visual Literacy Skills of Students in College-Level Biology: Learning Outcomes following Digital or Hand-Drawing Activities Visual Literacy Skills of Students in College-Level Biology: Learning. *CJSoTL*, *5*: 1-13.

Betz BJ. Dempsey BC (2015). Biological Drawing: A Scientific Tool for Learning. *Am Biol Teach, 63*: 271–279.

Bertoluzza A. Fagnano C. Morelli MA. Tinti A. Tosi MR. (1993) The Role of Water in Biological Systems. *Journal of Molecular Structure, 291:* 425-437

Bialek W. & Botstein D. (2004). Introductory science and mathematics education for 21st-century biologists. *Science*, *303*(5659), 788–90.

Bodner G. (2007). The Role of Theoretical Frameworks in Chemistry/Science Education. In Bodner, G., Orgill, M (Editors). *Theoretical Frameworks for Research in Chemistry/Science Education.* Upper Saddle River, NJ: Person Prentice Hall

Brewer C. & Smith D. (2011). *Vision and Change in Undergraduate Biology Education:A Call to Action*. American Association for the Advancement of Science: Washington DC, 1-79.

Briggs DC. Diaz-Bilello E. Peck F. Alzen J. Chattergoon R. & Johnson R. (2015). *Using a Learning Progression Framework to Assess and Evaluate Student Growth*. Center for Assessment Design Research and Evaluation (CADRE), 1-22.

Cafiso S. Di Graziano A. & Pappalardo G. (2013). Using the Delphi method to evaluate opinions of public transport managers on bus safety. *Safety Science*, *57*, 254–263.

Caldwell B. Rohlman C. & Benore-Parsons M. (2004). A Curriculum Skills Matrix for Development and Assessment of Undergraduate Biochemistry and Molecular Biology Laboratory Programs. *Biochemistry and Molecular Biology Education*, *32*(1), 11–16

Carlson JA. (2010). Avoiding Traps in Member Checking. *The Qualitative Report*, *15*(5), 1102–1113.

Cartrette D. & Mayo P. (2011). Students' Understanding of Acids/Bases in Organic Chemistry Contexts. *Chem Educ Res Pract, 12*: 29–39.

Cheng A. Kennedy G. & Kazmierczak E. (2010). Using Students' Visual Representations as a Window to Designing Learning Tools. Conference Proceedings; Ascillite. 174–178.

Cohen, L., Manion, L. & Morrison, K. (2000). *Research methods in education*, RoutledgeFalmer

Cook M. (2011). Teachers' Use of Visual Representations in The Science Classroom. *Science Education International*, *22*(3), 175–184.

Creswell JW. (2009). *Research design. Qualitative, Quantitative and Mixed Methods Approaches*, Sage Publications.

Dalkey NC. (1969). The Delphi Method: An Experimental Study of Group Opinion. RM-5888-PR. Santa Monica: Rand Corp.

Dasgupta AP. Anderson TR. & Pelaez NJ. (2016). Development of the "Neuron Assessment" for Measuring Biology Students' Use of Experimental Design Concepts and Representations. *CBE Life Science Education*, *15*(2).

DeBoer GE. Abell CH. Regan T. & Wilson P. (2008). Assessment Linked to Science Learning Goals: Probing Student Thinking Through Assessment, p. 231–252.

Degerman MS. & Tibell LAE. (2012). Learning goals and conceptual difficulties in cell metabolism—an explorative study of university lecturers' views. *Chemistry Education Research and Practice*, *13*(4), 447.

Delbecq AL. Van de Ven. AH. & Gustafson DH. (1975). *Group techniques for program planning*. Glenview, IL: Scott, Foresman, and Co.

Demircioğlu G. Ayas A. & Demircioğlu H. (2005). Conceptual Change Achieved Through a New Teaching Program on Acids and Bases. *Chemistry Education Research and Practice*, *6*(1), 36–51.

Dempsey BC. & Betz BJ. (2015). Biological Drawing: A Scientific Tool for Learning. *Am Biol Teac, 63*: 271–279.

Depelteau AM. Joplin KH. Govett A. Miller HA. & Seier E. (2010). Symbiosis: Development, Implementation, and Assessment of a Model Curriculum across Biology and Mathematics at the Introductory Level. *CBE Life Sciences Education*, *9*(3), 342–347.

Dikmenli M. (2010). Misconceptions of Cell Division held by Student Teachers in Biology: A Drawing Analysis. *Sci Res Essays*, *5*: 235–247.

Eilam B. (2013). Possible Constraints of Visualization in Biology: Challenges in Learning with Multiple Representations. In: Treagust DF, Tsui CY, editors. Multiple Representations in Biological Education, *vol. 7*. Dordrecht: Springer Netherlands; p. 55–73.

Fleming CB. Marchesini G. Elgin J. Haggerty KP. Woodward D. Abbott RD. Catalano RF. (2013). Use of Web Phone Survey Modes to Gather Data From Adults About Their Adult Children: An Evalauation Based on Randomized Design. *Field Methods, 25*(4): 388-404

Fletcher AJ. & Marchildon GP. (2014). Using the Delphi Method for Qualitative , Participatory Action Research in Health Leadership. *International Journal of Qualitative Methods*, *13*(200911), 1–18.

Garrett RH. & Grisham CM. (2010). *Biochemistry*. Boston MA: Brooks/Cole, Cengage Learning.

Gay LR. & Airasian P. (2003) Educational Research. Competencies for Analysis and Applications. New Jersey: Pearson Education.

Griffard PB. (2013). Deconstructing and Decoding Complex Process Diagrams in University Biology. In: Treagust DF, Tsui CY, editors. Multiple Representations in Biological Education, *vol. 7*. Dordrecht: Springer Netherlands; p. 165–183.

Gill P. Stewart K. Treasure E. & Chadwick B. (2008). Methods of Data Collection in Qualitative Research: Interviews and Focus Groups. *Br Dent J*, *204*: 291–295.

Glaser BG. (1992). *Basics of grounded theory analysis: emergences vs. forcing*. Mill Valley: Sociology Press.

Golafshani N. (2003). Understanding reliability and validity in qualitative research. *The Qualitative Report*, *8*(4), 597–606.

Grayson DJ. Anderson TR. & Crossley LG. (2001). A four-level framework for identifying and classifying student conceptual and reasoning difficulties. *International Journal of Science Education*, *23*: 611–622.

Green B. Jones M. Hughes D. & Williams A. (1999). Applying the Delphi technique in a study of GPs' information requirements. *Health & Social Care in the Community*, *7*(3), 198–205.

Green RA. (2014). The Delphi Technique in Educational Research. *SAGE Open*, *4*(2), 1–8.

Grisham T. (2009). The Delphi technique: a method for testing complex and multifaceted topics. *International Journal of Managing Projects in Business*, *2*(1), 112–130

Gross LJ. (2004). Interdisciplinarity and Undergraduate Biology Curriculum: Finding a Balance. *Cell Biology Education*, *3*(2), 85–92

Halstead SE. (2009). *A Critical Analysis of Research Done to Identify Conceptual Difficulties in Acid- Base Chemistry*, MSc Dissertation, School of Biochemistry, Genetics and Microbiology, University of Kwazulu-Natal: Pietermaritzburg South Africa.

Haudek KC. Prevost LB. Moscarella RA. Merrill J. & Urban-Lurain M. (2012). What are they thinking? Automated Analysis of Student Writing about Acid-Base Chemistry in Introductory Biology. *CBE Life Sci Educ, 11*: 283–93.

Helmer O. (1966). *The use of a Delphi Technique in Problems of Educational Innovations*. Santa Monica, California.

Herman JL. (2010). Coherence: Key to Next Generation Assessment Success. Los Angeles CA: 2010

Hoepfl M. (1997). Choosing qualitative research: A primer for technology education researchers, *9*(1), 47–63.

Hsieh HF. & Shannon SE. (2005). Three approaches to qualitative content analysis. *Qualitative Health Research* 2005; 15: 1277–88.

Jansen H. (2010). The Logic of Qualitative Survey Research and its Position in the Field of Social Research Methods. *Forum: Qualitative Social Research*, *11*(2).

Johnstone AH. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning, 7*:75-83

Judd R. (1972). Use of Delphi Methods in Higher Educatior. *Technological Forecasting and Social Change*, *4*, 173–186.

Justi & Gilbert. (2002). Taylor & Francis Online. *International Journal of Science Education*, *24*(4), 369-387.

Kane TM. & Bejar II. (2014). Cognitive Frameworks for Assessment, Teaching and Learning: Avalidity perspective. *Psicologia Educativa*, *21*(2), 117–123.

Kennedy CA. (2005). The BEAR Assessment System: A Brief Summary for the Classroom Context. Retrieved from https://bearcenter.berkeley.edu/sites/default/files/report - kennedy_bas_summary.pdf

Kennedy D. & James G. (2003). Is Bio2010 the Right Blueprint for the Biology of the Future? *Cell Biology Education*, *2*(4), 224–7.

Klug, WS, Cummings MR, Spencer CA, Palladino MA (2014). *Concepts of Genetics* 11th Edition. San Francisco: Benjamin Cummings/Pearson Education.

Koksal MS. & Cimen O. (2008). Perceptions of Prospective Biology Teachers on Importance and Difficulty of Organs as a School Subject. *World Applied Sciences Journal*, *5*(4), 397–405.

Köse S. (2008). Diagnosing Student Misconceptions: Using Drawings as a Research Method. *World Appl Sci J*, *3*: 283–293.

Kousathana M. Demerouti M. & Tsaparlis G. (2005). Instructional Misconceptions in Acid-Base Equilibria: An Analysis from a History and Philosophy of Science Perspective. *Science & Education*, *14*(2), 173–193.

Kozma RB. (2000). The Use of Multiple Representations and The Social Construction of Understanding In Chemistry. In: Jacobson M, Kozma R, editors. *Mahwah Innovations in Science and Mathematics Education: Advanced Designs for Technologies of Learning*. NJ: Erlbaum.

Kwak N. Radler B. (2002). A Comparison between mail web surveys: Response pattern, respondent profile, and data quality. *Journal of Official Statistics, 18*(2): 257-273

Labov JB. Reid AH. & Yamamoto KR. (2010). From the National Academies Integrated Biology and Undergraduate Science Education: A New Biology Education for the Twenty-First Century ? *CBE—Life Sciences Education*, *9*(1), 10–16.

Lawson AE. (2001). Using The Learning Cycle to Teach Biology Cncepts and Reasoning Patterns. *Journal of Biological Education*, *35*(4), 429 – 442.

Lerner N. (2007). Drawing to Learn Science : Legacies of Agassiz. *Journal of Technical Writing and Communication*, *37*(4), 379–394.

Lesney MS. (2003). A Basic History of Acid: From Aristotle to Arnold the Rise of Acid/Base Theory and its Associated. *Today's Chemist at Work*, *March,* 47–48.

Lincoln YS & Guba EG (1989). *Fourth Generation Evaluation.* Newbury Park, CA: Sage.

Linstone HA. & Turoff M. (2002). *The Delphi Method. Techniques and Applications*. http://is.njit.edu/pubs/delphibook/delphibook.pdf

Loertscher J. Green D. Lewis JE. Lin S. & Minderhout V. (2014). Identification of threshold concepts for biochemistry. *CBE Life Sciences Education*, *13*(3), 516–28.

Lodish H, Berk A, Kaiser CA, Krieger M, Scott MP, Bretscher A, Ploegh H, Matsudaira P. (2007). *Molecular Cell Biology* 6th Edition, New York, NY: W. H. Freeman.

Lodish H. Berk A. Zipursky SL. Matsudaira P. Baltimore D. Darnell J. (2000). *Molecular Cell Biology* 4th Edition, New York, NY: W. H. Freeman

Ludwig L. & Starr S. (2005). Library as Place: Results of a Delphi Study. *Journal of the Medical Library Association : JMLA*, *93*(3), 315–26.

Masters GN. (2013). *Australian Education Review Reforming Educational Assessment: Imperatives, Principles and Challenges*. Camberwell, Victoria,1-68.

Matthews KE. Adams P. & Goos M. (2010). Using the Principles of BIO2010 to Develop an Introductory, Interdisciplinary Course for Biology Students. *CBE Life Sciences Education*, *9*(3), 290–297.

Mayer RE. Wittrock MC. (1996). Problem Solving Transfer. In: Calfee R, Berliner R, editors. *Handbook of Educational Psychology.* New York: Macmillan.

Mayer RE. (1997). Multimedia Learning : Are we Asking the Right Questions ? *Educational Psychologist*, *32*(1), 1–19.

Mayer RE. (2002). Rote versus Meaningful Learning. *Theory into Practice*, *41*(4), 226–232.

Mayr E. (1999). This is Biology. The Science of the Living World. Harvard University Press. Cambridge: Massachusetts

McClary L. & Bretz S. (2012). Development and Assessment of A Diagnostic Tool to Identify Organic Chemistry Students' Alternative Conceptions Related to Acid Strength. *International Journal of Science Education, 34*(15), 2317-2341

McClary L. & Talanquer V. (2011). College Chemistry Students' Mental Models of Acids and Acid Strength. *Journal of Research in Science Teaching*, *48*(4), 396–413.

McClelland SB. (1994). Training Needs Assessment Data-gathering Methods: Questionnaires. *J Eur Ind Train*, *18*: 22–26.

Meijering JV. Kampen JK. & Tobi H. (2013). Technological Forecasting & Social Change Quantifying the Development of Agreement among Experts in Delphi Studies. *Technological Forecasting & Social Change*, *80*, 1607–1614.

Meredith DC. & Redish EF. (2013). Reinventing Physics for Life-Sciences Majors. *Physics Today*, *66*(7), 38–43.

Modell H. Cliff W. Michael J. McFarland J. Wenderoth MP. & Wright A. (2015). A Physiologist's View of Homeostasis. *Advances in Physiology Education, 39*(4): 259-266.

Mthethwa-Kunene E. Onwu GO. & de Villiers R. (2015). Exploring Biology Teachers' Pedagogical Content Knowledge in the Teaching of Genetics in Swaziland Science Classrooms. *Int J Sci Educ*, *37*: 1140–1165.

Muchtar Z. (2012). Analyzing of Students' Misconceptions on Acid-Base Chemistry at Senior High Schools in Medan. *J Educ Prac, 3*: 65–74.

Nakhleh M. & Krajcik J. (1994). Influence Of Levels Of Information as Presented by Different Technologies on Students' Understanding of Acid, Base, and pH Concepts. *Journal of Research in Science, 31*(10), 1077–1096.

National Research Council. (2003) *BIO2010: Transforming Undergraduate Education for Future Research Biologists*. Washington D.C: National Academic Press.

National Research Council. (2001). Knowing What Students Know: The Science and Design of Educational Assessment. *Issues in Science and Technology,19*. Washington DC: National Academic Press.

Nicholls JG. Martin AR. Fuchs PA. Brown DA. Diamond ME. Weisblat D. (2012). *From Neuron to Brain* 5th Edition. Sunderland, MA: Sinauer/W.H. Freeman

Oates T. (2009). The Cambridge Approach: Principles for Designing, Administering and Evaluating Assessment. Cambridge UK, 1-11.

Odom AL. & Kelly PV. (2001). Integrating concept mapping and the learning cycle to teach diffusion and osmosis concepts to high school biology students. *Science Education*, *85*(6), 615–635.

Orgill M. & Sutherland A. (2008). Undergraduate chemistry students' perceptions of and misconceptions about buffers and buffer problems. *Chem. Educ. Res. Pract.*, *9*(2), 131–143.

Osborne J. Collins S. Ratcliffe M. Millar R. & Duschl R. (2003). What ideas-about-science should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching*, *40*(7), 692–720.

Palomba CA. & Banta TW. (1999). Assessment essentials: Planning, implementing, and improving assessment in higher education. San Francisco, CA: Jossey-Bass.

Park EJ. & Choi K. (2013). Analysis of Student Understanding of Science Concepts Including Mathematical Representations: pH Values and the Relative Differences of pH Values. *International Journal of Science and Mathematics Education*, *11*(3), 683–706.

Patton M. Q. (2002). *Qualitative Reserach and Evaluation Methods*. California: Sage Publications Inc.

Pellegrino J. W. (2014). Assessment as a Positive Influence on 21st Century and Learning: A Systems Approach to Progress. *Psicologia Educativa*, *20*(2), 65–77.

Peña BM. Quílez MJG. (2001). The Importance of Images in Education. *International Journal of Science Education*: 1125-1135.

Prideaux D. (2003). Curriculum Design. *British Medical Journal*, *326*(February), 268–270.

Quillin K. & Thomas S. (2015). Drawing-to-Learn: A Framework for Using Drawings to Promote Model-Based Reasoning in Biology. *CBE Life Sciences Education*, *14*(1), es2.

Raven P. Johnson G. Losos J. Mason K. Singer S. (2008). *Biology* 8th Edition. New York, NY: McGraw-Hill Companies, Inc.

Redish EF. Bauer C. Carleton KL. Cooke TJ. Cooper M. Crouch CH. Dreyfus BW. Geller BD. Giannini J. Gouvea JS. Klymkowsky MV. Losert W. Moore K, Presson J. Sawtelle V. Thompson KV. Turpen C. Zia, RKP. (2014). NEXUS/Physics: An Interdisciplinary Repurposing of Physics for Biologists. *American Journal of Physics*, *82*(5), 368–377.

Redish EF. & Cooke T. (2013). Learning each other's ropes: negotiating interdisciplinary authenticity. *CBE Life Sciences Education, 12*(2): 175-186

Redish EF. & Hammer D. (2009). Reinventing college physics for biologists: Explicating an Epistemological Curriculum. *American Journal of Physics*, *77*(7), 629.

Reingold I. (2001). Bioorganic first: A new model for the college chemistry curriculum. *Journal Chemical Education, 78*(7): 869

Rhodes S. (2006). Getting Back to Basics (& Acidics). *The American Biology Teacher*, *68*(1), 24–27.

Roche VF. (2007). Improving Pharmacy Students' Understanding and Long-term Retention of Acid-Base Chemistry. *American Journal of Pharmaceutical Education*, *71*(6), 1–15.

Rossouw A. Hacker M. & Vries MJ. (2010). Concepts and Contexts in Engineering and Technology Education: An International and Interdisciplinary Delphi study. *International Journal of Technology and Design Education*, *21*(4), 409–424.

Roth WM. & Pozzer-Ardenghi L. (2013). Pictures in Biology. In: Treagust DF, Tsui CY, editors. *Multiple Representations in Biological Education*, *vol. 7*. Dordrecht: Springer Netherlands; p.39-53

Rowland SL. Smith CA Gillam EMA. & Wright, T. (2011). The Concept Lens Diagram: A New Mechanism for Presenting Biochemistry Content in Terms of "Big Ideas". *Biochemistry and Molecular Biology Education*, *39*(4), 267–79.

Rybarczyk BB. (2011). Visual Literacy in Biology : A Comparison of Visual Representations in Textbooks and Journal Articles. *Journal of College Science Teaching*, *41*(1), 106–113.

Sadava DE. Hillis DM. Heller HC. Berenbaum M. (2008). *Life: The Science of Biology* 9th Edition. Sunderland, MA: Sinauer/W.H. Freeman.

Saldana J. (2009). *The Coding Manual for Qualitative Researchers*. Los Angeles, CA: SAGE.

Schönborn KJ. & Anderson T. (2006). The importance of visual literacy in the education of biochemists. *Biochemistry and Molecular Biology Education,* 34**,** 94- 102.

Schönborn K. J. & Anderson, T. R. (2008). Bridging the Educational Research-Teaching Practice Gap: Conceptual Understanding, Part 2: Assessing and Developing Student Knowledge. *Biochemistry and Molecular Biology Education*, *36*(5), 372–9.

Schönborn KJ. & Anderson TR. (2009). A Model of Factors Determining Students' Ability to Interpret External Representations in Biochemistry. *International Journal of Science Education*, *31*(2), 193–232.

Schönborn KJ. Anderson TR. (2010). Bridging the Educational Research-Teaching Practice Gap: Foundations for assessing and developing biochemistry students' visual literacy. *Biochem Mol Biol Educ, 38*: 347-354.

Schönborn KJ. & Bögeholz S. (2009). Knowledge Transfer in Biology and Translation Across External Representations: Experts' Views and Challenges for Learning. *International Journal of Science and Mathematics Education*, *7*(5), 931–955.

Sheppard K. (2006). High School Students' Understanding of Titrations and Related Acid-Base Phenomena. *Chemistry Education Research and Practice*, *7*(1), 32.

Speth EB. Momsen JL. Moyerbrailean GA. Ebert-May D. Long TM. Wyse S. & Linton D. (2010). 1 , 2 , 3 , 4 : Infusing Quantitative Literacy into Introductory Biology. *CBE Life Sciences Education*, *9*(4), 323–332.

Story DA. (2004). Bench-to-Bedside Review: A Brief History of Clinical Acid-Base. *Critical Care*, *8*(4), 253–8.

Strauss AL. & Corbin JM. (1998). Basics of Qualitative Research : Techniques and Procedures for Developing Grounded Theory. California: Sage Publications Inc.

Streveler RA. Olds BM. Miller RL. & Nelson MA. (2003). Using a Delphi Study to Identify the Most Difficult Concepts for Students to Master in Thermal and Transport Science. In *American Society for Engineering Education Annual Conference & Exposition* (pp. 5–9).

Sun I (2014). *Introduction to Microbiology*. Minneapolis, MN: Blue Door Publishing.

Talanquer V. (2014). Threshold Concepts in Chemistry: The Critical Role of Implicit Schemas. *Journal of Chemical Education,9:*3-9.

Tansey JT. Baird T. Cox MM. Fox KM. Knight J. Sears D. & Bell E. (2013). Foundational Concepts and Underlying Theories for Majors in “Biochemistry and Molecular Biology”. *Biochemistry and Molecular Biology Education*, *41*(5), 289–96.

Thompson KV. Chmielewski J. Gaines MS. Hrycyna CA, & LaCourse WR. (2013). Competency-Based Reforms of The Undergraduate Biology Curriculum: Integrating the Physical and Biological Sciences. *CBE Life Sciences Education*, *12*(2), 162–9.

Thompson KV. Nelson C. Marbach G. Keller M. & Fagan WF. (2010). Online Interactive Teaching Modules Enhance Quantitative Proficiency of Introductory Biology Students. *CBE Life Sciences Education*, *9*(3), 277–283.

Tortora G. Derrickson B. (2014). *Principles of Anatomy and Physiology* 14th Edition. Hoboken, NJ: Wiley.

Treagust DF. Chittleborough G. Mamiala TL. (2002). Students’ Understanding of the Role Of Scientific Models in Learning Science. *International Journal of Science Education*, *24*: 357–368.

Trujillo CM. Anderson TR. & Pelaez NJ. (2015). A model of how different biology experts explain molecular and cellular mechanisms. *CBE Life Sciences Education*, *14*(2), 14:ar20.

Tsui C. Treagust DF. (2013). Introduction to Multiple Representations: Their Importance in Biology and Biological Education. In: Treagust DF, Tsui CY, editors. *Multiple Representations in Biological Education, vol. 7.* Dordrecht: Springer Netherlands.

Urry LA. Cain ML. Wasserman SA. Minorsky PV. Jackson RB. Reece JB. (2012). *Campbell Biology in Focus*. San Francisco: Benjamin Cummings/Pearson Education.

Van Hecke GR. Karuksti KK. Haskell RC. McFadden CS. Wettack FS. (2002). An Integration of Chemistry, Biology, and Physics: The Interdisciplinary Laboratory. *Journal of Chemical Education, 79*(7): 837-844

Van Meter P. & Garner J. (2005). The Promise and Practice of Learner-Generated Drawing: Literature Review and Synthesis. *Educational Psychology Review*, *17*(4), 285–325.

Van Wylen DGL. Abdella BRJ. Dickinson SD. Engbrecht JJ. Vandiver R. (2013) Interdisciplinarity: the right people, a supportive place, and a program Emerges. *CBE Life Sci Educ*, *12*: 140–143.

Voet JG. Bell E. Boyer R. Boyle J. O'Leary M. & Zimmerman JK. (2003). Mini-Series : The ASBMB Recommended Biochemistry and Molecular Biology Undergraduate Curriculum and its Implementation. Recommended Curriculum for a Program in Biochemistry and Molecular Biology. *Biochemistry and Molecular Biology Education*, *31*(3), 161–162.

Watkins J. Coffey JE. Redish EF. & Cooke TJ. (2012). Disciplinary Authenticity: Enriching the Reforms of Introductory Physics Courses for Life-Science Students. *Physical Review Special Topics - Physics Education Research*, *8*(1), 010112.

Watson FL. & Lom B. (2008). More than a Picture : Helping Undergraduates Learn to Communicate through Scientific Images, *7*, 27–35.

Watters DJ. & Watters JJ. (2006). Student Understanding of pH. *Biochemistry and Molecular Biology Education*, *34*(4), 278–284.

White HB. Benore MA. Sumter TF. Caldwell BD. & Bell E. (2013). What skills should students of undergraduate biochemistry and molecular biology programs have upon graduation? *Biochemistry and Molecular Biology Education*, *41*(5), 297–301.

Wiggins PM. (1990). Role of Water in Some Biological Processes. *Microbiol Rev* 1990; 54: 432-449.

Wolfson AJ. Hall ML. & Allen MM. (1998). Introductory Chemistry and Biology Taught as an Interdisciplinary Mini-Cluster. *Journal of Chemical Education*, *75*(6), 737–739.

Wright A. Provost J. Roecklin-Canfield JA. & Bell E. (2013). Essential concepts and underlying theories from physics, chemistry, and mathematics for “biochemistry and molecular biology” majors. *Biochemistry and Molecular Biology Education*, *41*(5), 302–8.

Yarden H. & Yarden A. (2013). Learning and Teaching Biotechnological Methods using Animations. In: Treagust DF, Tsui CY, editors. Multiple Representations in Biological Education, *vol. 7*. Dordrecht: Springer Netherlands; p. 93–108.

APPENDICES

Appendix A: IRB approval form

PURDUE
UNIVERSITY

HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	ANDERSON, TREVOR R
From:	DICLEMENTI, JEANNIE D, Chair Social Science IRB
Date:	03 / 27 / 2015
Committee Action:	Amended Exemption Granted
Action Date:	03 / 26 / 2015
Protocol Number:	1408015145
Study Title:	Identification of Biochemistry and Chemistry Concepts and Visual Representations Central to Biology Courses

The Institutional Review Board (IRB) has reviewed the above-referenced amended project and has determined that it remains exempt.

If you wish to make changes to this study, please refer to our guidance"**Minor Changes Not Requiring Review**" located on our website at http://www.irb/purdue.edu/policies.php. For changes requiring IRB review, please submit an **Amendment to Approved Study** form or **Personnel Amendment to Study** form, whichever is applicable, located on the forms pages of our website www.irb.purdue.edu/forms.php. Please contact our office if you have any questions.

Below is a list of best practices that we request you use when conducting your research. The list contains both general items as well as those specific to the different exemption categories.

General

- To recruit from Purdue University classrooms, the instructor and all others associated with conduct of the course (e.g., teaching assistants) must not be present during announcement of the research opportunity or any recruitment activity. This may be accomplished by announcing, in advance, that class will either start later than usual or end earlier than usual so this activity may occur. It should be emphasized that attendance at the announcement and recruitment are voluntary and the student's attendance and enrollment decision will not be shared with those administering the course.
- If students earn extra credit towards their course grade through participation in a research project conducted by someone other than the course instructor(s), such as in the example above, the students participation should only be shared with the course instructor(s) at the end of the semester. Additionally, instructors who allow extra credit to be earned through participation in research must also provide an opportunity for students to earn comparable extra credit through a non-research activity requiring an amount of time and effort comparable to the research option.
- When conducting human subjects research at a non-Purdue college/university, investigators are urged to contact that institution's IRB to determine requirements for conducting research at that institution.
- When human subjects research will be conducted in schools or places of business, investigators must obtain written permission from an appropriate authority within the organization. If the written permission was not submitted with the study application at the time of IRB review (e.g., the school would not issue the letter without proof of IRB approval, etc.), the investigator must submit

Appendix B: Questionnaire 1

Dear Biology Faculty: To follow up on the recent positive vote on the chemistry curricular revisions for undergraduate biology majors and to include all faculty members, we would greatly appreciate your valuable input regarding what chemistry and biochemistry you would like to assume that students know when they enter your course. Please e-mail your completed questionnaire to the head of the Department who will in turn give them to our committee.

Thank you for your support and involvement.

1. Briefly list up to TEN most important and useful chemistry/biochemistry topics of relevance to the biology course(s) you teach.

2. For EACH of the above listed topics, please give (or attach) ONE test question from your class that, in your view, requires students to use that knowledge in order to give a sound answer.

Appendix C: Questionnaire 2

Dear Biology Faculty: The following is a summary of the information obtained from questionnaire 1, regarding the chemistry and biochemistry knowledge that you and other faculty believe your students **need to know before they enter your Biology course(s).** The topics you and other faculty provided were analyzed and put into 14 categories (numbered 1-14 below).

1. Please rate the level of importance of each topic for your course(s), where 1=not important at all, 2 =not important, 3=undecided, 4=important, and 5= very important.
2. For each topic you rate as "Important or very important," please specify what you expect students to do with their knowledge of each topic they need in your course.

Notice that there are blank spaces at the end of each category. Please feel free to add more topics which you believe have not been included but are important for students to know when they enter your course. If you teach more than one course, please complete a separate form for each course.

1. Acids & Bases
    - Acid & base strength
    - Acid dissociation Ka & pKa
    - Lewis acids & bases
    - Buffers
    - Henderson-Hasselbalch
    - pH
    - Brønsted acids & bases
    - Amphipathic molecules

2. Properties of water
    - Surface tension
    - Cohesion
    - Heat capacity

Hydrophilicity
Hydrophobicity

3. Atomic Theory & Structure
   - VSEPR
   - Electronegativity
   - Structure of the atom
   - Atomic Orbitals
   - Cation(s) and Anion(s)
   - Charged particle interaction

4. Chemical Bonds
   - Non-covalent bonds
   - Polar & non-polar covalent bond
   - Hydrogen bonding
   - Ionic bonding
   - Coulombic interactions
   - Ester linkages
   - Dipole interactions or dipole-dipole forces

5. Chemical Reactions
   - Redox reactions
   - Nucleophilic substitution reactions
   - Hydrolysis reactions
   - Anabolic and catabolic reactions

6. Chemical Equilibrium
   - Nernst equation
   - Le Chatelier's principle

7. Enzymes
   - Enzyme kinetics
   - Activation energy
   - Property & function of enzymes
   - Role of inhibitors
   - Substrate binding

Signal transduction

8. Macromolecules
    - Lipids
    - Proteins
    - Amino acids
    - Function of proteins
    - Protein structure
    - Carbohydrates
    - Nucleic acids

9. Gas Laws
    - Henry’s Law of gas solubility
    - Dalton’s Law of partial pressure
    - STP

10. Metabolism
    - Glycolysis
    - TCA
    - ETC
    - Fermentation
    - Regulation of cell processes

11. Solubility
    - Molar concentration
    - Beer Lambert Law
    - Colloids
    - Suspension
    - Solutions

12. Thermodynamics
    - ATP structure & hydrolysis
    - Enthalpy
    - Entropy

Gibbs Free Energy
Diffusion
Osmosis
Osmotic pressure
Potential energy

13. Analytical Techniques
    X-ray crystallography
    UV spectroscopy
    Microscopy
    Liquid chromatography

14. Visual Representations
    Equations (e.g. Henderson-Hasselbalch, enzyme kinetics)
    Graphs (e.g. Enzyme kinetics graphs and pH solubility graphs)
    Structures of organic molecules (e.g. aspirin)
    Space filling models, ribbons and wireframes (e.g. amino acids, proteins & phospholipids)

Appendix D: Survey Questionnaire (Questionnaire 3)

1. Do you teach a course in biological sciences? YES/NO
2. Is knowledge from biochemistry and chemistry important for the biology course(s) you teach? YES/NO
3. Which of the following types of biochemistry and chemistry representations are important for the biology course(s) you teach?
    a. Molecular Model (give examples)
    b. Chemical equation (give examples)
    c. Mathematical equations (give examples)
    d. Graphs (give examples)
4. If you include molecular models in your exam questions, how do you expect students to use the provided molecular models to help them answer the question asked?
5. If you include chemical equations in your exam questions, how do you expect students to use the provided chemical equations to help them answer the question asked?
6. If you include mathematical equations in your exam questions, how do you expect students to use the provided mathematical equations to help them answer the question asked?
7. If you include graphs in your exam questions, how do you expect students to use the provided graphs to help them answer the question asked?

Appendix E: Interview Questions

Interview Protocol (Informed by Creswell, 2009)

Place: All interviews were conducted in the Biological Sciences Building (Offices of the participants), at Purdue University

Interviewer: Current researcher, Rethabile Tekane

Interviewees: Biology instructors

Instructions to follow/remember:

- Greet the participants
- State the importance of the interviews
- Ask the interview questions, remember where necessary, to use probes to understand or delve deeper into what the participant is saying
- Be neutral and maintain eye contact through-out the interviews
- Thank the participants

Dr. Wade T.I.

The following are the acid base concepts you identified as being relevant/important for the biology courses you teach:

1. Acid base strength
2. Buffers
3. pH
4. Amphipathic molecules

Interview questions:

a) What information about the above acid base concepts is important for the biology courses you teach?
b) Are there any visual representations (e.g. graphs, chemical equations, & mathematical equations) related to the above concepts that are important for the biology courses you teach? (Yes/No)
    i. If 'Yes' please give examples and state/clarify what the students need to know about each visual representation.

Dr. Hall Luda

The following are the acid base concepts you identified as being relevant/important for the biology courses you teach:

1. Acid base strength
2. Acid dissociation K_a and pK_a
3. Buffers
4. Henderson Hasselbalch
5. pH

Interview questions:

a) What information about the above acid base concepts is important for the biology courses you teach?
b) Are there any visual representations (e.g. graphs, chemical equations, & mathematical equations) related to the above concepts that are important for the biology courses you teach? (Yes/No)
    a. If 'Yes' please give examples and state/clarify what the students need to know about each visual representation.

Dr. Nicky Nelly

The following are the acid base concepts you identified as being relevant/important for the biology courses you teach:

1. Acid base strength
2. Buffers
3. Henderson Hasselbalch
4. pH

Interview questions:

a) What information about the above acid base concepts is important for the biology courses you teach?

b) Are there any visual representations (e.g. graphs, chemical equations, & mathematical equations) related to the above concepts that are important for the biology courses you teach? (Yes/No)
    a. If 'Yes' please give examples and state/clarify what the students need to know about each visual representation.

Dr. Sean Drake

The following are the acid base concepts you identified as being relevant/important for the biology courses you teach:

1. Acid base strength
2. Buffers
3. pH
4. Brønsted acids & bases

Interview questions:

a) What information about the above acid base concepts is important for the biology courses you teach?
b) Are there any visual representations (e.g. graphs, chemical equations, & mathematical equations) related to the above concepts that are important for the biology courses you teach? (Yes/No)
    a. If 'Yes' please give examples and state/clarify what the students need to know about each visual representation.

Appendix F: Assessment Guidelines (Anderson and Rogan, 2010, p. 56)

A. Before assessment: design of the instrument

1) Does the instrument assess at least one of the specified learning outcomes/objectives (i.e. does it assess what you think it is assessing—is it valid)? Some possible sub-questions informed by the CRM model:
   (a) What specific concept(s) do you think your question is designed to probe (**C**)?
   (b) Does it assess conceptual understanding (**R-C**)?
   (c) Does it assess any cognitive skills and, if so, which ones? (**R-C**)
   (d) Does it allow for a range of scientifically correct (creative) answers?
2) If the question includes a diagram:
   (a) Do you think the diagram and its constituent symbolism is clear and not too complex for the student to understand (**R**)?
   (b) Do you think the diagram will help the student to answer the question (**RM**)?
3) Do students have the necessary prior knowledge (**C**) and skills (**R-C & R-M**) to answer the question?
4) Will students understand the expectations and nature of the task? (i.e. do they understand the question? Is the language clear and unambiguous?)
5) Is the standard of the assessment appropriate for what will be assessed (e.g. assessment for mastery of concepts, skills, principles; for competence regarding use of equipment; and, for adequate proficiency regarding general course information)?
6) Is there a marking memorandum that will ensure that the answers can be fairly and reliably graded? If appropriate, is there a rubric?

B. After assessment: analysis of student responses

1) Was the instrument reliable, that is, did it probe for the targeted knowledge?
2) Did it reveal evidence of student difficulties and misconceptions?
3) Did you give qualitative feedback to students regarding their level of understanding and any difficulties they showed (i.e. not just grades obtained)?

C. Overall evaluation of the assessment plan for the course

1) Have all the outcomes/objectives of the course as a whole been adequately assessed?
2) Was any one of the outcomes/objectives over-assessed at the expense of some of the others?

Appendix G: Learning Objectives for an Organic Acid–Base Module

A. Define an *electron-pair displacement reaction* and its curved-arrow notation.

B. Understand the terms *nucleophile, electrophile,* and *leaving group,* and how these are applied to Brønsted acid–base reactions.

C. Understand how the strengths of acid and bases are expressed. *Key point:* K_a measures the strength of *both an acid and its conjugate base.* K_b values are unnecessary.

D. Understand the relationship between pK_a and the standard free energy of dissociation.

d1. Be able to represent the standard free energy of ionization graphically as an energy difference between two species.

E. Understand how to estimate the equilibrium constant for a general acid–base reaction. *Key Point:* Calculating the K_{eq} for an acid–base reaction from the pK_a values of the two acids allows us to see whether a reaction at equilibrium lies to the right or left. While students can use an ICE table to calculate exact concentrations at equilibrium, this is not necessary to get a semi-quantitative idea of the position of equilibrium.

F. Determine in specific cases whether an amphoteric compound is acting as an acid or a base, and which pK_a applies.

G. Apply the Henderson–Hasselbalch equations in specific cases.

g1. Be able to determine the fraction dissociation of a monoprotic acid at a given pH for biologically important molecules such as drugs.

g2. Be able to determine, or at least describe with a sketch, the fractions of the different species of a diprotic acid as a function of pH, given its pK_a values.

g3. Be able to calculate the pH of a solution as a function of fraction dissociation of an acid.

g4. Understand the difference between pH of the solution and the pK_a of an acid. *Key point:* The pH is an experimental variable; the pK_a is a property of a compound that is not experimentally variable.

g5. Define isoelectric point of an amino acid; calculate the isoelectric point given the relevant pK_a values.

H. Understand and give examples of the effects of structure on acidity and basicity.

h1. Understand the periodic trends in bond dissociation energies and electronegativities on acidity (the *element effect*).

h2. Understand how a charge on the atom to which an acidic proton is bonded affects acidity (the *charge effect*).

h3. Understand how substituents remote from the acidic group affect acidity (the *polar* or *inductive effect*).

h4. Understand how resonance in a conjugate acid or base affects acidity or basicity (the *resonance effect*).

h5. Understand how hybridization of the atom to which the acidic proton is attached affects acidity (*hybridization effect*).

h6. Understand how the presence of an atom in an aromatic ring affects its basicity or acidity.

I. Apply the reasoning used in Objective d1 to understand how energy differences in acids and bases result from the structural effects in Objectives h3, h4, and h5 and thus account for these effects on acidity.

J. Learn a relatively small number of biologically important pKa values than can be used as a "baseline" for applying the trends implied by the effects of structure in Objective H.

Appendix H: Assessment Questions

Examination 1 with Answers

The questions marked with an asterisk (*) are from the discussion portion of the exam. Note that the LAST QUESTION is *not* from the discussion portion.

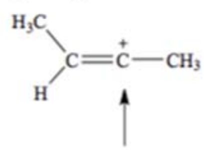
Useful data: $2.3RT = 5.71$ kJ mol^{-1} at 25 °C (298 K)

1. (11 points) The basicity of each of the following bases can be characterized by the pK_a of its conjugate acid. Match each base with the approximate pK_a of its conjugate acid. Choose from among the pK_a values 32, 20, 15.7, 10, 7, 4.5, 2, –1.7, –5.

   Then circle the *strongest base.*

Base	pK_a of conjugate acid	Base	pK_a of conjugate acid
$H_2\ddot{O}$	–1.7	HPO_4^{2-}	7
$(H_3C)_2\ddot{N}H$ (circled)	10	Et—C(=O)—$\ddot{O}$:⁻	4.5

2. (10 points) (a) (3 pts) What is the C—C—C bond angle in this carbocation (the angle with the positively charged carbon at the vertex)?



180° degrees

(b) (3 pts) What is the hybridization of the carbon indicated with the arrow in the carbocation in part (a)? (*Remember:* Hybridization and geometry are linked.)

sp

(*sp* hybridization is always associated with linear geometry.)

(c) (4 pts) Give the structure of the carbocation intermediate involved in the addition of HBr to the following alkene.

carbocation intermediate

3. (8 points) (a) (4 pts) Give the equilibrium constant for the following acid–base reaction.
You have to know that the pK_a of water is 15.7.

$$^{-}CN + H{-}OH \rightleftharpoons H{-}CN + {}^{-}OH$$

$pK_a = 9.4$ (for H—CN)

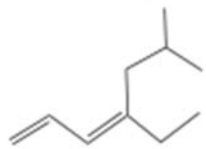
$K_{eq} = 10^{-6.3}$

$\log K_{eq} = 9.4 - 15.7 = -6.3$. Therefore $K_{eq} = 10^{-6.3}$, or 5×10^{-7}

(b) (4 pts) The standard free-energy change $\Delta G°$ for this reaction is $-2.3RT \log K_{eq}$ = $(-5.71)(-6.3)$ = 36 kJ mol^{-1}

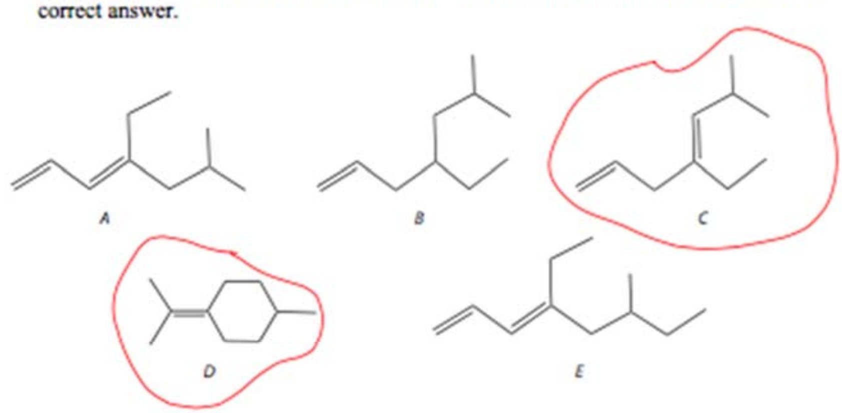
(Be sure the sign is correct.)

4. (10 points) (a) (4 pts) Name the following alkene; include stereochemistry if appropriate.



(Z)-4-ethyl-6-methyl-1,3-heptadiene

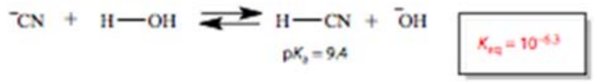
(b) (6 pts) Which of the following compounds are *constitutional isomers* of the alkene in part (a)? Circle as many as are correct. *Note:* Each wrong answer cancels credit for a correct answer.



A is a stereoisomer; *B* and *E* have different formulas because *B* has one less double bond and *E* has an additional carbon. Note that *D* has the same formula. "Same formula, different connectivity" is the criterion for constitutional isomers. The fact that one isomer is cyclic is irrelevant—it still fits the definition.

3. (8 points) (a) (4 pts) Give the equilibrium constant for the following acid–base reaction.

You have to know that the pK_a of water is 15.7.

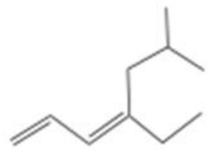


log K_{eq} = 9.4 – 15.7 = –6.3. Therefore $K_{eq} = 10^{-6.3}$, or 5×10^{-7}

(b) (4 pts) The standard free-energy change $\Delta G°$ for this reaction is $-2.3RT \log K_{eq}$ = (–5.71)(–6.3) = 36 kJ mol^{-1}

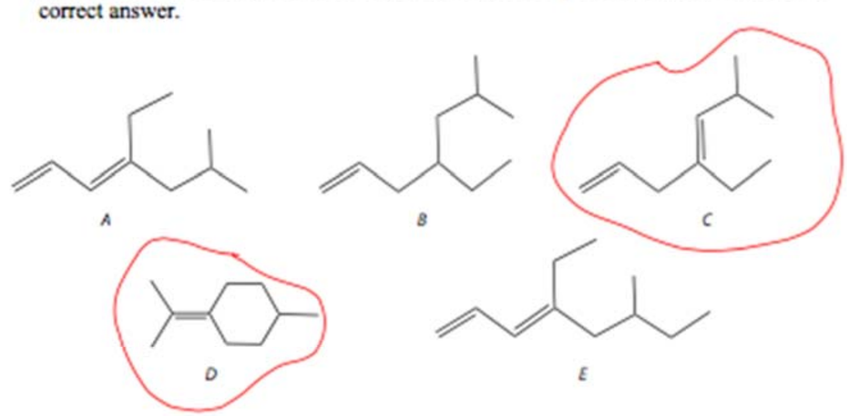
(Be sure the sign is correct.)

4. (10 points) (a) (4 pts) Name the following alkene; include stereochemistry if appropriate.



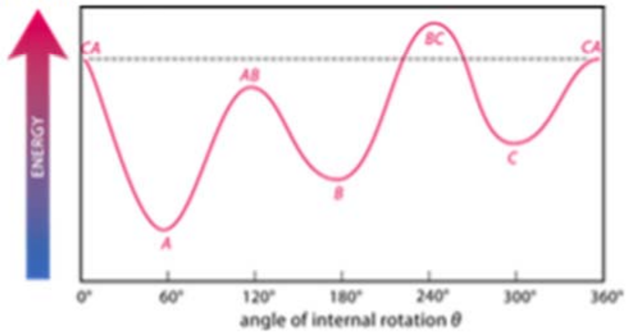
(Z)-4-ethyl-6-methyl-1,3-heptadiene

(b) (6 pts) Which of the following compounds are *constitutional isomers* of the alkene in part (a)? Circle as many as are correct. *Note:* Each wrong answer cancels credit for a correct answer.



A is a stereoisomer; *B* and *E* have different formulas because *B* has one less double bond and *E* has an additional carbon. Note that *D* has the same formula. "Same formula, different connectivity" is the criterion for constitutional isomers. The fact that one isomer is cyclic is irrelevant—it still fits the definition.

(c) (9 pts) On the axes below, *sketch* a plot of energy vs. angle of internal rotation about the projected bond. Arbitrarily start with *A* at $\theta = 60°$. Label conformations *B* and *C* on the graph. The goal is to be sure that the relative energies of all conformations are shown properly. The relative energies of the eclipsed conformations should be shown as well. (You do *not* have to provide numerical energy values—only the relative order.) In the space below the graph, explain how you ordered the energies. *Do not exceed the available space.*

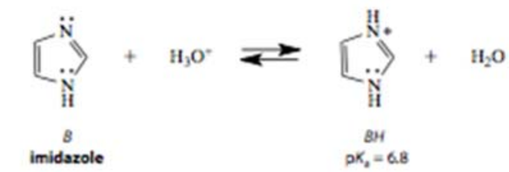


Energy follows the magnitude of the repulsions between groups.

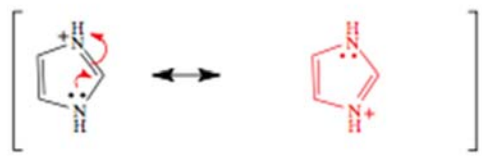
Form *A* has the smallest repulsions—only methyls are gauche. Form *B* has larger repulsions; the large *tert*-butyl group is gauche to the methyl. Form *C* has even larger repulsions, with both methyl–methyl and methyl–*tert*-butyl gauche interactions.

For the eclipsed forms: in form *AB*, all alkyl groups are eclipsed with only Hs; this has the lowest energy of all three eclipsed forms. In form *BC*, the *tert*-butyl and the methyl are eclipsed. This is clearly higher energy than form *CA*, in which two methyls are eclipsed.

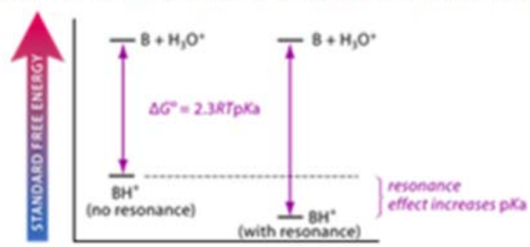
*7. (12 points) Imidazole is a nitrogen base that occurs in the side-chain of the amino acid histidine. The protonation of imidazole is shown in the following equation:



(a) (5 pts) The conjugate acid *BH* is stabilized by resonance. Draw one additional resonance structure for *BH* and show how it is derived from the first structure using the curved-arrow notation. Be sure to show all charges and unshared pairs on the atoms involved.



(b) (7 pts) How does this resonance interaction affect the basicity of *B?* Use a free-energy diagram to show the effect of resonance. That is, show the free energy of ionization diagrammatically as it would be if resonance were not important; then draw another diagram next to the first one showing the contribution of resonance; then, from your two diagrams, show how resonance affects the pK_a. Do not exceed the allowed space.

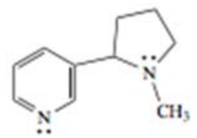


From the pK_a given, you know that the acid form is at lower free energy. (The pK_a is positive, so the $\Delta G°$ for dissociation must be positive; therefore form B is at higher energy.)

If the BH^+ form is stabilized by resonance, its energy is lowered. From the diagram, this must increase the standard free energy of ionization and therefore increase the pK_a. The basicity of B is therefore increased by resonance.

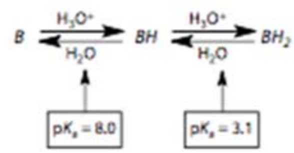
Notice that a higher pK_a can originate from *stabilization* of the undissociated state or *destabilization* of the dissociated state. The former effect is operating here.

8. (26 points) Nicotine is the highly addictive substance in tobacco.

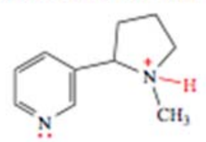


nicotine (form *B* in the equilibrium below)

Both nitrogens are basic, but they differ substantially in their basicities. The acid–base equilibria of nicotine and the relevant pK_a values are shown schematically below; note that the structure of *B* is given above. For simplicity, the charges are not shown in the abbreviations *BH* and BH_2.



(a) (3 pts) Draw the structure of *BH*. We have provided a partial structure to which you should add a proton, the appropriate charge, and any unshared pairs.



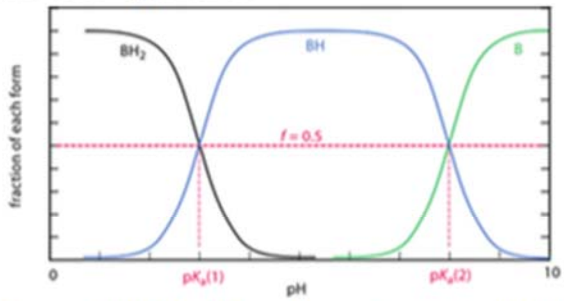
nicotine (form *BH* in the equilibrium above)

(b) (3 pts) Explain how you knew where to put the proton. *Do not exceed the allowed space.*

The hybridization effect lowers the basicity of the pyridine nitrogen (the one in the 6-membered ring). This means that the pK_a of its conjugate acid is lower. Consequently, the higher pK_a is associated with the conjugate acid of the other, more basic, nitrogen. As the pH is lowered, this is the first nitrogen to be protonated.

(Do not write below this line)

(c) (12 pts) Sketch (do not calculate) on the following set of axes the fraction of B, BH, and BH_2 as a function of pH. (There will be three superimposed curves.) On each curve label the corresponding form. On both axes, label the important reference points that were crucial in sketching your curves.

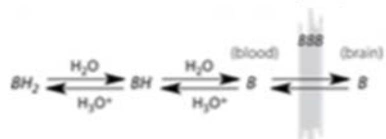


(d) (4 pts) Assuming that the $pK_a = 3.1$ dissociation can be ignored, calculate the fraction of nicotine in the BH form in blood (pH = 7.4). Show your work.

$$f_{BH} = \frac{1}{1+10^{\Delta}} = \frac{1}{1+10^{(7.4-8.0)}} = \frac{1}{1+0.25} = \frac{1}{1.25} = 0.8$$

We can see that on the blue curve above, BH is in fact is the predominant form, as we expect from the fact that the pH is well below its pK_a.

(e) (4 pts) The barrier between the blood and the brain (the blood-brain barrier, or BBB) is a biological structure that allows only the B form of nicotine to pass into the brain. However, it is the BH form of nicotine that is physiologically active in the brain. Explain (a) how nicotine can be physiologically active even though only B can cross the BBB, and (b) how the selective transport of B affects the *relative* concentrations of the various forms in blood. (Assume for purposes of this question that the pH is the same in blood and brain. Do not exceed the allowed space.)



As B is transported out of the blood and into the brain, by Le Châtelier's principle, the equilibrium between the three forms is continually re-established in blood. The ratio of the three forms in blood is determined only by the difference pH – pK_a. The *ratio* of the three forms never changes. (Remember acid–base reactions are typically *very* fast.)

Likewise, in the brain, the ratio of the three forms is determined by only by the difference pH – pK_a. Therefore, because the pH is 7.4, form B is rapidly protonated. Therefore, even though B is the form that is transported, the ratio of BH to B is the

same in brain as it is in blood. So, the physiologically active form BH is present even though it is not the form that is transported through the BBB. As more B is transported, more BH forms.

VITA

VITA

Rethabile Tekane was born and raised in Lesotho, a beautiful and mountainous country landlocked by the Republic of South Africa. After graduating from Machabeng, the International College of Lesotho in 2004, Rethabile was accepted at the University of KwaZulu Natal, Pietermaritzburg Campus in 2005 where she later graduated with a Master of Science degree in Biochemistry Education in 2011. Following this, she joined Purdue University in Fall 2011. Upon graduation in August 2016, Rethabile plans to go back home where she will join the University of Pretoria as a postdoc.

PUBLICATION

PUBLICATION

Manuscript: To be submitted for publication

Title: How to Identify Biology Instructors' Views Regarding Biochemistry and Chemistry Concepts and Representations Important for Undergraduate Biology Courses

Type of manuscript: Article

Number of characters in manuscript: about 57,000 (with no spaces) or 67,000 (with spaces)

Running title: Identifying Chem Knowledge for Biology **(39)**

R. R. Tekane,[a] N. J. Pelaez[b] and T. R. Anderson[a]

[a]Department of Chemistry, Purdue University, West Lafayette, Indiana 47907; [b]Department of Biological Sciences, Purdue University, West Lafayette, Indiana 47907.

Corresponding author: T. R. Anderson, Department of Chemistry, Purdue University, 560 Oval Drive West Lafayette, Indiana 47907. Email address: ander333@purdue.edu; telephone number: 7654945453

Key words: Representations, Concepts, Delphi Method, Reasoning, Undergraduate Biology

Abstract

This study aims to identify, from biology instructors at a single US institution, the biochemistry and chemistry concepts and representations they consider to be relevant for the courses they teach, and ways they expect students to reason with such concepts and representations. Data was collected using a simple three-step process informed by the Delphi method. Instructors' concepts were grouped into 6 consensus themes: Properties of water, chemical bonds and biomolecular structure and function; (Bio)chemical reactions, enzymes, cellular processes and their regulation; Thermodynamics including chemical equilibrium, ATP and membrane transport; Acids and bases; Solutions, mixtures and analytical techniques; and Atomic theory and structure and gas laws. Types of representations include a range of molecular models, graphs, chemical equations, and mathematical equations. Furthermore, instructors expect students to develop skills such as the ability to integrate, transfer and apply knowledge in order to develop sound explanatory frameworks, and the ability to decode representations, interpret and use them to explain and solve biological problems. The process used here illustrates how to identify biochemistry and chemistry concepts, representations and related ways of reasoning that could be used to provide key information as a catalyst for future curriculum discussions at both the present and other institutions.

Introduction

Biology research has become increasingly more interdisciplinary in nature (Gross, 2004; Kennedy and James, 2003; Van Wylen, Abdella, Dickinson, Engbrecht, and Vandiver, 2013). For this reason, the National Research Council (NRC) and others called for reform in biology curricula (AAMC-HHMI, 2009; Brewer and Smith, 2011; NRC, 2003) to meet modern trends and demands that biology graduates might face. In particular, the Vision and Change report (Brewer and Smith, 2011) emphasized the importance of identifying the core concepts and competencies that should be taught in undergraduate biology, including the ability to reason with, use and apply concepts and representations to solving problems across the disciplines. In addressing this issue, it is clear that biology undergraduate courses do not have the resources to teach all the core concepts and competencies necessary for mastering biology: they need to rely on introductory chemistry and biochemistry courses to prepare students for mastering biology.

The tenets of curriculum theory (e.g. Anderson and Rogan, 2011; Bovill, Morss and Bulley, 2008; McGoldrick, 2002; Prideaux, 2003) advocate that course curricula should ideally be negotiated by all stakeholders and curricular decisions should be informed by research rather than only intuition and experience. In this regard, although various authors and sponsored projects (e.g. AAMC-HHMI, 2009; Loertscher, Green, Lewis, Lin, and Minderhout, 2014; Rowland, Smith, Gillam, and Wright, 2011; Tansey *et al.*, 2013; White, Benore, Sumter, Caldwell, and Bell, 2013; Wright, Provost, Roecklein-Canfield, and Bell, 2013;) have exhaustively identified the key chemistry and biochemistry concepts and competencies important for teaching and learning of life sciences in general, when performing curriculum development at a particular institution with its own unique context, it is obviously additionally important to identify the specific content needs of that context. Thus the present study aimed to identify what concepts, representations and related ways of reasoning were considered key to biology majors for tackling the various prescribed courses within the specific institution under study. In this way curriculum discussion would be directly informed by empirical data from the same context. What people consider to be important at one institute may differ from what is deemed most important in another situation.

This study also aimed to reveal new knowledge about the representations important for learning biology at in the specific institution under study as well as the various reasoning processes that are key to the use of concepts and representations in explaining and solving problems in biology (See Anderson *et al*., 2013). The literature contains limited studies in these areas. Although it is apparent that representations are indistinguishable from their related concepts as shown in numerous textbooks, we found it important to ask the biology instructors to tell us, from their point of view, the biochemistry and chemistry representations they consider to be relevant to the courses they teach. The latter became important because not all instructors at the present institution use representations from textbooks; instead, some use representations from articles. Thus in the present study we used an approach informed by the Delphi method followed by a survey questionnaire to investigate the chemistry and biochemistry concepts and representations the biology faculty at one university consider important for biology students and how they expected students to use/reason with such knowledge in their biology courses.

As for physics and mathematics, some research has been done regarding the integration of biology with either chemistry or biochemistry (e.g. Abdella, Walczak, Kandl, and Schwinefus, 2011; Caple, Balda, Laughran, Thomas, and Çimer, 1991; Sounders 1993; Wolfson, Hall, and Allen, 1998). Furthermore, none of these studies have concentrated on identifying the biochemistry and chemistry concepts, representations and related competencies that are important to biology courses. Representations have been particularly neglected despite extensive research that has demonstrated the crucial role of representations for knowledge construction (e.g. Treagust, Chittleborough, and Mamiala, 2002). This is particularly important given the fact that learning in biology involves four levels of representations: the macroscopic level; the cellular or subcellular level; the molecular level; and the symbolic level (Tsui and Treagust, 2013). This implies that students are expected to "acquire knowledge and understanding that is diverse and embedded at different levels of complexity and abstraction; flexibly transfer knowledge during problem-solving; and, interpret and translate across multiple external representations" (Schönborn and Bögeholz, 2009, p. 931). Therefore, in this study, we found it important to also gather data about biochemistry and chemistry representations of relevance to biology and how biology instructors expected their students to use the representations.

Thus in the present study we addressed the following research questions, focusing specifically on the context of the biology major and participating instructors at one US Midwestern institution: i) Which biochemistry and chemistry concepts do the biology instructors consider relevant to the specific course they teach? (RQ-1), (ii) How do these biology instructors expect students to use the identified concepts in their particular courses? (RQ-2), (iii) Which biochemistry and chemistry representations do those biology instructors consider relevant for the specific courses they teach? (RQ-3), and, (iv) How do these biology instructors expect students to use the representations in their courses? (RQ-4)

Theoretical Framework

We identified the Concepts-Reasoning-Representational Mode (CRM) model of Schönborn and Anderson (2009) as an appropriate framework for this study because the model frames our thinking with respect to the concepts, representations and ways of reasoning that we aimed to identify by addressing our research questions. The CRM model has been fruitfully deployed to inform the coding of data as described in Anderson et al. (2013) and to guide the design of an original assessment in the context of a cutting edge research problem (Dasgupta, Anderson, Pelaez, 2016). The CRM model is composed of several factors including: (i) the conceptual factor (**C**) which relates to students' prior conceptual knowledge that is relevant to a particular representation; (ii) the mode factor (**M**) which relates to the nature of the representation; and (iii) the reasoning factor (**R**) which includes reasoning abilities required for both retrieving and applying the appropriate conceptual knowledge (**R-C**) and for making sense of the representation (**R-M**). All factors are interdependent because prior conceptual knowledge is required in order to make sense (**R-C**) of the presented representation and its graphical features (**R-M**). Moreover, a particular representation is meant to portray scientifically correct knowledge (**C-M**). Previous research has shown that the interpretation of the representation is successful if the students engage all factors of the model such that prior conceptual knowledge is used to make sense of the representation and its graphical features (**C-R-M**) (Schönborn and Anderson, 2009).

In the present study this framework guided our focus on key concepts (**C**; RQ-1); representations (**M**; RQ-3); and the way the concepts and representations are respectively used for reasoning (**R-C** and **R-M; RQ-2** and **RQ-4**). This allowed us to detect **R-C** and **R-M** type abilities that instructors expected students to develop when using concepts and representations to explain and solve problems in biology. In addition, by referring to the various specific cognitive and visual skills documented in previous studies (Anderson and Schönborn, 2008; Anderson *et al*., 2013; Schönborn and Anderson, 2010) we were able to identify specific reasoning abilities students should use when working with chemistry and biochemistry concepts and representations in their biology class.

Research Context

The research study was conducted at one doctoral research university in the Midwest of the United States where various faculty are revising the introductory chemistry and biochemistry curricula so that biology students are better prepared to tackle the challenges of modern biology (Thompson *et al.,* 2013). At this university, the programs of biology study are intended to provide excellent preparation for professional school (medicine, veterinary medicine, dentistry), or careers in academic or industrial research. Because fields in biology and chemistry overlap considerably, it is important to consider the sequence of courses provided for biology students in the context of this study. The undergraduate biology students taught by participants in this study are required to take a two-year plus one semester sequence of biology lab and lecture courses that cover Biodiversity, Ecology, Evolution, Development, Structure, and Function of Organisms, Cell Structure and Function, Genetics, Molecular Biology, Ecology and Evolution plus a more specialized Intermediate Biology course which opens a pathway to Upper Division elective courses for either a general Biology degree or a specialization in one of these areas: Biochemistry; Cell, Molecular, and Developmental Biology; Health and Disease; Ecology, Evolution, and Environmental Biology; Microbiology; Biology Education; Genetics; or Neurobiology and Physiology. As they complete their lower division course work, biology students at this university also take courses taught by faculty members in the chemistry department. Most opt to complete an accelerated two-year chemistry course sequence: one semester of general chemistry followed by two semesters of organic chemistry and one semester of biochemistry.

Methods

A process informed by the Delphi method (Dalkey, 1969) was used to survey biology instructors for the biochemistry and chemistry concepts (**C**) that they consider most relevant for the biology courses they teach and typical examples of test questions illustrating how they expect students to use the concepts (**RC**). The Delphi method is a group process that is normally used in situations that require opinions and consensus or divergence from selected experts about the topic being studied (Dalkey, 1969; Helmer, 1966). This method usually involves a series of two to four iterative rounds, combined with anonymous, controlled feedback (Dalkey, 1969; Judd, 1972). In the present study since consensus was reached after only two rounds no further iterations of the process were performed. The questions asked in round one were open-ended to allow experts to generate as many important ideas as possible without feeling restricted (Dalkey, 1969). Questions asked in round two were close-ended; hence they were more restrictive (Linstone and Turoff, 2002). Biology instructors who took part in the study remained anonymous: this was an advantage because they could communicate their ideas freely and effectively without feeling pressured to support ideas posed by other influential or highly respected expert biology instructors (Dalkey, 1969; Degerman and Tibell, 2012; Delbecq *et al.,* 1975;).

Selection of expert biology instructors

In our study, an "expert biology instructor" is defined as anyone who is competent in biology, holds an advanced degree in biology (either Masters or Ph.D.), and has taught biology course(s) at a major research university in the Midwest of the United States for at least three years. It is important to point out that in our study, the words "biology expert" and "biology instructor" are used interchangeably.

Questionnaire 1: Exploration Phase Informed by the Delphi Method

In round one, an open-ended Questionnaire 1 (Supplemental material) was given to expert biology instructors to identify up to 10 most important biochemistry and chemistry concepts (**C**) to the biology course(s) they teach (RQ1). The instructors were also asked to provide examples of their exam questions that require students to use one or more of these "important" biochemistry or chemistry concepts (RQ2).

The concept lists and the exam questions collected in round one were analyzed via inductive coding (Thomas, 2006): concepts were classified into categories based on similarity and relevancy. The concepts were first classified into fourteen categories and then validated by six other researchers with specialties in biochemistry, biology, chemistry and education. The exam questions were studied in order to identify (i) how students were expected to reason with concepts (**RC**) and representations (**RM**); and (ii) the types of representations used in the questions. The representations were classified into four categories based on similarity and relevance. These four categories, molecular models, graphs, chemical equations, and mathematical equations, were subsequently used to inform the design of a Qualtrics survey (Questionnaire 3).

Questionnaire 2: Confirmation Phase Informed by the Delphi Method

Questionnaire 2 (Supplemental material) asked expert biology instructors to rate the level of importance of the biochemistry and chemistry concepts that had been provided as responses to Questionnaire 1. Although we used a 5-point Likert scale, the number of ratings for 1 and 2 on the scale were added to give a total percentage of respondents who deemed that item unimportant. Similarly, the number of ratings for 4 and 5 were summed to give a total percentage of respondents who deemed an item to be important. The "undecided" ratings were not changed. Descriptive statistics in the form of percentages were used to analyze the Likert scale data as "important", "undecided" or "not important" to summarize responses from the expert biology instructors who participated in the survey. The CRM model was used to analyze experts' feedback regarding how they expected students to reason with/use the biochemistry and chemistry concepts identified as important for biology courses. The Likert agreement level was measured by calculating the percentage of experts who rated each concept as either important or not important. We decided to stop our study after round 2 because most of our concepts were confirmed to be either important or not important by 50% or more of the expert biology instructors. Once the data from the Exploration and Confirmation Phases were analyzed, member checking was conducted by interview with respondents. Member checking was done on the data compiled from Questionnaire 2 (Creswell 2001; Creswell, 2014). This was done in order to establish the authenticity of the analyzed data. The biology instructors verified that their ideas had been reported correctly. To facilitate the processing and interpretation of the data from the questionnaires and the exam questions, we further grouped the 14 categories into six common, overlapping themes. As described, in questionnaire 2, the biology instructors were asked to provide examples of exam questions that included the concepts they considered to be relevant for the courses they teach.

Questionnaire 3: Online Qualtrics survey for biochemistry and chemistry representations of importance to biology courses.

An open-ended, online Qualtrics survey (Supplemental material) was developed to further investigate the nature and use of chemistry and biochemistry representations in biology courses for this study. To increase the response rate (McClelland, 1994), we designed a simple survey that required approximately ten minutes to complete. The questions required participants to (i) state the various biochemistry and chemistry representations (**M)** that are relevant to the biology courses they teach (RQ3), and (ii) explain how they expect students to reason with/use the identified representations (RQ4) (**RM)**. To identify a comprehensive representation of biology faculty to participate in the survey, all the biology courses that students (biology majors) must take were identified, and then the biology faculty who had taught the identified biology courses in the previous three years were invited to participate.

Deductive analysis was used to categorize representations. During deductive analysis, the four categories of representation, *graphs*, *molecular models*, *mathematical equations* and *chemical equations*, were used as a categorization matrix which was, in turn, used to classify the representations from the data supplied in response to Questionnaire 3. The

CRM model was used to analyze the instructors' specifications regarding how they expected students to reason with the representations (**RM**). Prior to the study, research procedures were reviewed and approved by the Institutional Review Board (IRB protocol 1408015145). Table 1 summarizes the steps that were employed to address the four research questions posed in this study. Furthermore, table 1 also shows how the CRM model informed the collection and analysis of the data. As shown in table 1, data collected from Exploration Phase was comprised of concepts (**C**) and representations (**M**). These concepts and representations were further grouped into categories that were used in the Confirmation Phase of the study. The importance of the concepts and representations was rated and specifications of how students are expected to reason with the concepts (RC) and representations (RM) were provided. This was followed by interpretation of the data.

Insert Table 1 here

Results and Discussion

For all three rounds of data collection outlined in table 1, respondents were roughly representative of faculty members who teach biology at the current institution, although there is some evidence of self-selection since no one provided any information about upper division courses in ecology or evolution. Biology instructors were invited via email, which resulted in twenty expert instructors volunteering to participate in the Exploration Phase. These professors who responded to Questionnaire 1 (See Supplemental Material) provided exam questions from 11 different courses. In response to Questionnaire 2, seven biology professors provided information about eight different courses. In the final round, 13 biology professors who responded to an online Qualtrics Survey provided information about 23 biology courses. Although the methods and timing employed were in favor of a high response rate, the response rate at each round varied due to a number of reasons. Firstly, some biology instructors pointed out that biochemistry and chemistry concepts, and therefore related representations, were not at all relevant to their specific biology course, and thus they did not participate in the survey. Secondly, member-checking interviews revealed that some participants were at one time unavailable due to illness, sabbatical leave, an administrative assignment, or leaving their job. Thirdly, some biology instructors' working schedule was so hectic and busy that they were sometimes not able to participate, thus, for a variety of reasons, some did not provide responses for all rounds of this study.

As further evidence that a comprehensive representation of biology faculty participated and to further characterize the participants, the textbooks required by respondents for biology students at the current institution were identified. Those who participated in all three rounds used Alberts et al. (2013) *Essential Cell Biology*, Nicholls et al. (2012) *From Neuron to Brain*, Sadava et al. (2008) *Life: The Science of Biology*, and Sun (2014) *Introduction to Microbiology*. Participants who responded to the first and third but not the second stage required students to purchase Raven et al. (2008) *Biology* and Tortora & Derrickson (2014) *Principles of Anatomy and Physiology*. Participants who responded to the first and second but not the third round required students to use the Urry et al. (2012) *Campbell Biology in Focus*. Participants who required students to purchase Klug et al. (2014) *Concepts of Genetics* and Lodish et al. (2007) *Molecular Cell Biology* responded only to the first and third stage of the study respectively. Faculty members sometimes did not require students to purchase textbooks for upper division courses.

RQ-1: Biochemistry and chemistry concepts important to biology courses (C)

In addressing RQ-1 and in response to the Exploration Phase of the study, in which instructors' listed up to ten most important concepts of relevance to their courses, a total of 100 concepts were provided by the expert biology instructors. This number was decreased to 74 by merging descriptions of similar concepts. The 74 concepts were then grouped into 14 major categories (table 2) based on similarity and relevance, and used to prepare Questionnaire 2 in which biology instructors were asked to rate the level of importance of each concept to the particular courses they teach. The findings are presented in table 2.

Insert Table 2 Here

Since instructors were restricted to a maximum of 10 concepts, it is important to note that the 74 listed concepts (table 2) is not meant to provide a complete list of all the concepts the respondents considered key to mastering their courses. Clearly, there are many other concepts taught in chemistry and biochemistry courses that are necessary for biology understanding, and which have been sited in textbooks and published in comprehensive studies in the literature (Tansey *et al*., 2013; Wright, Provost, Roecklein-Canfeld, and Bell, 2013),. However, the importance assigned to these specific 74 concepts by biology instructors suggests that introductory chemistry and biochemistry courses at the current institution should especially focus on them and their significance and application to biological examples. This is supported by the fact that most of the listed chemistry and biochemistry concepts are among those included in the undergraduate biology curriculum proposed by the National Research Council (2003) as well as those identified in the ASBMB study of Voet et al. (2003).

Regarding the rating of importance (Questionnaire 2; Appendix B) of each concept shown in table 2, the data shows very little consensus that any of the listed concepts are not important to biology. In fact, only UV Vis Spectroscopy, atomic orbitals, and Lewis acids and bases were rated as not important to their biology courses by more than half of the expert biology instructors. Furthermore, all 74 concepts were considered important by at least one instructor for at least one biology course. When some biology instructors were questioned during member checking interviews, they indicated that they rated some concepts as “undecided” because knowledge of those concepts was important but not directly required for understanding the biology course(s) they taught.

As discussed in greater detail later in this paper, visual representations (Group 14) were highly rated by almost all instructors, reflecting the modern acceptance that science is a visual subject in which learning and research is considerably facilitated by the use of representations (e.g. Mayer, Bove, Bryman, Mars, and Tapangco, 1996; Schönborn and Anderson, 2010; Tsui and Treagust, 2013;). Indeed the fact that visual representations were rated as important by the majority of the instructors substantiates the fact that they are essential for knowledge construction (e.g. Peña and Quílez, 2001; Treagust *et al.,* 2002) and for promoting conceptual understanding and visualization of abstract phenomena (e.g. Kozma, 2000; Schönborn and Anderson, 2010).

The extensive nature of the 74 listed concepts, begs the question of how well all of this material can be covered in the two years of chemistry and biochemistry typically required for biology students at the current institution. This suggests the need to discuss the extent of coverage of each topic and the possibility of rationalization of certain areas to minimize repetition so that other areas can be covered in greater depth. For example, those topics in general- and organic chemistry textbooks, that do not appear on the list in table 2, could be considered less important to biology students and dropped from chemistry courses for life science students, or more effort made to help biology faculty and students grasp their importance. Another key consideration could be how the curriculum for biology students could be modified to facilitate students' logical construction of knowledge of concepts to enhance vertical progression between courses starting with the basics in chemistry and progressing to higher levels of understanding in biochemistry before their application in biology.

In summary, these findings suggest a strong need to consider molecules and reactions in a biological context when students learn how molecules interact with each other. For example, biology students need to understand how, the pH of an aqueous cellular environment, which may be partially organic in nature, impacts molecular interactions. These sorts of considerations are crucial for an understanding of how chemistry and biochemistry applies to living organisms.

RQ-2: How do biology instructors expect students to use their knowledge of biochemistry and chemistry concepts in their various biology courses? (R-C)

As per RQ-2 and our theoretical framework, the CRM model, we felt it was important to not only establish what concepts (**C**) biology instructors consider important to biology students but also how students are expected to use/reason with the concepts (**RC**). To address this question we used Questionnaires 1 and 2 to respectively collect two types of data from the biology instructors: 1) Quotations from instructors, about what they expected students to do with their knowledge of each topic or concept in their biology courses; and, 2) Examples of test questions from their courses that, in their view, require students to use their knowledge of each topic or concept in order to give a sound answer. In this section we use selected examples of questions and quotations to address RQ-2. To facilitate the clarity of the discussion we also group the 14 categories (table 2) into six common, overlapping themes.

Theme 1: Properties of water, chemical bonds and biomolecular structure and function
Extensive scientific research (e.g. Bertoluzzaa, Fagnanoa, Morellib, Tintia, and Tosic, 1993; Wiggins, 1990) has demonstrated the universal role that water plays as a medium within, and outside cells by virtue of its properties relating to solubility, hydrophilicity and hydrophobicity. Thus, as suggested by the following selected quotes, biology instructors expect students to be able to use their knowledge of properties such as hydrophobicity and hydrophilicity to explain how water has a strong influence on the structure and function of biomolecules, including bio membranes (**RC**).

"Needed for understanding behavior of DNA in solution which we discuss as background to DNA hybridization."
"Why chemicals & molecules exhibit these properties and importance in context of biological membranes."
"Apply to understand molecular partitioning and i/o in cell."

The properties of water, in turn, strongly influence the non-covalent interactions that determine macromolecular folding and structure, and the specificity of binding interactions with other molecules involved in multiple cellular functions. It is not surprising, therefore, that biology instructors would like students to be able to apply their knowledge of the role non-covalent interactions like H-bonds, ionic bonds, dipole-dipole and coulombic interactions, and van der Waal's forces to understanding of macromolecular and membrane structure, behavior and function. In this regard, the following quotes from the biology instructors illustrate what they expected students to do with their knowledge of non-covalent bonds in general to explain the structure and function of biomolecules.

"Things that hold biological molecules together in cell structures. Reversibility of non-covalent interactions. Protein tertiary structure."
"Understand these interactions among macromolecules in the cell."
"These are the mainstay of biomolecule interaction. H-bonds & van der Waals especially."

Taken together, the data from biology instructors presented above and in table 2 suggest that the basic concepts of this topic are of significance to biology due to the need to apply this conceptual knowledge to understanding and solving problems (**RC**) to do with the structure and function of biomolecules in living systems. This is supported by the following example of how instructors expected their students to use such basic concepts for assessments in their biology courses:

INSERT FIG 1 HERE

The question in figure 1 concurs with the above quotes in that it illustrates how the instructors expected the students to use their understanding of hydrophobicity, hydrophilicity and non-covalent interactions such as hydrogen-bonding and ionic bonds to relate biomolecular structure to function. The example of an answer in figure 1 is a typical response provided by one of three participants who were recruited to pilot this question. Typical of the nature of open-ended questions the three participants provided different but scientifically feasible answers, which included the use of common concepts. These concepts included knowledge of: different types of amino acids; non-covalent interactions such as hydrogen bonding, hydrophobic and hydrophilic interactions; charged and uncharged amino acids; and protein conformation. Overall, this question is a transfer-, application type question (R-C; Anderson *et al*. 2013) in that it requires students to transfer and apply their understanding of the above mentioned concepts in order to explain how they contribute to protein structure, function and flexibility. In order to successfully answer this question, we assume that students are expected to remember knowledge (RC) about different types of amino acids, hydrophobic and hydrophilic interactions, hydrogen bonding, and how the charges of different types of amino acids determine the structure, function and flexibility of proteins. Furthermore, we assume that students are expected to use a specific example of a protein, such as the potassium ion channel, to integrate (RC) and explain how different types of amino acid side chain properties and non-covalent interactions determine the shape and function of proteins such as a potassium channel. Moreover, we assume that students are expected to transfer and apply knowledge (RC) about the characteristics of the different types of amino acid side chains and the formation of non-covalent interactions in order to explain how they influence the function, shape and flexibility of proteins like, for instance, a potassium ion channel.

Theme 2: (Bio)chemical reactions, enzymes, cellular processes and their regulation

Instructors considered it important for students to learn how to apply (**RC**) their knowledge (**C**) of key (bio)chemical reactions, enzymes and cellular processes to understanding and solving problems (RC) to do with various biological systems and their regulation in cells. Of the basic chemical reactions, instructors particularly favored redox and hydrolysis reactions as these play major roles in cells in energy generation but also need to be understood in the context of laboratory work. The instructors provided the following specifications regarding how students should reason with concepts (RC) related to redox reactions and metabolism.

"*They need to know what in a microbiological media can serve as reductant/ oxidant/ e-source/sink for metabolism.*"

"Energy generation –what drives biochem. Rxns [reactions]"

Biology instructors see knowledge of basic chemical reactions and enzyme function coming together, not down to the organic mechanism level, but at the anabolic and catabolic level of metabolism and how the different cellular processes impact regulation of systems at the organism level. This is apparent from the following selected quotes:

“Talk about lac operon catabolite – I assume they know about catabolic reactions.”
“A major part [of my course] is a discussion of how bacteria obtain energy from catabolic reactions.”
“Absolutely critical for understanding bacterial metabolism.”

These expectations by instructors, on how they wish students to use their knowledge, are further supported by the following example of a test question that was provided in response to Questionnaire 1:

INSERT FIG. 2 HERE

This question is probing students’ understanding of concepts such as dosing regimen, rate of drug clearance, poor, normal and ultrafast metabolizers and thermodynamic and kinetic factors affecting drug metabolism. To successfully answer this question, students are expected to remember (RC) knowledge associated with these concepts, and to transfer and apply (RC) their knowledge of metabolism to explain the difference between poor, normal and ultrafast metabolizers regarding the rate at which they metabolize and clear drugs. Moreover, students are expected to know the local and system effects (RC) of being a poor, normal and an ultrafast metabolizer, that is, they are expected to explain how, for example, differences in the CYP2D6 gene affect the pharmacokinetics of patients and thus their dosing regimen. Furthermore, students are expected to be able to evaluate (RC) how and why dosing regimen is different for poor, normal and ultrafast metabolizers.

Theme 3: Thermodynamics including chemical equilibrium, ATP and membrane transport

An understanding of enzymatic reactions and metabolic processes is incomplete without the ability to apply knowledge of thermodynamics to answer important questions like: why does a metabolic reaction or pathway proceed in a particular direction and how does pathway efficiency contribute to thermoregulation? Thus biology instructors placed great emphasis on understanding the laws of thermodynamics to be able to predict the behavior of reactions, processes, pathways and even metabolic systems. Examples of quotes indicating what students need to be able to do with thermodynamic knowledge in general included the following:

"Predict equilibrium status of enzymatic reactions."

"What molecules can serve as an energy source."

"Membrane potential as a regulatory function -> photoreceptor and muscle function."

"Apply these in thinking about non-eq systems."

The above expectations on how students are expected to use their knowledge are supported by the following example of an exam question provided in response to Questionnaire 1:

INSERT FIG. 3 HERE

The above question is testing students' understanding of concepts such as K_{eq}, ΔG°, spontaneity, and thermodynamically favorable and unfavorable reactions. This question shows that the instructor expects students to have the ability to apply knowledge (RC) of thermodynamics to explain why a metabolic reaction or pathway proceeds in a particular direction. Therefore, in order to successfully answer this question, students are expected to remember, transfer and apply (RC) knowledge related to the stated concepts; critically analyze the given experimental information in order to know the values to use to calculate K_{eq}, ΔG°; use the appropriate equations to calculate K_{eq}, ΔG°; and use the calculated values to predict if the reaction is spontaneous or not. Interestingly, although this question was supplied by a biology instructor, the key influence of cellular concentrations of intermediates on the spontaneity of such reactions is ignored in favor of standard conditions of temperature and (1M) concentration which would never exist in a cell because of obvious toxicity. This suggests that even biologists may revert to a chemist's treatment of metabolic reactions. Once again, on the basis of the above, it is evident that expert biology instructors consider low order reasoning skills (**RC**) such as the mindful memorization of concepts, integration of related concepts (**RC**) and high order reasoning skills such as the ability to transfer and apply knowledge of concepts; and the ability to reason algorithmically (RC), to be important for biology courses.

Theme 4: Acids and bases

Several biology instructors expected students to be able to transfer and apply their knowledge of acid-base concepts, such as pH and buffers, to explain how they affect the structure and functional behavior of proteins at the molecular level while also playing a buffering role at the physiological level. Acid-base considerations are also considered key to laboratory practice. This expectation is evident by the following quotes about the use of acids and bases:

"Understand biological acids & bases, function[al] groups on proteins & nucleic acids."

"We discuss pH, students need to understand what pH is. We especially focus on alkaline pH denaturing DNA. And focus on specifics of southern blot and plasmid isolation via alkaline lysis methods."

"Basics of buffering- implications of variation- protein structure function."

How instructors, expect students to use their knowledge of acid-base, is further supported by the following example of an exam question:

INSERT FIG 4 HERE

The question in figure 4 above corresponds to some quotes given by the participants regarding how they expect students to use their understanding of pH. Interestingly, once again as in the case of the exam question in fig 3, students were not specifically asked to identify which ionic species predominates under cellular pH conditions, something of obvious importance to biology. The question in figure 4 above covers both theme-one (T1) and theme-four (T4): that is, the question addresses biomolecular structure and function (T1) and acids and bases (T4). Based on the above question, students are expected to be familiar with knowledge associated with concepts such as hydrogen bonds and their formation; characteristics of the R-groups of the given amino acids (H, G, E); peptide bonds and how they are formed; and the effect of pH and pK_a on the charge of the given amino acids (H, G, E). For this question, students are expected to remember knowledge relevant to the stated concepts; and integrate, transfer and apply understanding of these concepts (RC) in order to be able to draw the tripeptide (H-G-E), identify the hydrogens that will participate in hydrogen bonding and determine the charge of the tripeptide at the given pH values. On the basis of the above, it is evident that the expert biology instructors expect students to have attained reasoning skills (**RC**) such as the mindful memorization of concepts like hydrogen bonds and charge; integration of related concepts; and transfer and application of knowledge about pH and ionization.

Theme 5: Solutions, mixtures and analytical techniques

Based on the instructors' Likert scale ratings, concepts such as molar concentration, Beer-Lambert Law and solutions were selected to be important for biology courses. Some instructors showed that students needed to understand only basic information related to the stated concepts, whereas other instructors showed that students needed to be able to use the Beer-Lambert law for calculations related to spectrophotometry. The following quotes show how the instructors expect students to make use of these concepts:

"Concentration of ions and other molecules in cells."

"Very basic, must understand these."

"Calculations-Spectrophotometry."

Instructors provided examples of exam questions that illustrate how they expect students to use their knowledge of solutions and mixtures. Figure 5 below shows an example of an exam question supplied by an instructor.

INSERT FIG. 5 HERE

The question in figure 5 addresses both theme-three (T3) and theme-five (T5), that is, the question covers thermodynamics and equilibrium (T3) in addition to solutions, mixtures and analytical techniques (T5). Furthermore, this question requires students to apply (RC) their understanding of membrane potential to an experimental setting. What is even more interesting about this question is the fact that students need to be familiar with concentration units and know how to convert from one unit (mM) to the next unit (M). The above question is testing students' understanding of concepts such as equilibrium potential, membrane potential, Gibb's free energy, Nernst equation, conversion factors between the units of molarity, energetics of ion transport via the membrane and the Na/glucose symporter. In this question, students are expected to remember knowledge relevant to the stated concepts; integrate knowledge of these concepts with other related concepts in order to know the values to use, from the experimental information, to calculate the equilibrium potential and Gibb's free energy for each ion. The students are also expected to use appropriate equations in order to calculate the equilibrium potential and Gibb's free energy for each ion. Furthermore, students are expected to transfer and apply knowledge (RC) related to the stated concepts so as to explain why the Na/glucose symporter will not work under the described conditions and to suggest how the symporter could be changed. Students are also expected to be able to analyze the given experimental information so as to solve a problem about the transport of glucose into a cell using their knowledge of the values needed to calculate equilibrium potential and Gibb's free energy.

Theme 6: Atomic theory and structure and gas laws

These atomic theory and gas law topics were grouped together because of their basic chemistry nature and importance in underpinning much of biology understanding. Although nearly all the atomic theory concepts were shown to be important for biology courses, most instructors showed how they expect students to use concepts with examples of ions. According to the instructors' specifications, it is clear that the instructors expect students to know the biological importance of cations and anions. The instructors provided the following quotations regarding how they expect students to make use of these concepts:

"Discuss DNA as a polyanion & discuss counterions."
"Membrane potential, ion transport."

An example of a question that probes students' understanding of atomic theory and structure and gas laws is shown in figure six below.

INSERT FIGURE 6 HERE

The question in figure 6 above is testing students' understanding of Le Chatelier's principle, bicarbonate/carbonic acid buffering and partial pressure. In order to answer the question correctly, students are expected to remember knowledge associated with the stated concepts. They are expected to know the relationship between the gas law and acid-base concepts (integrate) and also be able to transfer and apply knowledge of these concepts in order to state the consequences of not breathing for 90 seconds.

In conclusion, and generally speaking, the instructor responses and the exam questions revealed that students are expected to know the importance of biochemistry/chemistry knowledge to biological systems. Furthermore, it appears that the instructors expect the students to have attained a meaningful understanding of the biochemistry/chemistry concepts. This is due to the fact that the exam questions did not only probe students' ability to mindfully memorize concepts. Instead, they probed for students' ability to integrate, transfer, apply and analyze knowledge of biochemistry/chemistry concepts to solve problems and explain biological phenomena (RC). Transfer has been defined by Mayer and Wittrock (1996) as the ability to use or apply knowledge of a concept to solve new problems, answer new questions, or facilitate learning of new subject matter. Indeed, according to the revised Bloom's taxonomy (Anderson *et al.,* 2001), Anderson et al. (2013), Anderson and Schönborn (2008), Mayer (2002), Schönborn and Bögeholz (2009), transfer, application and analysis/evaluation are among the most important reasoning skills (RC) students ought to have in order to construct a good and meaningful understanding of concepts. Thus mentioned, it is important that biochemistry and chemistry courses designed for life science students, specifically biology students, equip students by giving opportunities to practice both low and high order reasoning skills.

RQ-3: Representations important to biology students (M)

Analysis of the data from Questionnaire 1 revealed that biology instructors at the current institution under study use various representations in their courses. The representations were assigned to four categories, namely, molecular models, chemical equations, graphs, and mathematical equations. The importance of these categories was confirmed in instructor responses to Questionnaire 2. We therefore decided to further investigate these four representation categories through the design of a Qualtrics survey (Questionnaire 3). This survey asked instructors to elaborate on the different types of representations (M) they use within each category and how they expect students to use (RM) such representations (Supplemental Materials).

As shown in table 3, various types of biochemistry and chemistry representations were considered by the instructors to be important for the biology courses under study. This suggests that more time has to be spent teaching these representations and ensuring that students understand the importance of these representations to depicting abstract phenomena. It is not surprising that a large number of representations were shown to be important for biology courses. This is because, according to Schönborn and Bögeholz (2009), representations are “carriers of biological information” (p.935). The representations listed in table 3, above, are related to most of the concepts that were reported in the Confirmation Phase of the study as relevant for biology courses.

INSERT Table 3 Here

RQ-4: How do biology instructors expect students to use biochemistry and chemistry representations? (RM)

Molecular Models

Given that modern biology is a strongly visual subject (Tsui and Treagust, 2013); it was not surprising that the biology instructors in this study considered that molecular models are key to the success of their courses. They supported this opinion by providing a range of examples of how they expect students to be able to use such representations (RM). This allowed us to not only classify examples as RM-type activities, but to suggest what specific visual skills the student would need to use to perform such activities (Anderson *et al.,* 2013; Schönborn and Anderson, 2010), as discussed below.

Biology instructors suggested a range of ways they might ask students to use molecular models. For example, there was a strong emphasis on using models of macromolecules “To explain protein structure-function relationships," or to "Identify structures and functional groups." Related to this, one instructor stated, "I expect the students to know the general features of DNA and RNA structures, including strand polarity, base and sugar composition, and base-pairings." Thus, instructors expect students to be able to use molecular models to explain, identify and know- all important visual skills (R-M) as defined previously (Anderson *et al.,* 2001; Anderson *et al*., 2013; Schönborn and Anderson, 2010).

Instructors also emphasized the importance of their students being able to draw (RM) (Anderson *et al.,* 2013; Quillin and Thomas, 2015) or modify diagrams to explain and solve problems. This is evident by the following three examples of quotes:

"We only use sketches on the exams, not 3-D models. For example, I may ask students to modify a structure (mutation) and then explain how the modification would affect the function of the structure."

"Memorization of the complete structure of a molecule like phosphatidylcholine is not required, but students should be able to draw the structure of a phospholipid if given the structures of the fatty acids and the polar group. Know the structure of glycerol and how the ester linkages are formed."

"Relate the absorbance spectra for the two forms of the phytochrome molecule (Cis and Trans isomers), and… relate the form of the molecule to the absorbance spectrum and how the form impacts the biological activity of phytochrome molecules."

In order to fully perform tasks with 2D and 3D molecular models and drawings, students always need to be able to transfer their knowledge (RC) from the relevant content domain; to interpret (RM) the representation, they need to decode (RM) the symbolism in the representations (Anderson *et al.,* 2013); spatially rotate (RM) the model to perceive 3D structure; and evaluate the limitations (RM) (Schönborn and Anderson, 2010) of the models to establish what they do/do not represent of the 'real' structure. All these skills are necessary for working with representations and thus should be taught by giving students multiple experiences at working with representations. Some of the above quotes are supported by Figure 7, an exam question that was provided by an instructor in response to Questionnaire 1.

INSERT FIG 7 HERE

Regarding this question, students need to remember, integrate, transfer and apply relevant knowledge in order to successfully answer the question. However, since a molecular model of a lysine residue is provided in the question, students need to also reason with the representation (RM). That is, they need to decode the representation by identifying the symbolism depicting the R-group, the alpha carbon, the amine group and the carboxylic acid group. Furthermore, students are expected to know how to construct a lysine residue that shows the appropriate charge for this amino acid at pH 7. They may have memorized the ionic charges for lysine or they might have solved this problem based on the relative pK_a values of the titratable groups of lysine. Similar to this question, in figure 4, students were asked to draw a tripeptide (H-G-E), also decoding the structure to identify the functional groups, including the N-terminus and the atoms involved in peptide bond formation. Furthermore, students were expected to be able to translate vertically (RM) between the tripeptide and the alpha helix structure (Fig. 4, part B) in order to predict and identify the hydrogens that will be involved in hydrogen bonding to stabilize the alpha helix.

Overall, based on these questions and the instructor quotes provided above, it could be deduced that interpretation of diagrams and construction/drawing of diagrams (RM) is important to the biology courses taught by the participating instructors. Drawing is an important part of biology (Betz and Dempsey, 2015; Quillin and Thomas, 2015) because it has positive benefits towards student learning (Bell, 2014; Dikmenli, 2010; Lerner, 2007). For instance, drawing promotes thinking, communication, visualization, interpretation of results (Quillin and Thomas, 2015; Van Meter and Garner, 2005) and can be used as a tool for revealing students' misconceptions in a specified discipline such as biology (Dikmenli, 2010; Köse, 2008; Quillin and Thomas, 2015).

Graphs

Graphs are used extensively in biology for a wide range of purposes including to process and visualize data in biological experimentation, or to represent research outcomes and knowledge in the literature, including textbooks. Some instructors were more general while others were specific about the use of graphs in their biology course. In the case of general usage of graphs, some instructors made statements like the following:

"I expect them to know the importance of the graph. They should know what the graphs help us obtain. They should know the relationship between the y and x axis."

"[….] I expect they will be able to look at the graph and interpret how the dependent variable changes as the independent variable is altered during an experiment (i.e. to interpret the graph)[….]"

"Understand how dependent variables change with changes in independent variables. Compare responses in two difference conditions or states (e.g. proteins with slightly different function as a consequence of amino acid differences….) and the implications for function."

The majority of instructors cited specific examples of how they expect students to use the graphs. This is supported by the following quotes:

"Determine kinetic parameters for enzyme activity; identify optima or activity timing."

"I expect the students to be able to use a hyperchromatic shift graph to compare the base composition of two DNA species. In addition, I expect the students to be able to use a reassociation kinetics graph to compare the size and complexity of genomes from two different species."

"Use the graphs to calculate say the chloride excretion rate between hydrated and dehydrated individuals."

Based on the above expectations, it can be deduced that instructors expect students to know what the provided graphs represent and be able to interpret the graphs. These expectations were also portrayed in figure 8 with the exam question that an instructor provided in Questionnaire 1.

INSERT FIG. 8

In order to successfully answer this question, students are expected to remember, transfer and apply knowledge related to an action potential. Furthermore, since a graph is provided, students have to be able to interpret the graph (RM). However, in order to successfully interpret the graph, students have to decode the symbolism (RM) of the graph to explain what points A to E represent. They also have to be able to identify the limitations (RM) of the graph in terms of what the graph is, and is not showing about an action potential. For example, to answer this question, students would need to remember that the membrane prevents flow of ions into and out of the cell unless an ion channel opens to allow flow into or out of the cell, based on the electrochemical gradient for that particular ion. Thus the results suggest that in courses taught by the participating instructors, students must interpret a graph in relation to their biological knowledge

Chemical Equations

As shown in table 3, examples of chemical equations considered by instructors to be relevant to the biology courses at the institution under study include those pertaining to oxidation reactions and acid-base equilibrium such as reversible carbonic acid/bicarbonate reactions. Instructors also specified how they expect students to use some of the listed chemical equations. Examples of the instructors' expectations are shown below:

"Body fluids contain buffering substances including proteins and bicarbonate ions. Buffers absorb protons (H^+ ions) to neutralize acids. The major buffer in the blood is bicarbonate ions (HCO_3^-) that are formed from the dissociation of carbonic acid, which in turn is formed by the hydration of CO_2 according to the equilibrium reaction. How do bicarbonate ions (HCO_3^-) stabilize the blood pH?"

"I never have students just memorize equations. These are so easy to look up nowadays that there is not much point. I have students go to a website like KEGG or BioCyc and interpret metabolic flux through a pathway either in different bacteria (comparative metabolomics) or in cases of mutation, either spontaneous or designed."

“They should know how to use the equations to correctly answer the questions.”

When looking at these quotes, one can deduce that the instructors are expecting students to have attained abilities that will enable them to correctly use various equations. Based on the above quotes, the major skill that is emphasized is the ability to interpret and use the equations to solve problems (RM). Thus it is important that chemistry/biochemistry courses intended for biology students should equip students with this skill.

Mathematical Equations

As shown in table 3, many different mathematical equations were also listed as being important for biology courses. Examples include the Nernst, Henderson Hasselbalch and Michaelis Menten equations, and equations relating to Gibbs free energy and Fick’s and Boyle’s Law. . Instructors provided the following expectations regarding how students should use these equations:

“[…] I have them use an equation to solve a problem that requires a calculated answer, and occasionally to model data mathematically […]”

“E.g. Fick's Law of Diffusion.... use it conceptually to understand physiological adaptations of different animals to maximize flux. Think about trade-offs for optimizing one parameter in the equation.”

“If a cell has a total cytosolic solute concentration of 500 mM and the total solute concentration of the extracellular medium is 200 mM, what will be the turgor (hydrostatic) pressure of the cell if water is at equilibrium across the cell membrane? Use RT = 2.5 L MPa/mol as a conversion factor.”

“The movement of substances (the flux) can often be described by an equation of the form Flux = Constant times Driving Force, where the constant is determined by the properties of the substance and the pathway through which it is moving. Fick’s Law was given as an example of this kind of equation. What aspect of Fick's Law is dependent on aquaporins in

the membrane and how would changing the number of membrane aquaporins affect flux across the membrane?"

"Pretty simple stuff here--no calculus. But, they need to know how to use arithmetic and algebraic equations to solve problems."

The exam questions provided by the instructors in Questionnaire 1 support the expectations stated above. Examples of exam questions provided in figure 3 and figure 5 illustrate how instructors expect students to use mathematical equations to solve (RM) biological problems. Therefore, to successfully answer these questions, students are expected to remember, integrate, transfer and apply knowledge (RC) relevant to the problem to be solved. Furthermore, for each of these questions, students are also expected to firstly, know the relevant equations to use for calculating K_{eq}, ΔG° and the equilibrium potential. Secondly, students need to interpret these equations so that they know what each equation represents. However, in order to successfully interpret the equations, students need to decode the symbolism of the equations, that is, they need to know what each symbol represents so that they could know the relevant experimental values to use for calculating K_{eq}, ΔG° and the equilibrium potential. Once again, it appears that interpretation of equations is very crucial in the biology courses taught by the participating instructors. Therefore, it is important that students are trained how to interpret mathematical equations so that they are able to successfully use them to solve biological problems.

Since some of the exam questions (figures 1-8) provided in the Exploration Phase of the study include the use of representations, we found it important to determine if the representations used in the exam questions are comparable to those identified as being relevant to biology courses (table 3). Table 4 shows the various types of representations from table 3 that appear in the exam questions. The data shows that each exam question covered one or more representations. Furthermore, some of the exam questions covered the same types of representation (figures 1 and 4, for example) while others covered different ones (such as figures 2, 6, and 8). Collectively, though, the eight selected exam questions covered a broad range of the identified representations. This confirms the importance of the identified types of representation for the teaching of biology at the present institution.

INSERT TABLE 4HERE

Conclusions and Implications

The results of this study have provided key information from biology instructors at a large research university about the chemistry and biochemistry concepts, representations and related ways of reasoning with such concepts and representations that they believe are important for their biology courses. This in-house data could be used directly and synergistically with published information from other national studies (e.g. Tansey *et al*., 2013; Voet *et al.,* 2003; White, Benore, Sumter, Cartwell, and Bell, 2013; Wright, Provost, Roecklein-Canfeld, and Bell, 2013) to inform curricular discussions at the current institution. Such findings, however, should be used with caution by other institutions in which the educational and student context may be very different. Instead we advocate that the process we have deployed in this study (See Table 1) could be used at other institutions to yield local data about their own biology major program and any related curricular issues which could, in turn, serve as a springboard for curriculum discussions between stakeholders at that institution. The methods used in this study suggest the following potentially useful advice for practitioners (in no order of importance), both at the institution under study and other institutions:

• A sound grounding in basic chemistry and biochemistry is indispensable to the education of biology students.

• Such grounding should include a strong focus on equipping students with the necessary cognitive skills to enable them to use or reason with concepts (RC) and related representations (RM) to solve problems, rather than just memorization of information.

• Results in Tables 2 and 3 could inform ways of teaching about biochemistry and chemistry concepts which might be linked to their biological importance, so that students can more readily integrate, transfer and apply such knowledge to their future biology studies. Concurrently, these findings might help biology instructors know when to cue their students to link (transfer; RC) to what they learn in chemistry and biochemistry in order to reinforce the application of such concepts.

• Although the 74 concepts listed as important by biology instructors do not provide a complete list of the basic chemistry and biochemistry concepts required to master biology, they do provide a basis for discussion about the curriculum in the specific context of the current institution. These concepts may also provide a starting point for discussion and comparison by instructors at other institutions.

• The extensive nature of the 74 listed concepts begs the question of how well all of this material can be covered in the two years of chemistry and biochemistry typically required for biology students at the current institution. This suggests the need to rationalize the scope and sequence of topics and to minimize any repetition.

• There is clearly a need to discuss how the concepts and representations fit into an integrated curriculum where biology, biochemistry and chemistry material is sequenced to meet the needs of all stakeholders. Development of such a curriculum would help in the development of biologists who have the ability to see the interconnectedness of biology, biochemistry and chemistry.

The data presented in this paper provides evidence that molecular approaches to biology have become foundational. At the current institution, zoology and botany courses were replaced with cell and molecular biology core courses quite some time ago. The three-step process in Table 1 and the list of topics presented here could provide a launching point for discussing how to coordinate scope and sequence of course work between the disciplines to maximize benefit from an educational program for students.

Although, the sample size of this study, being highly dependent on (very busy) faculty volunteers, was rather small, the sample was representative of the majority of instructors responsible for undergraduate biology at the current institution. Thus the findings are generalizable to the needs of this single institution and, where necessary, could be used to stimulate curricular discussion between chemistry, biochemistry and biology instructors. More research is required to establish the various education levels at which the identified concepts and representations could be taught. This is important because it will help in the development of curricula that address each concept and representation at an appropriate level so as to promote sound construction of knowledge and logical progression and knowledge transfer.

This study permits us to pose the following important questions that could be the target of future research:

- To what extent are the findings at the current institution generalizable to other institutions and, if not, in what way do they differ across institutions?
- Will the research process we used in this study be transferable to other institutions wanting to launch their own curriculum discussions around the needs of biology majors?
- In what ways do the opinions expressed in this paper by biology instructors at the current institution concur or contrast with the opinions of chemistry and biochemistry instructors in terms of whether joint curriculum discussions could be valuable and productive?
- Are there any gaps in their learning or do biology students progress through the undergraduate educational levels across a sequence of chemistry, biology and biochemistry courses with a logical sequence for construction of knowledge? Related to this, is the question of which concepts and competencies should be taught by which departments in which sequence to ensure such a logical learning progression.

In summary, this study highlights the value of a simple three-step process (Table 1) for surveying biology instructors about the prior knowledge they expect their students to have acquired from chemistry and biochemistry courses so that the curricular decisions can be empirically-based and designed to ensure the logical and sound construction of knowledge as the students progress from freshman to more senior years of study. These studies will enable chemistry, biology and biochemistry instructors at the current institution to explore whether curriculum discussions are desirable and, if so, whether they could lead to a mutually beneficial process and an improved integrated undergraduate curriculum for biology students. This in turn, could have an important impact on how well such students are prepared for later challenges including graduate studies in biology.

In conclusion, whereas the data obtained is mainly relevant to curriculum change at the current institution, we advocate that the process deployed here and summarized in table 1, will be relevant to other institutions wishing to improve the cohesion and progression between their chemistry, biology and biochemistry courses.

Acknowledgements

HHMI and members of the NEXUS project at Purdue University are acknowledged for Research Assistance funding to Rethabile Tekane during the early stages of this project. A special gratitude goes to all the biology instructors who participated and to members of the Purdue International Biology Education Research Group (PIBERG) and the Visualization in Biochemistry Education (VIBE) Research Group for many fruitful discussions that contributed to the progress of this study. Some material presented here is based on research supported by the National Science Foundation under grant #1346567. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Drs. George Bodner and Marc Loudon are thanked for their critical feedback on earlier drafts of the manuscript.

References

Abdella BRJ, Walczak MM, Kandl KA, Schwinefus JJ. Integrated Chemistry and Biology for First-Year College Students. *J Chem Educ* 2011; *88:* 1257–1263.

Alberts B, Bray D, Hopkin K, Johnson A, Lewis J, Raff M, Roberts K, Walter P. *Essential Cell Biology* 4th Edition. New York, NY: Garland Science; 2006.

Anderson LW, Krathwohl DR, Airasian PW, Cruikshank KA, Mayer RE, Pintrich PR, Raths J, Wittrock CM. *A Taxonomy for Learning, Teaching and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives,* New York: Longman; 2001.

Anderson TR, Schönborn KJ. Bridging the Educational Research-Teaching Practice Gap: Conceptual understanding, Part 1: The multifaceted nature of expert knowledge. *Biochem Mol Biol Educ* 2008; *36*: 309-315.

Anderson TR, Rogan JM. Bridging the educational research-teaching practice gap. Curriculum development, Part 1: Components of the curriculum and influences on the process of curriculum design. *Biochem Mol Biol Educ* 2011; *39*: 68–76.

Anderson TR, Schönborn KJ, du Plessis L, Gupthar A, Hull T. Identifying and Developing Students' Ability to Reason with Concepts and Representations in Biology. In: Treagust DF , Tsui CY, editors. *Multiple Representations in Biological Education*, *vol. 7*. Dordrecht: Springer Netherlands; p. 19–38; 2013.

Association of American Medical Colleges and Howard Hughes Medical Institute. *Scientific Foundations for Future Physicians*, Washington, DC: HHMI; 2009.

Bell JC. Visual Literacy Skills of Students in College-Level Biology : Learning Outcomes following Digital or Hand-Drawing Activities Visual Literacy Skills of Students in College-Level Biology: Learning. *CJSoTL* 2014; *5*: 1-13.

Betz BJ, Dempsey BC. Biological Drawing: A Scientific Tool for Learning. *Am Biol Teach* 2015; *63*: 271–279.

Bertoluzza A, Fagnano C, Morelli MA, Tinti A, Tosi MR. The Role of Water in Biological Systems. *Journal of Molecular Structure 1993; 291:* 425-437

Bovill C, Morss K, Bulley C. *Quality Enhancement Themes: The First Year Experience. First Year Enhancement Theme Report, The Quality Assurance Agency (QAA) for Higher Education*: Glasgow, Scotland; 2008.

Brewer CA, Smith D. *Vision and Change in Undergraduate Biology Education: A Call to Action.* Washington DC: American Association for the Advancement of Science; 2011.

Caple G, Balda R, Laughran L, Thomas PE, Çimer A. Integrated Science Laboratory Programs- A Holistic Approach. *J Coll Sci Teach* 1991; *20*: 222–227.

Creswell JW. *Qualitative Inquiry and Research Design: Choosing Among Five Approaches*, Thousand Oaks CA: Sage Publications; 2001.

Creswell JW (2014). *Research Design: Qualitative, Quantitative and Mixed Methods Approaches*, Thousand Oaks CA: Sage Publications; 2014.

Dalkey NC. *The Delphi Method: An Experimental Study of Group Opinion*, Santa Monica CA: The Rand Corporation; 1969.

Dasgupta AP, Anderson TR, Pelaez NJ. Development of the 'neuron assessment' for measuring biology students' use of experimental design concepts and representations. *CBE Life Sci Educ* 2016; *15*, (in press).

Degerman MS, Tibell LE. Learning goals and conceptual difficulties in cell metabolism- an explorative study of university lecturers' views. *Chem Educ Res Pract* 2012; *13*: 447-461.

Delbecq AL, Van de Ven AH, Gustafson DH. *Group Techniques for Program Planning*. Glenview, IL: Scott, Foresman, and Co; 1975.

Dikmenli M. Misconceptions of cell division held by student teachers in biology : A drawing analysis. *Sci Res Essays* 2010; *5*: 235–247.

Gross LJ. Interdisciplinarity and the Undergraduate Biology Curriculum: Finding a Balance. *CBE Life Sci Educ* 2004; *3*: 85–92.

Helmer O. *The Use of a Delphi Technique in Problems of Educational Innovations*. Santa Monica, California: The Rand Corporation; 1966.

Judd R (1972). Use of Delphi Methods in Higher Education. *Technol Forecast Soc Change* 1972; 4:173–186.

Kennedy D, James G. Is bio2010 the right blueprint for the biology of the future? *CBE Life Sci Educ* 2003; *2*: 224– 227.

Klug, WS, Cummings MR, Spencer CA, Palladino MA . *Concepts of Genetics* 11th Edition. San Francisco: Benjamin Cummings/Pearson Education; 2014.

Köse S. Diagnosing Student Misconceptions : Using Drawings as a Research Method. *World Appl Sci J* 2008; *3*: 283–293.

Kozma RB. The use of multiple representations and the social construction of understanding in chemistry. In: Jacobson M, Kozma R, editors. *Mahwah Innovations in Science and Mathematics Education: Advanced Designs for Technologies of Learning*. NJ: Erlbaum; 2000.

Lerner N. Drawing to learn science: Legacies of Agassiz. *J Tech Writ Comm* 2007; *37*: 379–394.

Linstone HA, Turoff M. *The Delphi Method. Techniques and Applications*. Reading. MA: Addison-Wesley Publishing Company Inc; 2002.

Lodish H, Berk A, Kaiser CA, Krieger M, Scott MP, Bretscher A, Ploegh H, Matsudaira P. *Molecular Cell Biology* 6th Edition, New York, NY: W. H. Freeman; 2007.

Loertscher J, Green D, Lewis JE, Lin S, Minderhout V. Identification of Threshold Concepts for Biochemistry. *CBE—Life Sciences Education* 2014; *13:* 516–528.

Mayer RE. Rote versus meaningful learning. *Theor Pract* 2002; *41:* 226-232.

Mayer RE, Wittrock MC. Problem Solving Transfer. In: Calfee R, Berliner R, editors. *Handbook of Educational Psychology*. New York: Macmillan; 1996.

McClelland SB. Training Needs Assessment Data-gathering Methods: Questionnaires. *J Eur Ind Train* 1994; *18*: 22–26.

McGoldrick C. *Creativity and Curriculum Design: What Academics Think*. York, UK: LTSN Generic Centre: Learning and Teaching Support Network; 2002.

National Research Council. *BIO2010: Transforming Undergraduate Education for Future Research Biologists*. Washington, DC: National Academies Press; 2003.

Nicholls JG, Martin AR, Fuchs PA, Brown DA, Diamond ME, Weisblat D. *From Neuron to Brain* 5th Edition. Sunderland, MA: Sinauer/W.H. Freeman; 2012.

Peña BM, Quílez MJG. The importance of images in education. *Int J Sci Educ* 2001; *23*: 1125-1135.

Prideaux D. ABC of learning and teaching in medicine. Curriculum design. *BMJ* 2003; *326*: 268-270.

Quillin K, Stephen T. Drawing to learn: A framework for using drawing to promote model-based reasoning in biology. *CBE Life Sci Educ* 2015; *14*: 1-16.

Raven P, Johnson G, Losos J, Mason K, Singer S. *Biology* 8th Edition. New York, NY: McGraw-Hill Companies, Inc; 2008.

Rowland SL, Smith CA, Gillam EM, Wright T. The concept lens diagram: a new mechanism for presenting biochemistry content in terms of "big ideas". *Biochem Mol Biol Educ* 2011; *39:* 267–79.

Sadava DE, Hillis DM, Heller HC, Berenbaum M. *Life: The Science of Biology* 9th Edition. Sunderland, MA: Sinauer/W.H. Freeman; 2008.

Schönborn KJ, Anderson TR. A Model of Factors Determining Students' Ability to Interpret External Representations in Biochemistry. *Int J Sci Educ* 2009; *31*: 193–232.

Schönborn KJ, Anderson TR. Bridging the Educational Research-Teaching Practice Gap: Foundations for assessing and developing biochemistry students' visual literacy. *Biochem Mol Biol Educ* 2010; *38*: 347-354.

Schönborn KJ, Bögeholz S. Knowledge Transfer in Biology and Translation Across External Representations: Experts' Views and Challenges for Learning. *Int J Sci Math Educ* 2009; *7*: 931– 955.

Sounders JC. A Model of Interdisciplinary Capstone Course for the Basic Sciences. *J Coll Sci Teach* 1993; 22: 295-298.

Sun I. *Introduction to Microbiology*. Minneapolis, MN: Blue Door Publishing; 2014.

Tansey JT, Baird T, Cox MM, Fox KM, Knight J, Sears D, Bell E (2013). Foundational concepts and underlying theories for majors in "biochemistry and molecular biology." *Biochem Mol Biol Educ* 2013; *41*; 289–96.

Thomas DR. A General Inductive Approach for Analyzing Qualitative Evaluation Data. *Am J Eval* 2006; *27*: 237–246.

Thompson KV, Chmielewski J, Gaines MS, Hrycyna C, LaCourse WR. Competency-based reforms of the undergraduate biology curriculum: integrating the physical and biological sciences. *CBE Life Sci Educ* 2013; *12*: 162–169.

Tortora G, Derrickson B. *Principles of Anatomy and Physiology* 14th Edition. Hoboken, NJ: Wiley; 2014.

Treagust DF, Chittleborough G, Mamiala TL. Students' understanding of the role of scientific models in learning science. *Int J Sci Educ* 2002; *24*: 357–368.

Tsui C, Treagust DF. Introduction to Multiple Representations: Their Importance in Biology and Biological Education. In: Treagust DF, Tsui CY, editors. *Multiple Representations in Biological Education, vol. 7*. Dordrecht: Springer Netherlands; 2013.

Urry LA, Cain ML, Wasserman SA, Minorsky PV, Jackson RB, Reece JB. *Campbell Biology in Focus*. San Francisco: Benjamin Cummings/Pearson Education; 2012.

Van Meter P, Garner J. The Promise and Practice of Learner-Generated Drawing: Literature Review and Synthesis. *Educ Psychol Rev* 2005; *17*: 285–325.

Van Wylen DGL, Abdella BRJ, Dickinson SD, Engbrecht JJ, Vandiver R. Interdisciplinarity: the right people, a supportive place, and a program Emerges. *CBE Life Sci Educ* 2013; *12*: 140–143.

Voet JG, Bell E, Boyer R, Boyle J, Leary MO, Zimmerman JK. Mini-Series : The ASBMB Recommended Biochemistry and Molecular Biology Undergraduate Curriculum and its Implementation Recommended Curriculum for a Program in Biochemistry and Molecular Biology. *Biochem Mol Biol Educ* 2003; *31*:161–162.

White HB, Benore MA, Sumter TF, Benjamin D, Caldwell BD, Bell E. What skills should students of undergraduate biochemistry and molecular biology programs have upon graduation? *Biochem Mol Biol Educ 2013*; 41: 297–301.

Wiggins PM. Role of Water in Some Biological Processes. *Microbiol Rev* 1990; 54: 432-449.

Wolfson AJ, Hall ML, Allen MM. Introductory Chemistry and Biology Taught as an Interdisciplinary Mini-Cluster. *J Chem Educ* 1998; *75*: 737-739.

Wright A, Provost J, Roecklein-Canfield J, Bell E. Essential concepts and underlying theories from physics, chemistry, and mathematics for “biochemistry and molecular biology” majors. *Biochem Mol Biol Educ* 2013; *41*: 302–8.

Figure 1: An example of a question for Theme 1 (*Properties of water, chemical bonds and biomolecular structure and function*) from a lower division second year biology course.

Figure 2: An example of a question for Theme 2 *((Bio) chemical reactions, enzymes, cellular processes and their regulation*) from an upper division biology course

Figure 3: An example of a question for Theme 3 (*Thermodynamics including chemical equilibrium, ATP and membrane transport*) from a lower division second year biology course

Figure 4: An example of a question for Theme 1 (*Properties of water, chemical bonds and biomolecular structure and function*) and Theme 4 (*Acids and bases*) from a lower division second year biology course

Figure 5: An example of a question for Theme 3 *(Thermodynamics including chemical equilibrium, ATP and membrane transport)* and Theme 5 (*Solutions, mixtures and analytical techniques*) from lower division second year biology course

Figure 6: An example of a question for Theme 4 (*Acids and bases*) and Theme 6 *(Atomic theory and structure and gas laws)* from a lower division first year biology course

Figure 7: An example of a question probing for students' ability to interpret and use molecular models in a lower division first year biology course

Figure 8: An example of a question probing students' ability to interpret and use a graph in a second year lower division biology course