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Creative Exercises (CEs) in the Biochemistry Domain: An Analysis of Students' Linking of Chemical and Biochemical Concepts

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Abstract

Creative exercises (CEs), a specific form of open-ended assessment tools, have been shown to promote students' linking of prior and newly learned concepts within a course. In this study, we examined how often students in an upper-division undergraduate biochemistry course linked prior chemical concepts to biochemical ones in response to CE prompts. Thematic analysis of participant responses showed students making in response to the CEs multiple connections between prior chemical concepts and biomolecule structure, thermodynamics and enzyme kinetics. In the case of thermodynamics and enzyme kinetics CEs, most students tended to rely on contexts and concepts focused on specific materials from their current course whereas responses to biomolecule structure CE mostly invoked foundational concepts in acid-base and organic chemistry, such as pH/pK_a, pI, ionization, stereochemistry, and organic functional groups. Invoking cognitive resources activation framework in discussing the findings, we highlight the utility and relevance of CEs in upper division courses that rely on the application of prior chemical knowledge to explain new ones as well as the implications of the findings for research and teaching.

Introduction

Educational theories on learning often draw contrast between meaningful and rote learning, with the distinction between the two attributed to the learning outcomes associated with each, epistemological beliefs about knowledge acquisition, and the cognitive processes involved in knowledge construction (Ausubel, 2000; Mayer, 2002; Novak, 2002; Taber, 2014). In the most basic form, promoting meaningful learning requires the coordination and active linking of concepts learned in various settings in a coherent and meaningful manner. In chemistry, Taber (2014) specifically argues that instruction should help students view the subject as a set of linked concepts

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6 with explanatory and predictive power rather than an assembly of disjointed facts to be memorized.
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8 The author wrote, “Chemistry, as a science, is not primarily about isolated fact ... *but about*
9 *concepts that can be used to build extensive theoretical frameworks that offer explanatory value*”
10 *(Taber, 2014, p. 9)*. Biochemistry, a subject concerned with the study of chemical processes in
11 living things, illustrates Taber’s point well. As an interdisciplinary subject, it requires the
12 application of prior chemical concepts to explain how biological systems work. For example,
13 students will need to apply foundational concepts in acid-base chemistry, thermodynamics and the
14 nature of intermolecular forces as well as insights from organic chemistry to explain a host of
15 biochemical topics such as protein structure and dynamics (Villafane *et al.*, 2011a; Wolfson *et al.*,
16 2012). That is, students need to use concepts they learned in prerequisite courses as theoretical
17 frameworks that can explain biochemical behavior.
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31 In order to help students make links between foundational concepts and biochemical ideas, we
32 need to better understand the contexts that promote making such links. To our knowledge, there is
33 limited research in biochemistry that directly investigated this phenomenon. Much of the previous
34 research in this area focused on uncovering students’ incorrect chemical ideas brought to
35 biochemistry (see Grayson *et al.*, 2001; Minderhout and Loertscher, 2007; Villafane *et al.*, 2011a,
36 2011b) (incorrect ideas or alternate conceptions/misconceptions, as used in this study, refer to
37 ideas/concepts held by students but are inconsistent with scientifically accepted explanations). For
38 example, Villafane *et al.* (2011a) proposed the use of 21 multiple-choice diagnostic instrument to
39 identify students’ incorrect ideas related to prior knowledge required for biochemistry,
40 recommending the use of their instrument as a pre-post assessment tool to inform biochemistry
41 instruction. Several other instruments were specifically designed to uncover student
42 misconceptions/alternate conceptions in biochemistry, e.g., the Molecular Life Science Concept
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6 Inventory (MLS-CI; Wright & Hamilton, 2008, 2011; Howitt *et al.*, 2008) and the Enzyme-
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8 Substrate Interactions Concept Inventory (ESICI; Bretz and Linenberger, 2012)).
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10 Multiple other studies, such as the work of Schönborn and Anderson (2009, 2010) and
11 Linenberger and Bretz (2012), address student struggles with external representations in
12 biochemistry or put their energy into curriculum reform efforts (see Minderhout and Loertscher,
13 2007; Loertscher and Minderhout, 2010). Loertscher and colleagues have similarly worked to
14 identify threshold concepts in biochemistry (Loertscher *et al.*, 2014). Other studies, such as the
15 work of Wolfson *et al.* (2011), examine students' learning progressions from general chemistry to
16 biochemistry. Wolfson and colleagues specifically used energy transformations in biological
17 systems as a foci for probing student conceptions of energy. In addition to examining the alternate
18 concepts students held when solving energy problems in the context of biochemistry, these authors
19 also examined the information students transferred from introductory courses to solve
20 biochemically situated energy problems.
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36 Our contribution to the existing literature arises from our close examination of the links
37 students make between prior concepts and biochemical ones. Such examination is necessary if we
38 are to view students' conceptual struggles as a failure to understand the interconnectedness of
39 foundational concepts in prerequisite courses and those found in more advanced courses such
40 biochemistry. We also believe it is important to go beyond simple identification of students'
41 incorrect ideas to understanding the underlying processes in which the incorrect ideas form and
42 the contexts in which they are prompted. Understanding such processes requires close examination
43 of the links students make between prior knowledge and their ability to use it in new contexts.
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54 Because we were interested in understanding students' abilities to link prior chemical concepts
55 and biochemical ones, we utilized Creative Exercises (Trigwell and Sleet, 1990; Lewis *et al.*, 2010)
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6 as a mechanism to probe students' abilities to make such links. Creative Exercises (CEs) are open-
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8 ended assessment tools containing a single prompt in which students must develop a response.
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10 Lewis *et al.* (2010, 2011) describe the features of CEs as follows:

- 11 ○ students develop as many distinct, correct, and relevant statements to a single prompt
- 12 ○ the instructor decides the allowable maximum number of statements for receiving credit
- 13 (e.g., in this study, students receive one point for each correct statement in a prompt, with
- 14 a maximum of five correct statements resulting full credit)
- 15 ○ In order to receive credit, student responses must be relevant to the original prompt and
- 16 distinct from other statements for which the student has received credit
- 17 ○ the instructor develops a scoring rubric with possible correct responses and a room for add-
- 18 ons for additional correct answers per student responses
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32 Given the large range of possible answers students can develop in response to a prompt, CEs
33 are considered open-ended assessment tool (Lewis *et al.*, 2010). Unlike concept maps (Francisco
34 *et al.*, 2002; Stoddart *et al.*, 2000), CEs do not require students to show a network of relationships
35 between their statements but rather to develop a number of relations pertaining to the original
36 prompt. That is, whereas concept maps are concerned with showing how concepts are connected
37 to each other, with a possible central node or nodes in which ideas branch off (Francisco *et al.*,
38 2002), CEs are mainly concerned with developing a list of concepts related to the original prompt.
39 Consequently CEs have a simpler grading scheme than concept maps. Comparison of CEs with
40 other traditional science assessments as well as examples of CEs from General Chemistry can be
41 found in Lewis *et al.* (2010, 2011). These authors also examined the validity of CEs as an
42 assessment tool and found them to be comparable to other traditional measures used to assess
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6 student achievement such as the American Chemical Society's (ACS) Standardized General
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8 Chemistry Exam and concept maps.
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10 Our chose of CEs in biochemistry was in large part influenced by the work of the Lewis group
11 (Lewis *et al.*, 2010; Ye and Lewis, 2014) on CEs in a General Chemistry classrooms. Specifically,
12 their body of work showed students made considerable interconnections between materials learned
13 within the course. Given the prerequisite knowledge of foundational chemical concepts to explain
14 biochemical problems, this work motivated us to utilize CEs as a mechanism to probe biochemistry
15 students' ability to link prior chemical concepts to biochemical ones. It was our hope that by
16 incentivizing students to link the concepts through the use of CEs, they will be able to see the
17 inherent value of chemistry as a set of linked concepts with explanatory and predictive power
18 (Taber, 2014; Ye and Lewis, 2014). Thus, the guiding research questions for the study were: 1)
19 *how often do biochemistry students link prior chemical concepts to biochemical ones in response*
20 *to CE prompts?* And, 2) *what is the nature of students' linked chemical and biochemical concepts?*
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36 **Theoretical Framework**

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39 This study is grounded in the cognitive constructivist theory of learning (Ausubel *et al.*, 1978;
40 Bodner, 1986). In the cognitive constructivist perspective, meaningful learning occurs when
41 students incorporate new knowledge into existing schemas and refine it to make sense of the new
42 information (Bodner, 1986; Mayer, 2002; Ferguson, 2007). That is, students construct their own
43 meaning of new knowledge by matching new information against existing knowledge and making
44 necessary links between the prior and the new, and evaluating and re-evaluating their
45 understanding (Ferguson, 2007). Consistent with this view of knowing and learning, CEs posit that
46 students learn best when they are able to link previously learned concepts with newly presented
47 information. Lewis *et al.* (2011) summarized CE assessment as the act of assessing students "based
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6 on their ability to connect and incorporate new course information with information that was
7 presented previously in the course” (p. 159). Thus, because of the focus of mapping new
8 information against existing knowledge in CEs, cognitive constructivism provided us a useful
9 theoretical framework to probe student use of prior chemical concepts to explain biochemical ones.
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15 16 **Study Methods**

17 18 *Setting and Data Collection*

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20 This study was conducted at a primarily undergraduate university in the Midwestern United States.
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22 During the time of data collection there were roughly 12000 attendees at this comprehensive urban
23 university, with female attendees accounting for 56% of the student body and males 44%. Unique
24 among its sister institutions, the university is home to a diverse student body (38% of the student
25 body were students of color). Reflecting this make-up, 58% of the study participants were female
26 and 42% male.
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34 We collected data for the study from upper division biochemistry classrooms ($N = 48$) that met
35 twice a week for three-hour lecture/lab per day. The course was the first undergraduate
36 biochemistry course the participants took. The required textbook for the course was Lehninger’s
37 *Principle of Biochemistry* (Nelson and Cox, 2013). However, during lecture students worked in a
38 small cooperative groups of 3-4 members using POGIL (process-oriented guided inquiry learning)
39 reform materials called BioChemActivities. Using the learning cycle approach, the material was
40 carefully designed to guide students to construct biochemical knowledge through discussion and
41 active participation. For the interested reader, Loertscher and Minderhout’s (2010) *Foundations of*
42 *Biochemistry* provides equivalent problems in a commercially available workbook. The first of the
43 BioChemActivities provided mini-review of organic chemistry concepts (e.g., functional groups,
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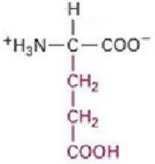
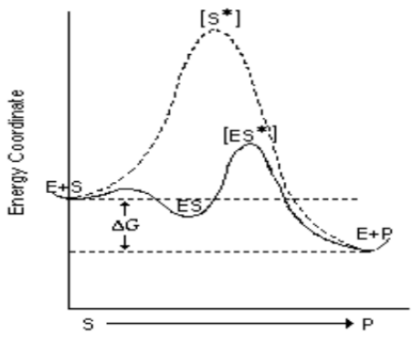
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6 polarity) and basic general chemistry concepts (acid-base concepts, solubility, etc.) during the first
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8 week of classes.
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10 We used a total of three CEs, listed in Table 1, to collect the data. The first of this, Structure
11 of Amino Acids CE, contained a single prompt showing the structure of glutamic acid. The
12 learning objectives assessed by this CE in the context of biochemistry included knowing the
13 acid/base properties of biochemical compounds; generalizing the concept of a titration to
14 biochemical measurements; identifying the type of intermolecular forces amino acids can
15 potentially form; identifying the organic functional groups present in an amino acid side chain;
16 and, knowing how protonating/deprotonating effects amino acid properties.
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27 The second CE contained a thermodynamics topic – the phosphorylation reaction of glucose
28 to glucose-6-phosphate coupled to ATP hydrolysis (Table 1). The glucose reaction is energetically
29 unfavorable while the hydrolysis of ATP is energetically favorable. The main learning objective
30 assessed by this CE, then, was for students to understand how coupling an energetically
31 unfavorable reaction to an energetically favorable one drives product formation forward. In this
32 case, students needed to generalize chemical concepts they learned in introductory courses to
33 biochemical concepts – for instance, using $\Delta G'^{\circ}$ values to predict whether a reaction is product or
34 reactant-favored, relating thermodynamic parameters to each other, identifying reaction types
35 present in the prompt, and the use of other possible foundational concepts.
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48 The third and final CE showed a reaction coordinate diagram depicting enzyme-catalyzed and
49 un-catalyzed reactions (see Table 1, enzyme kinetics CE). The learning objectives for this CE
50 included using the concept of activation energy in the context of enzyme-catalyzed reactions,
51 interpreting a reaction coordinate diagram and its elements, including any depictions of transition
52 state species, and explaining the function and purposes of catalysts such as enzymes.
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Table 1 Creative Exercises (CEs) used in the study and associated learning objectives assessed*.

Prompt Items	Generalizable Chemical Concepts to Biochemistry Assessed
i) Structure of Amino Acids CE 	<ul style="list-style-type: none"> acid-base properties of biochemical compounds Polarity, hydrophobicity Titration Intermolecular forces Organic functional groups Stereochemistry and chirality
ii) Thermodynamics CE $\text{Glucose} + \text{P}_i \rightarrow \text{glucose-6-phosphate} + \text{H}_2\text{O} \quad \Delta G'^{\circ} = 13.8 \text{ kJ/mol}$ $\text{ATP} + \text{H}_2\text{O} \rightarrow \text{ADP} + \text{P}_i \quad \Delta G'^{\circ} = -30.5 \text{ kJ/mol}$ <i>Sum:</i> $\text{Glucose} + \text{ATP} \rightarrow \text{glucose-6-phosphate} + \text{ADP}$	<ul style="list-style-type: none"> Relating thermodynamic parameters ($\Delta G'^{\circ}$, ΔG, and K_{eq}) to each other Understanding the thinking behind coupling energetically favorable and unfavorable reactions together Identifying reaction types (hydrolysis, group transfer, etc.)
iii) Enzyme Kinetics CE 	<ul style="list-style-type: none"> Using the concept of activation energy to describe catalysis Suggesting what the relationship might be between activation energy and the relative rates of the reactions depicted in the diagram Describing the purposes and function of catalysts such as enzymes Interpreting reaction coordinate diagram of un-catalyzed and enzyme-catalyzed reactions Knowing how energy diagrams provide information about the overall change in energy

*The following instructions accompanied each prompt (see Appendix A): Write as many correct, distinct, and relevant facts about [prompt shown]. Five statements will get you full credit for the problem. Recall the information you use should be information you learned in a chemistry course, including our current course. All other outside information, combined, will only count as one distinct fact towards the correct responses.

The underlying concepts in each CE were chemical ideas students learned in prerequisite foundational courses but generalized to biochemical problems – this particular biochemistry course required two semesters of general chemistry and one semester of organic chemistry as a prerequisite. For this reason we chose the specific CEs shown in Table 1 based on the extent in which they required the application of prior chemical concepts covered in the prerequisite introductory courses and not present fresh unique biochemistry concepts. To become familiar with CE expectations, students completed before data collection ensued practice CEs based on a

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6 separate concept to those for which data was collected. Only in-class CEs were used as part of the
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8 data collection as their validity is established (Lewis *et al.*, 2011). The first CE was administered
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10 as part of the first midterm exam and the second and third CEs as part of an optional 4th course
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12 exam. The lower participation numbers in CEs 2 and 3 reflects the number of students who chose
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14 not to take the exam or did not provide responses to the prompts. Before data collection ensued,
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16 the participants were informed about the purposes of the study and its voluntary nature. The human
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18 subjects' committee in our university has approved the study and consent forms were obtained
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20 from the participants.
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24 25 *Data Analysis*

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27 To analyze the data, we first used the method of Ye and Lewis (2014) and Lewis *et al.* (2011)
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29 by developing a scoring rubric for each CE such as shown in the supplementary material for the
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31 structure of amino acids CE. Once there was an agreement on the scoring rubric, we did a practice
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33 scoring session as recommended by Lewis *et al.* (2011), grading independently a set of four student
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35 responses to the structure of amino acids CE. Following the dry-run session, and upon negotiation
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37 of any differences that arose, we each graded independently a set of twenty-two student responses
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39 to the structure of amino acids CE for 100% overlap on grading and without the knowledge of the
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41 scores assigned by the other grader (see Lewis *et al.*, 2011, p161). Since inter-rater reliability based
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43 on this grading was high (Cohen's kappa, $\kappa = 0.86$) and disagreements were easily negotiated, one
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45 author (AW) scored all the remaining CEs.
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51 Once all responses were graded, we carried out thematic analysis by pooling the responses
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53 around common themes found in chemistry and biochemistry textbooks (Ye and Lewis, 2014). For
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55 example, in response to the structure of amino acids CE, statements referring to "*it [glutamic acid]*
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57 *will accept a proton; it will donate a proton*" and "*when in this form the pH is equal to its pI*" were
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6 themed together under the common chemistry topic of “acid-base concepts.” Statements directly
7 referring to titrations or buffer regions were more specifically organized under the common topic
8 of “titration.” Similarly, statements pointing out functional groups in the prompt structure or
9 invoked organic chemistry concepts such as “*there is stereochemistry*” or “*the molecule is chiral*”
10 were put under the common topic of “organic chemistry concepts.” We created the theme
11 “*Structure-Activity-Relationship*” for responses that made direct correlation between the structure
12 shown in the prompt and its function – for example, student statements such as “*when*
13 *deprotonated, its side chain can participate in ionic interactions as well as hydrogen bonding*” or
14 “*addition of another amino acids would form a peptide bond under the right conditions.*” Similar
15 thematic analysis was used for the other CEs. Responses in each CE were further coded for
16 correctness (i.e., response is correct, incorrect, or irrelevant) as described by Ye and Lewis (2014)
17 and using our scoring rubrics as guideline. Thus, tabulated data in the results’ section lists
18 emerging themes by topic and the frequency of correctness for each theme.
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36 **Results**

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39 Participant responses, organized in terms of the most to least common, as well as the frequency
40 of correct and incorrect statements in percentage is shown in Tables 2–4. Overall, our research
41 findings indicate students made considerable connections between foundational concepts in
42 chemistry and biochemical ideas. With respect to the structure of amino acids and enzyme kinetics,
43 students used various foundational concepts in response to the prompt questions whereas responses
44 to the thermodynamics CEs were confined to traditional energy topics with limited
45 interconnections with other chemical concepts. Responses to the enzyme kinetics CE revealed
46 multiple student struggles with free energy diagrams and confusions about the relationship
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6 between energy, equilibrium, and kinetics. Specific findings in response to each CE are detailed
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8 in the following sub-sections.

10 *The Structure of Amino Acids CE*

11 A total of 48 students completed the structure of amino acids CE. Their responses fell into one
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13 of seven broad themes based on the chemical concepts present in the responses. The themes and
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15 the frequency in which they occurred, summarized in Table 2, were: i) use of acid-base concepts
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17 ($N = 39$), ii) compound classification ($N = 36$), iii) structure identification ($N = 31$), iv) use of
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19 organic chemistry concepts ($N = 26$), v) structure activity relationship ($N = 19$), vi) titration ($N =$
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21 6), or vii) use of structure specific information ($N = 46$). Findings within each theme is further
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23 described below.

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28 The most common student response in this CE, mentioned by 39 students, used foundational
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30 concepts in acid-base chemistry to describe the structure of glutamic acid. Specific references
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32 included statements indicating the prompt structure can lose or accept proton(s) or that the pH of
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34 the shown structure will be equal to its pI (isoelectric point) in the form shown (see Table 2 for
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36 actual student responses). Some students drew the ionization steps of the compound, as shown in
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38 Figure 1, or mathematically calculated the pI value of the structure. Others indicated the molecule
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40 is in zwitterion form, with only one students erroneously indicating the structure has an overall
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42 charge of +2. That is, in the responses included in the acid-base theme, students touched upon the
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44 concepts of pH/pKa, pI, and used various terms associated with acid-base chemistry such as
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46 ionization, protonation and deprotonation. This indicates that, when incentivized to do so, students
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48 use foundational concepts in chemistry to describe biochemical molecules. Unsurprisingly, student
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50 responses tended to rely on current context and concepts, often commenting on the pH-charge
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52 relationships of the shown structure. Nevertheless, students referred continuously to foundational
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54 acid-base concepts such as the ability of the molecule to accept or donate a proton or the
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relationship between the pH of the structure and its pK_a . Moreover, as can be seen in Table 2, six students specifically described the titration behavior of the prompt structure. Students made comments such as “*there will be 3 bumps on the titration curve of this amino acid*” or “*It’s titration curve has three buffer regions,*” This suggests students were using foundational concepts in chemistry to describe biomolecule structure and chemical behavior.

Table 2 Themes used in the structure of amino acids CE ($N = 48$; *italics = actual student response*)

Theme	Sample Responses	Number Selecting Response (%)	Percent Correct (%)	Percent incorrect (%)
Acid-base concepts	i) “ <i>when in this form the pH is equal to its pI</i> ” ii) “ <i>It can lose two more protons (H^+); it can gain a proton on the C-terminus end</i> ” iii) “ <i>during ionization, COOH will deprotonate first as its pKa will always be smaller than NH_3^+</i> ”	39 (81.3%)	97.4%	2.6%
Compound classification	i) “ <i>It is a polar molecule</i> ” ii) “ <i>this is classified as acidic due to the COOH group in its side chain</i> ” iii) “ <i>polar, acidic amino acid</i> ”	36 (75.0%)	91.7%	8.3%
Structure identification	i) “ <i>This is glutamic acid</i> ” ii) “ <i>It is an amino acid</i> ”	31 (64.6%)	96.8%	3.2%
Organic chemistry concepts	i) “ <i>it is chiral [molecule]</i> ” ii) “ <i>It has carboxylic acid functional group</i> ”	26 (54.2%)	100%	0.0%
Structure activity relationship	i) “ <i>[it] can H-bond, giving it stronger force</i> ” ii) “ <i>when deprotonated, it’s side chain can participate in ionic interactions ...</i> ” iii) “ <i>it can peptide bond to form a protein</i> ”	19 (39.6%)	78.9%	10.5%
Titration*	i) “ <i>It’s titration curve has 3 buffer regions</i> ” ii) “ <i>There are 3 ‘bumps’ on the titration curve for this amino acid</i> ”	6 (12.5%)	-	-
Structure-specific information*	i) “ <i>The N-terminus is NH_3^+; the C-terminus is COO^-</i> ”	4 (8.3%)	-	-

*Given the small number of responses in these case, the frequency of correct and incorrect statements were not tabulated.

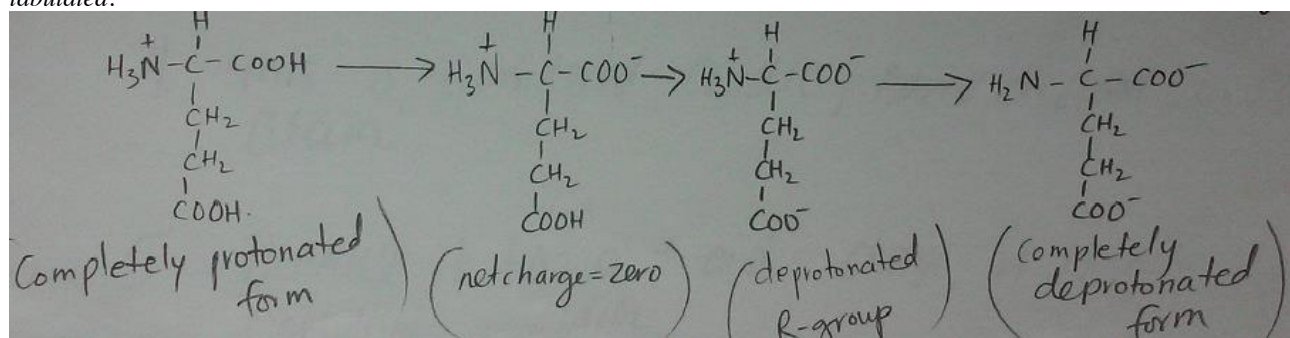
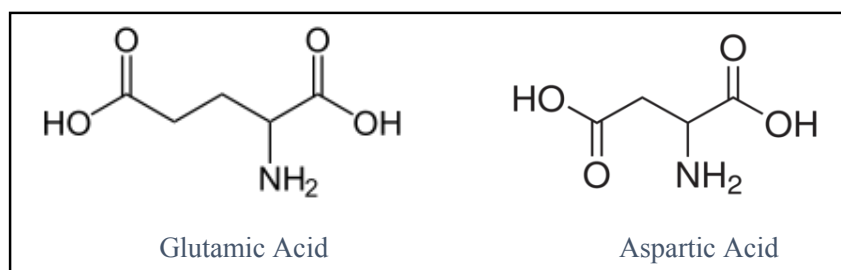


Fig. 1 Sample student drawing showing ionization steps of glutamic acid

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6 In the classification theme, 36 students ($N = 36$, Table 2) stated the molecule is polar or “*this*
7 *is acidic amino acid*.” Some justified their claim by further stating that the structure shown is acidic
8 due to the carboxyl group present in the side chain. We note this reflects material coverage in the
9 course – students engaged early in the semester activities that tasked them to classify the naturally
10 occurring twenty amino acids into polar, nonpolar, acidic or basic depending on the chemical
11 properties of their side chains. Thus, the focus on “*this is polar*” or “*this is acidic amino acid*” is
12 contextualized response. Three students incorrectly classified the structure as nonpolar, basic, and
13 hydrophobic respectively. When not classifying the amino acid as a polar or acidic, students simply
14 identified the shown structure as that of glutamic acid or simply stated “*this is an amino acid*.”
15 Responses from thirty-one students fit into the structure identification theme (see Table 2). Only
16 one student misidentified the shown structure as that of aspartic acid (2.1%, Table 2), a reasonable
17 mistake given that glutamic acid and aspartic acid differ only by one-methylene group (see Figure
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46 **Fig. 2** Comparison of the structures of glutamic acid and aspartic acid.

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Twenty-six students used organic chemistry insights in their response. These responses invoked stereochemistry, chirality and presence of carboxylic acid and amino functional groups to describe the prompt structure. Some commented on how the pK_a s of the carboxyl moieties would be lower than that of the amino group; others noted the resonance features of the carboxyl functional groups. There was uniformity in students' use of organic chemistry insights, with most

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6 noting the different functional groups present in glutamic acid and few using chirality and other
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8 organic concepts in their response. The students were therefore, in our view, linking concepts
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10 covered in prerequisite courses to the prompt question or at least able to mention such concepts
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12 when prompted to do so.

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15 Interestingly 19 students (Table 2) made direct correlation between the structure of glutamic
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17 acid and its function. We pooled such responses under the broad theme of Structure-Activity-
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19 Relationship, exemplified by the sample responses shown in Table 2. In one such response, a
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21 student wrote “*when deprotonated, its [glutamic acid] side chain can participate in ionic*
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23 *interactions as well as hydrogen bonding.*” Others mentioned that the structure would be water
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25 soluble, making connection between the shown structure and its chemical behavior in aqueous
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27 solutions. Another student wrote that “*if this amino acid were to be put into a pH that is bigger*
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29 *than its pKa, it would deprotonate; if this amino acid was placed into a solution with pH less than*
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31 *its pKa (acidic solution), it would be unaffected.*” This particular student is attempting to describe
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33 how the net charge of molecules with ionizable functional groups is dependent on pH conditions,
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35 with different net molecule charges expected at high pH vs. low pH. This response illustrates how
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37 students were attempting to make a generalization about when a structure is protonated,
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39 deprotonated, or remains unaffected by changes in the pH. The other responses illustrate student
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41 attempts to make connection between the structure and its ability to form hydrogen bonds, peptide
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43 bonds, or participate in electrostatic interactions. Two students incorrectly stated the structure is
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45 not soluble in aqueous environment or that it cannot hydrogen bond.

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48 Finally, in response to the structure of amino acids CE, a smaller number of students ($N = 4$,
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50 Table 2) provided structure-specific information that either labeled the N-terminus and the C-
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52 terminus of the structure or stated so – for example by writing the H_3N^+ would be the N-terminus
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6 and the COOH the C-terminus. While three of the four students invoked N-terminus and C-
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8 terminus language, the remaining student in this group simply wrote “covalent bond.” With respect
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10 to this theme, we caution making any claims based on the shown responses given the small number
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12 of students who invoked these ideas (4 and 6).

13 14 15 16 *Thermodynamics CE*

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18 Responses (($N = 28$) to the thermodynamics CE fell into one of five themes as summarized in
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20 Table 3. Three of the five represented traditional thermodynamic concepts of free energy, entropy
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22 and spontaneity and equilibrium. The exception were contextualized responses that described
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24 reaction types or mentioned how the reactions were part of the glycolysis pathway. There was no
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26 evidence in the responses on attempts to link the thermodynamic concepts to other foundational
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28 concepts in chemistry, as was the case with the structure of amino acids CE.

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32 Not surprisingly the most common response, mentioned by 26 students, featured free energy
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34 concepts (Table 3). All calculated correctly the ΔG° for the coupled reaction as -16.7 kJ/mol
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36 except one student who incorrectly calculated it to be $+16.7$ kJ/mol and subsequently concluded
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38 “*the reaction is nonspontaneous.*” This suggests most students correctly understand the
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40 conventional signs of ΔG° and how it is used to predict reaction spontaneity. Similarly, students
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42 related the ΔG° value to other thermodynamic values, e.g., by calculating the value of K_{eq} , and
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44 made statements such as “*it uses exergonic reaction to drive endergonic reaction*” or simply “*this*
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46 *reaction is exergonic.*” Only one student mentioned entropy as part of their response, stating “*an*
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48 *increase in entropy occurs as a result of this reaction.*”

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53 Twenty-two students invoked spontaneity and equilibrium principles. Within this theme, most
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55 indicated the overall reaction will be spontaneous or that the coupled reaction proceeds forward
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57 and favors product formation. One student wrote “ *$+\Delta G^\circ$ value of glucose + Pi \rightarrow glucose-6-*

phosphate + H₂O indicates the product is favored; when both reactions are coupled together, we get a $-\Delta G^\circ$ value (reactants favored),” correctly noting the conventional signs in ΔG° but incorrectly using them to describe reaction equilibrium and directionality. Most used equilibrium in conjunction with spontaneity by, for example, mentioning in their responses the reaction is spontaneous and subsequently stating the coupled reaction will proceed forward and favor product formation (see Table 3 for sample student responses).

Table 3 Themes used with the thermodynamics CE ($N = 28$)

Theme	Sample Responses	Number Selecting Response (%)	Percent Correct (%)	Percent incorrect (%)
Free energy	i) “ ΔG° for coupled reaction is -16.7 kJ/mol” ii) “ $\Delta G^\circ = -RT \ln K_{eq}$; “ $\Delta G^\circ = -16.7$; $K_{eq} = 845.27$ ” iii) “This reaction is exergonic” iv) “It uses exergonic reaction to drive an endergonic reaction” v) “ ΔG is Gibbs free energy”	26 (92.9%)	96.0%	4.0%
Spontaneity and equilibrium	i) “Since ΔG° is negative, the reaction will be spontaneous” ii) “The hydrolysis of ATP is spontaneous” iii) “The coupled reaction proceeds forward and favors the products” iv) “ K_{eq} for the ATP (reaction) and the coupled reaction is > 1 ”	22 (78.6%)	95.0%	5.0%
Reaction types	i) “The first reaction is a group transfer; the second reaction is hydrolysis” ii) “This is group transfer”	17 (60.7%)	76.5%	23.5%
Glycolysis	i) “First step of glycolysis” ii) “This is the rate-limiting step in glycolysis”	14 (50.0%)	100%	0.0%
Entropy*	i) “An increase in entropy occurs as a result of this reaction”	1 (3.6%)	-	-

*Given the small number of responses in this case, the frequency of correct and incorrect statements were not tabulated.

The remaining student responses to the thermodynamic CEs were contextualized to the particulates of their current course. Seventeen students identified the reaction types involved in the coupled reaction. Of these, 13 students correctly identified the phosphorylation of glucose to glucose-6-phosphate as group transfer reaction and the second reaction as that of ATP hydrolysis,

reflecting the emphasis of many biochemistry textbooks and instructors on the transfer of the phosphate group from ATP to glucose with little attention paid to the ester synthesis mechanism of the coupled reaction. Four students thought the coupled reaction involved oxidation-reduction, most likely misapplying memorized algorithms (Nyachwaya *et al.*, 2014). Half of the student respondents ($N = 28$) noted the reaction of glucose to glucose-6-phosphate constitutes the first step of the glycolysis pathway, with some mentioning that this is a rate-determining step for this pathway. From our perspective, the responses on reaction types and responses mentioning glycolysis reflect localized information recall and are not significant to the students' conceptual understanding or linking of chemical concepts to biochemical ones.

Enzyme Kinetics CE

The enzyme kinetics CE resulted the most variation among the responses. Of 25 students who completed the CE, 20 invoked activation energy in their response. Students made statements such “*the activation energy is lower with enzyme,*” and “*the non-catalyzed reaction is exergonic but has higher activation energy*” (see Table 4). We infer from the high percentage of students who invoked activation energy in their response as evidence that students understand the ability of enzyme catalysts to enhance reaction rates by lowering the activation energy. Given that students did not mention transition state theory in their response and there was no opportunity for follow-up questions, it was not possible to ascertain if students had a deeper level understanding of the mechanism by which the energy of transition state is lowered via enzyme catalysis.

Table 4 Themes used with the enzyme kinetics CE ($N = 25$)

Theme	Sample Responses	Number Selecting Response (%)	Percent Correct (%)	Percent incorrect (%)
Activation energy	i) “ <i>the activation energy is lower with enzyme</i> ” ii) “ <i>The non-catalyzed reaction is exergonic but has high activation energy</i> ”	20 (80.0%)	100.0%	0.0%

	iii) <i>"The enzyme lowers the activation energy required to form the product"</i>			
Free energy	i) <i>"This reaction has a negative ΔG and releases energy"</i> ii) <i>"This reaction is exothermic; energy is released"</i> iii) <i>"ΔG is the same for both reactions"</i> iv) <i>"ΔG is negative since E+S starts at a higher energy than E+P end up"</i>	19 (76.0%)	100.0%	0.0%
Catalysis	i) <i>"The enzyme is the catalyst"</i> ii) <i>"Reaction progresses much easier with enzyme present"</i> iii) <i>"Substrate can react w/ or w/o enzyme"</i>	12 (48.0%)	100.0%	0.0%
Visual Representation	i) <i>"The solid line is a reaction that is much more favorable considering the ΔG that is presented between the dashed horizontal lines"</i> ii) <i>"this appears to show noncompetitive inhibition"</i> iii) <i>"This reaction is a competitive inhibition."</i>	12 (48.0%)	50.0%	50.0%
Kinetics	i) <i>"with an enzyme, this reaction will proceed much faster"</i> ii) <i>"The enzyme increases the rate of the reaction"</i> iii) <i>"reaction is slower without enzyme"</i> iv) <i>"The rate-limiting step of the catalyzed reaction is the formation of [ES*]"</i>	10 (40.01%)	90.0%	10.0%
Chemical* Equilibrium	i) <i>"This reaction proceeds forward and favors products"</i> ii) <i>"Product is favored in the reaction"</i>	3 (12.0%)	-	-
Entropy*	i) <i>"The products are more disordered than the reactions"</i>	1 (3.6%)	-	-

*Given the small number of responses in these cases, the frequency of correct and incorrect statements were not tabulated.

Of ten students who invoked kinetics in their response, 9 correctly made a link between reaction rates and the function of enzymes (see Table 4). Students made statements such as *"reaction is slower without enzyme"* or *"the enzyme increases the rate of the reaction."* Moreover, almost half of those who completed this CE ($N = 12$, Table 4) noted the enzyme was the catalyst, making statements such as *"substrate can react with or without the enzyme"* or *"the enzyme is the catalyst."* A smaller number (3 students) invoked chemical equilibrium principles by stating that the reaction will proceed forward and favor product formation. One student mistook kinetics for equilibrium, stating *"it will take less time for the reaction with the enzyme to hit equilibrium."*

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6 Similar to the thermodynamic CE, most students ($N = 19$, Table 4) made links to free energy
7 concepts. For example, students made statements such as “*this reaction is exothermic; energy is*
8 *released*” or “*this reaction has a negative ΔG and releases energy.*” Others noted that ΔG is the
9 same for the enzyme-catalyzed and non-catalyzed reactions. However, the most problematic
10 responses to the enzyme kinetics CE were student struggles when directly attempting to describe
11 the free-energy diagram. We grouped 12 student responses under the theme of visual
12 representations based on student attempts to interpret information contained in the free energy
13 diagram (see Table 4), with six of the twelve incorrectly interpreting the diagram. Two thought
14 the diagram represented enzyme inhibition plots, stating “*this appears to show noncompetitive*
15 *inhibition*” and “*this reaction is a competitive inhibition.*” This finding seems to suggest some
16 students rely on memorized shapes of graphical data rather than localized concepts in the diagrams.
17 That is, from our perspective, the data doesn’t seem to suggest students struggled with interpreting
18 the graph but rather used memorized graphical sketches to interpret the given data, hence the
19 misapplication of enzyme inhibition plots for a free energy diagram. Further exploration of student
20 reasoning and the processes they used to interpret the graphical data will require in-depth data
21 based on interviews or other sources.
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43 Discussion

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46 The main purpose of this study was to examine how often students in an upper-division
47 undergraduate biochemistry course linked prior chemical concepts to biochemical ones in response
48 to CE prompts. Tables 2–4 provide the number of students who made these links as well as sample
49 of their responses. The data provided in these tables indicates students were successful in most
50 part in linking foundational concepts to biochemical problems. For example, the students made
51 links between the structure of glutamic acid (the prompt structure) and the acid-base concepts of
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pH/pKa, pI, titration, ionization steps and pH-charge relationships. Likewise, participants listed concepts of stereochemistry, chirality, and organic functional groups as relevant facts for the structure of glutamic acid. The thermodynamics CE similarly promoted students to link thermodynamic-related topics to each other though unsuccessful in facilitating links to other foundational concepts in chemistry. We observed similar findings with respect to the enzyme kinetics CE – students invoked free-energy, catalysis, kinetics, and equilibrium principles as relevant facts for the enzyme kinetics prompt. In our view, these findings suggest students are able to make links to foundational concepts when incentivized to do so and appropriate contexts for linking the ideas are presented to them.

The wide range of prior chemical concepts students listed as relevant facts for the biochemically situated problems suggests CEs are appropriate facilitative tools to promote students' linking of relevant concepts within or across courses. Furthermore, we agree with the Lewis group that student efforts to link concepts in response to the open-ended prompt questions in the CEs suggests the "*connections displayed are of the students' choosing and not an artificial contrivance to address a particular, targeted question*" (Ye and Lewis, 2014, p. 581). Moreover, given students in this study previously completed a year of general college chemistry and at least one semester of introductory organic chemistry, and thus were utilizing prior knowledge, we make the claim that CEs can facilitate students' conceptions of chemical ideas as interrelated and with explanatory power (Taber, 2014). Admittedly, for this claim to materialize, much will depend on how instructors utilize CEs as a facilitative learning tool to help students make the necessary links.

We note the results from our thermodynamics CE differs from the findings reported by Ye and Lewis (2014). In their study, participants were able to link the topics of stoichiometry, solution chemistry, compound classification, gas laws, atomic structure and thermodynamic-related topics

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6 with a thermodynamics prompt. Here, our students did not form such links. The differential
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9 outcome in the two studies is attributable to the nature of information provided in each prompt.
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11 While both CEs provided students with chemical reaction prompts (the dissociation of solid iron
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13 (II) chloride, FeCl_2 , in water in the Ye-Lewis study vs. the ATP-driven phosphorylation of glucose
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15 to glucose-6-phosphate in this study), different information was provided to the students in each
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17 CE – we provided only ΔG^0 values in our case whereas amounts of reactant and water, initial water
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19 temperature, and heats of formation (H_f) values were provided in the Ye-Lewis thermodynamics
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21 prompt (Ye and Lewis, 2014). Thus, the information provided in each CE differentially prompted
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23 students to make certain links with prior concepts or concepts learned within the course. That is,
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25 to use the language advanced by Hammer *et al.* (2005), the nature of the CE prompts *activated*
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27 certain knowledge resources in which each student population used to make links. In their study,
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29 Hammer *et al.* (2005) speak of context-sensitive *activation* of knowledge resources, e.g. prior
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31 conceptions students hold, in which learner's understanding of the phenomenon under study
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33 emerges. This suggests we need to pay close attention to contexts within the CEs that can promote
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35 students' link-making processes and ways to activate students' use of desired knowledge
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37 resources. This view is consistent with the notion of learners drawing upon their cognitive
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39 structures and combining the knowledge resources available to them in new ways so as to make
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41 sense of the information presented to them (Taber and Garcí'a-Franco, 2010).
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48 One of the findings in our study suggests some students confused free-energy diagrams with
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50 enzyme inhibition plots (see Table 4). Student struggles with visual representation in biochemistry
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52 is well documented in the literature (see Schönborn and Anderson, 2009, 2010; Linenberger and
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54 Bretz, 2012; Loertscher *et al.*, 2014; Wolfson *et al.*, 2014). However, findings in this study lead
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56 us to believe the faulty linking of enzyme inhibition plots with free-energy diagrams suggests there
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6 are underlying reasoning processes students utilize that cannot be explained by inability to interpret
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8 visual data. In the chemical education literature, it is known that students rely on memorized
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10 processes and ideas when balancing and describing chemical reaction equations, often incorrectly
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12 using the memorized algorithms (Nyachwaya *et al.*, 2014). We contend similar reasoning
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14 processes is at play here. Ascertaining whether our explanation is valid will require follow-up
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16 study in which students are interviewed in-depth about their reasoning or the use of other sources
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18 to probe their underlying reasoning processes for the observed behavior.
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22 23 **Implications for Research and Teaching** 24

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26 In chemistry and biochemistry, much effort has gone into developing instructional materials that
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28 help students overcome incorrect ideas or alternate conceptions/misconception – defined as those
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30 ideas/concepts that students held but are inconsistent with scientifically accepted explanations
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32 (Villafane *et al.* 2011a,b; Wolfson *et al.*, 2014). For instance, Villafane *et al.* (2011a) developed
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34 twenty-one multiple-choice diagnostic instrument to identify students' incorrect ideas prior to
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36 biochemistry instruction, with the goal of aiding faculty make targeted changes in instruction to
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38 address problematic areas. In addition to addressing students' pre-existing alternate ideas, there is
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40 also a need to focus on their emerging alternative ideas during biochemistry instruction as was the
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42 case in this study when students invoked enzyme inhibition plots to describe a free-energy diagram
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44 (see Table 4). Given the ubiquitousness of free-energy diagrams in introductory chemistry courses,
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46 it is reasonable to assume students who had a year and half of such courses would recognize these
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48 diagrams at will, yet the data revealed students erroneously thought the diagrams represented
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50 competitive or non-competitive enzyme inhibition plots. Wolfson *et al.* (2014) similarly reported
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52 that some of their students confused free-energy diagrams with electron transport or titration
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54 curves. We suspect the student mix-up of enzyme inhibition plots with free-energy diagrams is
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6 due to their over-activation of the knowledge resources available to them (multiple graphical
7 sketches which when activated some misapply) (Hammer *et al.*, 2005). Ascertaining this
8 hypothesis will require more extensive data collection in the future.
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13 The implication of the aforementioned discussion for biochemistry instruction is quite evident
14 – there is a need to focus attention on misconceptions/alternate conceptions that emerge during
15 biochemistry instruction. It is unlikely students came across enzyme inhibition plots or electron
16 transport before receiving biochemistry instruction. The misapplication of these plots suggests the
17 need for a model that accounts for the emergence of alternate conceptions/misconception in real
18 time. Consequently, knowledge learned in prerequisite courses such as free-energy concepts
19 should facilitate the (re)learning of that concept or related concepts in new contexts such as
20 biochemistry. We thus recommend the use of CE-like prompts as facilitative tools in instruction
21 to assist in the relearning of concepts in new contexts and dealing with incorrect ideas as they
22 emerge during instruction rather than confronting them as unitary concepts brought from previous
23 courses.
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39 On similar grounds, we note chemical educators often assume student difficulties in upper
40 division courses such as biochemistry stem from inability to transfer previously learned knowledge
41 into new contexts (Loertscher, *et al.*, 2014; Wolfson *et al.*, 2014). The findings reported in this
42 paper suggest participants were able to provide a varied list of foundational concepts in chemistry
43 as relevant facts for biochemically situated problems. Ye and Lewis (2014) similarly reported
44 students' linking of various chemical concepts presented in a General College Chemistry
45 classroom to each other. In our interpretation, this seems to suggest students can link prior and
46 newly learned concepts when primed to do so. Thus the interaction of the mind and context appear
47 to be an essential component of the knowledge construction process (Hammer *et al.*, 2005; Taber
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6 and Garcí'a-Franco, 2010). We therefore think the focus on transfer inability of prior concepts to
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8 new contexts may be misplaced. Rather, we argue for the need for research that examines how
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10 concepts learned in one context, such as thermodynamics in introductory courses, can facilitate the
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12 (re)learning of that concept in a different context such as in biochemistry.
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15 To be clear, we do not claim students' listing of relevant ideas/facts in response to CE prompts
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17 constitute evidence for deep or meaningful learning. Reaching such a conclusion would require
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19 further probing of individual students via in-depth clinical or think-aloud interviews to ascertain
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21 their understanding of the underlying principles of the concepts that the students are learning, e.g.
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23 thermodynamics. We note, for example, in focus group interviews as part of threshold concepts
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25 study in biochemistry, Loertscher and colleagues reported some of their students "*had superficial,*
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27 *memorized, or incorrect understanding of the physical basis of noncovalent interactions such as*
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29 *hydrogen bonds, dipole–dipole interactions, and van der Waals interactions*" (Loertscher *et al.*,
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31 2014, p. 522). That is, the students could name the interaction but failed during the interviews to
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33 provide the electrostatic basis of such interactions. Thus, the mere linking of ideas to each other or
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35 listing of related facts to a given prompt, while evidence for students' ability to link such ideas,
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37 does not of itself constitute evidence for meaningful learning.
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43 However, as an alternative to the transfer inability reasoning for noted student difficulties, we
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45 find the views of Hammer *et al.* (2005) and their construct of "*resource activation*" as a more
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47 appealing framework to theorize why certain students fail to utilize chemical knowledge they
48
49 already possess in biochemical contexts. Because individual learner's conceptual knowledge
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51 organization is influenced greatly by the context in which the pieces of knowledge they held is
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53 activated, as noted by Taber and Garcí'a-Franco (2010) and Maeyer and Talanquer (2010), it is
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55 likely the instructional approaches fail subsequent reactivation of existing resources. We suggest
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6 CE-like prompts can be used as a useful tool to activate certain knowledge resources and research
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8 the effects of (re)learning prior chemical concepts in the biochemical context.
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10 **Study Limitations and Future Work**

11 The findings reported in this paper came from a single institution and involved a smaller number
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13 of study participants and might not necessarily be representative of all biochemistry students. As
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15 pointed out to us by a reviewer, a “representative sample” would ideally involve different
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17 institutions or trajectories to make durable claims about the prevalence of ideas. Thus, in the
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19 absence of such data, one should be cautious with generalizations. As part of our ongoing research,
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21 we plan to solicit data from different institutions and students to further examine our hypothesis in
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23 a representative sample of all biochemistry students. A second limitation of our study is that
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25 students were instructed to use ideas from chemistry courses and this narrow focus was in line
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27 with our specific goal of examining the links students make between chemical and biochemical
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29 ideas. However, as interdisciplinary subject, biochemistry draws on science content beyond what
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31 is taught in general and organic chemistry. Thirdly, during data analysis, only one author (AW)
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33 scored the second and the third CEs following high inter-rater agreement on the first CE. This
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35 might represent a methodological limitation. A fourth limitations is related to student participation
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37 in exam four. Because this exam was optional (students had the opportunity to drop the lowest
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39 exam score), there is a greater likelihood of low-performing students oversampled. While we note
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41 that non-participants included both students with comparatively low exam scores and students with
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43 high exam scores, nevertheless the likelihood of oversampling low-performing students affects
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45 data interpretation with respect to CEs two and three. Finally, our study design does not permit us
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47 to make claims about the durability of the links student make in response to the CE prompts. We
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49 aim to address this limitation in our future work.
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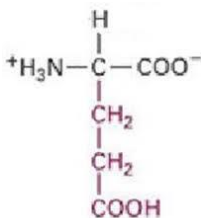
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Appendix A: Structure of Amino Acids CE Prompt and Grading Rubric

Prompt and instructions to students

Write down as many **correct, distinct, and relevant facts** you can about:



Five statements will get you full credit for the problem. Recall the information you use should be information you learned in a chemistry course, including our current course. All other outside information, combined, will only count as one distinct fact towards the correct responses.

Guiding Scoring Rubric – Any five of the following possible statements result full credit

- This is an amino acid [*not distinct*: this is Glutamic acid, aka glutamate, Glu, E)
- Any indication of molecule polarity
- Classification as an acidic amino acid [possible mentioning of carboxyl group side chain]
- Any mentioning of organic functional groups present in structure ($-\text{COOH}$, $-\text{NH}_2$)
- Mentioning of chiral center, stereochemistry
- Any indication of the overall net charge of the compound (*i.e.* it's zwitterionic form/has net charge of zero/normal physiological form, etc.).
- Titration curve shows three buffer regions.
- There are three ionizable groups (protonated vs. deprotonated groups).
- Mentioning of protonation-deprotonation
- Correct drawing of ionization steps
- Listing of any pKa values (e.g., $\text{pK}_{\text{a}1} = 2.2$, $\text{pK}_{\text{a}2} = 4.3$, $\text{pK}_{\text{a}3} = 9.6$)
- pI calculation ($\text{pI} = (2.19+4.25) = 3.22$)
- Calculations of molar mass ($M_r = 147.13 \text{ g/mol}$)
- Structure activity relationships, e.g.:
 - a. References for ability to peptide bonds
 - b. References to H-bonding or participation in ionic interactions
 - c. Water solubility of the compound as a result of structure properties
 - d. Participation in protein structure
 - e. Etc.

Appendix B: Sample student responses and grading notes

Following the method of Lewis *et al.* (2011), each student response is reported in verbatim, except for statement numbering when a student did not provide one. Following each response is a quick note on how we graded the student response and thematic analysis of the student responses. The appendix provides samples from seven students whose credit in responses to structure of amino acids CE ranged from 5–2 out of possible maximum 5 points. The spectrum is provided to illustrate the varied nature of student responses.

Students A and B – Sample student response that received 4/5 credit points out of 5

Pat I - Student Responses and Grading Notes

Statement	Student A	Student B
1.	Has carboxylic acid functional group	This is in its zwitterion form
2.	acidic and charged molecule	It has a carboxyl group
3.	molecule can deprotonate & protonate	It is an amino acid
4.	amino acid can peptide bond to form a protein	It will have 3 buffer zone
5.	molecule can hydrogen bond	It can form a peptide with another copy of it self

Grading Notes:

Student A received credit for four statements as follows:

- The student received credit for statement 1 for pointing the carboxyl functional group
- The student received credit for statement 2 for classifying the compound as acidic/charged
- The student received credit in statement 3 for listing protonation-deprotonation properties
- Per the scoring guidelines, student received credit for statements 4 but not 5 owing to the distinct criteria

Student B received credit for five statements as follows:

- The student received credit for statement 1 for pointing out the overall charge of the compound
- The student received credit for statement 2 for pointing out the organic functional group present
- The student also received credit for statement 3 for identifying the structure as that of an amino acid
- The student received credit for statement 4 for pointing out the buffer regions upon titration
- And finally, student B received credit for statement 5 for invoking structure activity relationship

Pat II - Thematic Analysis of Student A's Response

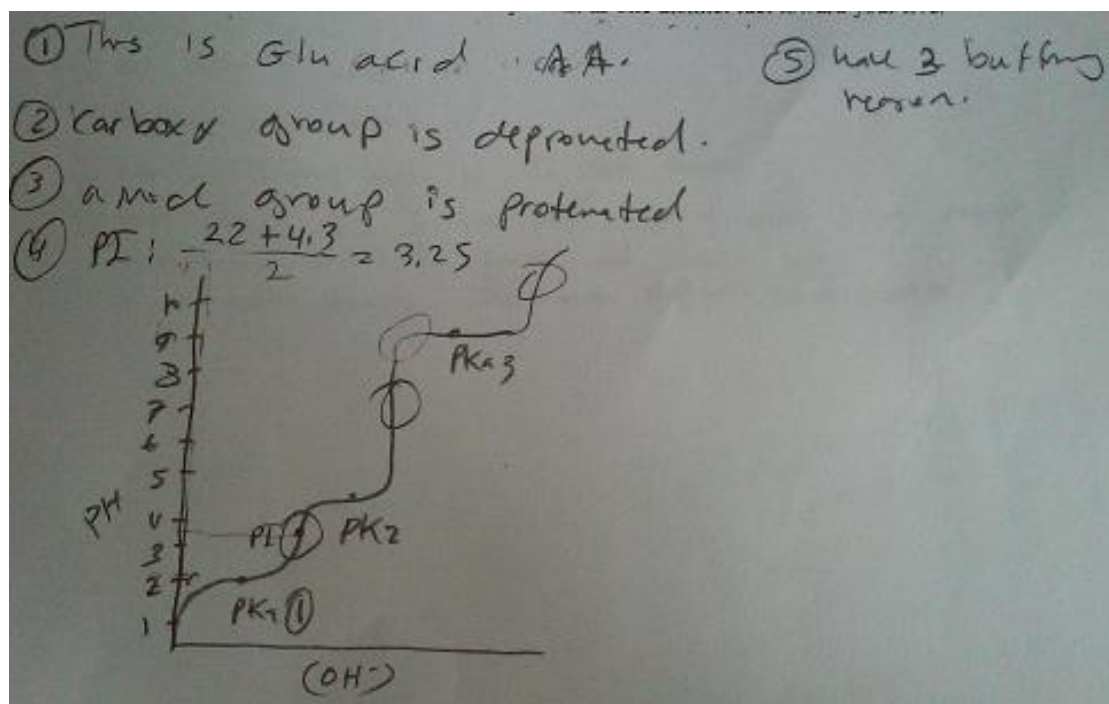
- Student A statements 1 was coded as *organic chemistry concepts* for listing organic functional group.
- Student A's statement 2 classified the shown structure as acidic and charged molecule and was codes as *compound classification*.
- Student A's statement 3 was codes as *acid-base* since students deal with protonation/deprotonation during acid-base chemistry
- Student A's statements 4 and 5 were coded as *structure-activity-relationship* since the student predicted the behavior of the shown structure – the ability to peptide bond to form proteins and participate in intermolecular forces (H-bonding).

Thus,

- Responses by student A are featured under the four themes of 1) organic chemistry concepts, 2) acid-base concepts, 3) compound classification, and 4) structure-activity-relationship.
- Responses by student B are featured under the five themes of 1) acid-base concepts, 2) organic chemistry concepts, 3) structure identification, 4) titration, and 3) structure activity relationships.

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8 **Student C – Sample response that received 4 credit points out of 5**

9 **Pat I - Student C's Response and Grading Notes**



34 **Fig. 1S** Response to the structure of amino acids CE by Student C

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36 **Grading Notes:**

37 Student C received credit for four statements as follows:

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- The student received credit for statement 1 for identifying the structure shown in the prompt as that of glutamic acid
 - Per the scoring guidelines, student received credit point for statements 2 but not 3 owing to the distinct criteria – both invoke protonation-deprotonation.
 - The student also received credit for calculating the pI in statement 4.
 - Similarly, student received credit in statement 5 for invoking buffering regions in the titration curve.

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49 **Pat II - Thematic Analysis of Student C's Response**

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- Statement 1 was coded as structure identification – identifies structure shown in the prompt
 - Because statements 2-4 deal with topics often dealt with in acid-base chemistry (protonation-deprotonation, pH/pI), they were coded as acid-base concepts
 - We made a separate category for statements such as statement 5 that specifically invoked titration concepts, consequently this statement was coded as titration.

57 Thus, the responses by student C are featured under the three themes of 1) structure
58 identification, 2) acid-base concepts, and 3) titration.
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 **Students D and E – Sample student responses that received 3 credit points out of 5**

Pat I - Student Responses and Grading Notes

Statement	Student D	Student E
1.	It is in zwitterionic form	This is a polar amino acid
2.	This is the form it would be in under normal physiological conditions	This is an acidic amino acid
3.	This is polar acidic amino acid	This is written at physiological pH
4.	The amino group is protonated and the carboxyl group is deprotonated	This is zwitterion
5.	It has a net charge of 0	There are 3 “bumps” on the titration curve for this amino acid

Grading Notes:

Student D received credit for three statements as follows:

- Per the scoring guidelines, the student received credit for statement 1 but not 2 and 5 owing to the distinct criteria – all three describe the overall net charge of the compound.
- The student received credit for statement 3 for classifying the structure as polar and acidic.
- The student also received credit for statement 4 for mentioning protonation/deprotonation.

Student E received credit for three statements as follows:

- Per the scoring guidelines, the student received credit for statement 1 but not 2 owing to the distinct criteria – both statements classify the prompt structure as polar and acidic
- Similarly, the student received credit for statement 3 but not 4 since both describe the overall charge of the compound.
- The student also received credit for statement 5 for specific references to titration curve.

Pat II - Thematic Analysis of Student Responses

- Because student D’s statements 1, 2, 4, and 5 invoke topics often dealt with in acid-base chemistry (zwitterion form/net charge and protonation/deprotonation), these statements were coded as acid-base concepts
- Student D’s statement 4 was coded as compound classification – classifies prompt structure as polar and acidic
- Student E’s statements 1 and 2 were coded as compound classification – both classify the prompt structure as polar and acidic
- Because student E’s statements 3 and 4 invoke topics often dealt with in acid-base chemistry (zwitterion form and structure form at physiological pH), these statements were coded as acid-base concepts
- Student D’s statement 5 was coded as titration – given the number of students who specifically mentioned titration, we created the separate code of “titration” for such statements

Thus,

- Responses by student D are featured under the two themes of 1) acid-base concepts and 2) compound classification, and
- Responses by student E are featured under the three themes of 1) acid-base concepts, 2) compound classification, and 3) titration.

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6 **Students F and G – Sample student responses that received 2 credit points out of 5**

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8 **Pat I - Student Responses and Grading Notes**

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Statement	Student F	Student G
1. 2 carboxyl groups		This is in zwitterion form
2. 1 amino group		This is physiologically neutral
3. amino acid		This is polar
4. hydrophobic		This is acidic
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18 ***Grading Notes:***

19 ***Student F received credit for two statements as follows:***

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- Note, this student listed only four statements
 - Per the scoring guidelines, the student received credit for statement 1 but not 2 owing to the distinct criteria – both list organic functional groups
 - The student received credit for statement 3 for identifying the structure as that of an amino acid.
 - The student also did not received credit for statement 4 as it is incorrect

27 ***Student E received credit for three statements as follows:***

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- Note, this student also listed only four statements
 - Per the scoring guidelines, the student received credit for statement 1 but not 2 owing to the distinct criteria – both refer to the overall charge of the structure
 - The student received credit for statement 3 but not 4, again due to the distinct criteria – both classify the structure as acidic and polar

35 **Pat II - Thematic Analysis of Student F's Response**

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- Statements 1 and 2 were coded as *organic chemistry concepts* – identifies the organic functional groups of carboxyl acids and amine.
 - Statement 3 was classified as *structure identification* since it simply identifies the prompt structure as that of an amino acid.
 - Statement 4 is incorrect for the shown structure but coded as *compound classification* as it simply lists “hydrophobic” to describe the structure.

45 Thus, the responses by Student F are featured under the three themes of 1) structure
46 identification, 2) organic chemistry concepts, and 3) compound classification.
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