

Supplemental Material

CBE—Life Sciences Education

Sabel *et al.*

Appendix A
Assignment and Exam Question Comparison

Topic	Unit 1 Assignment 3	Unit 1 Exam																																				
Alleles and genotypes	<p>There are two loci in wild radish that determine the petal length: gene A and gene B. Each gene has two alleles: A and a, B and b.</p> <p>1. [1 pt] Define an allele.</p> <p>3. [1 pt] Write down the possible gametes produced by a parent wild radish with the genotype AaBb.</p> <p>4. [1 pt] Create a Punnett square representing the potential offspring from a mating of two AaBb wild radish plants, assuming the alleles are unlinked.</p>	<p>Cystic fibrosis is the most common lethal inherited disease in the Caucasian population. Cystic fibrosis is caused by a defect in the CFTR gene located on chromosome 7. In healthy individuals, the normal allele (F) contains the information necessary for producing the CFTR protein, which regulates the movement of chloride ions in and out of cells. CFTR proteins are defective or absent in individuals with cystic fibrosis, resulting in an accumulation of thick, sticky mucus that builds up in the lungs, pancreas, digestive tract, and other internal organs. Individuals with cystic fibrosis experience frequent and serious bacterial infections, inability to absorb adequate nutrients, and chronic respiratory problems. Untreated, children with cystic fibrosis generally die before 5 years of age.</p> <p>13. [6 pts] Max is a 3-year old boy with the recessive genetic disorder, cystic fibrosis. Neither of Max's parents have cystic fibrosis. What are the genotypes for each of the family members [Max, his mother, and his father]?</p>																																				
How genotype affects phenotype	<p>2. [1 pt] How might an allele affect flower phenotype?</p>	<p>14. [4 pts] In a sentence or less, explain <u>how</u> inheriting Max's genotype impacts cell function?</p>																																				
Genotype frequency	<p>5. [1 pt] Use the information from the Punnett square to complete the first 2 columns (Genotype and Genotype Frequency) of the table.</p> <table border="1"> <thead> <tr> <th>Genotype</th> <th>Genotype Frequency</th> <th># of Long Alleles</th> <th>Petal Length (cm)</th> </tr> </thead> <tbody> <tr> <td>AABB</td> <td>1/16</td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>aaBb</td> <td></td> <td>1</td> <td>6.5</td> </tr> <tr> <td>aabb</td> <td>1/16</td> <td>0</td> <td>5</td> </tr> </tbody> </table>	Genotype	Genotype Frequency	# of Long Alleles	Petal Length (cm)	AABB	1/16																							aaBb		1	6.5	aabb	1/16	0	5	<p>16. [7 pts] In 2010, 0.027% of the US population had cystic fibrosis and 3% of the population were carriers of the allele for cystic fibrosis. What were the frequencies of genotypes and of the f and F alleles in the 2010 population? Show your work! We recommend considering a population of 10,000 individuals to calculate the f and F frequency.</p>
Genotype	Genotype Frequency	# of Long Alleles	Petal Length (cm)																																			
AABB	1/16																																					
aaBb		1	6.5																																			
aabb	1/16	0	5																																			

<p>Influence of allele on phenotype</p>	<p>6. [1 pt] Both the A gene and B gene influences petal length. The 'A' allele and 'B' allele both code for a protein that increases the length of the petal. The 'a' allele and 'b' allele result in a protein that does not increase petal length. As you can see in the table, a plant with zero long alleles, produces petals of length 5 cm. Each additional long allele (capital letters, either A or B) results in additional 1.5 cm of petal length. Complete columns 3 and 4 [in the table above] based on this information.</p>	<p>18. [2 pts] Why does a person who is heterozygous at the CFTR loci express the dominant phenotype with only one "F" allele? (Do not say "because there is one F allele;" tell us in terms of <i>function in alleles in cells.</i>)</p>
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Appendix B
Example of Enhanced Answer Key

Assignment Week 3
Radish Petals

Case Study: Wild Radish Petal Length

Points: 15 Points

Part 1. Quantitative Traits

There are two loci in wild radish that determine the petal length: gene A and gene B. Each gene has two alleles: A and a, B and b.

1. [1 pt] Define an allele.

A version of a gene that has a different nucleotide sequence

1 pt – alternative version of a gene and doesn't specify nucleotide or nucleotide sequence

1 pt – results in different protein

0 pts – within a gene, expresses a phenotype

2. [1 pt] How might an allele affect flower phenotype?

Alleles code for protein variants that may affect flower phenotype. The protein may do anything that is related to petal length, for example it may be a transcription factor that impacts cell division rates or cell size of petal cells.

Multiple answers are possible so long as the protein could potentially impact flower phenotype.

½ pt – no reference to proteins

3. [1 pt] Write down the possible gametes produced by a parent wild radish with the genotype AaBb.

AB Ab aB ab – remember that these gametes are for two genes, each with two possible alleles
Could you draw these gametes in a stick diagram? If you are given the nucleotide sequence (like HW2), could you draw their arrangement?

4. [1 pt] Create a Punnett square representing the potential offspring from a mating of two AaBb wild radish plants, assuming the alleles are unlinked.

	AB	Ab	aB	ab
AB	AABB	AABb	AaBB	AaBb
Ab	AABb	AAbb	AaBb	Aabb
aB	AaBB	AaBb	aaBB	aaBb
ab	AaBb	Aabb	aaBb	aabb

5. [1 pt] Use the information from the Punnett square to complete the first 2 columns (Genotype and Genotype Frequency) of the table.

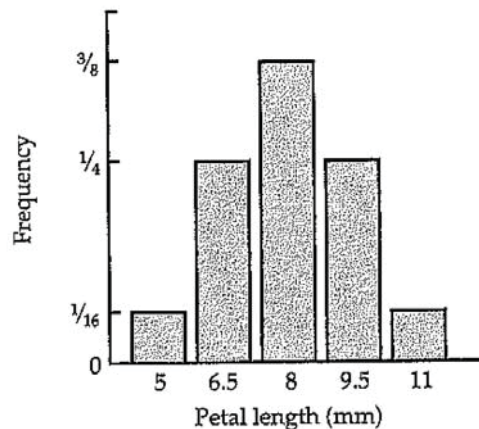
Genotype	Genotype Frequency	# of Long Alleles	Petal Length (cm)
AABB	1/16	4	11
AABb	1/8	3	9.5
AAbb	1/16	2	8
AaBB	1/8	3	9.5

AaBb	1/4	2	8
Aabb	1/8	1	6.5
aaBB	1/16	2	8
aaBb	1/8	1	6.5
aabb	1/16	0	5

6. [1 pt] Both the A gene and B gene influences petal length. The 'A' allele and 'B' allele both code for a protein that increases the length of the petal. The 'a' allele and 'b' allele result in a protein that does not increase petal length. As you can see in the table, a plant with zero long alleles, produces petals of length 5 cm. Each additional long allele (capital letters, either A or B) results in additional 1.5 cm of petal length. Complete columns 3 and 4 based on this information.

7. [1 pt] Plot genotype frequency on the y-axis of a graph, and plot petal length on the x-axis.

(A) 2 loci



Genotype	# long alleles	Frequency	Petal length
AA BB	4	1/16	11
AA Bb	3	1/8	9.5
AA bb	2	1/16	8
Aa BB	3	1/8	9.5
Aa Bb	2	1/4	8
Aa bb	1	1/8	6.5
aa BB	2	1/16	8
aa Bb	1	1/8	6.5
aa bb	0	1/16	5

A bar plot is most appropriate because there is 1 categorical variable – petal length with the y-axis being frequency.

Students could create a point graph if, and only if, there are 5 points representing the frequency for each petal length

0 pts – line graph where points are connected with a line, a smoothed line approximating the data

8. [1 pt] Write a 1-sentence conclusion about your graph.

Plants with petal length of approximately 8 cm were the most frequent while long and short petal lengths were less frequent.

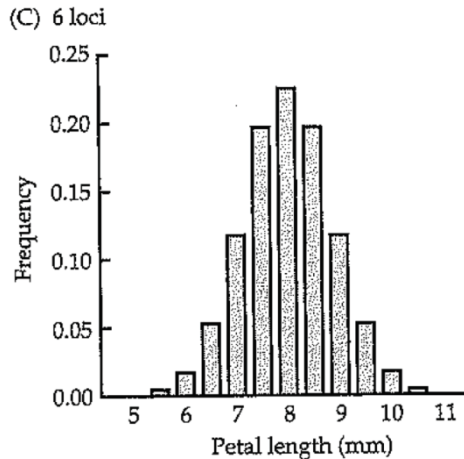
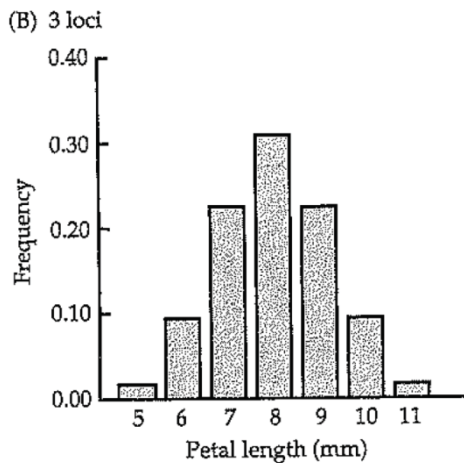
9. [1 pt] For a trait determined by proteins from a single gene with 2 alleles, there are 2 possible gametes (e.g., 'A' or 'a') and the frequency of inheriting either the 'A' or 'a' allele is $(1/2)^1 = 1/2$ or 50%. If there are 2 unlinked genes, like this problem, the frequency of inheriting a particular allele is 1/2. For example, you either inherit 'A' or 'a' and either 'B' or 'b'. Therefore you can produce 4 types of gametes: AB, Ab, aB, or ab. The frequency of inheriting each gamete is $1/2 * 1/2 = (1/2)^2 = 1/4$ or 25%.

If there were 3 loci for petal length, what would be the frequency for each possible gamete?

3 genes = $1/2 * 1/2 * 1/2 = (1/2)^3 = 1/8$, this is equal to 12.5%

10. [1 pt] How would your graph in Question 7 change if there were 3 unlinked genes that affected petal length? 6 unlinked genes?

The graph would be more continuous with a greater range of possible petal lengths. Don't need to graph the data.



11. [1 pt] Many traits in organisms are quantitative traits (result of 2 or more genes) and produce a range of phenotypes rather than categorical (e.g., tall or short) phenotypes. Name a trait in humans that produces a range of phenotypes and thus is likely a quantitative trait determined by more than 1 gene?

Height, eye color, IQ, learning ability, blood pressure,

Part 2. Pollination case study

Both small flies and larger honeybees pollinate wild radish. Small flies are more effective at pollinating smaller flowers and large bees are more effective at pollinating larger flowers.

12. [1 pt] How do you predict the loss of honeybee populations will affect flower size over time in wild radish populations?

The loss of the larger pollinator will lead to a decrease in reproductive success of larger flowers.

13. [1 pt] Would you predict to see more long alleles or more short alleles in populations in the absence of honey bees?

We would expect to see more small flowers and, thus, more short-petal alleles over time.

Part 3. Fitness

Devil's trumpet (*Datura wrightii*) grows throughout the state of Nebraska and can be found across a range of habitats and environmental conditions. It is a native plant. It is extremely toxic and can be fatal to humans if consumed. Its flowers produce a heavy sweet fragrance and are generally white with a fringe of purple. It is pollinated by hawkmoth (*Manduca sexta*) but can also self-fertilize (we'll discuss asexual reproduction later in the semester). Devil's trumpet produces trichomes that provide some protection from insect herbivores. It is thought the toxins that can kill humans may also provide protection against insects and pathogens.

A corolla is a portion of the flower (you can Google it to see images).

14. [1 pt] Corolla length can vary considerably among individuals. What are some potential advantages and disadvantages of having flowers with long vs. short corolla?

	Advantage	Disadvantage
Short Corolla	Less energy to maintain More exposed stigma and anthers make pollination easier Pollen is more accessible	Easily masked by leaves, other flowers, etc. Less protection for reproduction parts of the plant
Long Corolla	Better to attract pollinators More protection for reproductive parts of the plant	Susceptible to insect herbivores Harder for pollination to occur Requires more energy to maintain Pollen is less accessible

15. [1 pt] Access the data sheets on Blackboard (you don't need to print them). Plot the relationship between flower length and number of offspring for each population of Devil's trumpet.

Each figure worth 1/3 pt for completion.

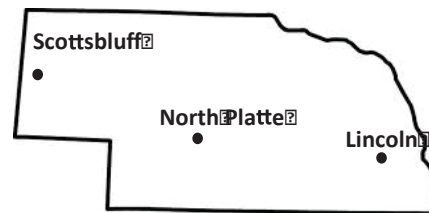
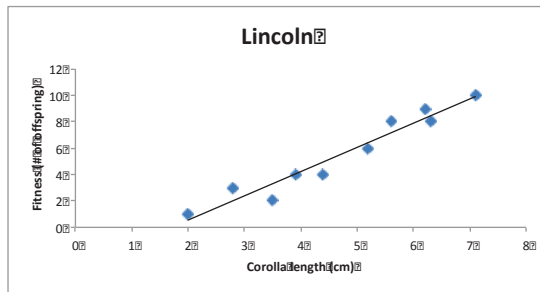
Scatter plot, best fit line is optional.

½ pt – incorrect plot (bar plot, line plot, connected the points)

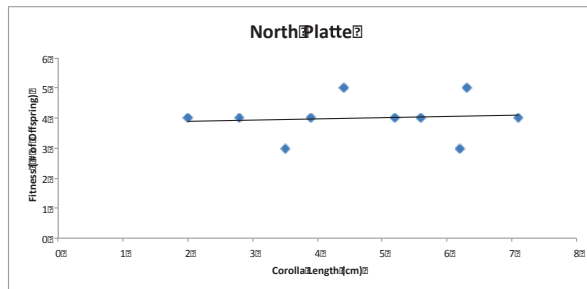
½ pt – only plotted 5 points (half of the total data)

0 pt - histogram

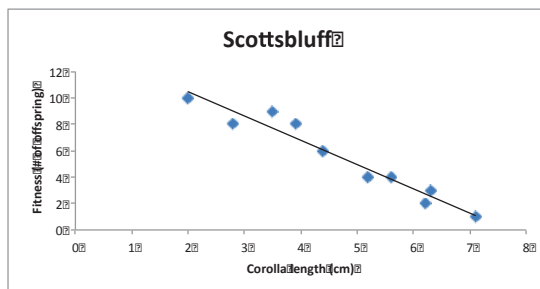
Lincoln



North Platte



Scottsbluff



Appendix C Reflection Questions

Instructions:

1. Read through the entire answer key, even for questions that you got correct.
2. Reflect on how your answer aligned with the answer provided on the answer key.
3. Use the following reflection questions to think about what you know now and what you still need to learn more about to fully understand the topic.
4. Adjust your studying to focus on the gaps in your understanding.

Reflection questions:

1. Do all of the answers on the answer key make sense to you? If not, what steps can you take to make sense of the concepts in the answers?
2. Do all of the answers provided seem like possible explanations to you given what you know about the topic? If not, what steps can you take to reach a greater understanding of the topic and the explanation?
3. Could you apply the explanations to a different context other than the one in the assignment? If not, what steps can you take to advance your understanding of this topic and be able to apply the explanations to other contexts?
4. Do you feel like you have a complete understanding of the concepts from this assignment? If not, what steps could you take to increase your understanding?
5. What connections can you make from the ideas in this assignment to the previous content you have learned in class?
6. What could you have done differently before or while you completed this assignment to better understand the topic?
7. What are some possible questions you might see on an exam about this topic? What steps can you take to reach greater understanding to be able to effectively answer those exam questions?
8. If you were to explain the topics on this assignment to a friend, what would you say? How well would you be able to explain it? Where would you struggle?

Appendix D
Survey Questions

1. When have you used the enhanced answer keys in this class? (Select all that apply)
 - Some, but not all, assignments
 - All assignments
 - Some, but not all, exams
 - All exams
 - I have not used the answer keys.

2. How have you used the enhanced answer keys? (Select all that apply)
 - To verify the score I received was correct.
 - To see why an answer I provided was incorrect.
 - To check how closely my correct answer aligned with the answer.
 - To better understand the question and answer.
 - To study for the exam.
 - To reflect on my understanding of the content
 - I have not used the answer keys.
 - Other: Please explain

3. If at any time you chose not to use an enhanced answer key, what was your reason? (Select all that apply)
 - I understood all of the material and didn't need to look at the answer key.
 - I understood why I got the score I did and didn't need to see the answer key.
 - I didn't have time to look at the answer key.
 - I was only interested in my grade, not in the particular answers
 - I forgot about them.
 - I didn't know they existed.
 - This does not apply because I have always used them.
 - Other: Please explain

4. In the future, how might you use the enhanced answer keys? (Select all that apply)
 - To verify that the recorded score was correct.
 - To see why an answer I provided was incorrect.
 - To verify why an answer I provided was correct.
 - To better understand the question and answer.
 - To study for the exams.
 - To reflect on my understanding of the content.
 - To enhance my overall understanding of a concept.
 - I do not plan to use the answer keys.
 - Other: Please explain

Put an X in the box that indicates how much you agree or disagree with the following statements.
A = strongly agree, B = somewhat agree, C = somewhat disagree, D = strongly disagree

5. After I review an assignment or exam I take time to reflect on my understanding of the material.
6. After an assignment or exam is returned to me, I consider how I could have improved my answers.
7. I just look to see what grade I get on an assignment or exam and don't follow up on how I answered the questions.
8. After an exam, I take time to reflect on how I could have improved my studying.
9. When I study a particular topic, I consider the types of questions I might see on an exam about that topic.
10. I try to explain concepts to a friend to see how well I understand them.
11. When I don't initially know the answer to a question, I consider how it might be related to other topics that I know.
12. As I study, I take note of the topics that I am unsure about or feel less confident about.
13. When I learn something new, I consider how it fits into what else I know about that topic.
14. I can see how using an answer key could help me to determine what I need to study further.
15. I can see how using an answer key could help me to better understand a concept.
16. I read all of the answers provided on the answer key, even for questions that I got correct.
17. When I compare my answer to the answer on the answer key, I reflect on the differences and how I could improve my answer.
18. I have understood a topic better after having read the answer key.
19. If I were to use the answer key on a question I missed, I would try to memorize what the answer key said for the test.
20. If I were to use the answer key on a question I missed, I would use it to try to reach greater understanding of the topic before the test.

Open response questions:

1. How do you study for this class?
2. How do you determine if you understand a topic or if you need to study further?
3. Do you plan to make changes to how you study for this course? If so, what changes do you plan to make and why do you plan to make these changes? If not, why don't you think changes are necessary?
4. Did the enhanced answer keys help you to evaluate your performance on the assignments? Why or why not? If you did not use the answer keys, please explain how you think they might help you in the future or why you do not plan to use them.

Survey 2 and 3

Likert question section (added to questions in Survey 1)

1. I think about the concepts I have learned over the whole semester and how they are connected.
2. Since the beginning of the semester, I have made changes to the way I study based on reflection on my study habits or on my progress.

3. The added section of the answer key with the reflection questions helped me to consider my understanding of the topics.
4. The added section of the answer key with the reflection questions caused me to make changes to the way I study.
5. The added section of the answer key with the reflection questions caused me to change the way I thought about the topics.

Open response questions (replaced open response questions in Survey 1):

1. How do you study for this class? (Please include how you study in general but also any changes you have made to your studying since the semester began.)
2. How do you determine if you understand a topic or if you need to study further?
3. Did the enhanced answer keys help you to evaluate your performance on the assignments? Why or why not? If you did not use the answer keys, please explain how you think they might help you in the future or why you do not plan to use them.
4. Did you use the added reflection questions on the enhanced answer key? If so, please explain how you used the added section and if some parts were more helpful or useful than others. If you did not, please explain why you did not and whether or not you plan to use them in the future.

Appendix E
Post-Assignment Interview Protocol

1. Biographical info
 - a. Major, year in school, career goals
2. How do you study for this class?
3. Do you typically make a plan for what you need to focus on when you study, or do you always study in the same ways?
 - a. If so, how do you decide what you need to study?
4. As you have studied so far, do you tend to focus on certain concepts or ideas or more than others?
 - a. If so, why did you decide to focus on those more than others?
5. How do you determine how well you understand a topic and whether or not you need to study for something further?
6. Do you typically take time to consider if the ideas make sense to you?
 - a. What do you do if an idea doesn't make sense to you?
7. Do you typically take time to consider how a new concept fits in with other concepts you have learned?
8. Do you typically take time to think about how a concept might apply in another situation?
9. Have you used the enhanced answer keys to evaluate your performance on the assignments?
 - a. If yes, how did you use it?
 - i. Did using the answer key influence how you studied at all? If so, how?
 - b. If no, why not?
 - i. Did you identify in any other way what you needed to focus on to improve your understanding?
10. Do you see a way to use the enhanced answer key to better understand a concept?
 - a. Do you see yourself using the answer keys in that way this semester?
11. Do you see a way to use the enhanced answer keys to evaluate your understanding of the topic or to monitor your learning progress?
 - a. Do you see yourself using the answer keys in that way this semester?

Provide enhanced answer key for assignment

12. How did you go about answering the questions on this assignment?
 - a. How did you decide what to include in your answers?
 - b. What did you do if you didn't immediately know an answer to a question?
13. How well do you think your answers align with the answers provided on the answer key?
 - a. What do you see that is similar or different about your answers?
14. Using this enhanced answer key, do you see things you did not previously understand or areas that you need to focus on to improve your understanding of this topic? Please explain.
15. Is there anything that you see in the answer on the answer key that helps you to make a connection you had not previously made? Please explain.
16. How do you plan to advance your understanding of this topic as you move forward? What, specifically, will you do?

17. After you got this assignment back, did you take any time to consider your answers and how you might have improved them?
18. If the answer on the answer key was different than the answer you provided on an assignment, how would that influence how you thought about the concept or what steps you took when studying?

Provide reflection questions (Group 2 interviews only)

19. Do you typically ask yourself these types of questions about your understanding of the material?
20. If the enhanced answer keys were to include questions like these, would you likely use them? Why or why not?
21. Do you think having these questions on an answer key would change the way you use the answer keys in any way? Why or why not?
22. Do you think these questions could help you to monitor what you know and what you still need to understand further? If so, how? If no, why not?
23. Do you think reflecting on questions like this would influence how you think about the content for this class? For example, would it help you understand how different topics fit together?
24. Do you think reflecting on questions like this would influence how you studied for the class? How?

Appendix F
Post-Exam Interview Protocol

1. How did you study for this exam?
2. Has how you study for this class changed over the semester? If so, how?
3. Did the way you studied for this exam change from how you studied for previous aspects of the course? If so, how?
4. When you study, in general, for the class do you tend to focus more on individual content topics or how those topics are related to each other?
5. As you studied for this exam, did you tend to focus on certain concepts or ideas or more than others? If so, which topics? Why did you decide to focus on those more than others?
6. How do you determine how well you understand a topic and whether or not you need to study for something further?
7. As you are studying, what do you do if an idea does not make sense to you?
8. Do you think about how ideas might apply outside of this class or focus on how they will apply to the next exam?
9. Did you use the assignments when you studied for the exam? If so, how?
10. How did your performance on the assignments help you to determine what you needed to study for the exam?
11. Do you see connections between the assignments you did leading up to this exam and the questions on the exam? Do you see connections from the assignments from the first unit?
12. Have you used the enhanced answer keys on previous assignments or exams?
 - a. If yes, how did you use them? Did using the answer key influence how you studied at all? If so, how?
 - b. If no, why not?
 - i. Did you identify in any other way what you needed to focus on to improve your understanding?
 - ii. Do you see a way that you could use the answer keys to evaluate your own understanding of the topic or to monitor your learning progress?
13. Did our conversation about the enhanced answer keys influence how you thought about using them? If so, how?
14. Did our conversation about the enhanced answer keys influence how you thought about studying for the exam? If so, how?
15. Do you plan to use the answer keys in the future to determine your understand of the content?
16. Did you use the added reflection question on the answer keys? If so, how? If not, why not?
 - a. What was most effective for you in using the reflection questions?
 - b. Were there any parts of the reflection questions that were not helpful?
17. Did using the reflection questions help you to see aspects of the content that you may not have realized without the reflection?

➔ Insert modified questions for Group 2 students

End

1. Do you plan to make any additional changes to the way you study as you move forward?

2. In what ways do you plan to use the enhanced answer keys moving forward?
3. Do you see any way to further improve the enhanced answer keys in a way that would help you study or help your understanding of the content?

Modified

1. Did our conversation about the additional questions on the enhanced answer keys influence how you thought about using the answer keys? If so, how?
2. Did our conversation about the additional questions on the answer key influence how you thought about studying for the exam? If so, how?
3. Did you use those questions to study for the first exam? If so, how? If not, why not?
4. Did you notice they had been added to the assignment answer keys after the first exam? Did you find that addition useful?

Appendix G
Metacognition Code Descriptions and Examples

Metacognition Dimension*	Description*	Example Quotes from Interviews	Explanation of Quote Coding
Intelligibility	<ul style="list-style-type: none"> • Considers the extent to which an idea makes sense. • Involves awareness of the sense-making process 	<p>Enhanced answer key: “I know I missed a couple on, like right here, I didn't quite understand it completely, I just took my best guess and then I went back and looked at the [enhanced answer key] and was like, well yeah, that makes sense now that I understood what it was trying to say or I hadn't used the right wording, like right there they had pointed that out to me” (Nicole, Interview 1).</p>	<p>In this example, Nicole used the enhanced answer key to make sense of what was missing from her own answer. She considered her mistakes and made sense of what she had done incorrectly or had not completely understood.</p>
		<p>Reflection questions: “I feel like that's more of a, alright, I don't understand, if you go through and you're like, none of these make sense, you're doing something wrong, how do you fix it, like it's almost like a brainstorming questionnaire” (Andrew, Interview 1).</p>	<p>Here, Andrew considered the extent to which ideas made sense and how he might need to make changes to reach greater understanding.</p>
Plausibility	<ul style="list-style-type: none"> • Considers the extent to which an explanation is a possible explanation • Includes evaluation of ideas and belief in those ideas based on their explanatory value 	<p>Enhanced answer key: “[The answer on the enhanced answer key] might [change how I thought about the topic] depending on how it was different because if mine was completely off and it for some reason didn't even relate to it, then yes I would change the way I was thinking about the question, what I was doing, and</p>	<p>Christopher recognized the plausibility of the answer provided on the enhanced answer key and used it to “retune” his own thinking. He considered how his ideas might change when he compared his initial answers to the correct answers on the enhanced answer key</p>

- Involves belief in an explanation

what I was writing. But, if it was close then maybe I just have to retune how I'm thinking and then think of it in a different aspect and then realize that for putting it on paper” (Christopher, Interview 1).

and was able to consider a revised idea as plausible.

Reflection questions: “Yeah, it definitely would [change the way I thought about the content]. Because I mean it forces you to think about why, not what the answer is, but why that's the answer” (Nick, Interview 1).

In this example, Nick indicated that using the reflection questions could help him to evaluate his own ideas and to reach a plausible, revised understanding.

Wide-applicability

- Considers the extent to which an explanation can be applied beyond a particular context
- Connected to transfer of ideas and application of concepts in other situations

Enhanced answer key: [using the enhanced answer key] might actually [cause me to change how I studied]. Just thinking in a different way, it might help me realize different things that I didn't before, it might help me visualize how things fit together better and I think that would be beneficial. (Will, Interview 1)

Will recognized the use of the enhanced answer key in helping him to think about topics in a different way, beyond the particular context, and to see how different concepts fit together.

Reflection questions: “I feel like just knowing this general process would help me to apply it to something if I saw it on a test. I don't need to know a specific example, but just knowing the whole general concept, there's a population, when they get separated, they stay

Matthew discussed how thinking through the reflection questions could help him to take a concept and apply it to another situation, such as on a test, and indicated the importance of thinking through “the whole general

separated, they become separate species, concept” rather than a specific
when they come back together things can example.
happen” (Matthew, Interview 2).

*Based on Grotzer & Mittlefehldt (2012)