Chief Reader Report on Student Responses:

2024 AP® Biology

Free-Response Questions

• Number of Students Scored	260,062		
• Number of Readers	1,050		
• Score Distribution	Exam Score	N	%At
	5	43,719	16.8
	4	60,178	23.1
	3	73,735	28.4
	2	56,358	21.7
	1	26,072	10.0
• Global Mean	3.15		

The following comments on the 2024 free-response questions for AP® Biology were written by the Chief Reader, Amy Dykstra, Bethel University (Minnesota); with substantial assistance from the Chief Reader Designate, Jay Mager, Ohio Northern University; the Operational Exam Leader, Tim Wakefield, John Brown University; and the Question Leaders, Rob Benedetto, Central Catholic High School, Lawrence, Massachusetts; Geoffrey Gearner, Morehead State University; Ross Sappenfield, Vail Mountain School, Vail, Colorado; Monika Biro, Aurora High School, Aurora, Ohio; Darla French, Oberlin College and Conservatory; and Michelle Solensky, University of Jamestown. The comments give an overview of each free-response question and outline how students performed on the question, including typical student errors. General comments regarding the skills and content with which students frequently have the most problems are included. Some suggestions for improving student preparation in these areas are also provided. Teachers are encouraged to attend a College Board workshop to learn strategies for improving student performance in specific areas.

Question 1

Task: Interpreting and Evaluating Experimental Results with Experimental Design
Topic: Kinetochore Proteins
Max Score: 9
Mean Score: 3.09

What were the responses to this question expected to demonstrate?

The stimulus of Question 1 explained that crossing over is necessary for proper alignment and segregation of chromosomes during meiosis I, and that crossing over frequency is higher in chromosomal regions called hotspots. Figure 1 showed a pair of homologous chromosomes labeled with fluorescent proteins. The primary experiment measured crossing-over frequency in the presence of different kinetochore proteins. A follow-up experiment then tested modification of one of these proteins to determine what function/domain of the protein might be affecting the crossing-over frequency.

In part (a)(i) responses were expected to describe the function of the S phase of interphase (Science Practices Skill 1.A; Learning Objective [LO] IST-1.B from the AP Biology Course and Exam Description [CED]). In part (a)(ii) responses were expected to explain why some of the haploid cells resulting from meiosis in this experiment would have only one fluorescent marker (Skill 1.C; LO IST-1.F).

In part (b) responses were expected to demonstrate an understanding of experimental design (Skill 3.C). In part (b)(i), responses were expected to identify a control group. In part (b)(ii), responses were expected to justify the purpose for a control treatment in the context of the follow-up experiment, and in part (b)(iii), responses were expected to identify the independent variable in this follow-up experiment.

In part (c) responses were expected to describe data from a graph (Figure 2) that presented results of the first experiment (Skill 4.B).

In part (d)(i), responses were expected to predict that, when a kinetochore protein that reduces crossing over is attached to the chromosomal hotspot, resulting daughter cells would be more likely to have a missing or extra chromosome (Skill 3.B; LO SYI-3.C). In part (d)(ii) responses were expected to justify the prediction by reasoning that nondisjunction would be more likely (Skill 6.C; LO SYI-3.C). In part (d)(iii) responses were expected to explain the relationship between the experimental results and a broader biological theory by explaining that crossing over could increase the likelihood of a population surviving "in the presence of selective pressures" (Skill 6.D; LOs EVO-1.E, SYI-3.D, and IST-1.H).

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

<u>Cell Cycle – S Phase</u>

- Many responses correctly described the function of the S phase of interphase as the period when DNA replication occurs (Skill 1.A; Essential Knowledge [EK] IST-1.B.2). Some responses incorrectly included descriptions of events/processes that occur outside of the S phase.

<u>Haploid Cell Production and Gene Distribution</u>

- Many responses struggled to recognize that the absence of an event (crossing over) resulted in a single fluorescent marker in a haploid cell (Skill 1.C; EK IST-1.G.1). Some acceptable responses included a correct description of Figure 1 in the explanation.

<u>Experimental Design (Skill 3.C)</u>

- Most responses correctly identified the control group in the primary experiment as Group 1 or the treatment with no kinetochore proteins attached to the chromosome (Essential Knowledge IST-1.H.2).
- Many responses could not justify the use of a modified CTF kinetochore protein with the DNA-binding region removed as the control treatment in the follow-up experiment. Many responses identified the treatment with which the control group would be compared and even described it as a negative control. However, to earn the point, the responses needed to explain that the use of this control group allowed the scientists to determine whether the binding of CTF to the DNA affected the crossing-over frequencies.
- Most responses correctly identified the independent variable in the follow-up experiment as the type of CTF used or the presence or absence of CTF. Some responses incorrectly identified the independent variable as a single treatment (i.e., "modified CTF").

<u>Evaluating Experimental Data</u>

- Most responses correctly described the data presented in Figure 2 by describing that CTF attachment results in a lower crossing-over frequency than does IML attachment (Skill 4.B; EK IST-1.H.2).

<u>Predictions Based on Disruptions of Biological Systems and Connections to Other Content</u>

- Few responses correctly predicted that haploid daughter cells would be likely to have zero (0) or two (2) copies of chromosome 8 if CTF is attached to the hotspot (Skill 3.B; EK SYI-3.C.1). Predictions of "fewer" or "more" chromosomes were excluded because these responses often referred to attributes of chromosomal replication rather than to attributes of nondisjunction.
- Few responses correctly justified the reduction or increase in chromosomal number as a result of a nondisjunction event that is more likely to occur when crossing over occurs at a lower frequency because of the addition of CTF (Skill 6.C; EK SYI-3.C.3). The information that crossing over is required for correct segregation of chromosomes during meiosis was provided in the question stimulus.
- Many responses correctly explained that increasing frequency of crossing-over events will lead to greater genetic diversity, which will then benefit populations as selective pressures change because some individuals will have greater fitness (Skill 6.D; EKs IST-1.H.2, SYI-3.D.1, EVO-1.E.3). Some responses neglected to include the reproduction element included in fitness (wrote only of survival) and did not earn the point.

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Part (a) • Misconception: The process of crossing over changes or replaces genes. • Misconception: The process of crossing over is a, or results in, mutation(s). • Misconception: Independent assortment occurs between genes and not chromosomes.	Part (a) • "DNA is replicated during the S phase of interphase." • "Some haploid cells will only have one fluorescent marker...because not all chromatids experience crossing over...and when sister chromatids separate...some daughter cells will have just one fluorescent marker."

Parts (b) and (c) • Skills Gap: 3.C (Identify experimental procedures that are aligned to the question) - Particularly justifying the *purpose* of a control treatment in the context of a specific experiment. • Skills Gap: 3.C - Particularly distinguishing between variables (independent) and treatments within the context of a specific experiment.	Parts (b) and (c) • "The control group was the cells without the kinetochore proteins labeled 'None'." • "The purpose of this control was to see if the reason why CTF decreases the frequency of crossing over is because it binds to DNA." • "The independent variable is the presence or absence of modified and unmodified CTF." • "CTF has a lower cross over frequency than does IML."
Part (d) • Knowledge Gap: The role of the two segregation events in meiosis to produce haploid cells.	Part (d) • "There will be no copies of chromosome 8." • "This is because CTF disallows crossing over. This will lead to nondisjunction during anaphase I in which the chromosomes will not separate properly." • "Crossing over leads to genetic variation...with this increase in genetic variation populations are better able to adapt to selective pressures because individuals will more likely be fit."

Based on your experience at the AP® Reading with student responses, what advice would you offer teachers to help them improve student performance on the exam?

- To assist with deepening understanding of biological processes (in this case: meiosis and crossing over), modeling activities may be helpful.
    - **TIP:** When students create or use models, be sure to add disruptions to those models and ask students to make new predictions and justify those predictions.
- Be sure to discuss nuances of complex themes. This includes themes as they apply across scales.
    - **TIP:** Break into small groups and then have the students find similarities and differences in these major concepts/themes across scales.
- When performing and designing experiments, make sure there is an understanding of the "*purpose of procedure.*"
    - **TIP:** Ask questions about variables, not just for them to be identified.
        - *"Why are we measuring these variables?"*
        - *"What happens if we change this part of the experiment?"*
        - *"What does this variable/treatment allow us to do/conclude?"*

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

From AP Classroom:

- Progress Checks from Units 4, 5, and 7
- AP Daily Videos, Topics 4.6, 5.1, 5.2, 5.6, and 7.2 as well as Faculty Lectures 4, 5, and 7
- Topic Questions from Topics 4.6, 5.1, 5.2, 5.6, and 7.2 for formative assessments

From the AP Biology Online Teacher Community:

- Data resources outlined in the *Online Resources Recommended by AP Teachers*

Question 2

Task: Interpreting and Evaluating Experimental Results with Graphing
Topic: Metabolism in Toads
Max Score: 9
Mean Score: 3.65

What were the responses to this question expected to demonstrate?

Question 2 presented a table of data from an experiment designed to determine the effect of temperature on metabolic rate in toads. In the experiment, researchers measured the rate of oxygen consumption and the rate of ATP synthesis in isolated liver cells at three different temperatures.

Part (a) expected responses to describe "the role of water in the hydrolysis of ATP." This prompt assessed student understanding that hydrolysis cleaves covalent bonds (Skill 1.A; LO SYI-1.B).

In part (b)(i), responses were expected to construct a bar graph representing the experimental data (Skill 4.A). Part (b)(ii) expected responses to use the error bars to "determine the temperature in °C at which the rate of oxygen consumption is different from the rate of oxygen consumption at 25 °C" (Skill 5.B).

In part (c)(i), responses were expected to describe a trend in the data by describing "the effect of temperature on the rate of ATP synthesis" (Skill 4.B). Responses to part (c)(ii) were expected to perform a calculation based on the data in the table (Skill 5.A).

Part (d) presented the additional information that oligomycin "can block the channel protein function of ATP synthase." Responses were expected to predict "the effects of using oligomycin on the proton gradient across the inner mitochondrial membrane" (Skill 6.E) and then justify the prediction (Skill 6.C). Responses were expected to demonstrate understanding that the gradient would increase as protons accumulate in the intermembrane space of the mitochondrion because the protons are prevented from flowing through ATP synthase into the mitochondrial matrix (LO ENE-1.K).

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

Describing a Biological Process

- A moderate number of responses correctly described a biological process (the role water plays in ATP hydrolysis) (Skill 1.A).

Constructing an Appropriately Labeled Graph and Describing/Evaluating Data in the Graph

- Most responses correctly constructed a bar graph (Skill 4.A).
- Many responses correctly labeled the graph and accurately plotted the data points and error bars (Skill 4.A).
- Many responses demonstrated proficiency in using standard errors or error bars to determine whether there are significant differences among the means of the graphed data (Skill 5.B).
- Most responses correctly described the relationship between an experimental variable (incubation temperature) and data (rates of oxygen consumption) (Skill 4.A).

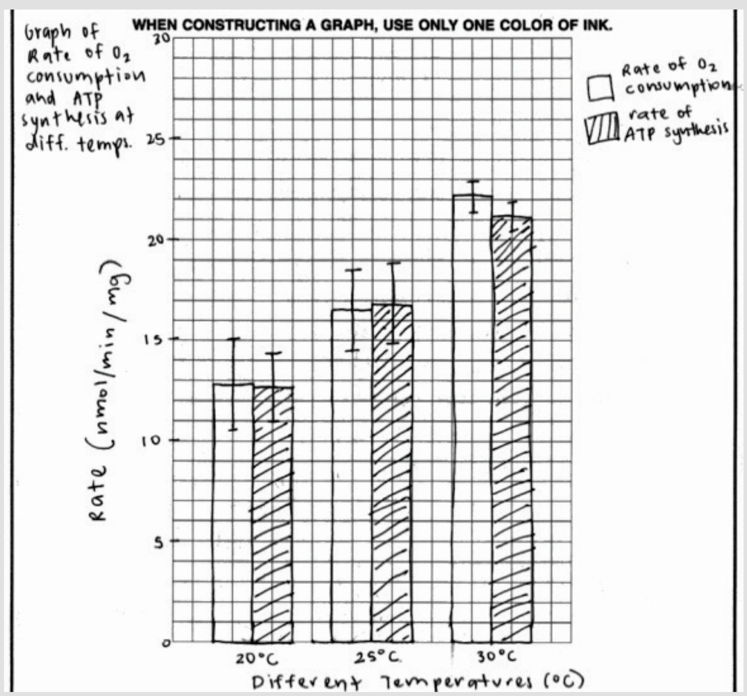
Performing a Mathematical Calculation

- Some responses correctly performed a mathematical calculation based upon data presented in a table (Skill 5.A).

Predictions Based on Disruptions of a Biology Process

- Very few responses made a correct prediction regarding the effect that a disruption (blocking the proton channel of ATP synthase) has on a biological process (maintenance of the proton gradient across the inner mitochondrial membrane and proton flow through the membrane-bound ATP synthase from the mitochondrial intermembrane space into the mitochondrial matrix; ENE-1.K.3.d). Very few responses provided an appropriate justification that blocking proton flow results in an increase in proton concentration in the mitochondrial intermembrane space (ENE-1.L.5).

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Part (a) • Knowledge gap: Inability to describe that hydrolysis is used to cleave covalent bonds (SYI-1.B). Some responses did not correctly identify that during hydrolysis, covalent bonds are broken, instead describing that hydrogen bonds or phosphodiester bonds are broken, while other responses were not set in the context of ATP or referred to the formation of ATP rather than its hydrolysis.	Part (a) • "The addition of a water molecule allows for the hydrolysis of ATP to occur. Covalent bonds in ATP are broken, resulting in ADP and inorganic phosphate."
Part (b) • Skill Gap: Inability to label a graph and accurately plot data points and error bars (SP 4.A). Some responses did not include all of the required information in the labels, e.g., did not define Rate as nmol/min/mg or did not indicate Temperature as °C . Some responses did not accurately plot the error bars—they were either misplotted and/or not evenly plotted over the means represented by the graphed bars.	Part (b) 

Part (b) • Skill Gap: Inability to use standard errors or error bars to determine whether sample means are statistically different (SP4.B). Some responses were unable to demonstrate that nonoverlapping standard errors or error bars between treatment groups indicates a significant difference.	Part (b) • "The rate of ATP consumption is different at 30 °C from the rate of ATP consumption at 25 °C."
Part (c) • Skill Gap: Inability to make a correct calculation based on data presented in a table (SP 5.A). Many responses miscalculated the amount of oxygen, in nmol, consumed per 10 mg of mitochondrial protein after 10 minutes of incubation at 25 °C.	Part (c) • "16.50 nmol/min/mg × 10 mg × 10 min = 1650 nmol"
Part (d) • Misconception: Instead of predicting the effect oligomycin (which blocks proton translocation across the inner mitochondrial membrane) has on the proton gradient across the inner mitochondrial membrane, many responses described the effect oligomycin has on the enzymatic function of ATP synthase. • Misconception: Rather than provide a justification for the correct prediction, most responses justified an incorrect prediction.	Part (d) • "The use of oligomycin would increase the proton gradient across the inner mitochondrial membrane." • "If ATP synthase is blocked, the protons in the intermembrane space of the mitochondria will not be able to go through ATP synthase back to the mitochondrial matrix. Protons will continue going from the matrix to the intermembrane space through proton pumps, but they cannot come back, causing the gradient to increase."

Based on your experience at the AP® Reading with student responses, what advice would you offer teachers to help them improve student performance on the exam?

- Review the types of chemical bonds: ionic, covalent (polar and nonpolar), and hydrogen, and their implications in biological processes.
    - **TIP**: Review the role water plays in the formation of covalent bonds by dehydration synthesis and the breaking of covalent bonds by hydrolysis.
- Review the different types of graphs and the seven assessment criteria for graphing in the CED (Science Practices 4 and 5).
    - **TIP**: Frequent practice of constructing graphs with regular instructor feedback on all seven assessment criteria, along with graph interpretation and analysis, of both student-constructed graphs and graphs published in the scientific literature, will improve the students' graphing skills.
- Many biological processes exploit gradients: energy, solute, pressure, proton, etc.
    - **TIP**: The terms "rate," "gradient," and "density" can be challenging concepts for students. Review these with students in the context of biological phenomena.
    - **TIP**: Review with students and provide examples of how living processes utilize gradients.
- Mitochondria and chloroplasts share common features in their functional anatomy.
    - **TIP**: Provide opportunities for students to explain the advantages that the arrangement of mitochondrial and chloroplast components confers on the overall function of these organelles.
- Disruption of a system or process has allowed investigators to elucidate the mechanisms by which they work.
    - **TIP**: Have students practice making and justifying the effects of disruptions on biological processes.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

From AP Classroom:
- Progress Checks from Units 1 and 3
- AP Daily Videos, Topics 1.3 and 3.6, as well as Faculty Lectures 1 and 3
- Topic Questions from Topics 1.3 and 3.6 for formative assessments

From the AP Biology Online Teacher Community:
- Data resources outlined in the *Online Resources Recommended by AP Teachers*
- For graphing supports and practice, utilize the resources within the Quantitative Skills Guide

Question 3

Task: Scientific Investigation
Topic: Glucose and Red Blood Cells
Max Score: 4
Mean Score: 2.39

What were the responses to this question expected to demonstrate?

Question 3 described an experiment in which scientists collected red blood cells from guinea pigs that ranged in age from one day old to seven months old. The cells were incubated with radioactively labeled glucose to determine the effect of guinea pig age on glucose uptake by the cells.

Part (a) expected responses to "describe a difference between passive transport and active transport" (Skill 1.A; LO ENE-2.E).

Part (b) expected responses to justify the experimental control of using "an equal number of red blood cells in each culture dish" (Skill 3.C).

Part (c) presented a claim that "the expression of the gene encoding [glucose] transporters decreases as guinea pigs age." Responses were expected to "predict the effect of increased age on the amount of radioactively labeled glucose present" in cells from animals of different ages (Skill 3.B).

In part (d), responses were expected to justify the prediction in part (c) by reasoning that there would be fewer glucose transporters and thus less glucose uptake (Skill 6.C; LO ENE-2.G).

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

- Many responses correctly described the difference between two common processes used by organisms to maintain solute and water balance: passive and active transport (LO ENE-2.E; Skill 1.A).
    - Many responses correctly described the differences in input of energy required or the differences in the movement of molecules according to concentration (LO ENE-2.E; Skill 1.A).
- While many responses accurately identified controls, fewer responses correctly justified the reason for appropriate controls *in the context* of the specific experiment (LO ENE-2.E; Skill 3.C).
- Many responses used the researchers' claim to correctly predict the results of the experiment (LO ENE-2.E; Skill 3.B).
- Fewer responses correctly justified the prediction by connecting predicted evidence (glucose uptake) to biological theories (the results of gene expression; LO ENE-2.E; Skill 6.C).

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Knowledge Gap: Describe the role of energy in cellular transport.	• "Active transport requires the use of ATP to move substances across a membrane." • "Passive transport does not require an input of extra energy while active transport does require the input of extra energy."

• Skills Gap: Justify the appropriate use of controls in alignment with the scientific investigation.	• "...so all of the glucose in the cells is due to the age of the guinea pig the blood was taken from and not the number of cells." • "...to eliminate the number of cells as a confounding variable that might alter the amount of glucose present in the red blood cells."
• Skills Gap: Predicting results.	• "As age of the guinea pigs increases, the amount of radioactively labeled glucose decreases in the cells."
• Knowledge Gap: Differential gene expression influences gene products and cell function.	• "Since there are fewer transporters due to decreased gene expression, glucose enters the cells at a lower rate and therefore there will be less glucose in the cells."

Based on your experience at the AP® Reading with student responses, what advice would you offer teachers to help them improve student performance on the exam?

- Perform and analyze authentic investigations.
  - **TIP:** Have students make predictions about how changing constants would affect the dependent variable.
  - **TIP:** Have students carry out experiments with the same dependent variable, but alter the independent variable or the constants between lab groups and compare results.
  - **TIP**: Analyze changes in variables in an experiment using computer-based modeling programs that allow changes in constants.
- Practice all task verbs in the context of an investigation.
  - **TIP**: Use the CED to determine how the verbs apply to a specific experiment or scenario. Have students practice and grade each other's responses.
- Apply the central dogma to novel situations.
  - **TIP**: Perform investigations or analyze authentic research articles where the normal flow of genetic information is disrupted. Have students predict and justify the changes in the dependent variable.
- Integrate kinetics into the study of cellular processes.
  - **TIP**: Use computer simulations to model molecular motion under different environmental conditions.
  - **TIP**: Practice drawing molecular motion (and many molecules) when illustrating diffusion and enzyme-substrate reactions as opposed to drawing single molecules and linear motion.
  - **TIP**: Give "drawing quizzes" as formative assessments of molecular kinetics applied to biological processes.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

From AP Classroom:

- Progress Checks from Unit 2
- AP Daily Videos, Topics 2.6 and 2.7
- Topic Questions from Topics 2.6 and 2.7 for formative assessments

From the AP Biology Online Teacher Community:

- Data resources outlined in the Online Resources Recommended by AP Teachers

Question 4

Task: Conceptual Analysis
Topic: Wild Oats
Max Score: 4
Mean Score: 2.16

What were the responses to this question expected to demonstrate?

Question 4 presented a report about the effects of an invasive species, the common wild oat, on a grassland community in central California. The stimulus of the question explained that aphids, which often carry plant viruses, have higher reproductive rates in grasslands invaded by the common wild oat than in grasslands with only native bunchgrass species and that the viruses appear to negatively affect native bunchgrasses but not affect the invasive species of plant.

Responses to part (a) were expected to describe "the change in resilience of an ecosystem when there is a decrease in the number of species" (Skill 1.A; LO SYI-3.F).

Responses to part (b) were expected to explain "how the addition of the common wild oat" affects the carrying capacity of the ecosystem (Skill 1.C; LOs SYI-1.H and SYI-2.A).

Part (c) described a suggested addition of ladybugs, predators of aphids, to the ecosystem. Responses were expected to predict that the effect of this disruption would be the increased abundance of the native bunchgrass population (Skill 6.E; LOs SYI-1.H and ENE-4-B).

Responses to part (d) were expected to justify the prediction in part (c) by reasoning that ladybug predation on aphids would decrease the abundance of aphids, which would decrease virus transmission to the plants (Skill 6.C; LO SYI-1.H).

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

- Many responses correctly described the relationship between ecosystem resilience and decreased species diversity (Skill 1.A; LO SYI-3.F)
- Fewer responses correctly explained how the introduction and density of an invasive species (wild oat) affects the available resources or the ecosystem dynamics among the aphids, viruses, and the native bunchgrass (Skill 1.C; LO SYI-1H, SYI-2A).
- Many responses correctly predicted how introducing a species (ladybugs) in an ecosystem affects other species in the ecosystem (Skill 6.E; LO ENE-4.B).
- Few responses justified correctly or completely the effect of introducing ladybugs into the California grassland by using the provided evidence (Skill 6.C; LO SYI-1.H).
- Few responses used clear terminology to describe directions of changes in the ecosystem (Skills 1.A, 1.C, 6.E).

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Misconception: Ecosystem resilience was frequently equated with genetic diversity.	• "The resilience of an ecosystem decreases when there is a decrease in the number of species."

• Misconception: The effect of an invasive species on native species is that invasive species thrive because they don't have natural predators. • Misconception: Carrying capacity was equated with resources. • Misconceptions: When a species is removed, the remaining species become more resilient, as compensation.	• "The wild oat acts as a competitor of the native bunchgrass using the same resources; water, soil, sunlight; that the bunchgrass does." • "The addition of the common wild oat in California decreases the number of native bunchgrass plants because they are competing for the same resources – water, soil, space and sunlight." • "An ecosystem becomes less resilient when there is a decrease in the number of species because each species contributes something to the ecosystem."
• Knowledge gap: Many responses demonstrated the inability to understand interspecific interactions in an ecosystem. • Skill gap: Many responses demonstrated the inability to justify, based on evidence, how the introduction of ladybugs affects other species that are present in the grassland ecosystem. • Skill gap: Many responses demonstrated the inability to choose a term to demonstrate directionality of changes in the ecosystem.	• "The ladybugs will eat and reduce the aphid population, thus only a smaller remaining population of aphids will be able to infect the native bunchgrasses." • "This is because the ladybugs will decrease the number of aphids. Aphids carry viruses that affect and hurt the native bunchgrass plants. This would reduce the deaths from the viruses." • "The addition of ladybugs will cause the native bunchgrass population to increase."

Based on your experience at the AP® Reading with student responses, what advice would you offer teachers to help them improve student performance on the exam?

- Provide sample questions where various task verbs are used all year long.
    - **TIP:** Let students score each other's responses and as a class look at sample responses with correct answers aligned with the task verbs in the CED.
    - **TIP**: Model the task verbs during assessments.
    - **TIP:** Use the definitions of task verbs provided in the CED for clarification with your students.
- Practice interspecific relationships among multiple species in an ecosystem.
    - **TIP**: Let groups of students use white boards or poster paper to create visual models of interspecific interactions from written text.
    - **TIP**: Use disruptions to model changes in ecosystems with predictions and justifications.
    - **TIP**: Use primary research data, field studies, or laboratory activities to analyze data on interspecific relationships in ecosystems.
        - Primary research papers can be "jig sawed" in class by dividing up segments of a paper, and students in groups can discuss the various parts of the paper with each other.
- Use words and phrases from the learning objectives and essential knowledge statements throughout the school year so that students are familiar with college-level biology terminology.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

From AP Classroom:

- Progress Checks from Unit 8
- AP Daily Video, Topic 8.4 and 8.6 as well as Faculty Lecture 8
- Topic Questions from Topics 8.4 and 8.6 for formative assessments
- Use analysis-level questions with visuals on assessments where appropriate and applicable.

Question 5

Task: Analyze Model or Visual Representation of a Biological Concept or Process
Topic: *ag* Gene Evolution
Max Score: 4
Mean Score: 0.80

What were the responses to this question expected to demonstrate?

Question 5 presented a figure illustrating the basic structure of an *ag* gene, which encodes an antifreeze glycoprotein in the Gadidae, the cod family of fish. A second figure showed a phylogenetic tree illustrating the evolution of *ag* genes in ten species of fish as well as the average water temperature of the habitat in which each species is typically found.

Responses to part (a) were expected to describe a post-zygotic mechanism that prevents gene flow (Skill 1.A; LO EVO-3.F).

Responses to part (b) were expected to explain that the addition of regulatory elements (promoter, *ag* repeat sequence, 3′ untranslated region) to a non-coding region of the genome led to the development of functional genes that enabled cod to survive and reproduce after a period of freezing temperatures (Skill 2.B; LO EVO-3.A).

In part (c), responses were expected to represent the origin of the functional *ag* gene by marking the correct location on a template of the phylogenetic tree (Skill 2.D; LO EVO-3.B).

Responses to part (d) were expected to explain how genetic differences among species represented in the phylogenetic tree determine the habitats in which the species can survive (Skill 2.C; LO EVO-1.E).

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

- While some responses correctly described an acceptable post-zygotic mechanism (e.g., hybrid inviability, hybrid infertility), many responses confused pre-zygotic and post-zygotic mechanisms. Additionally, many responses confused the “identify” task verb with “describe” (Skill 1.A; LO EVO-3.F).
- Few responses fully explained how changes to the genome enabled cods to survive and reproduce after a period of freezing temperatures in the evolutionary record. Many responses recognized that natural selection must have been acting on the antifreeze-glycoprotein phenotype. However, few responses articulated that the emergence of the new *ag* gene that encodes the glycoprotein was due to addition of necessary regulatory elements to the genome, demonstrating a lack of understanding of the role of regulatory elements in gene expression (Skill 2.B; LO EVO-3.A).
- While many responses attempted to represent the origin of the functional *ag* gene on the provided phylogenetic tree (Figure 2), few responses indicated the correct origin, demonstrating an incomplete understanding of how to interpret a phylogenetic tree that includes genetic evidence (Skill 2.D; LO EVO-3.B).
- Few responses fully explained how genetic differences determine in which habitats cod can survive over evolutionary time. Many responses equated the presence of an antifreeze-glycoprotein gene sequence with functionality of the antifreeze glycoprotein, demonstrating a lack of understanding of the role of regulatory elements in gene expression. Additionally, many responses demonstrated an inability to articulate specific evidence using Figure 2 to explain why different groups of cod could inhabit water of different average temperatures (Skill 2.C; LO EVO-1.E).

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Knowledge Gap: Describing a post-zygotic mechanism that prevents gene flow between populations.	• "Infertile offspring prevents gene flow because if an offspring is infertile, it can't spread its genes, enabling speciation."
• Misconception: The presence of the coding region of a gene is enough to result in translation of a functional protein.	• "The genome gained a promoter, ag repeat sequences, and 3′ UTR, which allowed functional ag genes to be created."
• Misconception: Exposure to colder (or warmer) habitats drove the evolution (or lack thereof) of functional *ag* genes (and thus the production of antifreeze glycoproteins), rather than natural selection acting on individuals that possessed functional *ag* genes that enabled the production of antifreeze glycoproteins.	• "Cod species with ag-encoded proteins can survive in near-freezing habitats because the antifreeze glycoprotein lowers their bodies freezing point, while those species without the genetic code to produce antifreeze glycoproteins can only survive in warmer habitats."
• Skills Gap: Identifying a post-zygotic mechanism instead of describing it.	• "Reduced hybrid fertility occurs when two individuals are unable to successfully... create offspring."
• Skills Gap: Writing complete explanations.	• "Genetic differences, namely the presence or absence of a fully functional coding AG gene, influence the habitat in which the fish can survive because fish with the functional coding AG gene can survive in much colder temperatures than fish without a coding version of that gene."

Based on your experience at the AP® Reading with student responses, what advice would you offer teachers to help them improve student performance on the exam?

- Prepare students to synthesize content from across Big Ideas.
  - **TIP**: Using samples of FRQs from the AP Classroom Question Bank may assist students with understanding content that cuts across multiple concepts. This will support their efforts when responding to questions that incorporate content from more than one of the four Big Ideas.
- Student responses showed confusion about what they were being asked to explain in parts (b) and (d) of the question.
  - **TIP**: Use FRQs from the AP Classroom Question Bank to assist students in determining what the question is asking them to do.
    - Highlight the specificity of each of the task verbs as described in the CED.
- Ask students to practice answering questions with Science Practice 6: Argumentation.
  - **TIP**: Coach students to fully support claims with evidence (SP 6.B) and provide complete reasoning to justify a claim (SP 6.C).
- Provide complex figures and diagrams for analysis.
  - **TIP**: Model the analysis of complex figures with students.
  - **TIP**: Have students identify parts of visual models that will support a hypothesis or prediction.
  - **TIP**: Introduce disruptions in complex models to enable students to make predictions and justifications related to the disruptions.
  - **TIP**: Let students create simple and complex figures from written descriptions.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

From AP Classroom:

- Progress Checks from Unit 7
- AP Daily Videos, Topics 7.2, 7.8, 7.9, and 7.10, as well as Faculty Lecture 7
- Topic Questions from Topics 7.2, 7.8, 7.9, and 7.10 for formative assessments

From the AP Biology Online Teacher Community:

- Data resources outlined in the *Online Resources Recommended by AP Teachers*

Question 6

Task: Analyze Data
Topic: Ribosome Profiling
Max Score: 4
Mean Score: 1.67

What were the responses to this question expected to demonstrate?

Question 6 explained how scientists use ribosome profiling to measure translation rates and presented data in the form of frequency distributions of translation rates for three different codons.

Responses to part (a) were expected to identify the translation rate recorded most often for the GAC codon (Skill 4.B).

Responses to part (b) were expected to "describe the variation in translation rate of the AUU codon compared with that of the UGG codon," based on the data (Skill 4.B).

Part (c) presented a hypothesis that "tRNA molecules that bind to UGG codons are available in lower abundance than are tRNAs that bind to AUU codons." Responses were expected to support the hypothesis using the data in the frequency distributions (Skill 5.D).

Part (d) explained that "amino acids can be encoded by multiple codons," and that "certain codons for the same amino acid occur more frequently in an mRNA than do other codons." Responses were expected to explain that the use of codons that are translated at faster rates than others would result in increased levels of protein production (Skill 6.D; LO IST-1.O).

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

- Many responses correctly identified the rate associated with the tallest bar on the histogram (Skill 4.B).
- Many responses accurately compared variation in rates illustrated in two graphs (Skill 4.B).
- Some responses demonstrated an ability to interpret graphed translation rates with the units ms/codon as being faster or slower and used that pattern to support a hypothesis about translation (Skill 5.D; LO IST-1.0).
- Some responses demonstrated an ability to use data from the graph to explain that codons having a faster translation rate would increase protein production (Skill 6.D; LO IST-1.0).

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Skills/Knowledge Gap: Variation in a data set is a distinct characteristic, different from the mean or distribution. Some responses described the mean or distribution instead of, or in addition to, the variation.	• "There is less variation in translation rate of AUU codon compared to the translation rate of the UGG codon. AUU has a range of 400 ms/codon and goes from 50–450 ms/codon , while UGG has a larger range of 900 ms/codon and ranges more widely from 50–950 ms/codon ."

• Skills Gap: A histogram is a specific kind of bar graph that shows the variable of interest on the x-axis and the number of observations on the y-axis. Some responses used the height of the bars as support for the hypothesis rather than an interpretation (faster/slower) of the average/typical translation rates, which was the x-axis variable.	• "Graphs B and C show that AUU codons take less time on average to translate than UGG codons, suggesting that tRNA molecules for AUU are more abundant than tRNA for UGG codons. This can be inferred since greater abundance of tRNA could cause faster translation."
• Skills Gap: Interpreting the units on a graph—in this case, a high value of ms/codon means a slow rate of translation.	• "There are much higher translation rates recorded for UGG which means that those processes took much longer, while AUU translation rates are lower meaning they translated faster." • "The scientists' claim that the tRNA that binds to the UGG codon is less abundant than those that bind to the AUU codon is supported by the lower mean rate in ms/codon of AUU to that of UGG , meaning less time is used on average to bind tRNA to AUU codons than UGG ."
• Knowledge Gap: Understanding that translation involves tRNA bringing an amino acid to a ribosome/mRNA complex where it binds and adds that amino acid to a protein that is being produced.	• "The UGG codons have a slower average rate because the tRNA to translate mRNA to amino acids is less abundant. This means, it takes longer for the amino acid to be brought to the corresponding codon."

Based on your experience at the AP® Reading with student responses, what advice would you offer teachers to help them improve student performance on the exam?

- Provide opportunities to interpret types of graphs other than bar graphs and line graphs (listed in Skill 4.A).
  - **TIP:** Incorporate beginning-of-class "do now" and end-of-class "exit tickets" where students are using examples of various types of graphs to identify data points and describe various patterns (variation, distribution, mean/median/mode).
  - **TIP:** Have students graph using a data set, then develop questions that use the "identify" and "describe" task verbs.
    - In a graph-and-switch activity, partners could give peer feedback on the graph and answer the questions that were developed.
  - **TIP:** Use free available resources that have lessons, and practice with graphing and data analysis.
- Have students graph/analyze/interpret their own data to help them connect data to concepts.
  - **TIP:** Use guided and open inquiries, where students hypothesize, design and conduct experiments, and evaluate their own claims and hypotheses using data they collected.
- Have students model the processes of transcription and translation.
  - **TIP:** Let students use whiteboards or chart paper to model the processes of transcription and translation, adding disruptions that might impact the processes.
    - Have students predict and justify outcomes of added disruptions.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

From AP Classroom:

- Progress Checks from Unit 6
- AP Daily Videos, Topics 6.4 as well as Faculty Lecture 6
- Topic Questions from Topics 6.4 for formative assessments

From the AP Biology Online Teacher Community:

- Data resources outlined in the *Online Resources Recommended by AP Teachers*
- For graphing supports and practice, utilize the resources within the Quantitative Skills Guide