Chief Reader Report on Student Responses:

2022 AP® Biology Free-Response Questions

- Number of Students Scored 237,338
- Number of Readers 902
- Score Distribution

Exam Score	N	%At
5	35,675	15.0
4	54,931	23.1
3	70,579	29.7
2	51,289	21.6
1	24,864	10.5

- Global Mean 3.11

The following comments on the 2022 free-response questions for AP® Biology were written by the Chief Reader, Amy Dykstra, Professor of Biological Sciences, Bethel University, with assistance from Operational Exam Leader John Mager, Ohio Northern University, and Question Leaders Jody Saxton West (Q1), Robert Benedetto (Q2), Ross Sappenfield (Q3), Amy Doling (Q4), Darla French (Q5), and Cynthia Beale (Q6). The comments give an overview of each free-response question and of how students performed on the question, including typical student errors. General comments regarding the skills and content that students frequently have the most problems with 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: Cholera toxin effects
Max Score: 9
Mean Score: 2.26

What were the responses to this question expected to demonstrate?

Question 1 described a G protein-related signal transduction pathway that stimulates the secretion of chloride ions from intestinal cells. The stimulus of the question then described an experiment designed to determine how cholera toxin affects the pathway and presented experimental results in tabular form.

In part (a) test takers were asked to demonstrate understanding of the structure of cellular membranes (Learning Objective ENE-2.C from the AP Biology Course and Exam Description) and explain why transport of an ion across a membrane results in the loss of water from the cell (Learning Objective ENE-2.H).

Responses to part (b) were expected to demonstrate understanding of the design of the experiment (Science Practice 3.C).

In part (c) responses were expected to describe the effect of cholera toxin, based on the experimental data (Science Practice 4.B) and perform a calculation based on the data (Science Practice 5.A).

Part (d) presented two disruptions: a drug that binds to cholera toxin and a mutation to the gene encoding adenylyl cyclase, an enzyme in the signal transduction pathway. Responses were expected to apply understanding of signal transduction pathways (Learning Objectives IST 3.C and IST 3.D) to predict the effect of the drug (Science Practice 6.E) and justify a scientist's claim about the effect of the mutant enzyme (Science Practice 6.C).

How well did the responses address the course content related to this question? How well did the responses integrate the skills required on this question?

<u>Membranes and Transport</u>

- Many responses correctly described membrane structure, indicating that cell membranes are composed of a phospholipid bilayer, and phospholipids are composed of hydrophilic (polar) heads and hydrophobic (nonpolar) tails, but some responses did not demonstrate an understanding of which specific characteristic of the structure of the membrane determines how ions interact with the membrane and their environment.
- Many responses demonstrated confusion about how and why relative concentrations of solutes inside and outside the cell resulted in water moving out of the cell.

<u>Experimental Design</u>

- Many responses correctly identified an independent variable, but some responses identified only one of the options (e.g., cholera toxin) rather than the range of options (presence or absence of cholera toxin). Other responses confused independent and dependent variables.
- Many responses correctly identified a negative control in the experiment.
- Some responses correctly justified the use of a given sample as a control treatment in the experiment, but many responses did not demonstrate an understanding of how to use the control as a baseline for comparison with another sample to arrive at a conclusion.

Data Analysis

- Many responses correctly described data from a data table, including the relationships between independent variables (alone and in concert) and their effect on the dependent variable.
- Some responses correctly calculated the expected percent change in the rate of cAMP production; however, many responses performed incorrect calculations despite selecting the correct data.

Signal Transduction Pathways/Interpreting Models and Representations

- Many responses demonstrated an ability to read and understand the model of a signal transduction pathway and synthesize that model with the data in the table to make supportable predictions of the rate of cAMP production in novel scenarios (introduction of a drug, mutation to a gene encoding an enzyme).
- Few responses gave a complete justification of the claim as to the impact of a disruption to the signal transduction pathway.

Integrating the Skills Required on this Question

- Many responses demonstrated an ability to synthesize information from the figure and the related data table.
- Responses indicated an effort to answer all parts of the question.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Misconceptions: Cl^- is too large to fit through the membrane unassisted; Cl^- is repelled by the charged phospholipid heads.	• "The charged chlorine ion cannot interact with the hydrophobic tails of the phospholipid, so it requires a chemically-compatible channel protein in order to diffuse across the interior of the membrane."
• Misconception: When substances require a protein for transport across a membrane, it is always active transport and/or because the substance is moving against its concentration gradient.	• "The presence of a channel protein allows the charged chloride ions to be passively transported (no ATP is required)."
• Misconception: A sample that serves as a control treatment provides the key piece of data to answer the experimental question, as opposed to serving as a baseline for comparison with another sample to gain an understanding of the relationship between variables.	• "Sample III tells us the rate of cAMP production with only cholera toxin (and no GTP). When this rate is compared with a sample containing BOTH cholera toxin AND GTP (sample IV), we can see that GTP is required for the cholera toxin to have an effect."
• Knowledge Gap: Knowing how to calculate percent change (this formula is not provided on the AP Biology Equations and Formulas resource sheet).	• "Percent change is (final (Sample IV) - initial (Sample II))/ initial (Sample II), so $(127-10)/10 \times 100 = 117/10 \times 100 = 11.7/10 \times 100 = 1{,}170$. So, the percent change in the presence of the cholera toxin is an increase of 1,170%."

• Skill Gap: Ability to write a complete justification of a claim based on a model of a process.	• "If there is mutant adenylyl cyclase in the cell, then even if cholera and GTP are present, the mutant adenylyl cyclase will block the production of $cAMP$. This means the protein kinase won't be activated by $cAMP$, so the PK won't result in the secretion of Cl^-, and there won't be the excessive water loss."

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

Membranes and Transport

- Have students consider the chemistry and structure of the fluid mosaic model, both the individual components and as a whole, and connect this structural knowledge to the function of transporting substances across the membrane. Provide students with scenarios containing various descriptions of substances crossing membranes (such as moving with a gradient versus against a gradient or moving charged/polar/hydrophilic substances versus uncharged/nonpolar/hydrophobic substances), and have the students describe the transport mechanism (such as passive versus active transport or requiring a protein versus passing directly through the phospholipid bilayer itself). Have the students practice using vocabulary to describe differences in relative concentration (hypotonic, hypertonic), as well as give meaning to terms such as (high versus low) osmolarity, solute potential, and water potential. Consider having students label diagrams to visualize the meanings of these concepts, and then explain how these differences motivate the movement of water and other substances.

Experimental Design

- Teach students about the various types of controls (positive, negative, as a baseline for comparison). Provide students with descriptions of experiments, and have them identify the various types of controls; provide students with an experimental question, and have them design an experiment that includes relevant types of controls.

Data Analysis

- To demonstrate to students how information-rich data tables are, provide students with a data table and no other description of an experiment, and have them use the data table title, headings, units, etc., to describe the "story" of the information provided, including relationships among variables.
- Teach students common analytical calculations, such as percent change, that are not included on the AP Biology Equations and Formulas resource sheet.

Signal Transduction Pathways/Interpreting Models and Representations

- Provide students with a labeled model of a signal transduction pathway (or other multistep process) without any additional descriptions or explanations, and have them describe or explain the pathway, making connections between pathway components.
- Additionally, provide students with a description of a pathway or process, and have them sketch a labeled diagram that represents the components and relationships described. These activities allow students to see the connections between descriptions of pathways/processes and the models used to represent them.
- Have students make predictions about the effects of potential disruptions to models, including justifying their predictions using evidence and reasoning.

General

- Reinforce topics taught earlier in the course, such as biochemistry, as you progress through units, making connections between topics.

- Provide opportunities to apply each science practice to multiple topics to reinforce the importance and utility of each skill.

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

- Teachers should guide students in designing experiments to teach and reinforce this type of complex experimental design with many samples serving as controls in various capacities.
- Teachers should direct students to AP Daily Videos from Topics 2.5 and 2.8 as well as Topic 4.2.
- Teachers should direct students to Higher Ed Faculty Lecture number 4.
- Teachers should assign topic questions, as well as progress-check items, to monitor progress being made in the mastery of content.
- To prepare students to meaningfully interact with data and experimental design, teachers should utilize the suggested data resources outlined in the Online Resources Recommended by AP Teachers.

Question 2

Task: Interpreting and Evaluating Experimental Results with Graphing
Topic: Double-strand breaks and crossing over
Max Score: 9
Mean Score: 2.83

What were the responses to this question expected to demonstrate?

Question 2 presented a figure showing that double-strand breaks in chromatids may result in crossing over or may be repaired without crossing over. The stimulus also included a table of data comparing the number of double-strand chromatid breaks with the average number of crossovers in several strains of corn.

Responses to part (a) were expected to describe that enzymatic hydrolysis between nucleotides is the process by which the double-strand breaks occur (Learning Objective SYI-1.B).

In part (b) responses were expected to graph the data from the table in an X,Y plot, using appropriate axis scaling and accurate error bars (Science Practice 4.A). Responses were also expected to use the error bars to determine whether three of the strains of corn differed in their average number of crossovers (Science Practice 5.B).

Responses to part (c) were expected to describe the positive relationship between the average number of double-strand breaks and the average number of crossovers in the strains of corn analyzed in the experiment (Science Practice 4.B).

The prompt of part (d) explained that physical connections between homologous chromosomes are required for their proper separation. Responses were expected to demonstrate understanding of chromosomal inheritance by predicting that, if crossing over only occurs among three of four pairs of homologous chromosomes in a diploid cell, two daughter cells will have three chromosomes and two daughter cells will have five chromosomes. Responses were also expected to justify the prediction by providing the reasoning that one pair of homologous chromosomes would not separate during meiosis I, and all chromatids would separate normally during meiosis II (Learning Objective SYI-3.C). Finally, responses were expected to explain that plant breeders could breed strains with high numbers of crossovers to increase genetic variation (IST-1.H).

How well did the responses address the course content related to this question? How well did the responses integrate the skills required on this question?

Molecular Genetics

- Many responses indicated a strong familiarity with the general structure of a DNA molecule.
- Responses often demonstrated confusion regarding which molecules make up a nucleotide and how nucleotides are connected, i.e., that covalent bonds hold together adjacent nucleotides in the backbone of the molecule.
- Many responses indicated familiarity with crossing over, when it occurs, and the genetic outcome (increased recombinants). The task in the question, however, required an understanding of the process by which these breaks may occur.
- A majority of responses indicated an understanding of the meiotic process of producing haploid cells from diploids (with some confusion of terms, i.e., chromosomes and chromatids), however the indicated task required that responses describe the process when a disruption (nondisjunction) occurs. Very few responses were able to accomplish this.
- Approximately half of the responses correctly indicated that homologous pairs were separated in meiosis I, and sister chromatids were separated in meiosis II.
- Most responses were not precise with word usage. The result was difficulty in creating a "biological argument." This was problematic as responses often equated "varieties" and "variation," which were not interchangeable in the context of the question.

Graphing and Data Analysis

- Responses demonstrated that there is basic understanding of graphing; however, responses were less proficient at graphing to discover correlations than at graphing independent and dependent variables. The question attempted to clarify this by prelabeling the axes, however many responses did not properly use this information to generate the appropriate graph type.
- Responses indicated that there are issues with axis scaling. These range from understanding whether or not the origin *must* be zero, to planning ahead, to being careful about being accurate. Responses often scaled the x-axis with the correct values listed in the data table but did not place the appropriate spacing between these values (i.e., values for "Number of Double-Strand Breaks" were treated as bins/categories).
- Responses indicated confusion about the type of graph that should be used for a particular type of analysis. In this question, respondents were instructed to construct a graph that "allows examination of a possible correlation between double-strand breaks and crossovers." Many responses incorrectly constructed a bar graph or line graph rather than an X,Y graph.
- Responses indicated a continuing trend toward being able to accurately graph error bars. There is a lag (although improving) in connecting the actual placement of error bars on a graph and the drawing of proper conclusions.
- Responses overwhelmingly demonstrated the ability to correctly identify and describe the relationships between variables within the context of this particular data set.

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: Chromosomal breaks (at chiasmata) and crossing over are not the same as, nor do they occur during, DNA replication.	• "[I]n meiosis, synapsis occurs between two homologous chromosomes which exchange genetic information at sites called chiasmata."
• Misconception: Hydrogen bonds hold together sequential nucleotide monomers.	• "Breaks break the phosphodiester bonds that hold the DNA nucleotides together along the backbone."
• Knowledge Gap: Responses demonstrated an adequate understanding of biological processes (i.e., meiosis). Responses could dictate the "script" of these processes. However, there was a gap in understanding what may happen when these processes are disrupted.	• "In two of the haploid cells, five chromatids will be present while only 3 chromatids will be present in the other two cells. This is called nondisjunction and would occur because the lack of crossing over in a pair of chromosomes led to an uneven amount of chromosomes in each cell after meiosis I. Thus, after meiosis II and the chromosomes have all separated, [the daughter cells] will have an uneven number of chromatids."
• Skill Gap: Responses demonstrated a skill gap in applying data to a novel situation in order to produce a desired outcome, in this case using the data to explain a process that could be implemented to increase the likelihood that new variants could arise.	• "If the breeder breeds two strains of corn that both have high averages of the number of crossovers, the genes of the corns will mix more and the offspring of the corn will be more genetically diverse … [the offspring] can then eventually become its own new variety of corn."

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

Molecular Genetics

- Have students use physical models to manipulate DNA molecules and chromosomes. It is important that they not only "construct" these polymers but model how the pieces interact and understand the limitations/characteristics of the structure.

Graphing and Data Analysis

- Expose students to all types of graphs.
- Have students construct all types of graphs and justify why they choose a particular type.
- Provide students with data sets, and have them graph the data sets in different ways and then determine what the data are communicating and what conclusions could be drawn. Allow them to critique one another's choices/decisions.

General

- Spend less class time explaining and describing the intricate details of complex biological processes (such as meiosis). Students have plenty of resources (text/videos/online interactives) to be exposed to the basics. Use class time to add disruptions to these processes, and have students make predictions as to how a process would be altered and justify those predictions. They can also hypothesize what disruptions would need to occur in order to obtain a desired outcome. If possible, completing these tasks in a laboratory setting would be ideal.
- Provide students with data sets or conclusions from a scientific study/experiment, and require them to use this information to solve novel problems or apply them to novel situations.

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

- Teachers should direct students to AP Daily Videos from Topics 1.3, 5.2, and 5.6.
- Teachers should direct students to Higher Ed Faculty Lectures numbers 1 and 5.
- Teachers should incorporate Science Practice 4.A into lessons where appropriate and often, taking into consideration the various types of graphs and graphing skills on which students may be assessed on the exam.
- Teachers should assign topic questions, as well as progress-check items, to monitor progress being made in the mastery of content.
- For graphing supports and practice, utilize the resources within the Quantitative Skills Guide.
- To prepare students to meaningfully interact with data and experimental design, teachers should utilize the suggested data resources outlined in the Online Resources Recommended by AP Teachers.

Question 3

Task: Scientific Investigation
Topic: Luciferase activity
Max Score: 4
Mean Score: 1.43

What were the responses to this question expected to demonstrate?

Question 3 described the chemical reaction that produces light in fireflies and presented the chemical equation. The stimulus also described a scientific investigation designed to determine the effect of temperature on the reaction in a solution containing ATP, the substrate D-luciferin, and the enzyme luciferase.

Responses to part (a) were expected to describe that luciferin has an active site compatible with its substrate (Learning Objective ENE-1.D).

Responses to part (b) were expected to identify the amount of light emitted as the dependent variable (Science Practice 3.C).

Responses to part (c) were expected to state the null hypothesis of the experiment (Science Practice 3.B).

Responses to part (d) were expected to support the claim that increased temperature results in an increase in light emitted by demonstrating an understanding that, as molecular movements increase, more collisions between the substrate and enzyme will occur (Learning Objective ENE-1.G).

How well did the responses address the course content related to this question? How well did the responses integrate the skills required on this question?

- Many responses described the substrate-specific shape found on an enzyme and frequently used "active site" properly in the context of the response.
- Many responses demonstrated an understanding that enzymes lower the activation energy of a reaction but did not describe the characteristics of the actual enzyme (and relationship to the substrate) that allows this to occur.
- Many responses demonstrated an understanding that increasing temperature speeds up reactions but often did not describe how or why this happens at the molecular level.
- Most responses identified the independent variable of the reaction correctly.
- Many responses included a correctly written null hypothesis for this experiment.

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: This experiment was conducted on living organisms.	• "[T]he temperature in the experimental environment has no effect on the amount of light emitted."
• Knowledge Gap: Writing a description of a structure or function rather than stating a word or a phrase.	• "[T]he enzyme has an active site with the proper shape and charge to bind to the substrate similar to how a lock can accept only one key."
• Knowledge Gap: Describing biochemical interactions at a molecular level.	• "[P]articles move faster because there is more kinetic energy so the enzyme and substrate are more likely to collide … so the reaction will occur more frequently."

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

Cellular Energetics—Enzyme Structure and Function

- Use images and molecular models to make abstract biochemistry more concrete.

Experimental Methods

- Identify and discuss the use of and reason for an independent variable, dependent variable, controls (positive and negative), and a null hypothesis during every lab.

General

- Avoid accepting analogies and phrases as proof of understanding. Many students can use terms like "lock and key," "lowers activation energy," and "induced fit" without molecular-level comprehension and do not demonstrate knowledge of content.

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

- Teachers should direct students to AP Daily Videos from Topics 3.1 and 5.3.
- Teachers should direct students to Higher Ed Faculty Lecture number 3.
- Teachers should assign topic questions, as well as progress-check items, to monitor progress being made in the mastery of content.
- To prepare students to meaningfully interact with data and experimental design, teachers should utilize the suggested data resources outlined in the Online Resources Recommended by AP Teachers.

Question 4

Task: Conceptual Analysis
Topic: Trout populations
Max Score: 4
Mean Score: 1.08

What were the responses to this question expected to demonstrate?

Question 4 described isolated brook trout populations that differ morphologically and genetically.

Responses to part (a) were expected to describe that geographic isolation serves as a prezygotic barrier and prevents gene flow among the trout populations (Learning Objective EVO-3.F).

Responses to part (b) were expected to explain that trout with longer fins have higher fitness than do shorter-finned individuals, because those with longer fins are more likely to catch their prey and reproduce (Learning Objective EVO-1.E).

Responses to part (c) were expected to predict that populations that remain isolated for many generations will become separate species (Learning Objective EVO-3.D).

Responses to part (d) were expected to justify the claim that there are more genetic differences between any two current brook trout populations than there are between any single current population and the ancestral brook trout population by explaining divergent evolution (Learning Objective EVO-3.E).

How well did the responses address the course content related to this question? How well did the responses integrate the skills required on this question?

Prezygotic Barrier

- Many responses correctly identified the prezygotic mechanism; however, some responses did not link the geographic isolation to the prevention of gene flow.

Predator–Prey Relationship

- Many responses correctly identified the predator–prey relationship.
- Some responses did not properly identify the trout as the predator and the fast-swimming fish as the prey.

Speciation

- Most responses demonstrated an understanding of the biological concept of species.
- Most responses did not fully justify why accumulation of mutations would differ as a result of different selective pressures or genetic drift.

Fitness

- Some responses explained the link between fitness and reproduction; some responses did not explain that fitness is linked to increased reproduction.

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: Predators consume prey. • Knowledge Gap: Increased fitness is linked to increased reproduction.	• "[L]onger-finned trout can move faster and more easily catch their fast-moving prey than shorter-finned trout, so they have more fitness because they are better adapted to survive and reproduce."
• Skill Gap: Knowing how to write a complete justification.	• "[T]hey split from each other as the frequency of alleles changed based on their environment … so they are more different from each other than from their ancestors."

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

- Emphasize that natural selection requires differential reproductive success, not just survival of the fittest.
- Provide students with scenarios of groups of related species, and ask the students to explain how evolutionary processes have resulted in the different species.
    - **TIP:** Have students work in small groups to construct diagrams illustrating how one ancestral species can diverge into multiple species over evolutionary time.
- Provide descriptions of ecological relationships, and ask students to construct food webs based on the descriptions.

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

- Teachers should direct students to AP Daily Videos from Topics 7.2 and 7.10.
- Teachers should direct students to Higher Ed Faculty Lecture number 7.
- Teachers should assign topic questions, as well as progress-check items, to monitor progress being made in the mastery of content.
- To prepare students to meaningfully interact with data and experimental design, teachers should utilize the suggested data resources outlined in the Online Resources Recommended by AP Teachers.

Question 5

Task: Analyze Model or Visual Representation of a Biological Concept or Process
Topic: Human effects on communities
Max Score: 4
Mean Score: .99

What were the responses to this question expected to demonstrate?

Question 5 presented models of the food webs of two communities that differ in species diversity.

Responses to part (a) were expected to describe that invasive species can exploit niches that are free from competitors or predators (Learning Objective SYI-2.A).

Responses to part (b) were expected to explain that removing a primary producer from community B that contains only two primary producers would decrease the energy available to all trophic levels, while removing a primary producer from community A that contains three primary producers would have less effect, because there are more paths for energy to move through community A (Learning Objective SYI-3.F).

Part (c) described an invasive species introduced to community B, the community with lower species diversity. Responses were expected to represent the relationships among the invasive species and other species in the community (Science Practice 2D).

Responses to part (d) were expected to explain that human activities could eliminate primary producers, resulting in reduced species diversity at higher trophic levels of the community (Learning Objective SYI-2.B).

How well did the responses address the course content related to this question? How well did the responses integrate the skills required on this question?

Ecology

- Many responses demonstrated an understanding that existence of natural predators (or lack thereof) would determine whether a species will be invasive in a particular community.
- Some responses demonstrated an understanding that competition (or lack thereof) would determine whether a species will be invasive in a particular community.
- Few responses demonstrated an understanding that disease susceptibility (or lack thereof) would determine if a species will be invasive in a particular community.
- Some responses incorrectly connected greater niche overlap/competition with a greater likelihood of becoming invasive. In fact, increased competition can control population growth of an exotic species, preventing it from becoming invasive.
- Some responses confused “invasive species” with “nonnative” species.
- Many responses demonstrated an understanding that removal of a primary producer species has a detrimental effect on the primary consumer of that species but a lack of understanding that the effect also carries through to all the other trophic levels/the rest of the food web.
- Some responses equated energy input at the primary producer level with overall movement of energy throughout the trophic levels.
- Few responses demonstrated an understanding that differing species diversities in communities could result in differing resiliencies of those communities to future environmental change.
- Many responses demonstrated a lack of proficiency in placing an introduced species into an appropriate trophic level based on a description of the introduced species’ feeding characteristics.
- Some responses demonstrated an understanding that toxin biomagnification could result in a reduction of species diversity at higher trophic levels.

- Many responses demonstrated an understanding that elimination of primary producers would negatively affect a community. However, many responses concluded that population size or genetic diversity would decrease, rather than the more likely result of a reduction in species biodiversity.
- Many responses equated "population" with "community."

Modeling

- Most students appeared willing to work through and answer all parts of the question.
- Most responses demonstrated proficiency in analyzing visual representations at simplified levels. Many responses demonstrated a lack of proficiency in analyzing visual representations at more complex levels.
- Many responses demonstrated a lack of proficiency in representing relationships with a diagram.
- Many responses demonstrated a lack of understanding that explanations require reasoning.
- Many responses demonstrated a lack of understanding that explanations of effects often require a direction (i.e., "it will be affected" is not sufficient—will it be affected negatively or positively?).

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: Removal of a primary producer species has a detrimental effect on the primary consumer of that species, but that effect does not extend to the rest of the food web.	• "Removing PP1 from Community B would mean that PC2 would have no food, essentially killing it off. This would lead to SC2 only having half of its food available, making its population drop & consequently TC2's as well. However, such glaring changes wouldn't occur in Community A because only PC1 solely depends on PP1. PC2 could still eat PP2 … with multiple sources of food, the loss of PP1 would have a much smaller impact on Community A."
• Knowledge Gap: "Population" is an equivalent term to "community."	• "[T]he number of species in the community would decrease throughout all higher levels of the food web."
• Skill Gap: Ability to write a complete explanation that requires a direction.	• "Adding toxins to the soil could harm primary producers directly by decreasing their survival … This effect … could continue up the food web, thus potentially causing species extinctions and a decrease in biodiversity."

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

Ecology

- Emphasize different community characteristics that can determine whether an introduced species will become invasive and provide examples.
- Emphasize that competitive and predatory pressures often prevent exotic species from becoming invasive within a community.
- Emphasize that removal of a primary producer species has a detrimental effect on all higher trophic levels/the rest of the food web, not just the primary consumer trophic level.
- Emphasize how energy moves through a community's trophic levels, and highlight that more diverse communities have more possible pathways for energy movement.
    - **Tip:** Ask students to interact with various models of food webs and food chains and the trophic levels included in those models.
- Explain how species biodiversity leads to community resiliency against future environmental change.
- Provide varying examples of the roles and impacts of introduced and invasive species.
- Distinguish between population size and community biodiversity.
- Distinguish between genetic diversity and (species) biodiversity.

Interactive Modeling

- Use models often.
- Have students summarize, analyze, and/or manipulate a variety of ecological models and use them to draw conclusions.
- Emphasize that explanations often require reasoning.
- Emphasize that explanations of effects often require a direction (i.e., "it will be affected" is not sufficient—does it increase or decrease?).

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

- Teachers should direct students to AP Daily Videos from Topics 8.6 and 8.7.
- Teachers should direct students to Higher Ed Faculty Lecture number 8.
- Teachers should incorporate Science Practice 2.D into lessons where appropriate and often, taking into consideration the various types of diagrams, flow charts, and illustrations students may encounter on the exam.
- Teachers should assign topic questions, as well as progress-check items, to monitor progress being made in the mastery of content.
- To prepare students to meaningfully interact with data and experimental design, teachers should utilize the suggested data resources outlined in the Online Resources Recommended by AP Teachers.

Question 6

Task: Analyze Data
Topic: Effects of cap on mRNA stability
Max Score: 4
Mean Score: 1.57

What were the responses to this question expected to demonstrate?

Question 6 described research aimed at developing RNA vaccines. A data table presented the half-life of mRNAs with various cap structures, as well as the total amount of protein translated from each mRNA.

Responses to part (a) were expected to identify modified cap II as the cap structure most likely to protect mRNA from degradation (Science Practice 4.B).

Responses to part (b) were expected to describe a positive correlation between mRNA half-life and total amount of protein translated (Science Practice 4.B).

Part (c) described the researchers' hypothesis that "each mRNA molecule with modified cap I was translated more frequently than was each mRNA molecule with the normal GTP cap." Responses were expected to make the evaluation that the data supported the hypothesis because the two mRNAs did not differ in half-life, but the amount of translated protein from mRNA with modified cap I was higher than that from mRNA with the normal GTP cap (Learning Objective IST-1.O).

Responses to part (d) were expected to explain that cells are more likely to produce foreign proteins from introduced mRNA than from introduced DNA because the mRNA can be directly translated, while the cell may not be able to transcribe the DNA or correctly process the transcripts produced from the introduced DNA (Learning Objective IST-2.C).

How well did the responses address the course content related to this question? How well did the responses integrate the skills required on this question?

Data Analysis

- Many responses were proficient in identifying information provided in a data table.
- Many responses were proficient in describing relationships and trends provided in a data table.
- Many responses demonstrated a lack of proficiency in interpreting the statistical data provided.

Molecular Genetics

- Many responses were proficient in explaining the differences between mRNA and DNA in steps required for protein production.
- Many responses demonstrated an understanding of the processes of transcription and translation. However, some responses confused processes involved in protein synthesis and which molecule was responsible for which part of the process.
- Some responses demonstrated a proficent understanding of regulation of gene expression.

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: Data with overlapping error bars indicate that data are similar, but not the same.	• "mRNA with the GTP cap and mRNA with modified cap 1 have the same half-life statistically, but modified cap 1 produces a statistically greater amount of protein."
• Misconception: Methods of regulation of gene expression do not need to be considered when inducing a genetically modified cell to create foreign proteins.	• "Production of foreign proteins is more likely with foreign mRNA than DNA because the DNA would have to go through the extra step of transcription, which often only happens in a significant amount in the presence of the right transcription factors."
• Misconception: mRNA uses the process of transcription to make protein.	• "The production of foreign protein will be more likely from the introduction of mRNA because the codons in mRNA are directly translated into an amino acid sequence and dictate the amino acids chosen while DNA codons must first be transcribed into a complementary mRNA strand, processed, and then translated."

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

Data Analysis

- Provide students with data tables that include standard errors.
    - **Tip:** Ask students to interpret the data using correct statistical terminology.

Molecular Genetics

- Have students model the steps of different methods of regulating gene expression.
    - **Tip:** Ask the students to explain the implications of gene expression regulation when using mRNA or DNA to produce foreign proteins in a cell.
- Go beyond the basics of DNA → RNA → Protein.

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

- Teachers should direct students to AP Daily Videos from Topics 6.4 and 6.6.
- Teachers should direct students to Higher Ed Faculty Lecture number 6.
- Teachers should incorporate Science Practice 4.B into lessons where appropriate and often, taking into consideration the various types of graphs that students will be asked to analyze on the exam.
- Teachers should assign topic questions, as well as progress-check items, to monitor progress being made in the mastery of content.
- For graphing supports and practice, utilize the resources within the Quantitative Skills Guide.
- To prepare students to meaningfully interact with data and experimental design, teachers should utilize the suggested data resources outlined in the Online Resources Recommended by AP Teachers.