

Teacher Preparation Notes for "Evolution by Natural Selection"¹

In this minds-on, hands-on activity, students develop their understanding of natural selection by analyzing specific examples and carrying out a simulation. The questions in the first section introduce students to the basic process of natural selection, including key concepts and vocabulary. The second section includes a simulation activity, data analysis, and questions to deepen students' understanding of natural selection, including the conditions that are required for natural selection to occur. In the third section, students interpret evidence concerning natural selection in the peppered moth and answer questions to consolidate a scientifically accurate understanding of the process of natural selection, including the role of changes in allele frequency. (Analysis and discussion versions of the first and third sections are available at <https://serendipstudio.org/exchange/bioactivities/NaturalSelectionIntro> and <https://serendipstudio.org/exchange/bioactivities/NaturalSelectionMoth>.)

We estimate that it will take roughly 150-200 minutes to complete all three sections of this activity.

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Learning Goals

In accord with the Next Generation Science Standards² and A Framework for K-12 Science Education³:

- Students will gain understanding of two Disciplinary Core Ideas:
 - LS4.B Natural Selection. "Natural selection occurs only if there is both (1) variation in the genetic information between organisms in the population and (2) variation in the expression of that genetic information – that is, trait variation – that leads to differences in performance among individuals. The traits that positively affect survival are more likely to be reproduced, and thus are more common in the population."
 - LS4.C Adaptation. "Natural selection leads to adaptation, that is, to a population dominated by organisms that are anatomically, behaviorally, and physiologically well suited to survive and reproduce in a specific environment. That is, the differential survival and reproduction of organisms in a population that have an advantageous heritable trait leads to an increase in the proportion of individuals in future generations that have the trait and to a decrease in the proportion of individuals that do not."

¹ by Drs. Ingrid Waldron and Jennifer Doherty, Department of Biology, University of Pennsylvania, © 2025. These Teacher Preparation Notes, the Student Handout for this activity, and an alternative version of the simulation are available at <https://serendipstudio.org/exchange/waldron/naturalselection>.

² <http://www.nextgenscience.org/sites/default/files/HS%20LS%20topics%20combined%206.13.13.pdf>

³ http://www.nap.edu/catalog.php?record_id=13165

Adaptation also means that the distribution of traits in a population can change when conditions change."

- Students will engage in several Scientific Practices:
 - Developing and Using Models: "Develop and/or use a model (including mathematical and computational) to generate data to support explanations, predict phenomena, analyze systems, and/or solve problems."
 - Analyzing and Interpreting Data: "Evaluate the impact of new data on a working explanation and/or model of a proposed process or system."
 - Constructing Explanations and Designing Solutions: "Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena and solve design problems, taking into account possible unanticipated effects."
- This activity provides the opportunity to discuss the Crosscutting Concepts:
 - Cause and effect: Mechanism and explanation – "In grades 9-12, students understand that empirical evidence is required to differentiate between cause and correlation and to make claims about specific causes and effects. They suggest cause and effect relationships to explain and predict behaviors in complex natural and designed systems. They also propose causal relationships by examining what is known about smaller scale mechanisms within the system."
 - Systems and System Models – Students can "use models and simulations to predict the behavior of a system, and recognize that these predictions have limited precision and reliability due to the assumptions and approximations inherent in the models."
 - Stability and Change – "Students understand much of science deals with constructing explanations of how things change and how they remain stable. They quantify and model changes in systems ..."

This activity helps to prepare students for the Performance Expectations⁴:

- HS-LS4-2, "Construct an explanation based on evidence that the process of evolution primarily results from four factors: (1) the potential for a species to increase in number, (2) the heritable genetic variation of individuals in a species due to mutation and sexual reproduction, (3) competition for limited resources, and (4) the proliferation of those organisms that are better able to survive and reproduce in the environment."
- HS-LS4-3, "Apply concepts of statistics and probability to support explanations that organisms with an advantageous heritable trait tend to increase in proportion to organisms lacking this trait."
- HS-LS4-4, "Construct an explanation based on evidence for how natural selection leads to adaptation of populations."

Additional Content Learning Goals

- Fitness is the ability to survive and reproduce.
- A characteristic which is influenced by genes and can be inherited by a parent's offspring is called a heritable trait.
- A heritable trait that increases fitness is an adaptation. An adaptation tends to become more common in a population. Because the adaptation increases fitness, individuals with this trait generally produce more offspring. Because the trait is heritable, offspring generally have the

⁴ This activity is designed for high school students, but it can be adapted to help middle school students prepare for the Performance Expectations, MS-LS4-4, "Construct an explanation based on evidence that describes how genetic variations of traits in a population increase some individuals' probability of surviving and reproducing in a specific environment." and MS-LS4-6, "Use mathematical representations to support explanations of how natural selection may lead to increases and decreases of specific traits in populations over time."

same trait as their parents. Therefore, the adaptation tends to become more common in the population. This process is called natural selection.

- Another way to describe the process of natural selection is as follows. Since (1) individuals with an adaptation are more likely to survive and reproduce and (2) parents pass their alleles to their offspring, the allele(s) that result in an adaptation tend to become common in the population.
- Natural selection does *not* cause changes in an individual. Instead, natural selection results in changes in the frequency in a population of an adaptation and the allele(s) that result in the adaptation.
- The effects of natural selection are more easily observed when the environment changes, so natural selection results in changes in the frequency in a population of an adaptation and the allele(s) that result in the adaptation.
- Evolution by natural selection only occurs if there is variation in a heritable trait which contributes to differences in fitness.
- Which characteristics are adaptations depends on which type of environment the population is in. The same population will evolve differently in different environments.

This activity counteracts several common misconceptions about evolution⁵:

- Individual organisms can evolve during a single lifespan.
- Natural selection involves organisms trying to adapt.
- The "needs" of organisms account for the changes in populations over time (goal-directed or teleological interpretation).
- The fittest organisms in a population are those that are strongest and/or fastest.

Equipment and Supplies for Simulation of Natural Selection⁶

- black cloth for the black forest habitat
- red cloth for the red grasslands habitat
 - Make sure there is a very good color match between each cloth and the camouflaged pom-poms.⁷ Both color cloths should be textured, since even pom-poms of a matching color tend to be readily visible on plain flat cloth. If possible, the textures

⁵ Most of these misconceptions are excerpted from Misconceptions about evolution, available at http://evolution.berkeley.edu/evolibrary/misconceptions_teacherfaq.php.

⁶ This section describes the equipment and supplies needed for the two-habitat, two-types-of-feeding-structures version of the simulation that is described in the Student Handout. An alternative version of the simulation (with only one habitat and one type of feeding structure) is available in Appendix 1. This one-habitat version may be suitable if you have a small class (<14-16 students), limited funds for purchasing the habitat cloth, or students who require close supervision (you may want to have a subset of your students perform the simulation as a demonstration). If you use this one-habitat version, you will need to adapt some of these Teacher Preparation Notes accordingly. Also, depending on the type of cloth you purchase, you may want to replace Black Forest with Red Grassland in the alternative version of the simulation described in Appendix 1.

This simulation can also be done with two different color poster board habitats and squares or circles of the same colors as the two habitats to serve as the prey; the student predators can use their fingers or tweezers. This is more economical than using cloth and pom-poms, at least in the short term. We prefer cloth that meets the above specifications, but poster board habitats and matching circles or squares will probably give better results than using cloth which is not highly textured and/or is a poor color match for the pom-poms. Some natural selection simulation activities suggest using beans, but we recommend against this. Beans of different colors often vary in size and weight and it is difficult to find a good color match for the background. These problems tend to distort the results of simulations that use beans.

⁷ If you have trouble matching red pom-poms and material, you may want to use white pom-poms and long-pile or high-pile fleece and change the wording in the Student Handout.

should be as deep as or deeper than the diameter of the pom-poms. If possible, the textures of the two cloths should be different in order to test whether different hunter feeding structures may be more successful in different habitats. For example, you can purchase black faux fur and long pile or high pile red fleece. You will want ~2 yards of each type of cloth. The size of each habitat should accommodate foraging by half the students in your class.

- 5 mm or 7 mm black and red pom-poms, 250-300 of each color.
 - Plastic forks and spoons for hunter feeding structures, one of each for each student in your largest class (plus a few extra)⁸
 - Cups, tubes or bottles for hunter stomachs (1 for each student in your largest class) (To make the hunting task a little more challenging, you can use small plastic test tubes or the small plastic tubes that florists put on the ends of cut roses. If you anticipate that your students may be prone to cheat by laying their cups on the habitat and shoveling multiple pom-poms in with their feeding structure, you may prefer to use plastic bottles with narrow necks.)
 - Calculators for calculating percents (question 14 in the Student Handout; not needed if you provide students with the percents)
 - Some way to time the feeding times (typically 10-15 seconds)
- See preparation instructions on pages 5-6.

General Instructional Suggestions

To maximize student participation and learning, I suggest that you have your students work in pairs to complete each group of related questions and then have a class discussion after each group of questions. In their responses to the Student Handout questions, students are likely to include some of the misconceptions listed on page 3 of these Teacher Preparation Notes. When these misconceptions come up in the whole class discussions, thoughtful questions often can elicit more accurate interpretations from your students.

A **key** for this activity is available upon request to Ingrid Waldron (iwaldron@upenn.edu). The following paragraphs provide additional instructional suggestions and biological information – some for inclusion in your class discussions and some to provide you with relevant background that may be useful for your understanding and/or for responding to student questions.

Background Biology and Instructional Suggestions

What is evolution by natural selection?

We recommend that you begin this activity with a class discussion of the guiding question for this section – “What do you think ‘evolution by natural selection’ means?”

After you have discussed student answers to question 1, it may be helpful to explain that the figure shows a simple example of natural selection.

The Student Handout defines fitness as the ability to survive and reproduce. A more general definition for fitness is "the extent to which an individual contributes genes to future generations..." (from Evolutionary Analysis by Freeman and Herron).

⁸ Fork and spoon feeding structures have different fitness on some textured fabrics, but you may not see a difference in fitness between fork and spoon feeding structures, particularly if you have fewer than 10 hunters on each habitat. If you want to ensure that there will be a difference in fitness between the two types of feeding structures, you can substitute plastic knives for either the forks or the spoons and make appropriate changes in the wording of the Student Handout and Instructions for Student Helpers.

We once had a problem with red pom-poms and fork implements, since the forks (but not the spoons) seemed to repel the red pom-poms by static electricity. We can't think of a reasonable explanation for what we observed, but you may want to check for this type of effect before your class.

Page 2 of the Student Handout provides a more detailed analysis of the example discussed in question 1. The chart on the top of page 2 of the Student Handout suggests that mice form pair bonds. Most mice are promiscuous, but *Peromyscus polionotus* is monogamous (https://animaldiversity.org/accounts/Peromyscus_polionotus/). The chart further suggests that each color mouse only mates with another mouse of the same color and all of their offspring have the same fur color. A more realistic scenario would necessitate discussing the complex genetics of inheritance of fur color. To keep the focus on natural selection, we have chosen to make the simplifying assumptions mentioned.

Students should understand that, in discussing natural selection, we use the word "adaptation" to refer to a heritable trait that increases survival and reproduction. This differs from the common usage of adapting to the environment which refers to changes in an organism's characteristics during its lifetime. To help your students understand this distinction, you may want to use the analysis and discussion activity "Evolution and Adaptations" (<http://serendipstudio.org/exchange/bioactivities/evoadapt>)

When you discuss question 7, you may want to emphasize that organisms are not evolving to some pre-ordained "perfection" but are evolving to greater fitness in a given environment. You may want to use the example that polar bears are adapted to the snowy Arctic environment, whereas bears with brown or black fur are found in lower latitudes.

In the Student Handout, evolution is defined as a change in the inherited characteristics of a population over time. (A population is a group of individuals of the same species living in the same geographic area at the same time.) Biologists often use other related definitions of evolution, e.g., a change in the genetic composition of a population over time (especially a change in allele frequencies) or a change in the inherited characteristics of species over generations. Other definitions of evolution are less closely related, e.g., the process by which new species develop from existing species or descent with modification.

One limitation of this activity is that most of the examples relate to camouflage. Question 9 provides the opportunity for you to discuss with your students the great variety of adaptations that have resulted from natural selection, including anatomical, physiological, molecular and behavioral adaptations. Plant defenses against herbivores include thorns or spines and chemical defenses (<https://www.nature.com/scitable/knowledge/library/plant-resistance-against-herbivory-96675700/>). The last page of the Student Handout mentions that natural selection has been observed for antibiotic resistance in bacteria (<https://sitn.hms.harvard.edu/flash/2011/issue103/>) and for insecticide and fungicide resistance (https://www.canr.msu.edu/grapes/integrated_pest_management/how-pesticide-resistance-develops).

You may want to add the following question to help your students understand that natural selection also acts on reproductive characteristics, independent of longevity. For any organism, there will be trade-offs between various favorable characteristics, including fecundity and longevity. For organisms that live in transient environments, natural selection tends to favor breeding early, rather than investing in longevity.⁹

⁹ If you include this question, it may be advisable to discuss with your students the fact that humans have been so successful at reproducing that we are degrading our environment (e.g., by climate change). In this context, there will be multiple advantages if humans decrease their fertility in order to limit population size.

9a. Natural selection affects many types of heritable characteristics. This table shows the effects of two alleles of a gene that influences female reproduction, but does not affect mortality. (Both types of mice survive for six months, on average.)

Allele	Average Number of Litters in Six Months	Average Number of Babies per Litter
R	3	4
r	2	3

Which allele would be favored by natural selection? **R** ___ **r** ___

9b. Explain your reasoning.

A follow-up activity that analyzes evidence from a real biological example of natural selection for fur color in mice is “Evolution of Fur Color in Mice – Mutation, Environment and Natural Selection” (<http://serendipstudio.org/exchange/bioactivities/NaturalSelectionMice>).

Simulation of Natural Selection¹⁰

Instructions for the Simulation

1. Before the class period when you will do the simulation:
 - a. Count out 2 batches of 90 pom-poms, with 45 pom-poms of each color in each batch. (If you have a particularly large class, you may want to have 60 pom-poms of each color in each batch.)
 - b. Scatter 45 black and 45 red pom-poms in each habitat. (The simulation works better if students do not have time to overcome the camouflage by searching for pom-poms ahead of time, so you may want to fold each habitat with pom-poms in half and unfold the habitats just before beginning the simulation.)
 - c. To speed the simulation activity, you will want to sort the remaining pom-poms into groups of 10 and 20 of the same color, ready to be included in the pom-poms that you will scatter for the second round of the simulation. To have the groups of 10 and 20 pom-poms of the same color ready for easy use, you may want to put them in a tray with compartments (e.g. ice cube tray or bead tray).
 - d. For each class you teach, you will need a copy of the data table on page 7 of these Teacher Preparation Notes. Record the number of pom-poms of each color for generation 1. Alternatively, you may want to prepare an Excel file version of the table.
 - e. For each habitat in each class, choose a student helper who will help to organize the simulation procedure. Give each of them a copy of the Simulation Instructions for Student Helpers (provided in Appendix 2 on the last two pages of these Teacher Preparation Notes). The activity will go more smoothly if your student helpers have a chance to read these instructions before the simulation begins.
 - f. Draw or project this table on the board. You will fill in the data for Generation 1 and your student helpers will fill in the data for Generation 2 and Generation 3.

¹⁰ These instructions can easily be modified for the one habitat, one type of feeding structure version of the simulation available in Appendix 1.

	Hunters in the Black Forest		Hunters in the Red Grassland	
	Spoon	Fork	Spoon	Fork
Number who have this feeding structure in:				
Generation 1				
Generation 2				
Generation 3				

2. When you are ready to begin the simulation, split the class in half (with each half becoming the hunters on one of the habitats). You may want to have your students stand with their backs to the simulation habitat until you are ready to have them begin feeding; we have found that the simulation works better if students do not have time to overcome the camouflage by searching for pom-poms ahead of time. For each habitat, give each student a fork or spoon (one half each). Record the numbers of hunters with each type of feeding structure for generation 1 in the above table on the board.
3. Remind the students of the rules of the game (the Simulation Procedure on the bottom of page 4 in the Student Handout).
 - a. Remind them to pick up each pom-pom with their feeding structure and put it in the cup. They must keep their cups upright at all times and are not permitted to tilt the cups and shovel pom-poms into them.
 - b. Competition for resources is okay, but once a pom-pom is on a feeding structure, it is off limits to other students.
 - c. Tell them how long they will have to feed. We have found that 15 seconds often works well, but you may need to adjust the number of seconds, depending on the number of students you have, cloth size, etc.
4. Start the students feeding and call stop after 15 seconds (or whatever time you have chosen).
5. After feeding, each student helper will lead the students in his or her habitat group in carrying out the instructions presented in the Simulation Instructions for Student Helpers (see the last two pages of these Teacher Preparation Notes).
6. Get the number of pom-poms of each color eaten in each habitat from your student helpers and use the table on the next page to calculate how many pom-poms of each color survived. Each surviving pom-pom reproduces, so, for each surviving pom-pom, you will add one pom-pom of the same color. Scatter the appropriate number of additional pom-poms of each color on each habitat. To expedite the process, you may want to have student helpers scatter the pom-poms, but make sure that students do not scatter pom-poms on the same habitat where they will hunt.

Habitat Type: Black Forest		
Pom-pom Color	Black	Red
# in generation 1		
# eaten		
# surviving in generation 1 (<i># in generation 1 - # eaten</i>)		
<i>For each color, add one additional pom-pom for each surviving pom-pom.</i>		
# in generation 2 (<i>2 x # surviving in generation 1</i>)		
# eaten		
# surviving in generation 2 (<i># in generation 2 - # eaten</i>)		
# in generation 3 (<i>2 x # surviving in generation 2</i>)		

Habitat Type: Red Grassland		
Pom-pom Color	Black	Red
# in generation 1		
# eaten		
# surviving in generation 1 (<i># in generation 1 - # eaten</i>)		
<i>For each color, add one additional pom-pom for each surviving pom-pom.</i>		
# in generation 2 (<i>2 x # surviving in generation 1</i>)		
# eaten		
# surviving in generation 2 (<i># in generation 2 - # eaten</i>)		
# in generation 3 (<i>2 x # surviving in generation 2</i>)		

- Once the new pom-poms have been scattered on the habitats and everyone has their feeding structures for the second generation, start the second round of hunting.
- After the second round is finished, repeat steps 5-6 above. After the student helpers record hunter numbers for generation 3 in the table on the board, all the students return to their seats and answer question 13 in the Student Handout.

Use the information from the above data table to display the numbers of red and black pom-poms in each habitat for generations 1, 2 and 3. Your students will record these results in the table in question 14 in the Student Handout. You may want to calculate the totals and percentages of each color for each generation in each habitat, or you can have your students calculate the totals and percentages. Then, your students will complete the graphs in question 15. We recommend that you have your students make dot and line graphs similar to the graph shown on page 11 of the Student Handout.

Discuss student answers to questions 13 and 15-17 to guide your students in interpreting the results of the simulation and developing their understanding of natural selection.

Questions 18-20 will help students to understand the necessary conditions for natural selection by considering what would happen if any of these conditions is not met. In question 18b, students are asked whether natural selection could occur if the black forest habitat became red grassland due to a prolonged drought, but only black pom-poms had survived in the population. The simple answer is that without any variation there would be no opportunity for natural selection; however, more sophisticated students may point out that natural selection could occur

if a mutation for red color occurred in the population or if red pom-poms migrated in from another population.

To conclude this section, we recommend a discussion of the strengths and weaknesses of this simulation as a model of natural selection. The strengths of this simulation include that it demonstrates the basic features of natural selection and helps to correct the following common *misconceptions*: individual organisms can evolve during a single lifespan; natural selection involves organisms trying to adapt; and the fittest organisms in a population are those that are strongest, fastest, and/or largest.

As discussed in question 21, there are several important differences between this simulation and natural selection in nature. In the simulation differences in survival and reproduction are due entirely to the effects of predation, which can be reduced by camouflage. In contrast, in real biological populations there are multiple factors that influence mortality and reproductive success. Also, in this simulation offspring are identical to their parents. In contrast, for sexually reproducing organisms, the characteristics of offspring are similar, but not identical to their parents. These differences between this simulation and biological reality help to explain why this simulation suggests that natural selection occurs more rapidly than it actually does in nature. This illustrates a typical weakness of simulations – namely that they are simplified and omit important aspects of the actual biological process.

This discussion will illustrate the Crosscutting Concept, Systems and System Models – Students can “use models and simulations to predict the behavior of a system, and recognize that these predictions have limited precision and reliability due to the assumptions and approximations inherent in the models.”

Natural Selection and the Peppered Moth

If you have trouble finding the speckled peppered moth in the figure on the left, it may help to know that it is near the lower left-hand corner, with its head upward.¹¹

As discussed on the bottom of page 8 of the Student Handout, the allele for melanism is dominant relative to the allele for the speckled form. These two alleles are the most common alleles in the populations studied.¹²

Question 24 will reinforce student understanding of the conditions required for natural selection to occur.

In question 25, students predict the effects of changes in air pollution in regions of England that became industrialized. In question 26, these predictions are compared with the data in the graphs on the top of page 10 of the Student Handout, which provide representative data for an industrial region of England. These graphs show the trends in the proportion of peppered moths that were dark and the prevalence of the allele for melanism (which was estimated from the data on the trends in phenotypes). In these graphs, the total width of the shaded line represents 99% confidence intervals, and the width of the darkest part of the line indicates 50% confidence intervals.

¹¹ For middle schoolers, after question 1, you may want to introduce the information and hunting game, available in “Peppered Moths – Natural Selection in Action” (<https://askabiologist.asu.edu/peppered-moths-game/>).

¹² Evidence for England indicates that the mutation that resulted in the dark form of the peppered moth occurred around 1820. This single origin of the melanic allele in peppered moths contrasts with other types of moths where melanic forms appear to have been present as polymorphisms in preindustrial rural regions.

Questions 25-26 introduce the importance of changes in allele frequency as part of the process of natural selection.

I suggest that, at this point in the activity, you reinforce student understanding of natural selection of peppered moth color forms by showing them the 4-minute video, “Natural Selection Song: The Ballad of the Peppered Moth” (<https://www.youtube.com/watch?v=uV5-FKT16r0>). I suggest that you stop the video at 3 minutes and 31 seconds, before the part about Kettlewell and Majerus, which is not relevant for high school students.

A goal of question 27 is to counteract the common misconceptions that:

- The "needs" of organisms account for the changes in populations over time (e.g. “the peppered moths needed to become speckled so they would not be eaten by birds”).
- Evolution involves individuals trying to adapt and changing during their lifetime (e.g. “Most of the peppered moths became dark”).

Question 28 primes students to understand the graph on the top of page 11 of the Student Handout. A quick glance at the graphs on the top of pages 10 and 11 of the Student Handout could suggest that during the second half of the twentieth century the trends were much faster in England than in the US. If this misimpression arises, you will probably want to challenge your students to figure out whether this is true; if necessary you can give them a hint to compare the scales for the X axis in the two figures.

Taken together, the graphs on pages 10-11 of the Student Handout illustrate the following important points.

- Different characteristics are adaptations in different environments.
- Environmental changes that are subsequently reversed may result in evolutionary changes that are similarly reversed.
- Natural selection typically requires multiple generations (although this was partly due to gradual changes in the environment).
- In response to similar environmental changes, natural selection can result in similar trends in the characteristics of different populations.

Discussion of student answers to question 29 should include the important point that natural selection is occurring continuously, although it is more difficult to see the effects of natural selection when population characteristics are already well-suited to a stable environment (which can be observed for ~1800-1850 and ~1900-1950 in the graphs on page 10 of the Student Handout and for the rural regions in the graph on page 11 of the Student Handout). In rural regions, natural selection kept the frequency of the dark form of the peppered moth very low and, in stable polluted environments, natural selection kept the frequency of the speckled form of the peppered moth low. The effects of natural selection can be seen more easily when environmental changes result in natural selection for a different characteristic (which can be observed for ~1850-1900 and ~1950-2000 in industrial regions). These points lead naturally to a discussion of this Crosscutting Concept: Stability and Change – “Students understand much of science deals with constructing explanations of how things change and how they remain stable. They quantify and model changes in systems ...”

There has been some controversy concerning the cause of the trends in the speckled and dark forms of the peppered moth (see "Industrial Melanism in the Peppered Moth, *Biston betularia*:

An Excellent Teaching Example of Darwinian Evolution in Action", *Evo Edu Outreach* (2009) 2:63-74). Some aspects of this controversy have been beneficial since they have identified flaws in some of the earlier research and stimulated improved research which has provided strong evidence for the importance of natural selection due to predation by birds on peppered moths (see e. g. <http://rsbl.royalsocietypublishing.org/content/roybiolett/8/4/609.full.pdf>).

Bats are also important predators on adult male peppered moths (the females fly very little so they are less subject to bat predation). However, unlike birds, bats are not visual predators and are equally likely to eat speckled or dark peppered moths. The caterpillars of the peppered moth are also subject to predation, and these caterpillars have a different type of camouflage that is independent of the adult dark vs. speckled forms. When caterpillars molt, they can change color to match the color of the branches that they live on.¹³ The available evidence indicates that bat predation, predation on caterpillars, and other causes of mortality appear to be generally equal for both color forms; therefore, the selective disadvantage for the color form of the adult peppered moth that is mismatched with the environment is not as strong as we might expect. This is one reason why natural selection for dark or speckled forms of the peppered moth resulted in gradual changes in the proportions of moths with each color form.

Reasons why natural selection has slower effects in real populations such as the peppered moths compared to the rapid changes observed in the pom-pom simulation are summarized in the following table.

	Peppered Moth Example	Pom-Pom Simulation
Generation Time	One or two generations per year	Two generations in half an hour
Inheritance of Traits	Offspring trait generally, but not always, the same as their parents' trait	Offspring trait always the same as their single parent's trait
Mortality	Mortality influenced by visual predation on moths, but also by mortality unrelated to moths' appearance (e.g. bat predation at night)	Mortality influenced only by visual predation of pom-poms

These points illustrate the Crosscutting Concept, Systems and system models – Students can “use models and simulations to predict the behavior of a system, and recognize that these predictions have limited precision and reliability due to the assumptions and approximations inherent in the models.”

Question 31 asks students for peppered moth examples of two important generalizations about natural selection. The phenotype (color form or camouflage) of individual peppered moths influences whether they survive to reproduce. As a result, there were changes in the proportion of the population that had the dark color form and corresponding changes in the frequency in the population of the alleles that influence color form.

You may also want to discuss with your students the multiple processes that can result in changes in allele frequencies in populations, including mutation, gene flow, genetic drift, and natural selection. Of these processes, only natural selection can explain why:

¹³ This is an example of phenotypic plasticity (the ability to adapt to different environments within an organism's lifetime). The analysis and discussion activity, "How Animals Adapt to Changes in Their Environments – Examples and Evolution" (<http://serendipstudio.org/exchange/bioactivities/evoadapt>), helps students to understand natural selection for phenotypic plasticity.

- When similar environmental changes occurred in industrial regions in England and the US, similar trends are observed in the populations of peppered moths in both countries.
- In both England and the US, the trends observed in industrial areas were not observed in peppered moth populations in rural regions away from industrial regions.
- Increased prevalence of darker moths in polluted forests has been observed for over 100 other species of moths (this is called industrial melanism; <https://askabiologist.asu.edu/peppered-moths-game/>).

Follow-up Activities

"Resources for Teaching and Learning about Evolution"

(<http://serendipstudio.org/exchange/bioactivities/evolrec>).

These Teacher Notes provide (1) suggestions for teaching evolution to students with religious concerns, (2) a review of major concepts and common misconceptions concerning natural selection, with recommended learning activities, (3) a review of major concepts and common misconceptions about species, descent with modification, and the evidence for evolution, with recommended learning activities, and (4) recommended general resources for teaching about evolution.

Sources of Figures in Student Handout

- Figures on Page 8 from <http://www.ucl.ac.uk/~ucbhdjm/courses/b242/OneGene/peppered.html>
- Figures on page 10, adapted from Extended Data Figure 4 in van't Hof et al., 2016, "The industrial melanism mutation in British peppered moths is a transposable element", <https://www.nature.com/articles/nature17951>.
- Figure on page 11, adapted from Grant and Wiseman, 2002, "Recent History of Melanism in American Peppered Moths", <https://www.ncbi.nlm.nih.gov/pubmed/12140267>.

All other figures prepared by the authors.

Appendix 1. Simulation of Natural Selection¹⁴

Now, you will play a simulation game to demonstrate how natural selection works. This simulation involves a population of pom-poms that lives in a Black Forest habitat. The only threat to these pom-pom creatures is the presence of hungry hunters (that's you!).

Each pom-pom is either red or black. The differences in pom-pom color are heritable. If a pom-pom survives to reproduce, its offspring will have the same color as their parent.

11a. At the beginning of the simulation, the pom-pom population will have 50% red pom-poms and 50% black pom-poms. How do you think the percent red pom-poms will change after you and your classmates have hunted for pom-poms?

11b. Why do you think that?

Simulation Procedure

- Rules for Feeding:
 - Start and stop when your teacher says to.
 - You must pick up each pom-pom with your feeding structure and drop it into your cup. You may **not** tilt your cup and scoop in pom-poms.
 - Once a pom-pom is on a classmate's fork or spoon it is off limits.
- After feeding, count how many red, black, and total pom-poms you have eaten. Line up with the other hunters, from fewest total pom-poms eaten to most total pom-poms eaten. Then, follow the instructions from the Student Helper for your group.
- Next, you will run through the simulation one more time.

¹⁴ This one habitat, one type of feeding structure version can be substituted for pages 4-7 in the Student Handout. (See footnote 6.)

12. Copy the class pom-pom data into this table. Then, for Generation 2 and Generation 3, calculate the total number of pom-poms and the percent of each color.

	Pom-poms in the Black Forest		
	Black	Red	Total
<u>Generation 1</u> Number			
Percent	50%	50%	100%
<u>Generation 2</u> Number			
Percent			100%
<u>Generation 3</u> Number			
Percent			100%

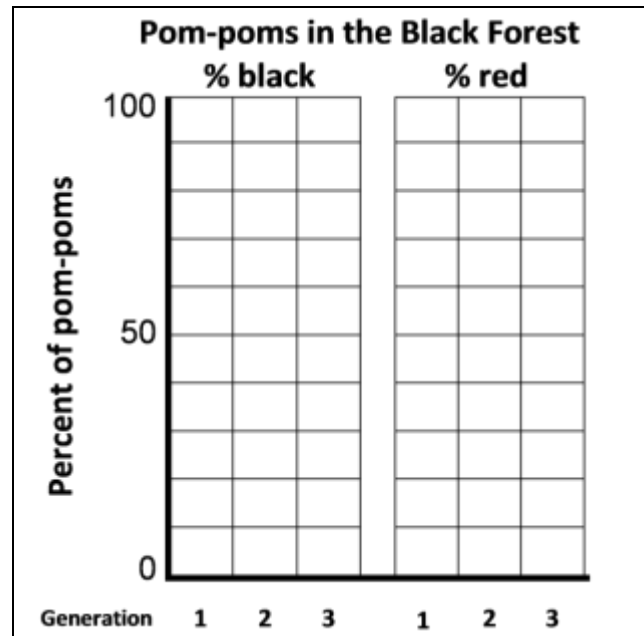
13. Use the data in the table to complete these graphs. This will help you see the trends in the percent of pom-poms of each color over the three generations.

14a. Describe the changes in the percent red vs. black pom-poms.

14b. Do the results of your simulation match your predictions in question 11?

yes ___ no ___

14c. If no, suggest a reason for the observed trends.



15a. Did any individual pom-poms change color? yes ___ no ___

15b. If no, then why did the percent red vs. black pom-poms differ between Generation 1 and Generation 3?

Notice that natural selection does not refer to individuals changing. Rather, as a result of natural selection, the frequency of adaptations in a population increases.

16a. Suppose that the black forest experienced a prolonged drought, so all the trees died and the habitat became red grassland. What do you think would happen to the pom-pom population? First, make your prediction if the population of pom-poms at the beginning of the drought included both red and black pom-poms.

16b. Next, think about a different scenario. Suppose that natural selection over many generations had eliminated all the red pom-poms in the black forest habitat so the population in this habitat only had black pom-poms. After that, a prolonged drought resulted in this habitat turning into a red grassland. Would natural selection for pom-pom color occur? Why or why not?

16c. Based on this example, explain why evolution by natural selection can only occur if there is variation in a trait.

17a. Suppose that your class repeated the simulation, but this time all the hunters were blindfolded so they could only find pom-poms by touch. What fraction of the pom-poms would be red at the end of the simulation? (Remember that at the beginning of the simulation half the pom-poms were red and half were black.)

17b. Explain your reasoning.

17c. Based on this example, explain why evolution by natural selection can only occur if differences in a trait result in differences in fitness.

18a. Next, think about what would happen if your class repeated the simulation, this time with hunters who could see their prey. However, pom-pom color would not be heritable. No matter what color the pom-pom parent was, half of its babies would be red pom-poms, and half would be black pom-poms. After each pom-pom parent had babies, it would die. What fraction of the baby pom-poms would be red in each generation?

18b. Describe the long-term trends in the population of pom-poms.

18c. Based on this example, explain why evolution by natural selection can only occur if the variation in a trait is heritable.

19. This simulation helps us to understand the basic process of natural selection. However, a simulation simplifies the biological process that it mimics, so there will be differences between the simulation and the actual biological process. Describe one way that natural selection in real biological populations is more complex than our simulation.

Appendix 2. Instructions for Student Helpers¹⁵

1. Have the students in your group count how many pom-poms they have in their cups and line up in order of how many pom-poms they have (least to most).

2. Go down the line and, for each hunter, record in the table below:

- how many pom-poms of each color he or she ate
- his or her feeding structure (F = fork; S = spoon).

Remind the students in your group that they should give you the pom-poms that they have eaten and their feeding structures. The pom-poms they ate are dead, so they should not be put back on the habitat. Also, each hunter only survives for one round of hunting, so each student should return his or her feeding structure and will need to be reborn as a hunter with a new feeding structure in the next generation.

	Hunter															Total	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		
# Black Pom-Poms Eaten																	
# Red Pom-Poms Eaten																	
Feeding Structure in Generation 1																	

3. Calculate the total number of red pom-poms eaten and the total number of black pom-poms eaten and give these numbers to your teacher.

4. The half of the students who ate the most pom-poms survive long enough to reproduce. Each of these students will have two “offspring” with the same feeding structure as the “parent”. In the table above, circle the feeding structures for the half of the students who ate the most pom-poms. If you have an odd number of students in your group, see C in the table below. Complete this table to calculate the number of hunters with each type of feeding structure in Generation 2.

	Fork	Spoon
A. Number of Generation 1 hunters with each feeding structure who were in the top half of pom-poms eaten		
B. Number of offspring with this feeding structure (2 x number in A)		
C. If there are an odd number of students in your group, the student in the middle for number of pom-poms eaten produces one offspring, so enter a 1 in the appropriate column.		
D. Total number of Generation 2 hunters with this feeding structure (B + C)		

5. Use the results in row D of this table to record the number of Generation 2 hunters with forks and the number of Generation 2 hunters with spoons in the appropriate row in the table on the board. Distribute forks and spoons to the hunters in your group so you have the right number of Generation 2 hunters with each type of feeding structure.

6. Next, your group should discuss the questions at the top of page 5 of the Student Handout.

¹⁵ These are instructions for student helpers for the two-habitat simulation in the Student Handout.

7. After the second round of the simulation, repeat the same procedure, using the table below to record the data for pom-poms eaten and feeding structures. Tell your teacher the number of red pom-poms eaten and the number of black pom-poms eaten.

	Hunter															Total
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
# Black Pom-Poms Eaten																
# Red Pom-Poms Eaten																
Feeding Structure in Generation 2																

8. Complete the table below to calculate the number of hunters with each type of feeding structure in Generation 3.

	Fork	Spoon
A. Number of hunters with this feeding structure who were in the top half of pom-poms eaten		
B. Number of offspring with this feeding structure (2 x number in A)		
C. If there are an odd number of students in your group, the student in the middle for number of pom-poms eaten, produces one offspring, so enter a 1 in the appropriate column.		
D. Total number of Generation 3 hunters with this feeding structure (B+ C)		

9. Record the number of Generation 3 hunters with forks and the number of Generation 3 hunters with spoons in the table on the board.

10. Each student should return to his or her seat and answer question 13 on page 5 of the Student Handout.