FEATURE ARTICLE

Using the I^2 Strategy to Help Students Think Like Biologists about Natural Selection

KAREN LUCCI, ROBERT A. COOPER

Abstract

Many students have very robust misconceptions about natural selection, stemming from intuitive theories that form a child's earliest understandings of the natural world. For example, students often imagine that species evolve in response to environmental pressures that cause a need for change and that all individuals in the population simultaneously respond to this need by adapting in order to survive. While children's intuitive theories are essential for comprehending many events in their daily experience, they can make learning the counterintuitive theories of science, like natural selection, challenging. To help students develop an understanding of natural selection, teachers need to guide them through an evaluation of the intuitive theory and its well-established scientific counterpart so that they see the failure of the intuitive theory to adequately explain the evidence. In other words, it is critical for the learner to confront his or her misconceptions to break them down, rather than fail to address them. This can be done by presenting students with graphical illustrations of how natural selection works and providing the tools to interpret them. Here we illustrate how to use such a tool, the Identify and Interpret (I^2) strategy.

Key Words: *Data analysis; data interpretation; evolution; graphs; misconceptions; natural selection; science practices.*

○ Introduction

Natural selection is one among many scientific concepts that are frequently misunderstood by students. Students tend to hold misconceptions resulting from their application of intuitive theories about the world. These misconceptions develop early in life and have consistently been found in people of all ages, across many different cultures, and throughout history (Bloom & Weisberg, 2007; Shtulman, 2017). One common student misconception about natural selection is that species evolve in response to environmental pressures that cause a need for change and that all individuals in the population simultaneously respond to this need by adapting in order to survive. This misconception stems from the fact that students' intuitive theories cause them to focus their attention only on the individual organisms, when they should be dividing their attention between the fate of the individual organisms and the resulting changes in the makeup of the population.

Evolution by natural selection is an emergent process whereby interactions between individual organisms (e.g., herbivory, predation, and parasitism) result in changes in the population distribution over time (Ferrari & Chi, 1998; Chi, 2005; Cooper, 2017). Ernst Mayr (1982) referred to this as "population thinking." The distribution of traits in a population changes over time as a result of differences in the survival and reproductive success of the individuals. Changes in a population distribution over time can be observed by analyzing graphs that model these changes. Here, we employ an instructional strategy called Identify and Interpret (I^2) that can be used for either formative or summative assessment (BSCS, 2012a, b). We illustrate how to use the strategy to guide students in their analysis of graphs that show changes in populations of rock pocket mice and Darwin's finches, two excellent examples of evolution in action.

The I^2 strategy can be used to scaffold students' efforts to understand any type of figure found in scientific papers and textbooks.

○ Reading & Interpreting Graphs Using I^2

Reading and interpreting graphs is a skill that must be explicitly taught. The *Next Generation Science Standards* (NGSS) call for students to learn to analyze and interpret data (Science Practice 4):

> Once collected, data must be presented in a form that can reveal any patterns and relationships and that allows results to be communicated to others. . . . Such analysis can bring out the meaning of data – and their relevance – so that they may be used as evidence. (NGSS Lead States, 2013, p. 390)

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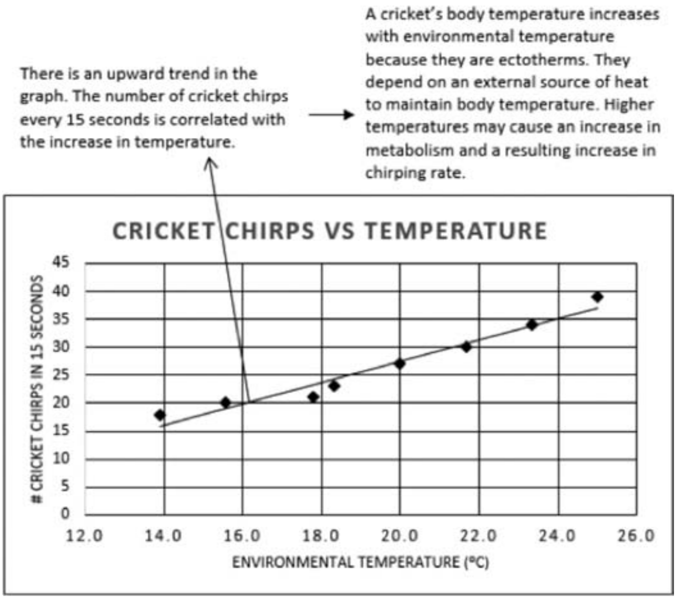
But just how do we go about teaching students to analyze data presented in a graph? BSCS developed the I^2 strategy to scaffold students' efforts to bring out the meaning of data presented in graphs, figures, sketches, and other forms of data representation found in scientific papers and textbooks (BSCS, 2012a, b).

Students should begin their analysis of a graph by taking note of the variables on the x and y axes, making sure they understand what those variables represent. Then, using the I^2 strategy, students consider "What I see." They look for any patterns, changes, trends, or differences they can find. From each pattern, change, trend, or difference, they draw an arrow pointing to a "What I see" statement. For example, in Figure 1, students should note the upward trend in the graph – the number of chirps increases with temperature. Next the students consider "What it means." From each "What I see" statement they've written on the graph, students draw an arrow to a statement explaining the meaning of the pattern, change, trend, or difference they have identified. In Figure 1, the upward trend likely results from the fact that crickets are ectotherms and their body temperature, and therefore their metabolism, increases with environmental temperature. It can be helpful in the classroom to have students use different colors to clearly show and separate the "What I see" statements from the "What it means" statements. In addition, having students work together in small groups to interpret graphs using I^2 enables teachers to facilitate the kind of student talk that promotes learning of both content and science practices (Handelsman et al., 2004; Tanner, 2009).

After students have recorded all their "What I see" statements and explained the meaning of each with a "What it means" statement, they write a caption – a paragraph explaining the meaning of the graph. The caption begins with a topic sentence that describes what the graph shows. Each of the remaining sentences joins a description of a specific pattern, change, trend, or difference in the graph with the explanation of what it means. The following could be an appropriate caption for the graph in Figure 1:


There is an upward trend in the graph. The number of cricket chirps every 15 seconds is correlated with the increase in temperature.

A cricket's body temperature increases with environmental temperature because they are ectotherms. They depend on an external source of heat to maintain body temperature. Higher temperatures may cause an increase in metabolism and a resulting increase in chirping rate.

Figure 1.

> Figure 1 shows the change in the number of cricket chirps during 15-second periods as environmental temperature (°C) increases. The number of cricket chirps is correlated with the environmental temperature. A possible explanation depends on the fact that crickets are ectotherms, animals that depend on an external source of heat to maintain their body temperature. Higher temperatures may cause an increase in metabolism and a resulting increase in chirping rate.

Teachers should note the use of hedging language in the explanation of the cricket chirp graph ("Higher temperatures may cause an increase in metabolism and a resulting increase in chirping rate"). Students may be inclined to claim a causal relationship based on the graph. It is essential that students understand that these are observational data that only show a correlation between environmental temperature and chirping rate. Correlation is not causation. The tentative explanation provided in the caption above serves as a hypothesis that could motivate a laboratory experiment to establish causation. It would be necessary to perform a control experiment to simultaneously measure both metabolic rate and chirping rate as temperature is varied while other potential causal variables are held constant.

Students' captions can be collected and graded as either a formative or a summative assessment. Using the I^2 strategy with graphs also affords teachers the opportunity to teach, or review, basic graphing skills and basic descriptive statistical concepts like distribution, average, and variance that are essential for understanding natural selection. According to NGSS (HS-LS4-3), students who demonstrate understanding of natural selection can

> 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. [Clarification Statement: Emphasis is on analyzing shifts in numerical distribution of traits and using these shifts as evidence to support explanations.]" (NGSS Lead States, 2013, p. 272)

The importance of statistical concepts for understanding natural selection has also been noted elsewhere (Endler, 1986; Gould, 1996; Petrosino et al., 2015; Cooper, 2017).

The two cases of natural selection in action presented below, the rock pocket mouse and Darwin's finches, provide graphs that clearly illustrate changes in populations over time resulting from differences in individual survival and reproductive success. The graphs come from several HHMI BioInteractive instructional resources that illustrate the fact that many organisms die during the process of natural selection, and that no individuals adapt by changing their anatomy in order to survive. By using the I^2 tool to analyze these graphs and contrasting their intuitive theories with the theory of natural selection, students begin to develop a better understanding of population thinking and the process of natural selection.

○ Changing Color Variations in Rock Pocket Mice

Our first example of evolution in action is the story of the adaptation of the rock pocket mouse to the appearance of areas of dark, black basalt rock that formed in the sandy deserts of Arizona and

New Mexico over the past one or two million years. There are two color varieties of the rock pocket mouse, a sandy-colored variety that lives predominantly on sandy-colored rock and a black variety that lives predominantly on black basalt (Figure 2). The difference in color has been linked to variation in a single gene, the melanocortin-1 receptor gene (*Mc1r*), which is one of several genes involved in the synthesis of pigments in the melanocytes, specialized pigment-producing skin cells (Hoekstra & Nachman, 2003). The wild-type, sandy-colored mice produce more pheomelanin, a lighter-colored pigment, than eumelanin, the darker pigment. Mutations in the *Mc1r* gene result in the production of more eumelanin in the black mice.

The mutated form of *Mc1r* that produces black mice is maladaptive if the mice live in the sandy-colored desert, but it provides an advantage if the mice happen to live on the black rock. The mice are eaten by various predators, including owls, foxes, and coyotes, that rely predominantly on sight to detect their prey. Mice whose fur color does not match the substrate are at a considerable disadvantage when it comes to avoiding predators. Predators will eat either sandy-colored or black mice, but given the conditions on the lava flow, black mice are more likely to avoid predators; while on the sandy-colored desert, sandy-colored mice are more likely to avoid predators. Mutations occur randomly, providing the ultimate source of genetic variation. But more importantly, genetic recombination (random assortment and crossing over) shuffle the existing variant alleles in different combinations, resulting in the observed phenotypic variations. Natural selection then preserves those phenotypic variations that are advantageous. Once the lava flows had produced the black rock, a population of predominantly black mice could have evolved from an ancestral sandy-colored population in <100 generations (HHMI BioInteractive, 2005).

An HHMI BioInteractive activity suitable for middle school or high school provides students the opportunity to analyze data and use it as evidence to construct an explanation for the two color varieties in the rock pocket mouse (HHMI BioInteractive, 2015a). Students first watch a short film that tells the story of selection and adaptation in the rock pocket mouse (HHMI BioInteractive, 2011). After the video, they are presented with four sets of images like the one shown in Figure 3 and asked to place them in a logical sequence based on information from the video. The sets of images are snapshots showing rock pocket mouse populations at two locations over four different times. Location A is a sandy desert and remains so through all four snapshots. Location B starts out as a sandy desert but changes to dark black following a lava flow. Students sequence the images based on data collected by counting the number of mice of each color variety at each location and using information from the video. Location A has predominantly sandy-colored mice and there is little change across all four snapshots. However, when the snapshots are sequenced correctly, Location B starts out with predominantly sandy-colored mice (10 sandy, 2 black) but ends up with predominantly black mice (10 black, 2 sandy).

After sequencing the images, counting the mice, and recording the data in a table, students construct graphs like those shown in Figure 4. Working in small groups using the I^2 strategy on their graphs, students first identify the trends they see, then write "What I see" statements and "What it means" statements. Figure 5 provides examples of what students might write as they annotate the graphs.

Once students have completed their analysis of the graphs, a whole-class discussion gives them the opportunity to share what they've found and argue for a particular interpretation of the evidence until the class arrives at some agreement on the relevant

Figure 2. Used with permission from the Howard Hughes Medical Institute, © 2005. All rights reserved. https://www.hhmi.org/biointeractive. Original source: Nachman et al. (2003).

Figure 3. Used with permission from the Howard Hughes Medical Institute, © 2015. All rights reserved. https://www.hhmi.org/biointeractive.

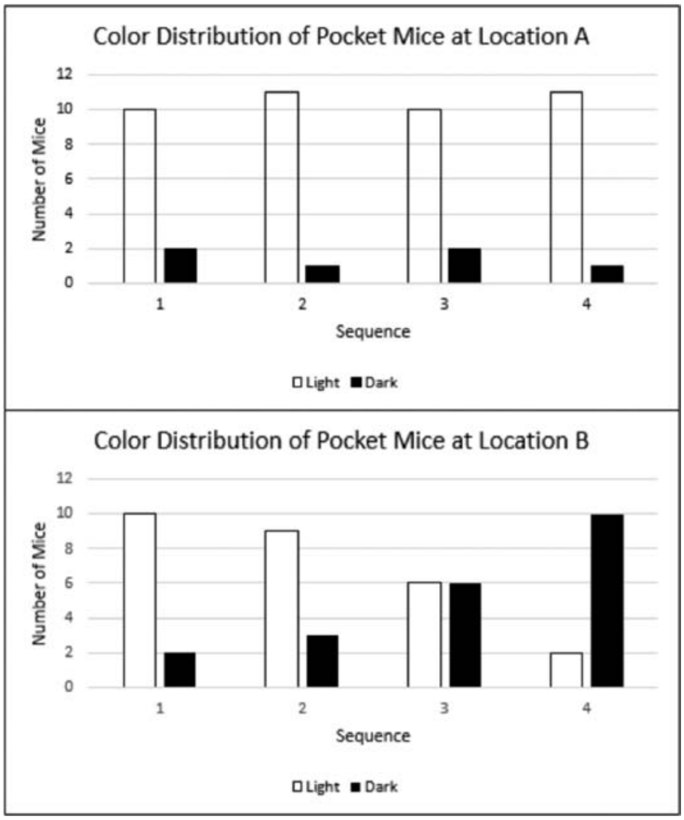
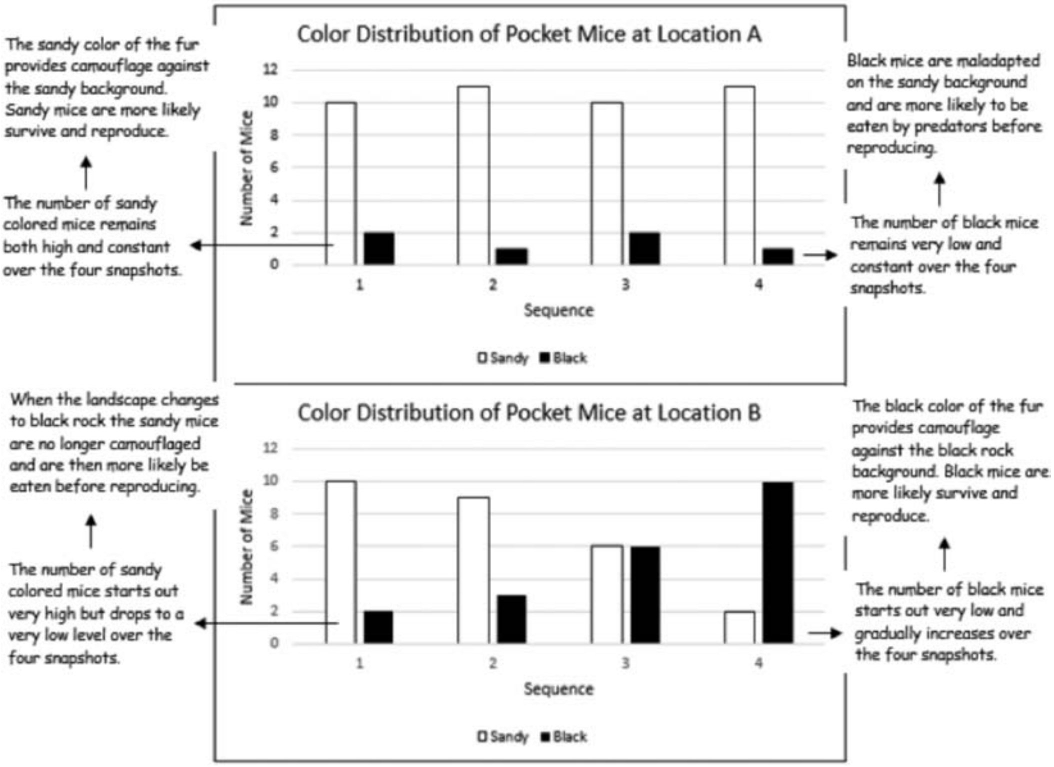


Figure 4. Used with permission from the Howard Hughes Medical Institute, © 2015. All rights reserved. https://www.hhmi.org/biointeractive.

features and their meaning. When the class has reached a consensus, students individually write a detailed caption for the graph by combining the "What I see" and "What it means" statements into a coherent paragraph. The following key points should be stressed with students during discussion. Darwin's mechanism of evolutionary change is a two-step process. The first step is the production of genetic variations without any awareness of what traits might be adaptive under current conditions in the environment. This occurs during the normal process of reproduction through mutation and genetic recombination. The second step is selection, which acts on individuals differently on the basis of the traits they inherited. Those with maladaptive traits are most likely to die before reproducing successfully, while those with adaptive traits are more likely to survive and reproduce, passing on their adaptive genes to the next generation. As a result, the proportions of different genetic variations in the population may change.

It is important to stress that variations are produced by the random processes of mutation and genetic recombination that occur prior to selection. They do not arise because of a need imposed by the environment. Individuals born with maladaptive traits are simply at a disadvantage, and they cannot change their traits to become better adapted. The rock pocket mouse video (HHMI BioInteractive, 2011) makes this apparent by discussing the variety of predators that feed on the mice and by illustrating the changes in proportions of black and sandy-colored mice in the population over generations in an animation. The animation is also available as a stand-alone resource (HHMI BioInteractive, 2005).



The sandy color of the fur provides camouflage against the sandy background. Sandy mice are more likely survive and reproduce.

The number of sandy colored mice remains both high and constant over the four snapshots.

Black mice are maladapted on the sandy background and are more likely to be eaten by predators before reproducing.

The number of black mice remains very low and constant over the four snapshots.

When the landscape changes to black rock the sandy mice are no longer camouflaged and are then more likely be eaten before reproducing.

The number of sandy colored mice starts out very high but drops to a very low level over the four snapshots.

The black color of the fur provides camouflage against the black rock background. Black mice are more likely survive and reproduce.

The number of black mice starts out very low and gradually increases over the four snapshots.

Figure 5. Used with permission from the Howard Hughes Medical Institute, © 2015. All rights reserved. https://www.hhmi.org/biointeractive.

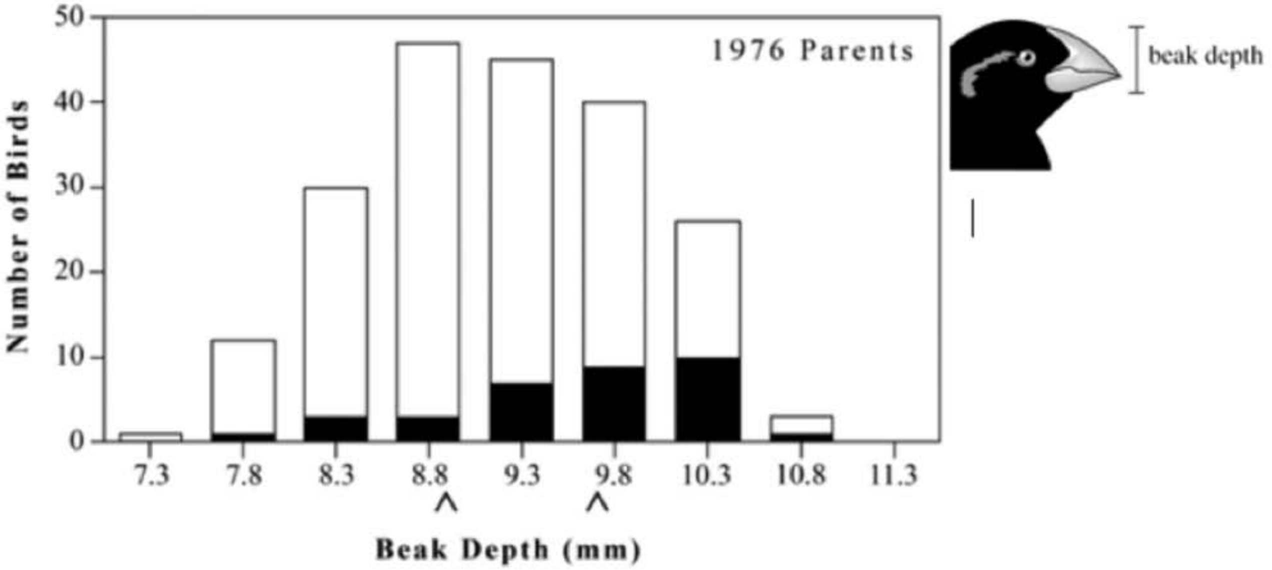
○ Changes in Beak Depth of Darwin's Finches

The story of the adaptation of Darwin's finches during a 1977 drought provides our second example of evolution in action. This example involves a quantitative trait, beak depth. Quantitative traits produce a continuous distribution of different phenotypes rather than a dichotomous split between two contrasting phenotypes. Variants of the trait can be displayed on a graph called a histogram that may approximate the shape of a normal distribution, and can be characterized with two numbers, the average and the standard deviation. By examining histograms from successive generations, students can see that evolution involves cumulative changes in the proportions of different variations at the population level, not changes in individual organisms.

An HHMI BioInteractive resource (HHMI BioInteractive, 2015b) presents students with the histogram in Figure 6, which displays data collected by Peter and Rosemary Grant. The histogram shows the distribution of beak depths of Darwin's finches in 1976 (white bars), with the finches that survived a drought overlain in black. In the early 1970s, the Grants selected the small island of Daphne Major in the Galápagos archipelago as a laboratory to study evolution. Since the island was small, they could manage the task of measuring all the medium ground finches on the island. During the first four years of their study, they caught, banded, and measured birds but observed little change in their traits. However, in 1977, a severe drought lasting 18 months hit the island. In May 1976, before the drought, the Grants measured an average beak depth of 9.42 mm for the population of medium ground finches. In 1978, after the drought, the average beak depth of the finches had increased to 9.96 mm, 6% larger than in 1976 (Boag & Grant, 1981). The drought altered the food supply, creating conditions in which many of the birds from the 1976 population were ill-equipped to survive. Before the drought there was a range of seeds varying in size and hardness, but as the drought persisted the only seeds remaining were large, hard seeds from the cactus bushes that were able to weather the drought. Smaller finches were unable to crack these large, hard seeds and died at a higher rate than birds with larger beaks. The survivors that reproduced had, on average, larger beaks and produced offspring that also had, on average, larger beaks. Parents tend to produce offspring that look like themselves. The shift in the population distribution toward larger average beak depth was a result of differences in survival and reproductive success for individual birds with different beak depths. This is natural selection in action.

To begin the study of this case, students must be provided with the backstory about the Grants and their study of the finches on Daphne Major without telling them the final outcome. They need to know that the Grants were collecting data on finch beak depth, body weight, wing length, and leg length for a number of years, with little change in the finches until a drought occurred in 1977. The drought caused a change in the vegetation and a resulting change in the types of seeds available for the finches to eat. Before the drought there was a range of seeds varying in size and hardness, but following the drought there were only large, hard seeds. Ask students to predict what happened to the finches as a result of the changing conditions caused by the drought. It is likely that many will suggest that individual finches had to grow larger beaks, or produce offspring with larger beaks, in order to survive on the supply of large seeds.

Once the students have made their predictions, they can be shown the histogram in Figure 6. Working in small groups using



The histogram shows the distribution of beak depths of medium ground finches on Daphne Major in 1976 (white bars). The number of finches at each beak depth that survived the 1977 drought (black bars) are also shown. The carets mark the locations of the means for all finches (left) and the survivors (right).

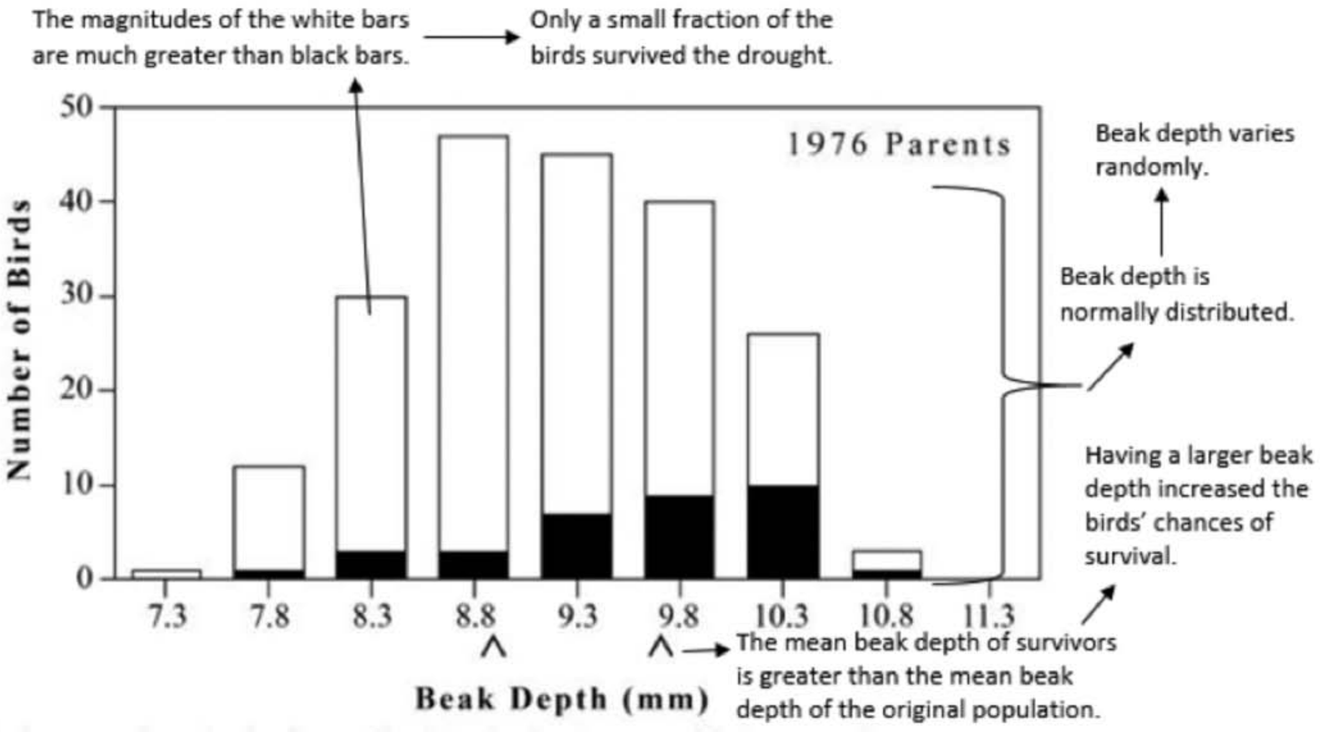
Figure 6. Used with permission from the Howard Hughes Medical Institute, © 2017. All rights reserved. https://www.hhmi.org/biointeractive.

the I^2 technique, students take note of the variables on the axes of the histogram and make sure they understand their meaning. Then they identify any patterns or differences they see, followed by writing the corresponding "What it means" statements. One important feature for students to note is the difference in the magnitudes of the white bars and the black bars. A comparison shows that large numbers of finches died as a result of the drought. A related video (HHMI BioInteractive, 2013), which can be shown after students analyze the histograms, states that 80% of the birds died, resulting in a change in the average beak depth. Examples of "What I see" statements and their associated "What it means" statements are shown in Figure 7.

Once students have completed their analysis of the histogram showing the parents, they should be presented with the two histograms in Figure 8 comparing the beak depths of the offspring in 1976 with the beak depths of the offspring in 1978. Students use I^2 on these two histograms and relate them back to the histogram in Figure 7. Students should see that the distribution of beak depths of the 1976 offspring is similar to the 1976 parental distribution and that both have similar averages. The same can be said for parents that survived the 1977 drought and the 1978 offspring. These similarities in the respective population distributions suggest that beak depth is an inherited trait, and that selection for larger beak depth during the drought increased the average beak depth.

Once students have completed their analysis of the histograms, a whole-class discussion gives them the opportunity to share what they've found and argue for a particular interpretation of the evidence until the class arrives at some agreement on the relevant features and their meaning. When the class has reached a consensus, students individually write detailed captions for the histograms by combining the "What I see" and "What it means" statements into coherent paragraphs. By examining the histograms in Figures 7 and 8 together, the two-step process of natural selection is made apparent to students. The beak depths of the 1976 parents in Figure 7 (white bars) are normally distributed, showing variation around an average beak depth of ~8.8 mm. Comparing this histogram to the 1976 offspring in Figure 8, we can see that the distribution is a very similar normal distribution with a similar average of ~8.8 mm, illustrating the fact that beak depth is inherited. Since inheritance is randomized through mutation and genetic recombination, the two distributions are not exactly identical, but they have very similar averages and standard deviations. Had the drought not occurred, it is very likely that the distribution of beak depths in the 1978 offspring would have been similar to both the 1976 parents and offspring, with an average in the neighborhood of ~8.8 mm and a similar range of variation. However, the environmental conditions during the 1977 drought caused the distribution of surviving parents to shift toward a larger average beak depth of ~9.8 mm, as shown in Figure 7 (black bars). Since beak depth is an inherited trait, when the surviving parents reproduced, the distribution of beak depths in their offspring in 1978 as shown in Figure 8 was also very similar, with an average of ~9.8 mm and a similar range of variation.

As stated in the rock pocket mouse section above, Darwin's mechanism requires inheritable variation in a trait, and a specific variation of that trait must enable those individuals who possess the variation to leave more offspring than other variants. If these criteria are met, then the distribution of traits among the offspring will differ predictably from that of all the parents beyond what



The magnitudes of the white bars are much greater than black bars. → Only a small fraction of the birds survived the drought.

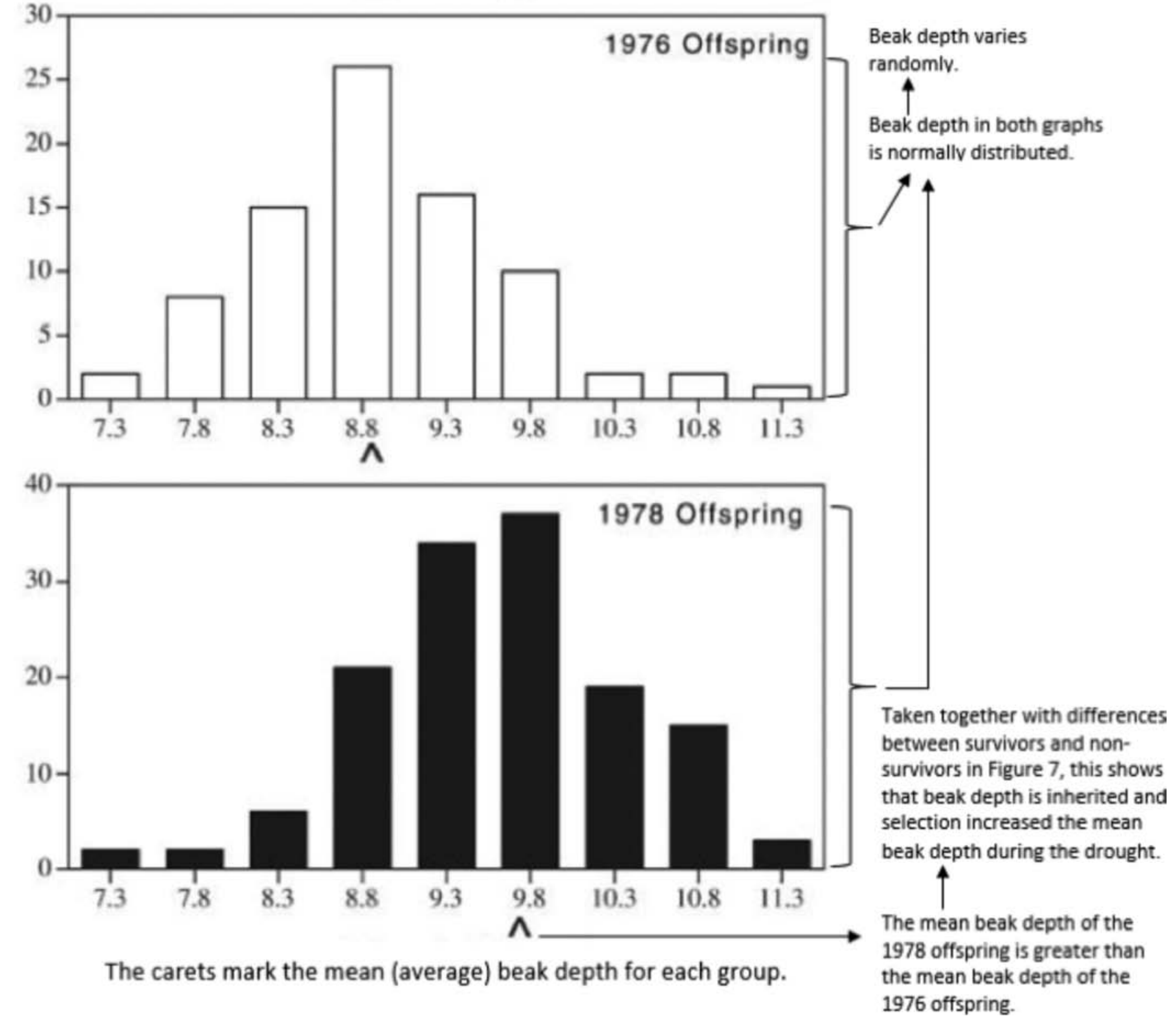
Beak depth varies randomly.

Beak depth is normally distributed.

Having a larger beak depth increased the birds' chances of survival.

→ The mean beak depth of survivors is greater than the mean beak depth of the original population.

Figure 7. Used with permission from the Howard Hughes Medical Institute, © 2017. All rights reserved. https://www.hhmi.org/biointeractive.



Beak depth varies randomly.

Beak depth in both graphs is normally distributed.

Taken together with differences between survivors and non-survivors in Figure 7, this shows that beak depth is inherited and selection increased the mean beak depth during the drought.

The mean beak depth of the 1978 offspring is greater than the mean beak depth of the 1976 offspring.

The carets mark the mean (average) beak depth for each group.

Figure 8. Used with permission from the Howard Hughes Medical Institute, © 2015. All rights reserved. https://www.hhmi.org/biointeractive.

would be expected from variation and inheritance alone (Endler, 1986). The survivors of the 1977 drought had, on average, larger beak depths than the nonsurvivors. As a result, they produced a new generation in 1978 that also had, on average, larger beak depths. Comparing the initial population of parents from 1976 with the offspring in 1978, students can see that there was a change in the population distribution over generations – in other words, evolution by natural selection has occurred.

Once students have written their captions, show the video describing the Grants' research (HHMI BioInteractive, 2013). A short segment of the video (5:17 minutes long: from 5:56 to 11:13) is sufficient for the students to compare their conclusions to those of the Grants. Students will see that they have arrived at the same conclusions reached by the Grants. The rest of the 16-minute video explains how natural selection contributes to the formation of new species.

Conclusion

Many students have very robust misconceptions about natural selection that may seem immune to instruction (Chi, 2005). The misconceptions are robust because they stem from intuitive theories that form a child's earliest understandings of the natural world (Shtulman, 2017). While these intuitive theories are essential for comprehending many events in a child's daily experience, they can make learning the counterintuitive theory of natural selection challenging, but certainly not impossible. Shtulman (2017, p. 245) writes, "Any educator who wants to help students confront and correct their intuitive theories needs to tailor his or her instruction to those theories." The key is to guide students through an evaluation of the intuitive theory and its well-established scientific counterpart. Students need a clear demonstration of how the intuitive theory fails to adequately explain the phenomenon in question, followed by a clear demonstration of how the scientific theory adequately explains the phenomenon. The approach suggested here is to employ graphs and some basic statistical concepts to guide students through the process of population thinking. In other words, they need to be aware of the emergent and transgenerational nature of evolution by natural selection. This requires that students have an understanding of basic concepts from statistics, like the concepts of distribution, average, and variance. When the I^2 strategy is used on the graphs derived from the two cases of natural selection in action described here, students see that selection acts on individuals and many of them die; individual organisms do not change in order to survive. Evolutionary change emerges at the population level, in the proportions of individuals with different variations.

The I^2 strategy can be used to scaffold students' efforts to understand any type of figure found in scientific papers and textbooks. When students work on the I^2 strategy in pairs or small groups, teachers can facilitate the kind of student talk that promotes learning of both content and science practices. In short, using I^2 to guide students in the interpretation of data helps them learn to think like biologists (Handelsman et al., 2004; Tanner, 2009; BSCS, 2012a, b).

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