Evolutionary Simulations in SLiM

Teacher Guide

Activity Overview

To understand evolution, one cannot go out in nature and see species evolve in a reasonable timeframe. However, computer models can be used to understand how species evolve, how long evolution takes to occur, and what factors contribute to their evolution. A computer simulation tool called SLiM: An Evolutionary Simulation Framework allows users to create a genome and see how it evolves over time according to a number of factors. Students will learn how to use the program, and explore an evolving genome.

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Focus Question

How does population size, competition, mutation rate, and strength of selection affect the evolution of a population?

Objectives

Students will be able to:
- Use a simulation to model how populations evolve
- Understand what factors contribute to the evolution of a population
- Explain how evolution factors interact with each other to change a population

Learning Level

High School (9th - 12th)
Undergraduate

Duration

Class time: 30 - 40 minutes
Teacher preparation: 5 minutes

Next Generation Science Standards

HS-LS4-2 Biological Evolution: Unity and Diversity
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-LS2-2 Ecosystems: Interactions, Energy, and Dynamics
Use mathematical representations to support and revise explanations based on evidence about factors affecting biodiversity and populations in ecosystems of different scales.

Attributions

This activity, created by Sara Schaal, is based on research conducted in Dr. Katie Lotterhos' Lab at the Northeastern University Marine Science Center. The development of this activity was funded by NSF-OCE 1635423 and NSF-DEB 1655701 to Dr. Katie Lotterhos.

Background

This information is also on the student worksheet, shown at the end of the packet

This activity teaches students how **simulations** in SLiM work and how to edit these simulations to understand how **adaptation** changes in a population. To see how a population evolves on the landscape, users will change population size, competition, mutation rates, and **strengths of selection**. All of these parameters work together to influence where certain traits are favored on the map. This is similar to what is seen in many species, but for example Atlantic cod show different traits depending on where they are found in the ocean. If they are in shallow water they are sometimes more red in their coloration and in deeper waters are more olive.

Competition

Competition is when individuals compete for resources, including food, mates, and/or space. When competition is strong, subpopulations may form in the population that either vary in their phenotype or vary in the location of the habitat that they are using. For example, in Darwin's finches of the Galapagos, competition for the food resource was strong, and finches needed to adapt in order to survive. Over evolutionary time, finches evolved different beak length and shape in order to specialize on the different food sources available to them (Figure 1A). If competition is strong, variation in traits can occur in tandem with variation in spatial distribution. Subpopulations with different traits may dominate different regions of the species distribution as seen in the African cichlids (Figure 1B).

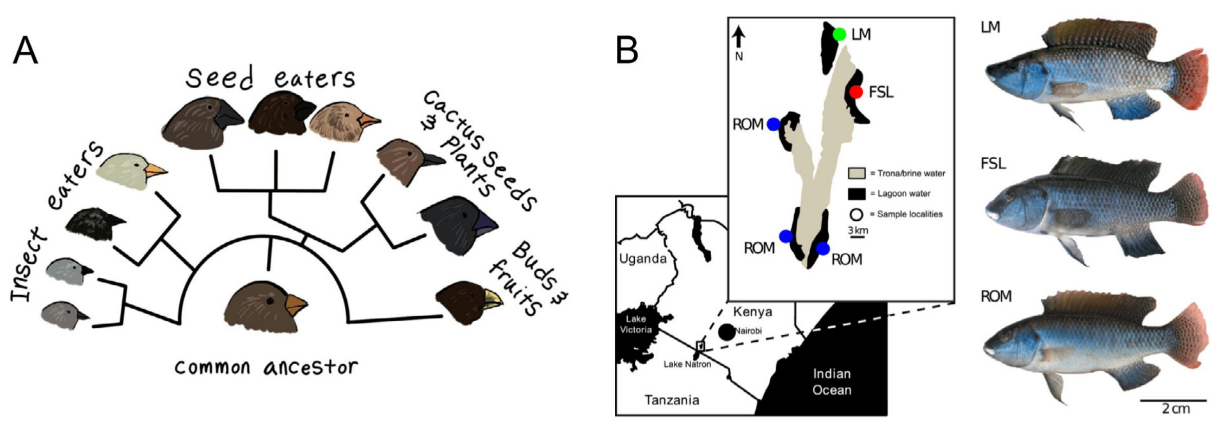


Figure 1. Adaptation in different species due to competition for resources. Panel A) Example of adaptation to different food types in finches due to competition for food. The shape and size of the beaks vary based on what type of food each bird population specializes in. Panel B) competition for space has caused adaptation in different body shape traits that are specific to each region these populations occupy (From Kavembe et al. 2016).

Strength of Selection

Selection acts to reduce the variation in a given phenotype (i.e. a trait). There are varying strengths of selection ranging from very strong, where only a few variations of a trait are beneficial in a habitat (Figure 2A), to very weak, which allows many traits to coexist in a habitat (Figure 2B). For this simulation, strength of selection is determined by the extent to which selection reduces the variation in trait values. When selection is strong, the variation in trait values is reduced and becomes a much smaller/narrower curve (blue curve in Figure 2A). Whereas, when selection is weak, the variation in trait values is reduced by a much smaller degree. Therefore, when adjusting strength of selection, the width of the distribution of traits changes (blue curves in Figure 2). Keep in mind that small values mean STRONG selection (narrow width) and large values mean WEAK selection (wide width).

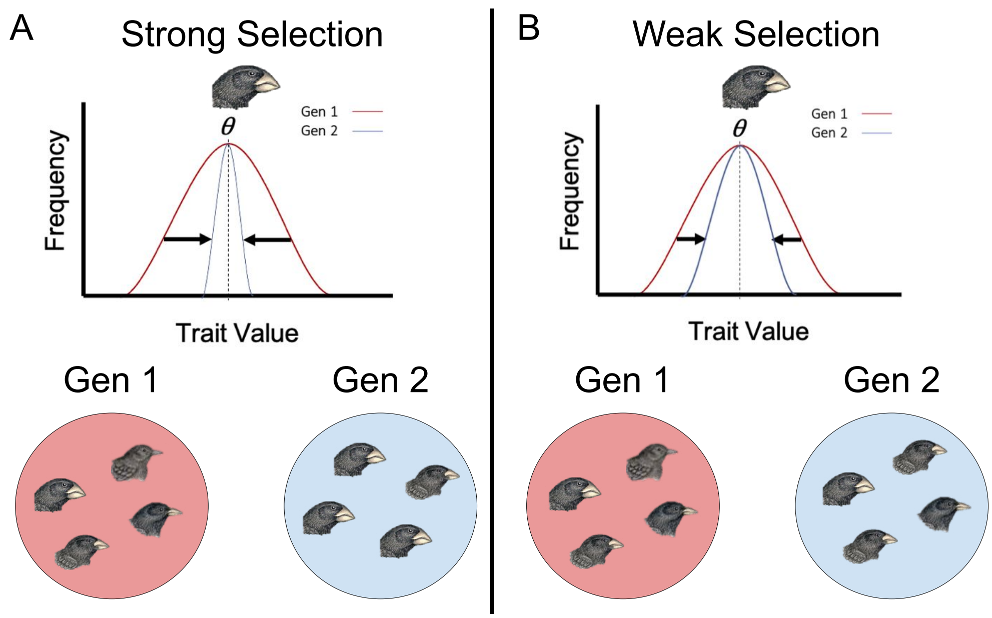


Figure 2. The effect of the selection on the distribution of trait values of beak shape in the population. Panel A depicts how strong selection acts to reduce the variation in trait values (x-axis) from Generation 1 (red line) to Generation 2 (blue line) to all be closer to the population optimum (Theta). The bottom of Panel A shows the distribution of traits before selection (Generation 1 in red) and after selection (Generation 2 in blue). Panel B shows the same information for weak selection.

Population Size

In nature, populations can take on many different sizes. When a population is endangered, there can be as few as a couple of individuals in the population. Their ability to adapt to the environment will be very different from a healthy population with many reproducing individuals. In small populations, a process called **genetic drift** occurs more frequently. Genetic drift is the evolutionary process where mutations are randomly lost from the population due to individuals carrying those mutations not reproducing in the next generation. When population sizes are small, we expect genetic drift to happen more often (e.g., Figure 3). Although the effect of population size on adaptation is complex and can be influenced by a number of different factors, here we will simplify things with our simulation and try to understand how genetic drift influences the evolution of traits across the landscape.

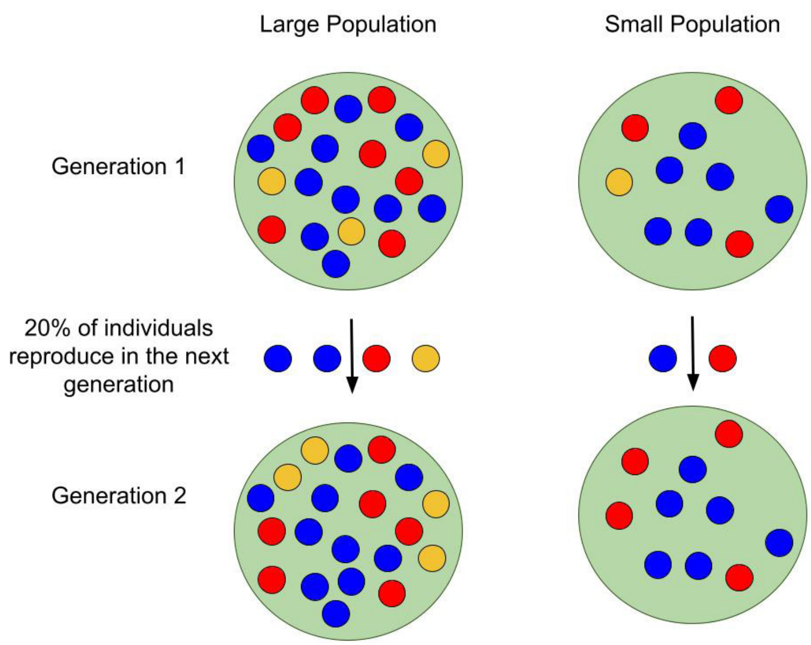


Figure 3. Example of how population size can influence how much genetic drift occurs in a population. A large population size of 20 individuals is on the left and a small population of 10 individuals is on the right. Here let's pretend 20% of individuals can be parents in the next generation. Parents are chosen at random to reproduce, but by chance in the smaller population the yellow phenotype is lost because it wasn't chosen to reproduce, but it was chosen and remains in the large population.

Mutation Rate

Mutations in the genome are what cause new phenotypes to arise and the rate at which they arise in a genome or population is called the **mutation rate**. Selection will act on these new phenotypes that are formed and the mutations underlying the phenotype can persist in the population if they are beneficial or they can be lost because selection in that environment does not favor them. To determine an individual's phenotype in our simulations, the mutations in that individual's genome are added together to determine its color. For example, an individual may have one mutation that gives it a more yellow phenotype and another mutation somewhere else in its genome that gives it a more blue phenotype. However, when the two phenotypes are added together, the individual's overall phenotype is green (parent Figure 4). Then, if in the next generation it's offspring is born with a new mutation that gives it more of a blue phenotype, its color may start to turn teal (offspring Figure 4). Keep in mind, because mutation rates are so small, scientific notation is used when we report or define them. In our simulation, the default mutation rate of 1e-6 is 0.000001.

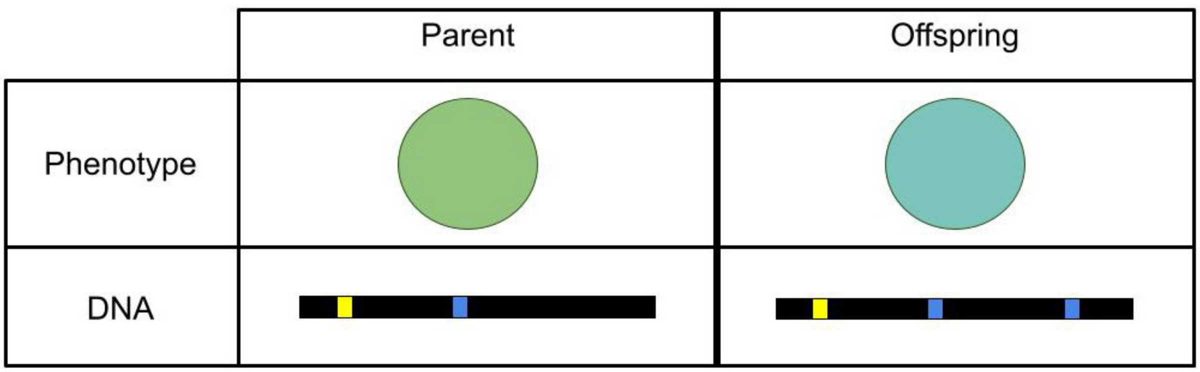


Figure 4. The phenotype of individuals in our simulations result from the sum of the values of all the mutations in its genome. In this example, the parent's yellow and blue mutations give it a trait color value of green. If the offspring is then born with a new second blue mutation, this changes its color phenotype to more of a teal color compared to its parent's phenotype.

Materials

For each student:
- Mac computer with the SLiM program installed
- 'Evolutionary Simulations in SLiM' student worksheet
- Writing utensil

Teacher Preparation

1. Make sure each student (or a small group of students) has access to a Mac computer. The SLiM program unfortunately is not compatible with Windows computers. If needed, this activity could be converted in a demonstration/discussion if there is limited access to Mac computers.
2. Download SLiM onto each computer
    i. Go to messerlab.org/slim and download SLiM version 3.5 by clicking on the macOS Installer hyperlink
3. Print out the 'Evolutionary Simulations in SLiM' worksheet for each student
4. If desired, go through the simulation yourself to understand the layout and questions of the activity

Procedure

Step 1. Introduce focus question to the class
Pose the focus question, *"How does population size, competition, mutation rate, and strength of selection affect the evolution of a population?"*, to the class and begin the lesson with a short discussion. Can students explain each of these four factors? How do they think these would affect the evolution of a population? Ask them to explain their thinking.

Step 2. Provide the context for the activity topic
Once the short discussion finishes, begin introducing the topic of the activity that addresses the focus question: simulating the evolution of a population. More detailed information about this topic can be found in the 'Background' section of this packet (p. 2-5).

Discuss how evolution cannot be observed in a reasonable timeframe, so simulations are used to understand how species evolve. A program called SLiM: An Evolutionary Simulation Framework allows users of the program to create a genome and see how it evolves over time according to a number of factors including strength of selection (how much an environment favors a traits), mutation rate (how often mutations occur), amount of competition (how limited resources are in the population), population sizes (how many individuals there are in the population).

Step 3. Set up the activity
Provide the printed worksheet to each student. Ensure that each student has access to a working Mac computer that has the SLiM program already downloaded.

Step 4. Explain the activity
Briefly go over the directions on the worksheet and ask the students if they have any questions that need clarification. If necessary, project your computer screen to the front of the classroom to give a brief overview of what the simulation program looks like and what each window does. However, this information and screenshots of the program are given on the student worksheet.

Step 5. Have students conduct the activity
The student worksheet explains what students must do to complete the activity. There are six different sections: Introduction, Competition, Strength of Selection, Interplay of Selection and Competition, Population Size, and Mutation Rate. After each section are a few questions for the students to answer. The student worksheet is included in the last 14 pages of this packet.

Step 6. Discuss main takeaways and evaluate understanding of the topic
To evaluate the understanding of the topic, return back to the focus question at the beginning, *"How does population size, competition, mutation rate, and strength of selection affect the evolution of a population?"*. Ask students to explain either to the class or in small groups how each factor (competition, strength of selection, population size, and mutation rate) influences evolution. Be sure they reference the simulation to support their answers. As a summarizing statement, reiterate that evolution cannot be seen in real-time in a reasonable timeframe, so simulations are conducted. These simulations help us to understand how evolution of a population occurs when different factors are changed.

Vocabulary

adaptation: physical or behavioral changes in an organism that result from exposure to new environments

competition: biological interaction among organisms when a common resource is shared and limited (e.g., food or space)

divergence: when traits that are expressed in two or more groups of a species have distinct values in opposing directions to one another (e.g., long peaks and short beaks)

genetic drift: the evolutionary process where mutations are randomly lost from the population due to individuals carrying those mutations not reproducing in the next generation

mutation rate: how often a new genetic change occurs in an individual or population

selection: non-random difference in reproduction between individuals due to phenotypes being closer or further away from the phenotypic optimum in a given environment

simulation: use of models to imitate a real-life process

speciation: formation of new species through the evolution from a common ancestor

strength of selection: the amount of variation in trait values that have high fitness in a given environment (e.g., strong selection strength means few trait values will have high fitness)

References

Kavembe, G. D., A. F. Kautt, G. Machado-Schiaffino, and A. Meyer. 2016. Eco-morphological differentiation in Lake Magaditilapia, an extremophile cichlid fish living in hot,alkaline and hypersaline lakes in East Africa. *Molecular Ecology* **25:** 1610-1625.

Student Worksheet Solutions

Activity 1 - Introduction to the Simulation

1. What do the different colors represent in the simulation window?

Solution: Different phenotypes or traits that are evolving in the population

2. As the simulation proceeds does the phenotype get more or less variable on the landscape?

Solution: More variable, you can see more colors representing different phenotypes that are moving away to the edges of the simulation window

3. Just to make sure we don't forget, what color is selected for on the left side of the simulation, in the middle, and right side?

Solution: Yellow on the left, green in the center, and blue on the right

Activity 2 - Alter Competition

4. How does high competition alter where the individuals are in the population?

Solution: When we increase competition, the populations move to the outskirts of the simulation window. This is because competition is so strong that the populations cannot come into close proximity of one another without then going extinct due to competition for space.

5. Why do moderate levels of competition result in more phenotypes?

Solution: You should start to see some groups with a new phenotype arise and persist, but then split off from that original group. This is because with reduced competition these new phenotypes can survive in closer proximity to the original phenotype, but because competition is still fairly high populations need to specialize with specific phenotypes.

6. How does reducing competition to low values change what phenotypes evolve?

Solution: The lowest values result in populations that are still adapted to regions of the landscape with their phenotype, but look very similar because they do not need to compete and show extreme phenotypes that vary from the rest of the population because competition is extremely low. You can think of this as there are plenty of resources available for everyone to survive so they do not need to specialize in a specific phenotype and can take on a more generalist phenotype.

Activity 3 - Strength of Selection

7. How does reducing selection change what phenotypes evolve on the landscape?

Solution: Students should see the population remains in the center of the landscape and the phenotype stays relatively constant. This is because strong selection is acting to keep the phenotype close to the optimum and have little variance around that optimum phenotype which in this example is the green phenotype.

8. How does increasing selection change what phenotypes on the landscape?

Solution: Students should see that multiple phenotypes evolve with different colors evolving across the landscape. This is because selection is not strong across the landscape and different phenotypes that normally wouldn't arise in an area due to selection for the optimum can arise because our selection strength allows for high variation in phenotypes.

Activity 4 - Interplay of Selection and Competition

9. How does having both high competition and strong selection influence the phenotypes that evolve on the landscape?

Solution: Students should see when they increase selection (make the value smaller) and then increase competition, you'll see new phenotypes do not arise because selection is very strong. Competition moves the populations to the edges of the environment so as not to compete with each other, but each population has similar phenotypes.

10. How does decreasing selection influence the distribution of individuals and the range in phenotypes?

Solution: Students should see when they decrease selection, competition still moves populations to the edges, but they can take on many more phenotypes because the strength of selection is weaker.

Activity 5 - Population Size

11. How does a smaller population size influence the number of phenotypes on the landscape?

Solution: The small population size makes the number of phenotypes slightly erratic across the landscape with phenotypes appearing and quickly being lost due to genetic drift. This is because with a small population size, individuals with unique phenotypes are randomly lost because they don't reproduce in the next generation.

12. When watching the dynamics of the simulation, what kind of variation did you observe in the trait values?

Solution: Looking at the sd column of their simulation run they should notice that the variance changes significantly between the different generations. This is another representation of the erratic nature of adaptation with small sample sizes.

13. Are populations more or less adapted across the landscape compared to the higher population size simulation?

Solution: The smaller population size results in phenotypes that aren't well adapted to the region they are in on the landscape (remember yellow on left, green in the middle and blue on the right). In the example here you have a green phenotype that is in the blue region of the landscape. The larger population is more efficient at adapting across the landscape and phenotypes closer to the optimum for each region of the landscape.

Activity 6 - Mutation Rate

14. How does increasing the mutation rate affect what phenotypes arise on the landscape? Are they more or less adapted to their respective locations?

Solution: A lot of different phenotypes are arising because of the high mutation rate, but are also selected against in regions where those phenotypes aren't optimal. That results in a lot of phenotypes arising and being lost because of the high mutation rate. Overall the populations are still adapting to the given environment they are in (green in the center and a teal blue on the right), but there is much more variance in the trait values (sd of the output table).

15. How does increasing competition with the high mutation rate influence the number of phenotypes and where they are located on the landscape?

Solution: Similar phenotype dynamics with populations on average adapting to their environment (yellow/orange on the left and blue/teal on the right), but now the population splits to different locations on the landscape due to high competition moving them to the outskirts.

Name: ______________________________ **Date:** ________________

Evolutionary Simulations in SLiM

Activity Worksheet

Focus Question

How does population size, competition, mutation rate, and strength of selection affect the evolution of a population?

Objectives

Students will be able to:

- Use a simulation to model how populations evolve
- Understand what factors contribute to the evolution of a population
- Explain how evolution factors interact with each other to change a population

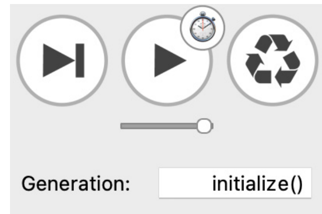
Activity Procedure

To understand evolution, we typically cannot go out in nature and see species evolve in a reasonable timeframe. However, we can use computer models to understand how species evolve, how long evolution takes to occur and what factors contribute to their evolution. A computer **simulation** tool called SLiM: An Evolutionary Simulation Framework allows users of the program to create a genome and see how it evolves over time according to a number of factors including **strength of selection** (how much an environment favors a traits), mutation rate (how often mutations occur), amount of **competition** (how limited resources are in the population), population sizes (how many individuals there are in the population).

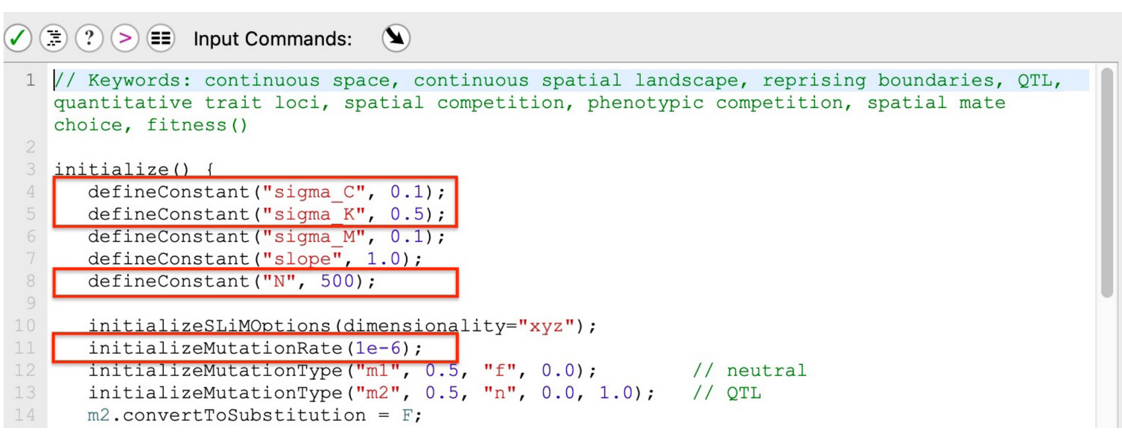
Today we'll learn about how simulations in SLiM work and how we can edit these simulations to understand how **adaptation** changes in a population. We'll change population size, competition, mutation rates and strengths of selection and see how our population evolves on the landscape. All of these parameters work together to influence where certain traits are favored on the map. This is similar to what we see in many species. For example Atlantic cod show different traits depending on where they are found in the ocean. If they are in shallow water they are sometimes more red in their coloration and in deeper waters are more olive! Let's try and simulate how this could happen!

Activity 1 – Introduction to the Simulation

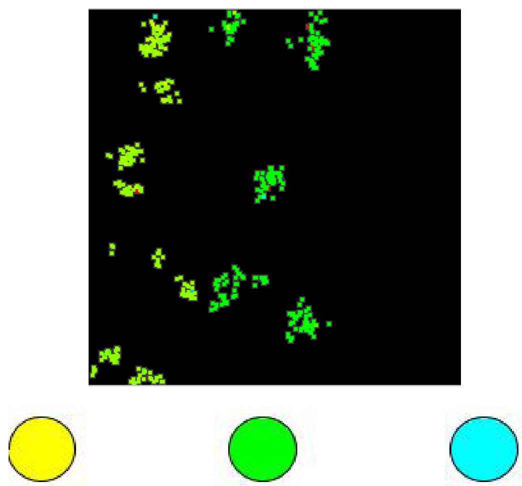
1. Download SLiM version 3.5 from messerlab.org/slim by clicking on the masOS Installer hyperlink
2. Open SLiM recipe 15.9: **Speciation** due to spatial variation in selection
    a. Go to File > Open Recipe > 15 – Continuous-space models and interactions > 15.9: Speciation due to spatial variation in selection
3. Once the recipe is opened, the window should have three buttons in the top right corner, shown on the right. The play button in the middle starts the simulation. To pause, simply click the play button once more. When paused, you can use the forward button on the left to move forward by one generation. If you need to reset the simulation, either for watching it again or to update with new parameters, you can click the reset button on the right. Finally, the Generation window below the buttons will show what generation the simulation is on as it runs.



4. In the Input Commands window on the bottom right corner, you will see the code for the simulation. For the purposes of this activity, the only code you need to focus on are the following parameter levels: 1) on line 4 is competition level, Sigma_C, 2) on line 5 is strength of selection, Sigma_K, 3) on line 8 is population size, N, and 4) on line 11 is mutation rate, initializeMutationRate (mu). The locations of these parameters are shown in red boxes in the image below. Initial levels are as follows:
    a. Sigma_C: competition is 0.1
    b. Sigma_K: strength of selection is 0.5
    c. N: population size is 500
    d. mu: mutation rate is 1e-6

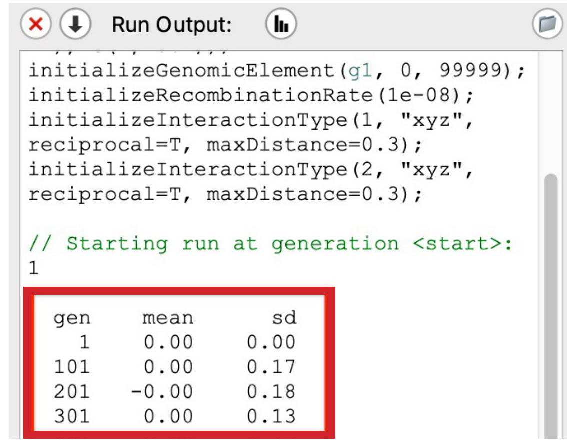


5. Click the play button to run the initial simulation. Allow the simulation to run completely. It will stop automatically when finished, which will take 1-2 minutes. Once the simulation finishes, you will see more information on your screen.
6. The black square with colored dots (shown below) in the top middle of the window shows the adaptation on the landscape. Dots are individuals in the simulation, and the color of the dots corresponds to the phenotype of the individuals. Different colors mean there are different phenotypes present in the population. In this specific simulation, when moving from left to right across the square (landscape), different phenotypes (colors) are selected for — in other words are more beneficial in that area. So in the figure below the yellow phenotype is selected for on the left side of the screen, green in the middle of the screen and blue is selected for on the right side of the screen.



7. The genome bar (shown below) represents the frequency of mutations across the entire population. Colored bars excluding yellow are any mutation that affect the phenotype, while yellow bars are neutral mutations that do not affect the phenotype. As the simulation runs, these bars move up and down, showing the frequency of the mutation changing with each subsequent generation.

8. In the “Run Output” window on the right, there are three columns with information about the simulation run: 1) the generation of the simulation, 2) the average phenotype in the population, and 3) the standard deviation of the phenotype (how variable the trait is in the population). If the trait is **diverging** in the population, the mean may stay the same, but the variation around the mean may increase because different subpopulations have different phenotypes.



9. Click the recycle button to refresh the simulation. For this next simulation run-through, pay attention to certain parameters: the number of phenotypes in the top square, the mean of the population, and the standard deviation of the population.
   a. Let the simulation run only for ~100 generations and pause
      i. Record the number of phenotypes you see after 100 generations on your worksheet, the mean phenotype, and the standard deviation of the phenotype
   b. Click play once more and let the simulation run to the end while observing the dynamics.
      ii. Fill out Activity 1 on your worksheet

Activity 2 – Alter Competition

Competition is when individuals compete for resources, including food, mates, and/or space. When competition is strong, subpopulations may form in the population that either vary in their phenotype or vary in the location of the habitat that they are using. For example, in Darwin’s finches of the Galapagos, competition for the food resource was strong, and finches needed to adapt in order to survive. Over evolutionary time, finches evolved different beak length and shape in order to specialize on the different food sources available to them (Figure 1A). If competition is strong, variation in traits can occur in tandem with variation in spatial distribution. Subpopulations with different traits may dominate different regions of the species distribution as seen in the African cichlids (Figure 1B).

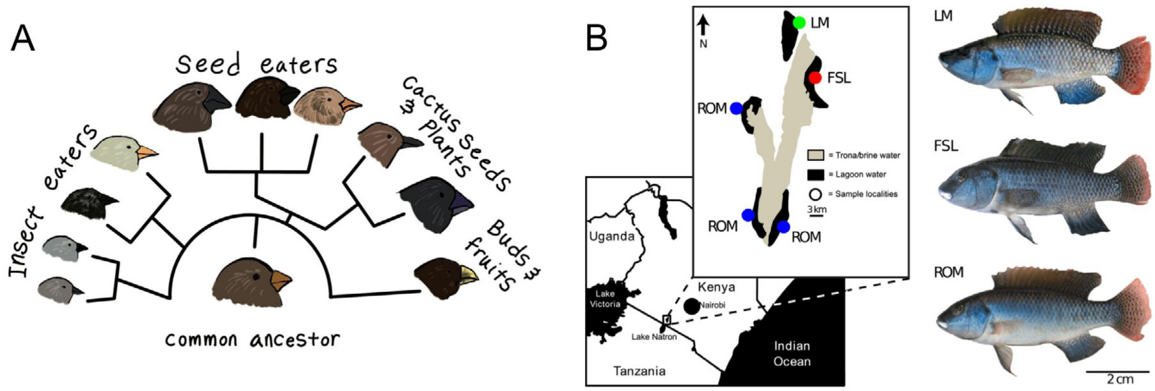
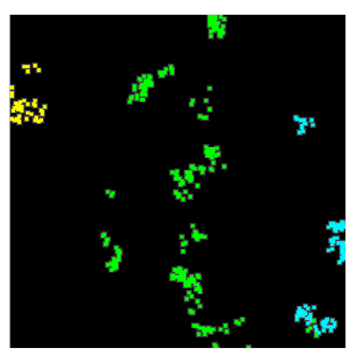


Figure 1. Adaptation in different species due to competition for resources. Panel A) Example of adaptation to different food types in finches due to competition for food. The shape and size of the beaks vary based on what type of food each bird population specializes in. Panel B) competition for space has caused adaptation in different body shape traits that are specific to each region these populations occupy (From Kavembe et al. 2016).

To better understand how competition drives adaptation, the competition value will be changed while leaving the rest of the parameters as is.

1. Change parameters according to Activity 2a in your worksheet. In this case, change competition to 0.8 (on line 4, change 0.1 to 0.8) and leave the other parameters alone.
2. Click the recycle button on the top right corner to reset the simulation
3. Let the simulation run for ~100 generations and pause
4. On Activity 2a of your worksheet record the number of phenotypes you see after 100 generations, the mean phenotype, and the standard deviation of the phenotype
5. Click play and interpret the dynamics that you see
6. Explore how different values of competition change the dynamics of the population and when adaptation occurs. Use the parameters in Activity 2b on the worksheet (changing Sigma_C to 0.5), and record the dynamics of a moderate competition simulation.
7. Now compare this to what we saw for the low competition parameter (Sigma_C = 0.1) in our original simulation. Here is an example run of our original simulation



Activity 3 – Strength of Selection

Selection acts to reduce the variation in a given phenotype (i.e. a trait). There are varying strengths of selection ranging from very strong, where only a few variations of a trait are beneficial in a habitat (Figure 2A), to very weak, which allows many traits to coexist in a habitat (Figure 2B). For this simulation, strength of selection is determined by the extent to which selection reduces the variation in trait values. When selection is strong, the variation in trait values is reduced and becomes a much smaller/narrower curve (blue curve in Figure 2A). Whereas, when selection is weak, the variation in trait values is reduced by a much smaller degree. Therefore, when adjusting strength of selection, the width of the distribution of traits changes (blue curves in Figure 2). Keep in mind that small values mean STRONG selection (narrow width) and large values mean WEAK selection (wide width).

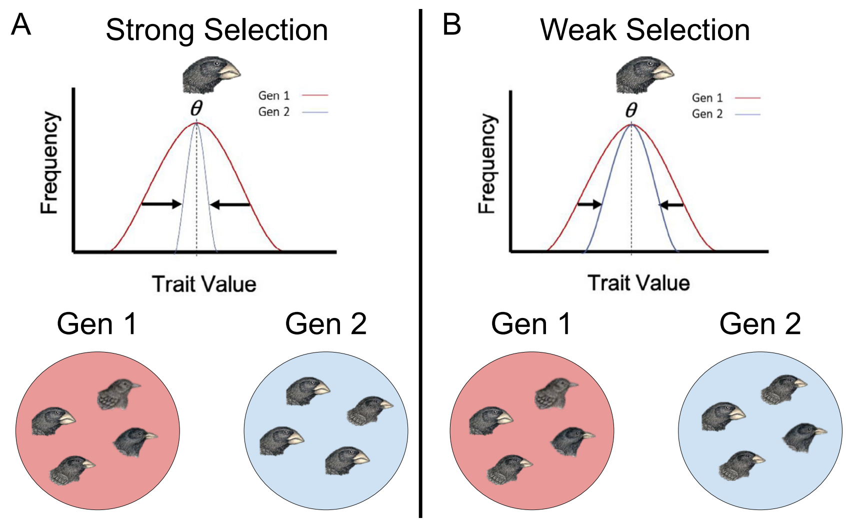


Figure 2. The effect of the selection on the distribution of trait values of beak shape in the population. Panel A depicts how strong selection acts to reduce the variation in trait values (x-axis) from Generation 1 (red line) to Generation 2 (blue line) to all be closer to the population optimum (Theta). The bottom of Panel A shows the distribution of traits before selection (Generation 1 in red) and after selection (Generation 2 in blue). Panel B shows the same information for weak selection.

1. Set values back to the "initial simulation" values (Activity 1 in worksheet table)
2. Adjust the strength of selection to a low value of 0.1 (Activity 3a in worksheet table). Remember, lower values mean a stronger strength of selection (see description above)
3. Fill out Activity 3a on your worksheet with data from this simulation and describe the dynamics that you see
4. Now adjust the strength of selection to a higher value of 0.8 (weak selection) and describe the dynamics that you see
5. Fill out Activity 3b on your worksheet with data from this simulation and answer the questions

Activity 4 – Interplay of Selection and Competition

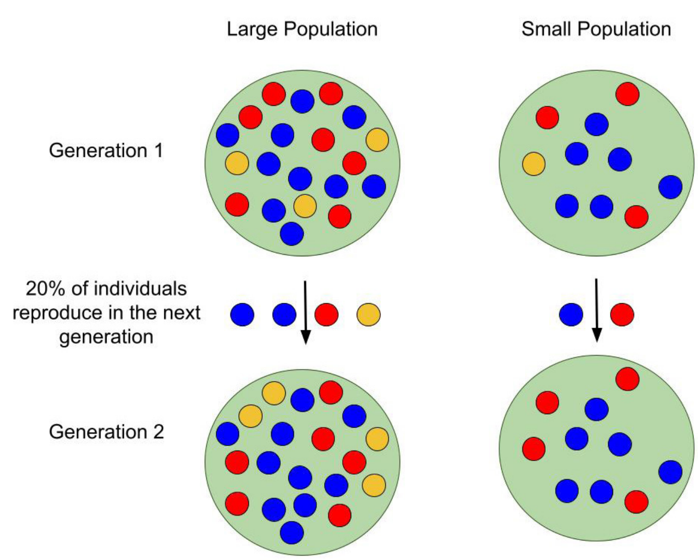
In real-world populations, competition and selection interact together to change how adaptation occurs on the landscape. Let's explore some of those cases!

1. Change parameters to those on Activity 4a. Competition should be high (0.8) and strength of selection should be strong (0.1 - remember low values mean stronger selection).
2. Fill out activity 4a on your worksheet
3. Change selection to 0.9 (weaker selection), but keep competition high at 0.8
4. Fill out activity 4b on your worksheet

Activity 5 – Population Size

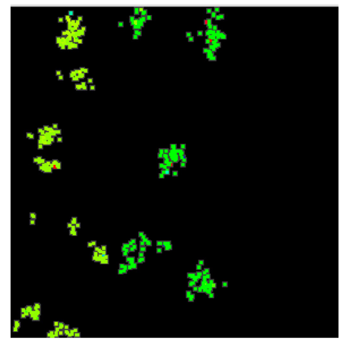
In nature, populations can take on many different sizes. When a population is endangered, there can be as few as a couple of individuals in the population. Their ability to adapt to the environment will be very different from a healthy population with many reproducing individuals. In small populations, a process called **genetic drift** occurs more frequently. Genetic drift is the evolutionary process where mutations are randomly lost from the population due to individuals carrying those mutations not reproducing in the next generation. When population sizes are small, we expect genetic drift to happen more often (e.g. Figure 3). Although the effect of population size on adaptation is complex and can be influenced by a number of different factors, here we will simplify things with our simulation and try to understand how genetic drift influences the evolution of traits across the landscape.

Figure 3. Example of how population size can influence how much genetic drift occurs in a population. A large population size of 20 individuals is on the left and a small population of 10 individuals is on the right. Here let's pretend 20% of individuals can be parents in the next generation. Parents are chosen at random to reproduce, but by chance in the smaller population the yellow phenotype is lost because it wasn't chosen to reproduce, but it was chosen and remains in the large population.



Important note: If you want to explore changing population size values, do NOT go above 1000. It will freeze your computer!

1. Return values to original in Activity 1 of your worksheet.
2. Now change population size (N) to a value of 100.
3. Click play to run the simulation. Begin filling out Activity 5 in your worksheet.
4. Allow the simulation to finish and complete the activity. For this simulation, pay attention to what is occurring with the population mean and sd of trait values over time.
5. If you need to remind yourself of what happened with the original parameters, reset the simulation and change population size (N) to the original value of 500.
6. Click play to run the simulation. To the right is an example run result for the original parameters
7. Compare the dynamics and the values in the output table that you recorded for the two different population sizes.



Activity 6 – Mutation Rate

Mutations in the genome are what cause new phenotypes to arise and the rate at which they arise in a genome or population is called the **mutation rate**. Selection will act on these new phenotypes that are formed and the mutations underlying the phenotype can persist in the population if they are beneficial or they can be lost because selection in that environment does not favor them. To determine an individual's phenotype in our simulations, the mutations in that individual's genome are added together to determine the it's color. For example, an individual may have one mutation that gives it a more yellow phenotype and another mutation somewhere else in its genome that gives it a more blue phenotype. However, when the two phenotypes are added together, the individual's overall phenotype is green (parent Figure 4). Then, if in the next generation it's offspring is born with a new mutation that gives it more of a blue phenotype, its color may start to turn teal (offspring Figure 4). Keep in mind, because mutation rates are so small, scientific notation is used when we report or define them. In our simulation, the default mutation rate of 1e-6 is 0.000001.

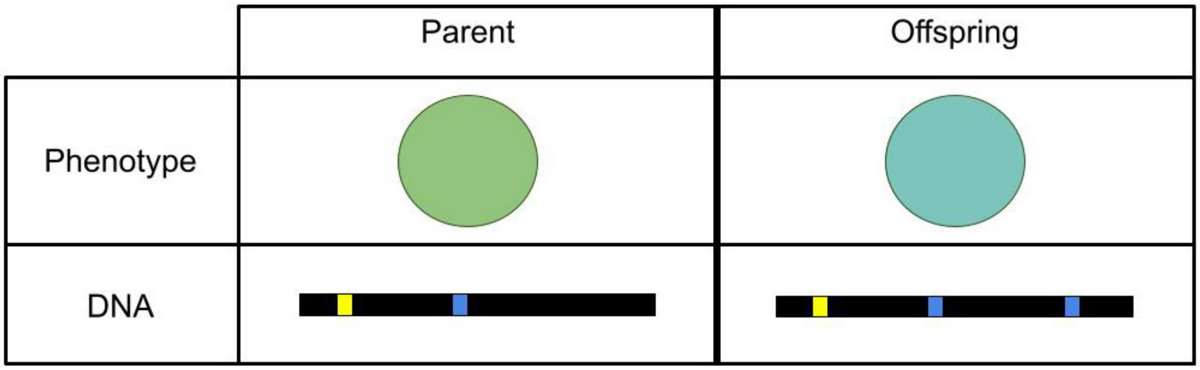
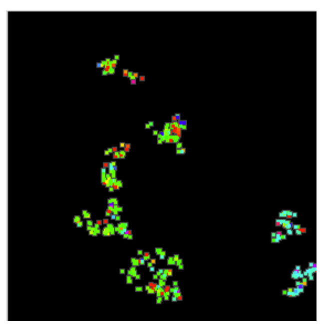


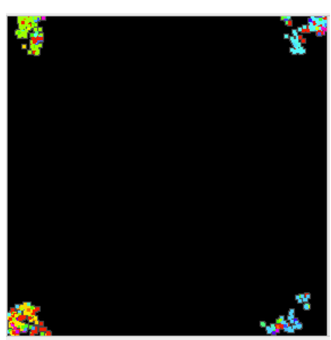
Figure 4. The phenotype individuals in our simulations result from the sum of the values of all the mutations in its genome. In this example, the parent's yellow and blue mutations give it a trait color value of green. If the offspring is then born with a new second blue mutation, this changes its color phenotype to more of a teal color compared to its parent's phenotype.

Important note: If you want to explore changing mutation rate values, do NOT go above 1e-4 (e.g. 1e-2). It will freeze your computer!

1. Return values to original parameters on Activity 1 of your worksheet. Then, move down to line 11 in the simulation and increase mutation rate to 1e-5 (0.00001) for Activity 6a.
2. Click play to run the simulation. Here's an example run result for these parameters:



3. Now play with some of the other parameters like increasing competition now to a high value (sigma_C = 0.8)
4. Note what dynamics you see for Activity 6b on your worksheet. Here is an example run result for these parameters:



Data Table

#	Activity	sigma_C	N	m2	sigma_K	# of Phenotypes First Gen	# of Phenotypes Last Gen	Mean Phenotype First Gen	Mean Phenotype Last Gen	SD Phenotype First Gen	SD Phenotype Last Gen
1	Initial Parameters	0.1	500	1e-6	0.5						
2a	Increase Competition (sigma_C)	0.8	500	1e-6	0.5						
2b	Moderate Competition (sigma_C)	0.5	500	1e-6	0.5						
3a	Increase Strength of Selection (sigma_K)	0.1	500	1e-6	0.1						
3b	Decrease Strength of Selection (sigma_K)	0.1	500	1e-6	0.9						
4a	High Competition (sigma_C) & Strong Selection (sigma_K)	0.8	500	1e-6	0.1						
4b	High Competition (sigma_C) & Weak Selection (sigma_K)	0.8	500	1e-6	0.9						
5	Population Size (N)	0.1	100	1e-6	0.5						
6a	Mutation Rate (m2)	0.1	500	1e-5	0.5						
6b	Mutation Rate (m2) & High Competition (sigma_C)	0.8	500	1e-5	0.5						

Questions

Activity 1 - Introduction to the Simulation

1. What do the different colors represent in the simulation window?

2. As the simulation proceeds does the phenotype get more or less variable on the landscape?

3. Just to make sure we don't forget, what color is selected for on the left side of the simulation, in the middle, and right side?

Activity 2 - Alter Competition

4. How does high competition alter where the individuals are in the population?

5. Why do moderate levels of competition result in more phenotypes?

6. How does reducing competition to low values change what phenotypes evolve?

Activity 3 - Strength of Selection

7. How does reducing selection change what phenotypes evolve on the landscape?

8. How does increasing selection change what phenotypes on the landscape?

Activity 4 - Interplay of Selection and Competition

9. How does having both high competition and strong selection influence the phenotypes that evolve on the landscape?

10. How does decreasing selection influence the distribution of individuals and the range in phenotypes?

Activity 5 - Population Size

11. How does a smaller population size influence the number of phenotypes on the landscape?

12. When watching the dynamics of the simulation, what kind of variation did you observe in the trait values?

13. Are populations more or less adapted across the landscape compared to the higher population size simulation?

Activity 6 - Mutation Rate

14. How does increasing the mutation rate affect what phenotypes arise on the landscape? Are they more or less adapted to their respective locations?

15. How does increasing competition with the high mutation rate influence the number of phenotypes and where they are located on the landscape?

Vocabulary

adaptation: physical or behavioral changes in an organism that result from exposure to new environments
competition: biological interaction among organisms when a common resource is shared and limited (e.g., food or space)
divergence: when traits that are expressed in two or more groups of a species have distinct values in opposing directions to one another (e.g., long peaks and short beaks)
genetic drift: the evolutionary process where mutations are randomly lost from the population due to individuals carrying those mutations not reproducing in the next generation
mutation rate: how often a new genetic change occurs in an individual or population
selection: non-random difference in reproduction between individuals due to phenotypes being closer or further away from the phenotypic optimum in a given environment
simulation: use of models to imitate a real-life process
speciation: formation of new species through the evolution from a common ancestor
strength of selection: the amount of variation in trait values that have high fitness in a given environment (e.g. strong selection strength means few trait values will have high fitness)

Attributions

This activity, created by Sara Schaal, is based on research conducted in Dr. Katie Lotterhos' Lab at the Northeastern University Marine Science Center. The development of this activity was funded by NSF-OCE 1635423 and NSF-DEB 1655701 to Dr. Katie Lotterhos.

About the Scientist

Behind this activity is a scientist at the Northeastern University Marine Science Center working on valuable research. **Sara Schaal** is a doctoral candidate working in the lab of Dr. Katie Lotterhos. Ms. Schaal is interested in fisheries management, evolutionary adaptation to climate change, how local adaptation leads to population divergence and understanding ecology and evolution through the use of mathematical models. Her dissertation is using an integrated genomic approach to improve our understanding and management of the Atlantic cod fisheries. To learn more about Ms. Schaal's research, please follow the information below.

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