Natural Selection: A Simple Model of Selection in a Variable Environment

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Abstract

This activity is derived from the early (1981, Proceedings Volume 2) ABLE lab by James Waddell called Ecology: Predator-Prey Simulation. Our derivation keeps the original ecological interaction and adds evolutionary consequences. Students act as predators who hunt for prey items in a tabletop arena. The arena, made of aquarium stones and confetti, comes in light-colored and dark-colored versions. The prey population starts as an equal mixture of light- and dark-colored beans; the proportions of the mixture change as student-predators hunt through multiple rounds of foraging and the prey reproduce. We chose beans and adjusted the composition of the aquarium stones so our students typically see directional selection in each arena, which we decided was the most desirable outcome for our freshman-level non-majors' lab. In other contexts the general setup would allow students to explore the effects of manipulating these variables on their own. Our students find this to be a very engaging group activity, as was the original Waddell lab. The activity has a remarkable parallel in the ecological genetics of the rock pocket mouse in Arizona, and a wonderful video of Sean Carroll explaining natural selection of coat color in the rock pocket mouse can be shown at the end of the lab.

Introduction

Evolution does not always play a large part in introductory biology courses and it is often more of a lecture topic than a lab topic when it does appear in the syllabus. Yet the laboratory ought to be an effective forum for teaching evolution. If suitable lab activities were available, students could engage physically and mentally in activities that would lead to relevant conclusions about the subject. If students have pre-formed negative attitudes about evolution, peer group interactions might make the subject less confrontational for them. What we need, it seems, are more lab activities that deal with evolutionary concepts.

The activity presented here engages students in working with each other around a simple, easy-to-accept ecological (predator-prey) interaction that has natural selection consequences. Groups of four or five students work as a team, with the role of visual predator rotating among members of the group. The predator hunts for beans in an environment that makes some beans more cryptic than others. The evolutionary dynamics are worked out graphically at the end of the activity, though students are well aware of the changes that are occurring as they do the activity.

The model includes two environments, made of light-colored and dark-colored aquarium stones, and two kinds of beans, light-colored and dark-colored, that represent morphs of a single prey species.

This is an exact match for the rock pocket mouse (*Chaetodipus intermedius*) in its habitat in Arizona. The mouse appears in a tawny form and a black form. The environment consists of light-colored rocky soil with intrusions of black lava. Sean Carroll explains the genetics of coat color and addresses whether mutation and selection are sufficient to account for the observed facts in an 8-minute segment of a video available from Howard Hughes Medical Institute.

Student Outline

Introduction

Charles Darwin and Alfred Russel Wallace independently discovered the idea of evolution by natural selection. Their ideas were presented at the same scientific meeting in London in 1858. In the years since then, natural selection has become a very important concept in biology. It consists of three parts and is easy to understand.

First, biological populations are *variable*. In other words, there are differences among individuals in a population. This is obviously true for human populations. We see differences among people's faces and bodies, we hear differences among voices, observe differences among behaviors, etc. It is also true of animal and plant populations; if we look for variability, we find it.

Second, differences among individuals are *heritable*. In other words, there is a genetic basis for the differences among individuals. It is not necessary for differences to be 100% determined by genes. A trait like human height can be partly determined by nutrition and partly determined by genes and still be influenced by natural selection. Again, we know that variable traits in plant and animal populations are commonly under genetic control.

Third, the differences among individuals can produce differences in how those individuals survive and reproduce. For example, a predator is more likely to pick off an animal whose coloration stands out against its background than an animal that blends in well with its background. Because a better-camouflaged animal lives longer, it will leave more offspring than a poorly camouflaged animal. Another way of saying this is that the environment is *selective* in how it affects different individuals.

Many aspects of the environment vary from place to place as well as over time, so the selective fate of genetically variable individuals changes over space and time.

Experimental Model

The lab activity you are going to do will explore the third point. The activity is a *model* of predator-prey interactions in a variable environment. The model is intentionally kept very simple. There is a prey population represented by small beans and it is variable, so the first criterion for natural selection is built into the model. This variation among prey is the simplest possible: the beans are either light-colored or dark-colored.

The second criterion for natural selection, heritability, is also built into the model. At certain times the prey will reproduce; when this happens, you will add a second bean of the same color for every bean that has survived up to that point. In other words, the light/dark color trait is 100% genetically determined.

In your experiment you are going to test the third criterion for natural selection: the environment acts selectively to determine which individuals survive to reproduce.

The physical appearance of the model environment is variable in the simplest possible way: it is either light-colored or dark-colored. It is made up of small stones with a thin covering of “leaf-litter,” all bounded by a Hula-hoop™. The last piece of the model is the predator. The predator has to be a visual hunter since the key variation in prey is coloration. As a human, you have sharp vision, so you get to be the predator! Your job as predator is to get enough food to survive. Dark-colored and light-colored beans are equally nutritious, so you should eat every bean you encounter.

Rules for the Model

Read over these rules before you begin the experiment.

1. One person is the predator. The others in the group record data, keep time, manage the environmental arena, and cheer on the predator.
2. The predator can use two hands and can move stones or leaf-litter around in search of prey, but cannot remove either stones or leaf-litter from the arena.
3. Each prey (bean) that is caught has to be removed immediately from the arena and placed in the “Captured” container.
4. Each round of foraging lasts 30 seconds. The predator must capture 10 prey items in that time in order to survive. If a predator captures fewer than 10 prey in 30 seconds, it dies of starvation. The role of predator changes after each round, rotating among the members of the group (even if you die in one round you get to return as predator when your turn comes up again).
5. After each round of predation, data must be recorded in the appropriate place in the data-collection table and the total number of beans remaining in the arena must be calculated.
6. If the total number of beans remaining is less than 30, then the prey reproduce, i.e., the number of beans doubles. The proportion of light-colored and dark-colored beans in the arena does not change during reproduction – for each bean that survived in the arena, another bean of the same color is added.
7. The captured beans must be returned to their source containers after each round, so the “Captured” container is empty at the start of the next round.
8. The beans should be dispersed throughout the arena in an approximately random fashion. The leaf litter should be scattered on top. The predator should not watch as the arena is prepared.
9. Each experiment consists of ten rounds of predation. At the end of the experiment, *all* beans must be removed from the arena and put back in their source containers.
10. The starting point for the initial experiment is 15 light-colored and 15 dark-colored beans.

How to Record Data

You are almost ready to start, but first you need to get familiar with how the data are to be handled. Table 1 gives an example of how the first round of an experiment might turn out. There were 15 light-colored and 15 dark-colored beans in the arena at the start. After 30 seconds of hunting there were 3 dark beans and 6 light beans in the “Captured” container. These numbers get recorded and the numbers of beans that must be left in the arena are calculated by subtraction; these numbers are recorded also.

Because fewer than 10 prey were caught in this example, the predator dies of starvation.

Twenty-one beans were left in the arena at the end of Round 1. Since this is less than 30, prey reproduce before the start of the second round. You would add 12 dark-colored beans and 9 light-colored beans to the arena, so the next round starts with a total of 42 beans, 24 dark and 18 light. These numbers must be recorded under Round 2.

The last two columns are for recording the percentages of light and dark beans remaining after the round of predation. These values will be used for graphing the results of the experiment. You can do these calculations after each round, or wait until the end of the experiment to calculate the whole set. In the example the calculations are (12/21 * 100) = 57.1428… and (9/21 * 100) = 42.8571… It will be sufficient to record the percentages to one decimal point.

Table 1. Example of how data are recorded for one round of the natural selection experiment.

Experiment date: Background color:		Dark beans	Light beans	Total beans	Percent dark beans remaining after round	Percent light beans remaining after round
Round 1	Number of prey at start of round	15	15	30		
	Number of prey caught during round	3	6	9	57.1%	42.9%
	Number prey remaining in arena after round	12	9	21		

Run the Experiment

You are now ready to run the experimental model. Record your data in Table 2.

Turning Your Results into a Graph

(Have you already calculated the "% dark" and "% light" percentages in Table 2? If not, do so now.)

How did your experiment turn out? The most useful way to show what happened is to illustrate the results in a graph. A blank graph has been prepared for you. It has everything in place except the data. (There are two blank graphs, Figure 1 and Figure 2, for graphing data from the two different environments. Read the legends of the two figures to determine which one you should use for graphing the data you collected.)

Take a look at how this graph is set up. The y-axis (vertical axis) is labeled "Percent of Population." It is divided into equal parts and these are labeled (0, 10, 20, etc.). This is the conventional way graphs are set up, with the dependent (response) variable on the vertical axis.

The horizontal axis (x-axis) is set up similarly, but to record the independent (manipulated) variable. In this experiment, the independent variable is time, measured in how many rounds of predation have been run since the start of the experiment.

There is a legend under the graph. Notice that a) graphs are called figures in scientific literature, b) figures are numbered consecutively in the document, c) legends are placed under figures but above tables, d) a legend provides enough information about the experiment so it is easy to understand the graph without having to read accompanying text.

Round "0" on the x-axis represents the start of the experiment and the starting percentages were 50%, so place a small circle (representing dark beans) and a small x (representing light beans) on top of each other at the intersection of the 50 line of the y-axis and the 0 line of the x-axis. Then continue to plot the rest of the data points at the appropriate x, y positions.

Finally, draw a smooth line that seems to best represent the pattern of the data points - two lines, actually, one for the dark-colored beans and one for the light-colored beans. The lines won't pass through each data point exactly because there is some *chance* involved in the way each data point was produced. The smooth line represents what you think the result would be if you repeated this experiment many, many times and plotted the average values for each round.

Combining Results from Two Backgrounds

Another group at your lab bench did the same experiment you did, except that they worked with a differently colored background environment. Trade data with them so you can make a graph that shows what happens to the prey population in the other environment.

Interpretation and Summary

As the predator in the model, your immediate goal was to find enough prey to survive. In the real world animals act similarly: they do the things that help them survive and reproduce in their environment. We can think of these things as the day-to-day activities of individuals; the time frame is fairly short, never longer than the lifespan of an individual.

There are important consequences in a longer time frame. In the model we saw this in the prey (bean) population, rather than in the predator population. Over multiple generations of prey, the actions of the predator changed the composition of the prey population. We can say that the prey population became more *adapted* to its environment.

In general, we say that changes of this kind are caused by *natural selection*. Darwin came to the idea of natural selection after thinking hard about the changes farmers had produced in domesticated animals and plants. He realized that herdsmen and plant breeders carefully selected the next set of parents at each generation. Darwin called this *artificial selection* because change was produced by human intervention. He realized that various factors in the environments of wild plant and animal populations constantly affect which individuals become parents of the next generation, and he adopted the phrase "natural selection" to describe what happens in the world when there is no human intervention.

In our model, the visual predator (you) was a key part of the preys' environment. The inanimate background (stones and "leaf-litter") was also a key component of the environment. The selective environment of the model included both these factors and together they determined which prey reproduced.

The take-home message about natural selection can be stated this way: Populations are constantly and unavoidably being shaped by interactions with their complex and changeable environment because these interactions affect which individuals survive and reproduce.

An alternative statement can be found in Darwin's own words (from chapter IV of *On the Origin of Species*): "It may metaphorically be said that natural selection is daily and hourly scrutinising, throughout the world, the slightest variations; rejecting those that are bad, preserving and adding up all that are good; silently and insensibly working, whenever and wherever opportunity offers, at the improvement of each organic being in relation to its organic and inorganic conditions of life."

Table 2. Results of the natural selection model experiment.

Exp't date: Background color:		Dark beans	Light beans	Total beans	% dark	% light
Round 1	# at start					
	# caught					
	# remaining					
Round 2	# at start					
	# caught					
	# remaining					
Round 3	# at start					
	# caught					
	# remaining					
Round 4	# at start					
	# caught					
	# remaining					
Round 5	# at start					
	# caught					
	# remaining					
Round 6	# at start					
	# caught					
	# remaining					

(**Table 2.** Continued.)

Round 7	# at start					
	# caught					
	# remaining					
Round 8	# at start					
	# caught					
	# remaining					
Round 9	# at start					
	# caught					
	# remaining					
Round 10	# at start					
	# caught					
	# remaining					

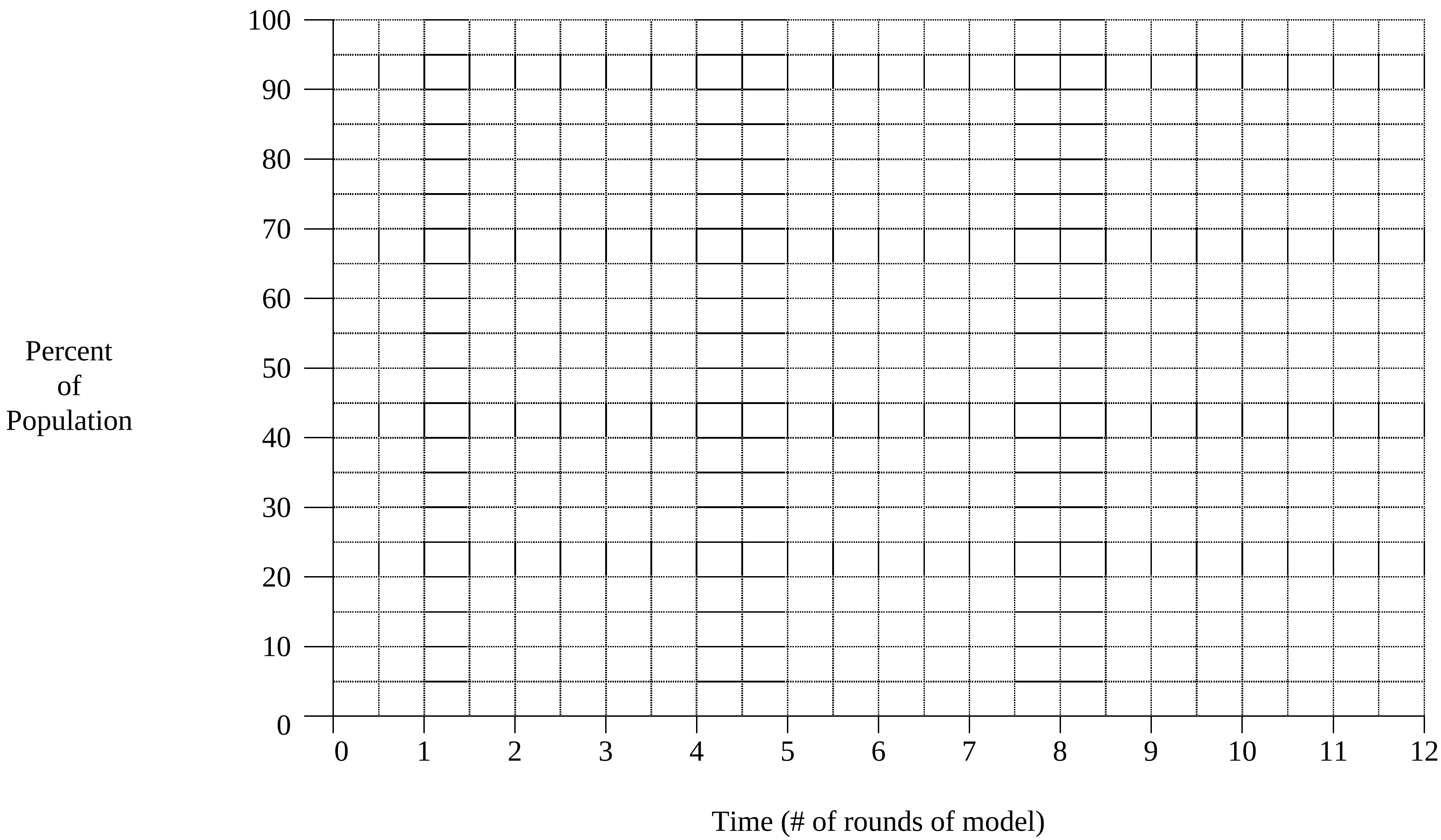

Figure 1. Results of natural selection model experiment using light-colored and dark-colored beans as prey, and humans as "predators". In each round one predator removed prey items during a 30-second hunting period. Prey "reproduced" by doubling when prey population size fell below 30 individuals. Experiment was run in a light colored environmental background. A circle represents dark-colored prey and an x represents light-colored prey.

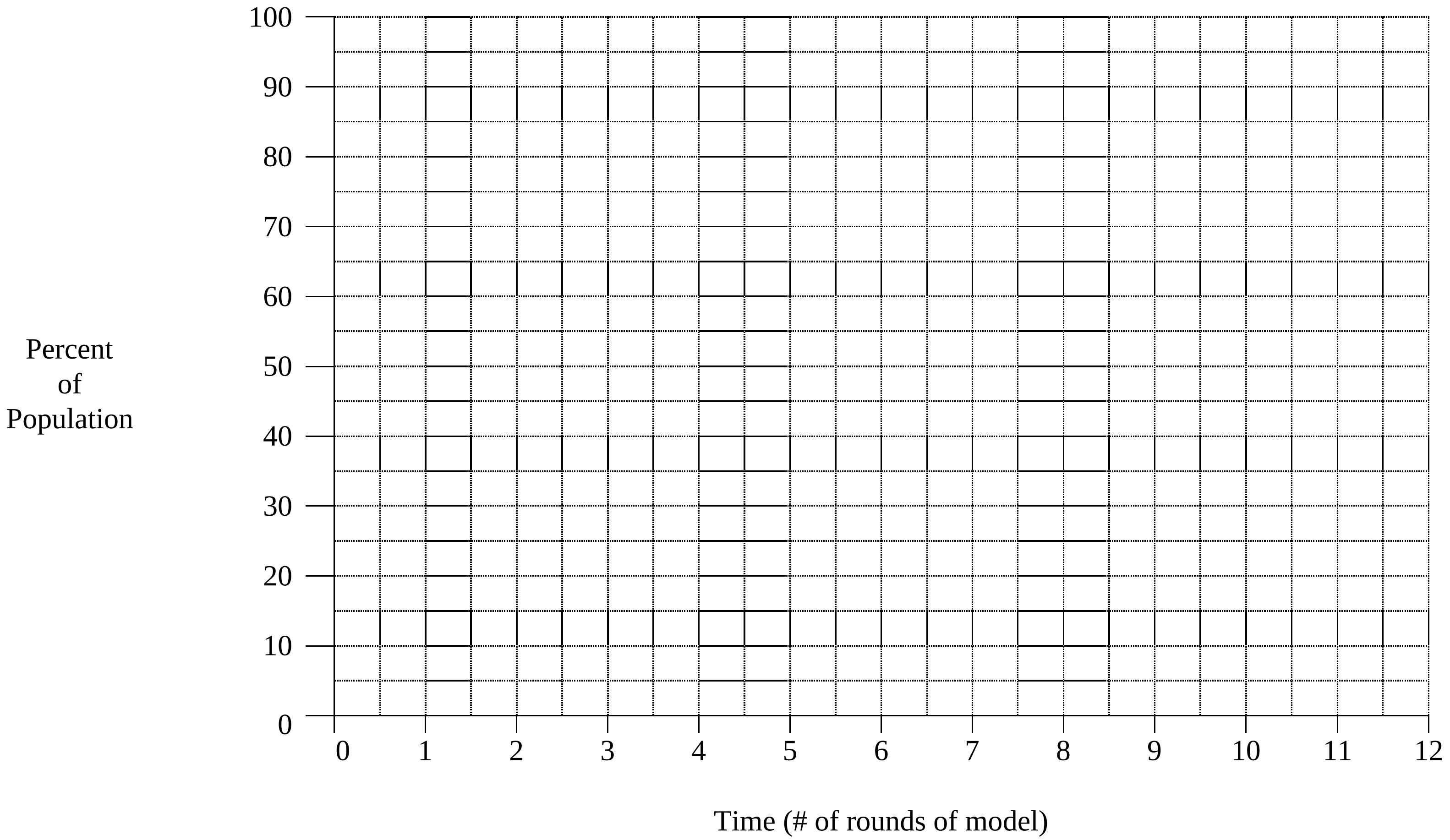

Figure 2. Results of natural selection model experiment using light-colored and dark-colored beans as prey, and humans as "predators". In each round one predator removed prey items during a 30-second hunting period. Prey "reproduced" by doubling when prey population size fell below 30 individuals. Experiment was run in a dark colored environmental background. A circle represents dark-colored prey and an x represents light-colored prey.

Instructor's Notes

When we implement this lab, we set up pairs of arenas, one with light-colored stones and one with dark-colored stones. If we have a full lab period available, the two groups of students trade places after running the activity in one arena and each group generates data for both environmental backgrounds. If we have less than a full lab period available, we have the two groups trade their results, as described here.

There are many different aquarium stones available in pet stores. There are also many choices for beans. In developing this lab, we tried a few of the many possible combinations. We saw interesting outcomes, including cases where beans that look quite different outside the arena become equivalent inside the arena, i.e., no differential selection occurs, and cases where the beans effectively disappear when put in the arena. The general system might make an interesting lab for an upper-level ecology class, where the protocol was more open-ended and students explored the dynamics produced with different combinations of materials.

For our situation, which is a large-enrollment, non-science majors' class, we decided we wanted to produce directional selection in both environments. We achieved this with aquarium stones that were predominantly off-white for one environment and predominantly dark brown for the second environment. Each arena contains one 25-pound bag of stones. We found it necessary to supplement both environments with a small quantity, about ½ cup, of black stones in order to disrupt predators' search patterns.

Our stones came from a local pet supply store. They were manufactured by Clifford W. Estes, Inc., 40 Vreeland Ave., Totowa, NJ 07512, www.estesco.com. The particular stones we use are: (White) Ocean Beach Pebble, 34562 10702 (UPC code); (Brown) Deep River Pebble, 34562 11711; (Black) Black Special, 34562 40506.

The base for each arena is a 36" circle of corrugated cardboard (salvaged from shipping cartons and double layered to eliminate bending) covered in black or white disposable plastic tablecloth material. The Hula-hoop™ is 32" in diameter. Our "leaf litter" is a large handful of mixed paper confetti from a party supply store; colors of confetti don't seem to affect the experimental outcome, so we chose the most "leafy" looking ones.

Our beans are small black beans and black-eyed peas (Goya brand). They are very similar in size and one is black while the other is very light colored except for the black spot. We tried small white beans but they disappeared so completely into the stone that predators almost never found them. The small black spot on the black-eyed peas serves as a good mark for distinguishing the bean from stones.

The other supplies needed are a timer and three containers, one for each kind of bean and one labeled "Captured." Roughly 50–100 beans of each kind are provided to each team. It is also helpful to provide them with a small dustpan and brush.

In an early version we "rewarded" predators who captured 10 or more beans in a round by letting them continue to hunt until they failed to capture 10 beans. An occasional human predator was so sharp that s/he never failed, which left the rest of the students in the group with nothing interesting to do. For this reason we modified the rule so the predator changes after each round, whether s/he gets 10 beans or not.

Sean Carroll lecturing on the rock pocket mouse is from the Howard Hughes Medical Institute Holiday Lectures on Science, December 2005. These lectures are available on DVD from HHMI, 4000 Jones Bridge Road, Chevy Chase, MD 20815-6789, www.hhmi.org. Also see www.biointeractive.org. The rock pocket mouse presentation is the last 8 minutes of lecture one.

About the Author

Robert Ketcham works at the University of Delaware. Since 1988 he has coordinated large-enrollment labs for both science majors and non-science majors. He is currently working with the non-science majors' class, which is titled *Principles of Biology with Laboratory*. His goal is to have students in this class get rich lab experience in three "principle" areas: Cell Theory, Chromosomal Theory of Inheritance, and Evolutionary Theory. Cell Theory and Chromosomal Theory of Inheritance are in place now. He is working on Evolutionary Theory.