Virtual Laboratories as a Tool for Teaching the Scientific Method

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Whereas virtual laboratories or simulations are frequently used to reduce expenses or allow students to try experiments that would otherwise be too dangerous or time-consuming, another less discussed use is to help students better learn how science is done. The key advantage to using simulations for this purpose is that rich simulations allow students to design their own experiments and to design additional experiments after evaluating the results of the initial experiment. Thus, students can carry out the entire scientific process from initial observations to designing follow-on experiments based on the results of earlier experiments. As a specific example of how this can be done, I will describe below how I use some of the Biolab simulations in an upper-division genetics course to teach both genetics and how science is done.

Traditional science laboratories are popular and effective teaching tools because the students learn the subject matter actively and also get some experience at the real-life activities of a scientist. Many instructors are concerned about the use of computer-based simulations of laboratories because, although they may retain the active learning component, the actual hands-on experience is lost. Thus, the physical skills of manipulating laboratory equipment, reagents, and material, along with the actual experience of setting up an experiment and collecting data in real time, are all absent. Even for non–science major students who don't need the practical lab skills, the experience of being a scientist, even for a little while, is considered very important. Given the importance of having the students experience the reality of doing science, computer-based simulations are normally used to recreate at least the active learning aspect of a laboratory for experiments that are impractical in the normal educational setting.

Some common reasons for using simulations are that they are safer, are cheaper, and can take less time than the real experiment. Experiments that require radioactivity or dangerous reagents such as poisons or explosive chemicals are usually too dangerous for an introductory class. Many experiments don't fit well in the normal 2- or 3-hour time block available in most labs, so a simulation's ability to compress time can allow experiments that would normally take days, weeks, months, or even years to be done in minutes or hours. This time compression creates an opportunity to also use simulations to have students do many more experiments than is possible with normal laboratories, and this aspect is the focus of how I use simulations.

A central problem with many traditional laboratory experiments is that the limited time available and the student's lack of good laboratory skills force the instructor to carefully control all aspects of the student's activities. Instructions for what the students are to do must be very carefully written and explained clearly to the students, the students must be watched at each step to make sure they don't "blow it," and, usually, the experimental materials have been carefully chosen so that there is little chance of student error. All of these precautions are taken to ensure that the students are able to generate usable data that when interpreted will produce the same results as the explanations in the textbook. Unfortunately, the end result is that the students go through an experimental experience that is nothing like how science is really done, even though one of the main reasons for doing experiments is to expose students to what science is like. Teaching students that doing science is to carefully follow explicit instructions exactly as written is probably not what most instructors intend, but would seem to be the result of their attempts to make sure that students have a successful lab experience.

The speed with which experiments can be done using simulations provides a mechanism to allow students to really design and interpret experiments as scientists actually do. As experimental results can be produced in seconds or minutes, students can be allowed to design their own experiments, evaluate the results, and then design new experiments if the original ones don't provide enough information to figure out what is going on. There is also no defined end point in this type of laboratory; students do experiments until they have enough evidence to convince themselves and others that they understand what is happening, just like real scientists. For this approach to work, the simulation must be rich enough that there are many possible experiments that the student could do; thus, they really have to think about what they are trying to do to decide on the appropriate experiment. This lack of richness is a common problem in traditional laboratory experiments where the students will get only one chance, so they can't be allowed to do the "wrong" experiment. Unfortunately, many simulations lack the flexibility and richness needed so that the student must make reasonable choices, but as the technology improves and educators become more experienced in using simulations, this problem should go away. One example of a set of simulations that is rich enough to allow many possible experiments is the set of Biolab simulations.

The Biology Labs Online simulations (http://biologylab.awlonline.com) were created by a collaboration between the California State University, the book publisher Addison Wesley Longman (now part of Benjamin Cummings), and the NSF. There are 12 different simulations available ranging from simulations of fruit fly genetics to human population growth. All of the simulations were designed so that students would have the flexibility to design many different experiments and analyze large amounts of data (Bell, 2003).

An example of how simulations can be used to give students practice at doing science while also learning some science knowledge is the assignment given to the students in an upper-division genetics class in the first week. This assignment uses the Fly Lab simulation from the Biolab collection. The Fly Lab is based on classical Mendelian genetics, and students breed various mutant fruit fly traits to determine the genetics of the different traits. The simulation includes 26 different traits, and there are over a million possible combinations of traits that can be investigated. While written for an upper-division course, this assignment would be appropriate for any introductory genetics unit. The assignment below is the student's second assignment; the first assignment has detailed instructions like many traditional laboratories and is designed to familiarize the student with how to use the simulation and how to do genetic crosses.

Investigate the Lobe Eye Trait (5 points)

Cross a wild-type fly with a Lobe-eyed fly to produce the F1 generation. What does the F1 generation look like? What conclusions can you draw from this result? What do you expect to see in the F2 generation? Propose hypotheses, make predictions, design crosses and diagram the results both phenotypically and genotypically, and draw all appropriate conclusions. Do not worry about proposing hypotheses that turn out to be incorrect; as long as you demonstrate that the hypothesis was false, you will be doing fine. You should always test your hypothesis with at least two different crosses (F1 × F1 and a test-cross). Reciprocal crosses (mutant male × wild-type female and wild-type male × mutant female) are also frequently a good idea.

This assignment has several suggestions for crosses to help the student get started; later assignments have fewer and fewer hints until the assignments become simply, "Investigate the purple eye and curved wing traits." The idea is that students will do an initial cross and then, from observations of the progeny, they should develop a hypothesis about the genetics of the trait. From their hypothesis, they then design an experiment to test their hypothesis and make a prediction about the result they expect if their hypothesis is correct. After doing the experiment, they have to evaluate the results and then design additional experiments depending on the results. This process continues until they have collected enough results to be confident that they have thoroughly tested their hypothesis, just as happens in real science.

As the problems become more challenging, students may need to do several different experiments to figure out the underlying genetics of a trait. This is possible in the simulation because a cross with 10,000 progeny can be carried out in a few seconds, as opposed to the several weeks that the real experiment would take. Because students can so easily try different experiments, they can be given the freedom to

Table 1. Grading Rubric for the Lobe Eye Assignment

Criteria	Value	Evidence
Student sets up crosses and gathers data and tries to interpret the results.	0.5	Phenotypic descriptions of the crosses and the results are included in the report.
After each cross, the results are analyzed and there is a clear statement of the current hypothesis.	1	Report has a short paragraph after each cross that discusses whether the results of the cross support the current hypothesis and, if not, proposes a new hypothesis.
All crosses are diagramed both phenotypically and genotypically with clear symbols that reflect the hypothesized inheritance pattern.	1	Symbols for alleles are used to describe the genotypes along with the phenotypic symbols, and the allele symbols are used correctly to show the type of inheritance and correct number of alleles.
Predictions based on the hypothesis are made for each cross (after the first cross) before doing the cross, and the crosses chosen are appropriate for testing the current hypothesis.	1	After analyzing each cross, there is a sentence or two describing what the next cross will be, what progeny ratios are expected in the progeny, and why those ratios are expected.
Student perseveres and attempts to figure out what is going on even when there is no obvious answer.	0.5	If the results do not support a hypothesis, it is stated in the report that the hypothesis is false and at least one alternative hypothesis is then tested.
There is a proper conclusion to the report.	0.5	There is a summary paragraph at the end of the report that states the hypothesis that the student feels is most likely and describes the results that support the chosen hypothesis.
Student shows an understanding of all genetics principles covered in class.	0.5	Appropriate hypotheses are tested and are rejected if not supported by the data, and correct allelic and genotypic descriptions are given for P, F1, and F2 flies.

design their own experiment, as an experiment that is poorly designed only takes a little time to do. Although students may spend some additional time analyzing the results before they realize that the experiment was not useful or that their initial hypothesis was incorrect. Students who are struggling with the concepts or with how to design experiments may do as many as 15 different experiments for one assignment before they feel comfortable with their results, whereas other students can accomplish the same thing with only three or four experiments. Examples of these more challenging assignments and their rubrics can be found in the MERLOT (Multimedia Educational Resource for Learning and

Online Teaching) database (http://merlot.org) in the assignment section of the Fly Lab entry.

Another aspect of assignments such as the one above with Lobe eye is that there is no required correct answer. Students are expected to test at least two hypotheses, and if both of their hypotheses are incorrect, they can stop and still get full credit for the assignment. This is also part of the way science really works, because sometimes all a scientist can do is prove some false ideas. This is especially difficult for some students to grasp, because most of their traditional laboratory experiences have always had a correct answer they needed to find. An important aid to help them understand what they really need to do that is used with these assignments is a grading rubric that they have access to before doing the assignment. Table 1 has the grading rubric for the Lobe eye assignment above.

The grading rubric is very important, since many students are uncomfortable with turning in a report that doesn't have a definitive answer. Although the Lobe eye assignment only uses genetics that students have already been exposed to in previous classes, many of the later assignments require an understanding of genetic concepts that the students have not been exposed to before starting the assignment (lethal traits, linked traits, epistasis, etc.). This is done deliberately, because in real science, you do not normally know the answer before you start your experiments. Because they have not been exposed to the "correct" answer and the scientists who originally worked out the genetics may have taken years to do so, it is unreasonable to expect students to figure it out in a short period of time, even with the ability to do many more experiments.

An additional benefit of this approach, besides giving students authentic practice at doing science, is that students have wrestled with trying to explain unexpected results before being given the normally accepted solution. Having already tried to come up with their own explanation, they can much more critically examine the traditional explanation. Even better, some of the students do arrive at the traditional explanation independently and are thus much more likely to be able to remember the standard explanation, as it is also their explanation.

Given that there are benefits to using a simulation to help students better understand how science is done, what is lost by using a simulation instead of having the students do the traditional laboratory? For the assignment described above, the instructor would normally have done the initial crosses, because they require virgin females and a 2-week incubation period. The students would thus get a description of what the first generation of progeny looked like and what flies were crossed and would then count flies and score them for their phenotype for several hours. They would then write up an analysis of the numbers and try to come up with a hypothesis supported by the numbers. Most of the student time would be spent looking at the flies under a dissecting microscope while scoring them for their phenotype. They would also spend some time getting flies out of the bottles and anesthetizing them. Thus, the missing elements in the simulation are learning the physical skills of manipulating the fruit flies, practice at using a dissecting scope, and several hours of practice at close examination of fruit flies to determine the phenotype of their eyes and their sex.

As it is unlikely that any of the students of this class will ever do any experiments with fruit flies after finishing the course, not learning the skills of how to manipulate fruit flies or identify a specific eye phenotype is probably not significant. The experience of closely examining a complicated living entity is also missing, and this may be a real deficiency of the simulation. Another important aspect of doing real science that is missing in the simulation is training in repeating a boring and repetitious task over and over very carefully. This is required to accurately score several hundred fruit flies and is an important aspect of successfully doing much science. In exchange for losing these aspects of doing real science, the students are getting much more experience at designing and interpreting the results of their own experiments. Probably the ideal educational method would be to use a mixture or real experiments with simulations, so that the benefits of both approaches could be realized.

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