

# Promoting Creative and Critical Thinking Skills in College Biology

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**Abstract:** A model of creative and critical thinking is presented in which analogical reasoning is used to link planes of thought and generate ideas that are then tested by employing and “*if/and/then*” pattern of reasoning. Data are also presented suggesting that such thinking skills develop first in familiar and observable contexts before they can be used in less familiar and unobservable contexts. The principles of curricular design, based on the model and developmental sequence, are then used to construct an introductory college biology course in which students attempt to use the thinking skills as they inquire into increasingly complex and abstract phenomena. During a recent semester, a comparison of student pre-test and post-test scores on a test of reasoning skills found significant improvements suggesting meaningful gains in student thinking skills.

**Key Words:** Creative and critical thinking skills, general biology, curriculum design, inquiry, hypothesis and theory testing

## Introduction

This paper describes a college biology curriculum designed to promote the development of students' creative and critical thinking skills as they participate in a series of biological inquiries. The paper first examines selected science case histories to develop a model of creative and critical thinking. It then derives the principles of curricular design based on the model. Two example of inquiry lessons are then presented along with data attempting to assess the extent to which student-thinking skills have been improved by the course.

## A Model of Creative and Critical Thinking

According to Webster, to create means to bring into existence; cause to be; evolve from one's own thoughts or imagination (Merriam-Webster, 1986). Scientific creation has been described in terms of sequential phases of preparation, incubation, illumination and verification (Wallas, 1926; Sternberg & Davidson, 1995). During the creative process, the conscious mind mulls over a question or problem only to give up and turn it over to the subconscious. The

subconscious then operates until it somehow produces a novel combination of ideas that spontaneously erupt into consciousness to produce a tentative answer or solution. From here the conscious mind guides a more critical testing of the novel idea to discover whether or not its value is real or illusionary (cf., Amsler, 1987; Boden, 1994; Koestler, 1964; McKellar, 1957; Wallace & Gruber, 1989).

Consider for example, Koestler's (1964) version of the often-told story of Archimedes and the golden crown. As Koestler tells the story, Hiero was given a crown, allegedly made of pure gold. He suspected the crown was adulterated with silver, but did not know how to tell for certain. So he asked Archimedes. Archimedes knew the specific weights of gold and silver -- their weights per unit volume. Thus, if he could measure the crown's volume, he could determine whether it was made of pure gold. But he did not know how to measure the volume of such an irregularly shaped object. Clearly he could not melt down the crown and measure the resulting liquid. Nor could he pound it into a measurable rectangular shape. With

these easy solutions blocked, Archimedes had a problem.

Using Wallas' terminology, Archimedes was engaged in the preparation phase of creative thought. Having hit numerous dead ends, Archimedes put the problem aside. Nevertheless, his mind was well prepared for progress as several blind alleys had been tried and rejected. In a sense Archimedes now shunted the problem to his subconscious to let it incubate. The next phase, illumination, presumably began while Archimedes was about to take a bath. While lowering himself into the tub, he noticed the water level rise. And in a flash it occurred to him that the rise in water was an indirect measure of his bodies' volume. Thus, presumably at that moment, Archimedes "saw" how he could also measure the crown's volume -- simply by immersing it in water. And once he knew its volume, he could calculate its specific weight to know if it were made of pure gold. Eureka! Archimedes had the solution.



*Painting of Archimedes by Jusepe de Ribera (Spanish 1591-1652) in the Museo del Prado, Madrid Spain.*

In Koestler's view, Archimedes' creative act can be understood essentially as one of joining two planes of previously unconnected thought to reach a target solution T. For example, Figure 1 depicts the plane of thought  $P_1$  that contains the starting point S and several thought paths that have unsuccessfully sought the

target. Thus  $P_1$  presents the habitual rules that Archimedes used to measure volumes and weights, to determine the nature of materials, and so on. But as you can see, the target T is not contained on  $P_1$ . Instead, it is located on  $P_2$  -- the thought plane associated with taking a bath. Thus no amount of thinking on  $P_1$  can reach T. Archimedes needs to shift his thinking from  $P_1$  to  $P_2$ . To do this he needs a link L. As Koestler points out, the link may have been verbal (for example, the sentence: rise in water level in the tub equals melting down of my body); or it may have been visual in which the water level rise was seen to correspond to body volume and hence crown volume. Either way, the key notion is that both planes of thought must be active in Archimedes' mind -- albeit not both on the conscious level -- for the link to occur and for him to consciously "see" the solution. Once illumination occurs, verification can take place. To do this, Archimedes presumably thought through the steps of his newly-created path from S to T to satisfy himself that no crucial steps had been left out -- that the path really led to T. Another aspect of the verification phase is to actually put the new strategy to work to discover if Hiero's crown had in fact been adulterated.

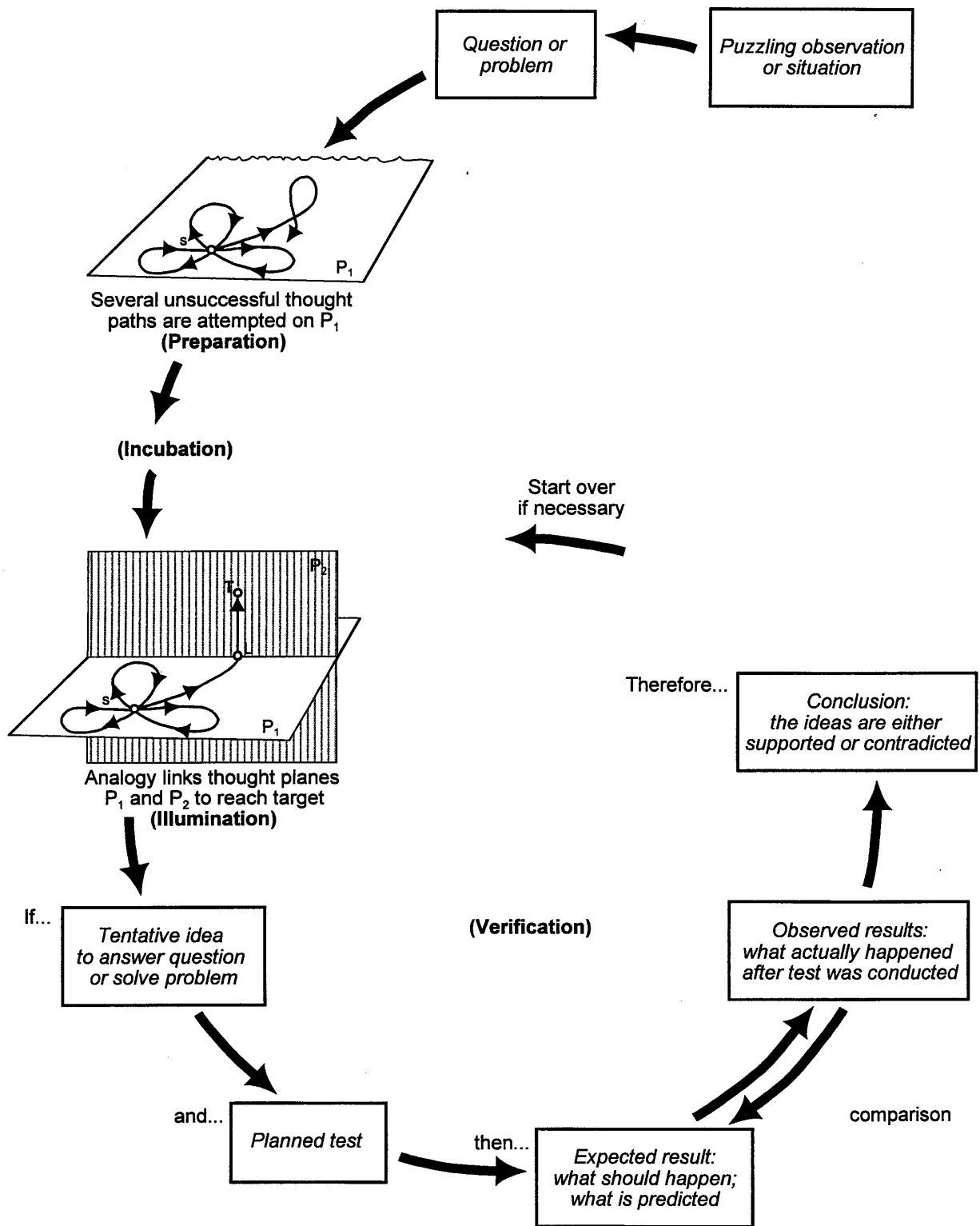
The following summarizes the key argument:

- If** ... the crown is made of pure gold (pure gold hypothesis)
- and** ... the crown is immersed in water and the displaced water is measured (planned test)
- then** ... the crown should displace the same volume of water as displaced by a known sample of pure gold of equal weight (expected result).

On the other hand,

- If** ... the crown has been adulterated by silver or by some other less dense metal (adulterated hypothesis)
- then** ... it should displace a greater volume of water than displaced by a known sample of pure gold of equal weight (alternative expected result).

Notice how the preparation, incubation and illumination phases of Archimedes' thinking were creative in the sense that they brought into existence a new piece of procedural knowledge (i.e., a procedure for measuring the volume of irregularly-shaped objects). On the other hand, the verification phase of his thinking can be characterized as critical in the sense that once Archimedes created the new procedure, he used it to analyze the metals in Hiero's crown. This critical thinking produced a new piece of declarative knowledge (i.e., the crown was not pure gold).



**Figure 1.** A model of creative and critical thinking depicting the phases of preparation, incubation, illumination and verification (after Wallas, 1926; Koestler, 1964; Lawson, 1995).

## Linking Thought Planes

At the heart of this model of creative thinking lies the linking of two or more previously disconnected “planes” of thought. Consequently, the issue of how these planes are linked becomes of central importance. To see how thought planes might be linked, let’s turn to the research of two biologists. As told by Beveridge (1950), while his family had left for a day at the circus one afternoon in 1890, Elie Mechnikoff half-heartedly watched some transparent starfish larvae as he tossed a few rose thorns among them. To his surprise, Mechnikoff noticed that the thorns were quickly surrounded and dissolved by the larvae. The thorns were being swallowed and digested. This reminded Mechnikoff of what happens when a finger is infected by a splinter. The splinter becomes surrounded by pus which, Mechnikoff surmised, attacks and eats the splinter. Thus, Mechnikoff’s observation of the swarming larvae struck him as analogous to human cells swarming around a splinter. In this way the use of an analogy helped Mechnikoff “discover” the bodies’ main defense mechanism – namely mobile white blood cells (phagocytes) that swarm around and engulf invading microbes.

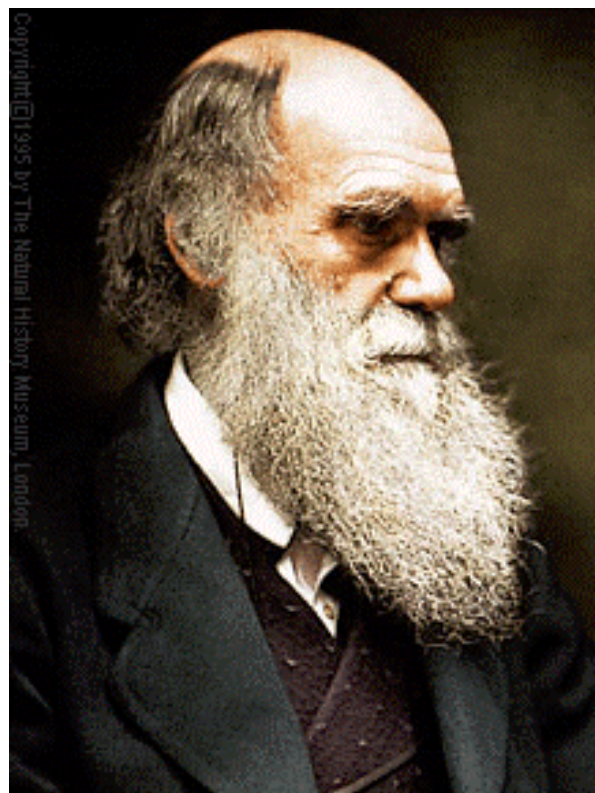
Is Mechnikoff’s use of analogy common in the history of biology? For example, can Charles Darwin’s invention of natural selection theory also be traced to an analogy? Consider Darwin’s words:

It seemed to me probable that a careful study of domesticated animals and cultivated plants would offer the best chance of making out this obscure problem. Not have I been disappointed; in this and all other perplexing cases I have invariably found that our knowledge, imperfect though it be, of variation under domestication, afforded the best and safest clue (Darwin, 1898, p. 4).

Armed with this clue, Darwin tried to put the evolutionary puzzle pieces together. His attempt involved several unsuccessful trials until September of 1838 when he read Thomas Malthus’ *Essay on Population* and wrote, “I came to the conclusion that selection was the principle of change from the study of domesticated productions; and then reading Malthus, I saw at once how to apply this principle” (quoted in Green, 1958, pps. 257-258). As Gruber and Barrett (1974) point out, Darwin had read Malthus before, but it was not until this reading that he became conscious of the analogical link between “artificial” selection and evolutionary change. Now that the link had been established, Darwin began marshalling the evidence favoring his new theory of “natural” selection.

Other examples of the use of analogy are numerous in the history of science. Kepler borrowed the idea of the ellipse from Apollonius to describe planetary orbits. Mendel borrowed patterns of algebra

to explain heredity. Kekulé borrowed the idea of snakes eating their tails (in a dream) to create a molecular structure for benzene, and Coulomb borrowed Newton’s ideas of gravitational attraction to describe the electrical forces that exist at the level of sub-atomic particles. The use of analogy -- the act of borrowing old ideas and applying them in new situations to invent new insights and explanations -- is sometimes called combinatorial thinking, analogical reasoning, or analogical transfer (cf., Biela, 1993; Boden, 1994; Bruner, 1962; Dreistadt, 1968; Finke, Ward & Smith, 1992; Gentner, 1989; Hestenes, 1992; Hoffman, 1980; Hofstadter, 1981; Hofstadter, 1995; Holland, et al., 1986; Johnson, 1987; Koestler, 1964; Wong, 1993). Thus, often (always?) an analogy provides the link -- the L -- between the thought planes so that the thinker can pass to the second plane and arrive at the target.



## A Sequence in the Development of Thinking Skills

In addition to this model of creative and critical thinking, one more element needs to be in place before we can construct a curriculum to promote thinking skills. The three quizzes in Table 1 ask students to propose tests of two hypotheses. As you can see, students are asked to generate If/and/then/But/Therefore arguments complete with evidence that contradicts each hypothesis. During a recent semester, the quizzes were administered following lab activities in which the hypotheses in question were actually tested. In spite of this, quiz performance varied widely. Performance on the

*Mealworm Quiz* was relatively high as 82 % of the students succeeded in designing tests and in suggesting evidence that would lead to rejection of the hypotheses.

But performance on the "*A*" *Mountain Quiz* dropped to 53 % and performance on the *Osmosis Quiz* dropped still further to only 18%.

**Table 1.** *The Mealworm, "A" Mountain, and Osmosis Quizzes.*

### **Mealworm Quiz**

A student recently placed some mealworms in a rectangular box to observe their behavior. She noticed that the mealworms tended to group at the right end of the box. She also noticed that the right end had some leaves in it and that the box was darker at that end. She wondered what caused them to group at the right end.

Hypothesis 1: They went to the right end because it had leaves in it.

Hypothesis 2: They went to the right end because it was darker than the left end.

How could you test these hypotheses? 1. Describe your experiment. 2. What are the predicted results (assuming that the hypotheses are correct)? 3. What result would show that hypothesis 1 is probably wrong? 4. What result would show that hypothesis 2 is probably wrong?

### **"A" Mountain Quiz**

A recent survey of organisms on "A" Mountain revealed more grass on the north-facing slope than on the south-facing slope. In response to the causal question, Why is there more grass on the north-facing slope?, a student generated the following hypotheses:

Hypothesis 1: Lack of moisture in the soil on the south-facing slope keeps grass from growing there (i.e., north is better shaded from the sun's drying rays).

Hypothesis 2: The sunlight itself is too intense for good grass growth on the south-facing slope (i.e., very intense rays disrupt the grasses' ability to conduct photosynthesis).

How could you test these hypotheses? 1. Describe your experiment(s). 2. What are the predicted results of your experiments) assuming that the hypotheses are correct? 3. What result would show that hypothesis 1 is probably wrong? 4. What result would show that hypothesis 2 is probably wrong?

### **Osmosis Quiz**

When a thin slice of red onion cells are bathed in salt water the red portion of each cell appears to shrink. What causes the red portion to appear to shrink?

Hypothesis 1: Salt ions (i.e.,  $\text{Na}^+$  and  $\text{Cl}^-$ ) enter the space between the cell wall and the cell membrane and push on the cell membrane.

Hypothesis 2: Water molecules (i.e.,  $\text{H}_2\text{O}$ ) are charged (i.e., thus leave the cell due to attractive forces of the salt ions).

How could you use model cells made of dialysis tubing, a weighing devise, and solutions such as salt water, distilled water, and glucose to test these hypotheses? 1. Describe your experiment. 2. What are the predicted results assuming that the hypotheses are correct? 3. What result would show that hypothesis 1 is probably wrong? 4. What result would show that hypothesis 2 is probably wrong?

Why did student performance vary so widely? The answer may lie in differences in the abstractness of the contexts as well as in subtle differences in complexity. For example, consider the following argument used to test hypothesis 1 of the Mealworm Quiz:

*If* ... the mealworms went to the right end because of the leaves,

*and* ... we place 10 leaves in one end of another box and then place 10 mealworms in the center,

*then* ... most of the mealworms should move toward the leaves.

*But* ... suppose they do not.

*Therefore* ... the leaves hypothesis would be contradicted.

Now consider this argument used to test hypothesis 1 of the Osmosis Quiz:

*If* ... the onion cells shrink because ions push on their membranes,

**And** ... a dialysis bag, with membrane-like properties, is filled with a glucose solution and then placed in salt water,

**Then** ... the dialysis bag should appear smaller, but it should not lose weight. (The bag should not lose weight because the push presumably "compacts" molecules inside the bag but does not cause molecules to escape. This statement represents a theoretical rationale).

**But** ... suppose the bag does lose weight.

**Therefore** ... the ion push hypothesis would be contradicted.

Notice how the hypothesized cause in the mealworm argument (i.e., the leaves at one end of the box) is observable and familiar. The same can be said of the dependent variable of the planned test (i.e., mealworm movement). Notice also that the independent variable of the planned test (i.e., the number of leaves at each end of the new box) and the hypothesized cause are one and the same. However, things are more abstract and more complex in the osmosis argument. Here the hypothesized cause (i.e., moving ions) is non-observable. Further, the test requires an assumption about the similarity of cell membranes and dialysis bags. Still further, there is no direct connection between the experiment's dependent variable (i.e., change in bag weight) and the hypothesized cause, hence the need for a theoretical rationale. Presumably all of these factors, and perhaps others, make the osmosis argument more difficult to generate and comprehend. Consequently, student performance suffers. A similar analysis of the "*A*" *Mountain Quiz* reveals that it has characteristics intermediate to those of the Mealworm and Osmosis quizzes.

### Curriculum Design Principles

With the above sequence and with the model of creative and critical thinking in mind, we can derive the following principles for the development of a curriculum designed to promote creative and critical thinking skills:

- Provide students with novel inquiries that provoke them to raise causal questions for which they have no ready answers (but do have several previous experiences that are in some way analogous so that they can serve as hypothesis sources).
- Challenge students to propose several possible explanations (hypotheses/theories) to answer the questions. Challenge students to design and carry out tests of their proposed explanations.

- Sequence experiences so that the complexity of the explanations and tests progresses from the observable and relatively simple to the non-observable and relatively complex.

### Building the Curriculum

Table 2 provides an overview of the major topics and central questions raised during the course. As you can see, the course sequence attempts to take advantage of natural historical paths of inquiry -- an ontogeny recapitulates phylogeny approach to curriculum development. Consequently, the course starts at the familiar organismic level and extends into lower levels and into higher levels, and then returns to the familiar to follow additional inquiry paths extending farther down or up each time.

More specifically, students first explore whole-organism questions such as: Why do gazelles jump in the air when being chased by cheetahs? How do salmon locate their home streams to spawn? Initial theories include the ancient Greek four-substance theory and the theories of spontaneous generation and biogenesis. From here the course moves to basic theories of inheritance (cell theory, theories of mitosis and meiosis, and classic Mendelian genetics). Developmental theories are then addressed followed by general questions about plant growth (e.g., What materials do plants need for growth and where and how do they get them?). These questions allow the introduction of phlogiston theory, general atomic-molecular theory and very general theories of photosynthesis, respiration, combustion and decay.

Next, the course addresses theories of origins. Specifically, special creation theory is pitted against evolution theory as rival explanations for present-day species diversity. Introduction of the natural selection theory follows with a look at various mechanisms of speciation and extinction. The course then explores life's origin and its evolutionary products starting with prokaryotes, then protists, fungi, plants, animals and ending with humans. Next, basic concepts of behavior are explored as are basic ecological theories (e.g., kin selection theory, ecosystem dynamics theory, theories of biogeochemical cycling, competitive exclusion theory, succession theory and theories of biodiversity). Then comes physiological theories, first of plants and then of animals. Lastly, the course concludes with a look at very abstract and unfamiliar topics including kinetic-molecular level theories of photosynthesis, cellular respiration, and gene structure and function. We now turn to a description of two example inquiries.

### Introducing Natural Selection Theory

Natural selection theory is introduced using a modification of a simulation inquiry first introduced by Stebbins & Allen (1975) and later revised by Maret & Rissing (1998). In the present version, students play the role of Gooney birds (*Gooney birdicus*), which feed

on mice known as *Microtus coloriferii* (i.e., 10 colors of paper "chips"). Students begin by spreading patterned fabric representing an environment such as a pond, meadow, or cave, over their table. They then take 10 mice of each color and distribute them randomly throughout the environment. At the instructor's signal, students capture mice and deposit them in nearby "nests". Each group captures 75 mice.

The 25 survivors are then removed and reproduction occurs by adding three paper chips of the same color for each survivor. Students then repeat the predation and reproduction process at least two more times. Finally, the resulting numbers of surviving mice of each color are graphed, posted and compared.

**Table 2. Curriculum Sequence and Central Questions Raised**

**THE NATURE OF BIOLOGICAL SCIENCE**

1. What is Biology?
2. What are Scientific Theories?

**BASIC THEORIES OF INHERITANCE, DEVELOPMENT AND GROWTH**

3. How are Characteristics Inherited?
4. How Do New Organisms Develop?
5. What Materials Do Plants Need For Growth?

**BASIC THEORIES OF EVOLUTION AND SPECIATION**

6. Were Organisms Created or Did They Evolve?
7. Why Do Some Species Evolve While Others Go Extinct?

**THE EVOLUTION OF ORGANIC DIVERSITY**

8. How Did Early Life Originate and Evolve?
9. What Protists, Fungi, and Plants Evolved?
10. What Animals Evolved?

**BEHAVIORAL AND ECOLOGICAL THEORIES**

11. What Behaviors Help Organisms Survive?
12. How Do Organisms Interact With Their Environments?
13. How Do Organisms Interact With Each Other?

**THEORIES OF PLANT STRUCTURE AND FUNCTION**

14. How Do Materials Move Through Plants?
15. How Do Plants Control Growth and Development?

**THEORIES OF ANIMAL STRUCTURE AND FUNCTION**

16. How Do Materials Move Through Animals?
17. How Do Animals Digest Food and Eliminate Wastes?
18. How Do Animals Process Sensory Stimuli and Protect Themselves From Disease?

**ATOMIC AND MOLECULAR LEVEL THEORIES**

19. How Do Living Cells Obtain and Use Energy?
20. What are Genes Made of and How Do They Work?

During the ensuing discussion, students note that the colors that increased seemed to be the ones harder to see. Conversely, those that decreased seemed to be the ones easier to see. To this the instructor adds that the colors that increased were "selected for" and those that decreased were "selected against". And because an analogous selection process presumably takes place in nature, biologists call it "natural" selection. The instructor then points out in more detail how the simulation and the process of natural selection are analogous (i.e., both require prey population variation, prey population increase is limited, one or more variable characteristics are heritable, and selection occurs over several generations). Thus, just as Darwin

used the analogy of artificial selection to "invent" his theory of natural selection, students use the simulation analogy to "reinvent" Darwin's theory.

Next students are asked to generate another possible explanation for the changes in mice colors during the simulation. To this, one or more students invariably suggest that the color changes could have occurred randomly. In other words, some mice just happened to land on a spot that the predator just happened to glance at first, thus the mice just happened to be eliminated, and so on. Upon hearing this alternative hypothesis, the instructor introduces the phrase genetic drift to label the random process and

challenges students to use the simulation materials to test the alternatives in the context of the simulation.

Most groups come up with a plan that can be summarized as follows:

*If* ... the mice color changes are caused by "directional" selection (natural selection hypothesis)

*and* ... we conduct the simulation two or more times using identical environments,

*then* ...the colors that increase and those that decrease should be the same each time.

On the other hand,

*If* ... the mice color changes are caused by "nondirectional" selection (genetic drift hypothesis)

*then* ... the colors that increase and those that decrease should not be the same each time.

When these tests are conducted and students find similar results using identical environments, the natural selection hypothesis is supported. But the fact that the results are similar but not identical also provides some support for the genetic drift hypothesis. The lecture portion of the course now discusses "real world" tests and filings.

### Using Analogies to Introduce Mendelian Genetics

Analogical reasoning is also used to help introduce Mendel's inheritance theory. This inquiry begins by posing the question: How do characteristics vary within species? Students know that members of a species share many characteristics, some of which are variable. But, are there patterns to this variation? And if so, what are they? To answer these questions, students obtain several mollusk shells and sort them into groups representing different species. Students then collect about 100 individuals of one species with at least one variable characteristic. For each individual, they determine the value of the characteristic chosen. Lastly, they plot frequency graphs, which are later posted on the board.

Student groups also obtain Indian corn and count the number of kernels of each color on each ear. Again they plot and post frequency graphs. Two additional frequency graphs are plotted and posted. For one, students roll two dice approximately 100 times and plot the sum of each roll. For the other, they flip two coins approximately 100 times and plot the number of flips resulting in one head and one tail, two heads, and two tails. The class then considers the shell graphs and tries to identify similarities. Most graphs show few shells with values at the extremes of the ranges but many near the middle. When this pattern is noted, the

instructor tells students that the pattern is called a normal distribution. Other populations with normally distributed characteristics are discussed. The instructor now poses the following causal question: What might be occurring in nature to cause variations to be distributed normally? Students brainstorm to generate multiple explanations. They typically generate several environmentally-inspired hypotheses (e.g., there are few small shells because they are too weak to withstand wave pounding; and there few big ones because they are easy targets of predators). To insure a variety of hypotheses, the instructor randomly calls on students. Shell graphs that do not show normal distributions are also discussed and students speculate on why these non-normal patterns emerged. As mentioned, student hypotheses typically center around environmental causes. However, one or more students may suggest a hereditary cause. Even so, students are not likely to explain in any detail how heredity might lead to a normal distribution. This is okay because the dice graphs are then used to explicate the process. Students now compare the shell and dice graphs and note the similarity in pattern. Again normal distributions are seen and students are asked to discuss how the dice rolling activity might be related to the shell situation.



To introduce Mendel's theory, students are asked to imagine that one die is analogous to the female eggs and the other to the male sperm. They are asked to imagine that the members on the dice represent "factors" that somehow dictate observable characteristics in offspring -- the values of those characteristics being determined by the sum of the numbers shown in each combined egg and sperm. If one imagines that six possible "types" of sperm and six possible "types" of eggs (i.e., 1, 2, 3, 4, 5, 6) exist, then there are 36 total combinations of sperm and egg types: one combination totaling two ( $1 + 1 = 2$ ), two combinations totaling three ( $1 + 2 = 3$ ,  $2 + 1 = 3$ ), three combinations totaling four ( $1 + 3 = 4$ ,  $2 + 2 = 4$ ,  $3 + 1 = 4$ ), and so on. It helps if the instructor draws the six



hypothesized sperm and egg types on the board and draws an arrow from each sperm to each egg to represent possible combinations resulting from fertilization. These combinations are then plotted on a frequency graph to show that a normal distribution results, just as was the case for the shells. Thus, if one assumes that such factors (now called genes) exist and behave as the rolling dice, we have an explanation for the observed normal distributions.

Now the class considers the corn graphs. With some hints, they see that the graphs reveal 3:1, 1:2:1, and 1:1 kernel color distributions. How can these distributions be explained? Do we need a new explanation or can Mendel's theory be somehow modified to work? When these questions are posed and the instructor lets student groups ponder, one or more students (ones who no doubt have previously heard about dominant and recessive genes) invariably comes up with the idea that the Indian corn has a small number of genes for color and that one gene may be dominating the expression of the other. When this idea strikes (Eureka!), the instructor has the opportunity to explicate the process and to introduce the terms dominance, recessive and blending inheritance to the entire class. The terms allele, genotype and phenotype can also be introduced.

Finally, the instructor emphasizes the point that no one has directly observed genes behaving in these ways. But we can imagine that they exist and can argue that:

- If* ... genes exist and behave as claimed,  
*and* ... the values of a variety of characteristics are measured and plotted on frequency graphs,  
*then* ... normal distributions, 3:1, 2:1 and 1:2:1 ratios should be observed.  
*And* ... these distributions were observed.  
*Therefore* .. we have initial evidence consistent with Mendel's theory.

### Presenting Arguments and Evidence in Lectures

Lectures also present both historical and contemporary examples. At least once during each lecture, clues are provided and student groups are challenged to generate arguments and post them for others to evaluate.

For example, during the lecture on development, students imagine that they have unfertilized frog eggs, frog blastulas, and the ability to perform microsurgery. They then design an experiment to test the hypothesis that each new daughter cell of a developing embryo receives a complete set of genes from its mother cell. In other words, they try to complete the following argument:

- If* ... each new daughter cell receives a complete set of genes (no-lost-genes hypothesis)  
*and* ... \_\_\_\_\_ (planned test)  
*then*... \_\_\_\_\_ (expected result).

On the other hand,

- If* ... some genes are lost during successive cell divisions (alternative lost-genes hypothesis)  
*then* ... \_\_\_\_\_ (alternative expected result).

You might want to try the assignment yourself before reading on. Most student groups are at least partially successful in generating an argument that goes something like this:

- If* ... each new daughter cell receives a complete set of genes (no-lost-genes hypothesis)  
*and* ... the genes contained in the nucleus of one blastula cell are injected into a frog egg that has had its nucleus removed (planned test),  
*then* ... the egg should develop into a normal frog (expected result). The egg should develop normally because it presumably contains a complete set of genes, i.e., a complete set of "instructions" (theoretical rationale).

On the other hand,

- If* ... some genes are lost during successive cell divisions (alternative lost-genes hypothesis)  
*then* ... the frog egg should not develop normally because it presumably lacks some necessary instructions (expected result).

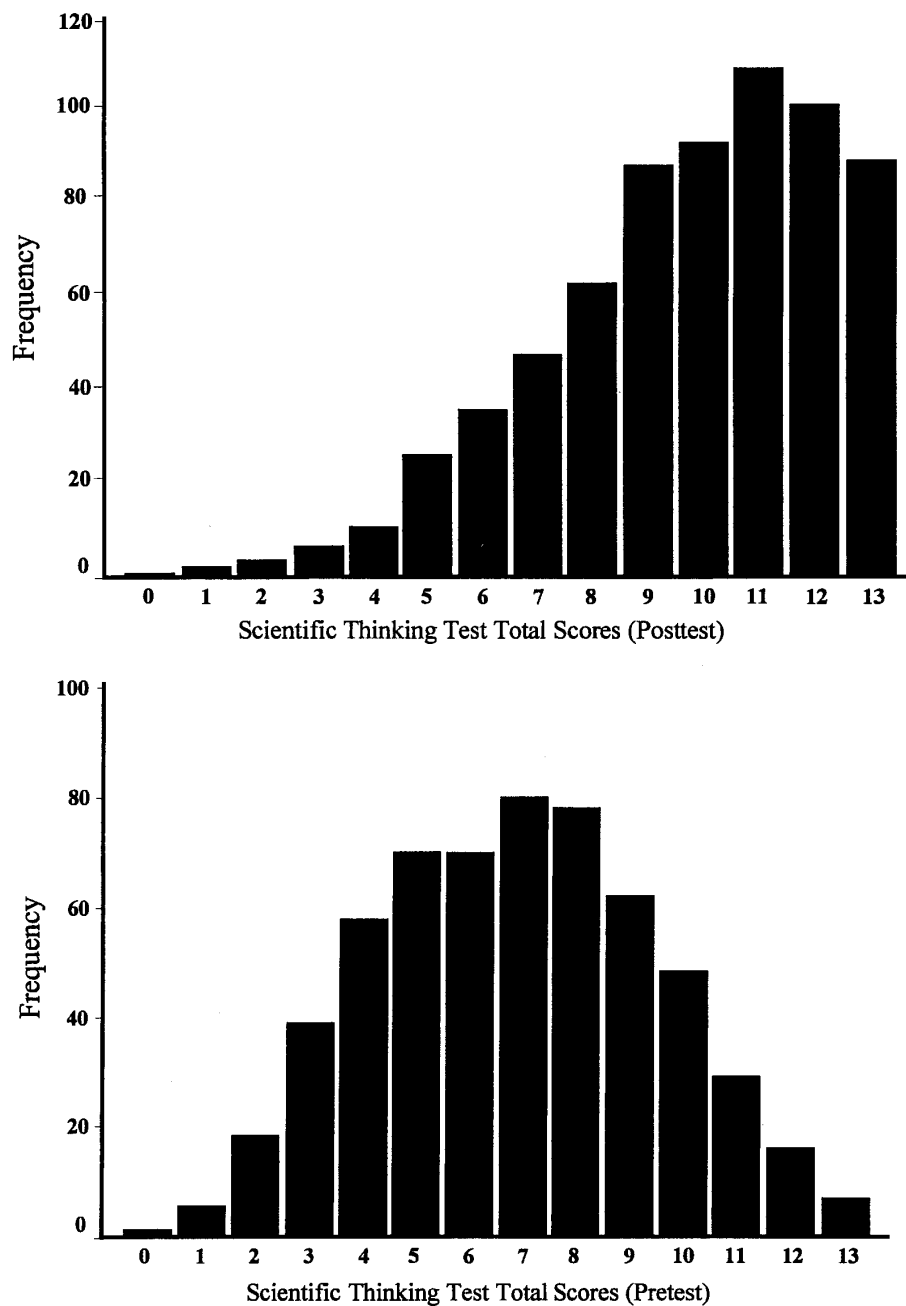
Once students have constructed these arguments, the observed experimental results are introduced, which are that the injected frog eggs develop into normal frogs. Therefore the no-lost-genes hypothesis has been supported. Lastly, the term cloning is introduced and medical and ethical implications are discussed.

### Do Student Thinking Skills Improve?

During a recent semester, a test of scientific thinking skills was administered at the start of each semester and again at the end. The test consists of 13 written items based on reasoning patterns associated with hypothesis generation and test, i.e., identification

and control of variables, analogical, correlational, probabilistic, proportional, and combinatorial reasoning (Lawson, 1978; Lawson, 1996). Test reliability and validity has been established by several studies (e.g., Lawson, 1978; 1980; 1983; 1992x; 1992b; Lawson & Weser, 1990; Lawson, et al., 1993). Figure 2 shows student performance on the test at the

start and end of the semester -- a semester that enrolled 514 non-science majors ranging in age from 15.8 years to 47.1 years; mean age = 19.64 years, SD = 3.02. As you can see, post-test scores improved considerably (dependent T = 29.6, df = 513,  $p < .001$ ).



**Figure 2.** Distribution of student scores on a test of scientific thinking at the start and again at the end of the semester.

Small pre- to post-test improvements have been traced to a test-retest effect (e.g., Lawson, et al., 1974). However, our former students' relatively poor performance on quizzes such as the "A" *Mountain and Osmosis Quiz* (see Table 1), suggests that the substantial improvements found here are difficult to come by and not likely to have been caused by a test-retest effect. Rather a more likely explanation is that our students did in fact become better at thinking scientifically. This conclusion is consistent with those of previous studies that have found that thinking skills develop if students are given repeated opportunities to generate and test hypotheses in familiar and observable contexts prior to attempting to do so with unobservable entities. For example, Westbrook & Rogers (1994) found that a 6-week ninth-grade unit on simple machines (e.g., levers, pulleys, and inclined planes) with readily observable variables was successful in promoting hypothesis-testing skills when students were explicitly challenged to generate and test alternative hypotheses. Also, Shayer & Adey (1993) found that the "Thinking Science Program" (Adey, et al., 1989) was successful in boosting the achievement of students on the British National examinations, not only in science and mathematics, but in English as well. The "Thinking Science Program" is designed to promote scientific thinking by exploring patterns and testing hypotheses first in observable contexts such as pitch

pipes, shopping bags, and bouncing balls and then in unobservable contexts such as dissolving and burning chemicals. In short, it appears that efforts similar to those in the present course paid off for many students in a variety of courses.

### Conclusion

In conclusion, evidence suggests that college students can obtain gains in creative and critical thinking skills when the curriculum is designed to explicitly promote such skills by sequencing inquiry instruction from the familiar and observable to the unfamiliar and abstract. Determination of the extent to which such improvements are generalizable to contexts beyond biology remains for future research. Nevertheless, previous research results, some of which were mentioned above, as well as anecdotal evidence gathered from some of our students, suggest that such improvements are generalizable to other college courses and perhaps to non-academic contexts as well.

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# Biology in the Light of Evolution

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