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From Skeletons to Bridges & Other STEM Enrichment Exercises for High School Biology

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Abstract

The national Science, Technology, Engineering, and Math (STEM) Education Initiative favors a curriculum shift from the compartmentalization of math and science classes into discrete subject areas to an integrated, multidisciplinary experience. Many states are currently implementing programs in high schools that provide greater integration of math, sciences, and technology. Program evaluation results indicate that students participating in multidisciplinary team projects of this type exhibit significantly higher levels of motivation and develop greater cognitive skills than students in the traditional, compartmentalized curriculum (Ross & Hogaboam-Gray, 1988; Venville et al., 2000).

Key Words: *STEM enrichment; biology integration; multidisciplinary biology.*

The national Science, Technology, Engineering, and Math (STEM) Education Initiative has focused mostly on the physical sciences, chemistry, and physics. These sciences have a more direct link to math and engineering than biology has. However, modern biological constructs have an underlying quantitative framework. Likewise, technological advances often stem from investigations of biological systems. For example, the engineering discipline biomimicry quantitatively examines the adaptive solutions of organisms to various problems they face in nature. The goal of such investigations is to adapt these solutions to human problems (Benyus, 1997). Examples of some of the technological contributions made by the field of biomimicry are presented in Table 1.

> *Technological advances often stem from investigations of biological systems.*

Similar ties between biology, physics, and engineering exist in all the engineering disciplines. Utilizing these ties to broaden the educational perspective of high school students can provide a multidisciplinary experience involving the wonders of the living world, something we are inherently interested in.

○ Adding an Engineering Unit to the *Biology in a Box* Project

One way to integrate biology, physics, math, and engineering principles into the respective classrooms or into a multidisciplinary program is to add an engineering theme to the *Biology in a Box* science education project. Riechert initiated this outreach project in 1995 with primary funding from the Howard Hughes Foundation to enrich curriculum content in biology and math in K–12 classrooms. *Biology in a Box* exercises employ inquiry methodology in which teachers act as facilitators and student teams as collaborators. Each *Biology in a Box* exercise within a theme provides the background introduction to a particular concept and the blueprint and materials necessary to explore it. Math educators from the National Institute for Mathematical and Biological Synthesis (NIMBioS) collaborate with the project by incorporating math elements in the exercises where appropriate. Just as the science presented is designed to meet grade-appropriate federal standards, all mathematical computations are presented in a didactic format that reinforces fundamentals taught in K–12 math classes.

Table 1. Technological contributions of the engineering field of biomimicry.

Technology Application	Biological Source
Swimsuit materials	Dermal denticles of shark skin
Inexpensive solar cells	Light capture & transfer processes in leaf chloroplasts
Velcro fasteners	Hitchhiking seed (bur) design
Bioactive coronary stents	Internal artery wall function
Dry adhesive applications	Gecko foot hairs
Walking robots	Kinematic configurations of a stick insect

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Materials needed for completion of the exercises contained in the units are completely reusable and are housed in a wooden trunk, the size of which varies according to the materials required by the particular theme. Ten themes are currently offered: Fossils; Of Skulls & Teeth; Fur, Feathers, Scales: Insulation; Simple Measures; It's in Your Genes; Animal Kingdom; Backyard Naturalist; Everything Varies; Forestry; and Behavior. Sets of the thematic units are donated to school systems (79 partners to date), and MS PowerPoint® and pdf versions of the exercises for each theme are available at the project's Web site (http://eeb.bio.utk.edu/biologyinbox/default.htm).

An engineering box to complement the 10 current themes will enrich the curriculum by interconnecting math, physics, biology, and technology. The topic of biomimicry is so broad that conceivably we could develop several engineering themes ranging from the molecular level (e.g., catalysts and hydrogen fuels) to ecosystem processes (design of waste disposal facilities). However, we have chosen mechanical engineering for this initial *Biology in a Box* engineering theme because of its strong links to physics. Also, the materials required are appropriate to *Biology in a Box* in that they are reusable and can fit inside a wooden trunk.

○ Descriptions of Example Engineering Unit Exercises

Exercise 1: From Skeletons to Bridges

D'Arcy Thompson (1860–1948), a Scottish mathematical biologist, was among the first to apply mathematics and physics to the study of the form and structure of organisms. In his famous book *On Growth and Form* (Thompson, 1992; first published in 1917), he provided example after example of correlations between biological forms and mechanical phenomena. One of his most famous comparisons was between the skeletons of four-legged animals (quadrupeds) and bridges. He proposed that bridges are simply well-designed skeletons. In his analogy, a mammal's front and hind legs are the supporting piers of the bridge and its backbone is the span. Specifically, he stated that the vertebral column is "strictly and beautifully comparable to the main girder of a double-armed cantilever bridge."

In our exercise "From Skeletons to Bridges," we introduce students to the principles of bridge construction by investigating tension, compression, and bending as they apply to bridges and other engineering structures as well as to animal bones and spinal columns. After the forces are defined for the students, in Exercise 1a volunteers in a classroom demonstration will apply the three forces to a series of materials supplied in the trunk to determine the forces (if any) that most limit each material. In Exercise 1b, student teams will be given plastic connectors (uncooked spaghetti and glue are commonly used in physics classes to make these structures) with which to design a suspension bridge of specified length and width. After completing its bridge, each team will draw a picture that shows the elements of the design in appropriate scale. Each team will also measure the mass of its bridge by setting it on a kitchen scale and record this on their drawing. The class will then determine the structural integrity of the various bridge designs (corrected for mass differences) by spanning each bridge between two tables and loading a bucket suspended below it with weights until the structure collapses.

In a subsequent set of trials, Exercise 1c, the teams will compete in designing new bridges that more closely resemble the vertebral columns of quadrupeds, with two pairs of supporting piers (front and rear legs). The goal will be to design bridges of increasing span while maintaining structural integrity. The students will be provided a series of pictures of the skeletons of different mammals to help them in planning their designs. They can decide among themselves the rules of the competition. After an initial trial is completed, the class might read Thompson's chapter on the vertebral column as a double-cantilever bridge, which stresses the need to increase the arch of the vertebral column and bridge as span and load increase. If no group implemented this strategy in the trial, a second trial might be completed.

Open-ended exploration can follow the formal exercises. For instance, student teams might examine additional mechanical properties of organism design discussed by Thompson or suggested by themselves. Thus, they might choose to examine tree shape as a function of size (tower construction), the jumping ability of fleas (springs), the process of walking (pendulums), or power generation versus speed in millipede and centipede gaits (gears). Students might also investigate technological advances in the construction of bridges, towers, buildings, skyscrapers, cables, beams, vehicle frames, and airplane body and wing structures, all of which follow the basic engineering principles seen in animal skeletons.

Exercise 2: Sound Communication, Animal & Engineered Speakers

Sound is simply the vibration of molecules, whether in air, water, or the ground. Sound communication is extremely important in the animal world because it has many advantages over olfactory (chemical) and visual communication systems. For example, sound waves can be transmitted around obstacles such as clusters of trees, achieve communication in the dark, and are much faster than chemical communication. This form of communication is also more flexible than others: a single sound-producing organ can vary frequency, amplitude, pitch, tone, and intensity to produce a variety of sounds. Thus, animals can produce lengthy and complex messages through sound waves. This set of exercises explores sound production and its use in animal communication.

In Exercise 2a, we will introduce students to the basic mechanics of sound production through our audio-guided exercise that shows how various sound parameters can be translated into a two-dimensional graphic representation (audiospectrogram or sonogram) for quantitative examination. We will expose students to the parameters of frequency/pitch, amplitude/loudness, and complexity as they listen to and follow the corresponding audiospectrograms that may either be copied for individual use or projected at the front of the room using PowerPoint®. The challenge at the end of this exercise is for students to correctly assign each of the songs of five species of courting male frogs and toads to the five sonograms displayed.

In Exercise 2b, the students will examine sound production mechanisms in different animal systems and compare and contrast these mechanisms to engineered speakers used in cars, computers, televisions, public announcement systems, etc. To do this, each team of three to four students will examine the sound-generating mechanism in a working model of each of the four main sound systems in animals: vibrating a drum-like membrane (tymble), file and scraper, vibrating a membrane in an air flow (voice box), and hitting a substrate (drumming). Each group will then build a speaker using the instructions and materials provided: plastic cards, magnets, wire, tape, and a plastic cup. They will play audio tracks of the sounds produced by the different animal sound-production mechanisms through their speakers. For subsequent class discussion, each group will develop a list of similarities and differences in how the sounds are produced among the different natural systems and the engineered sound production system. The teams will also provide a qualitative analysis of the sounds produced by the different natural mechanisms, as communicated through their speakers.

The open-ended biological inquiry might involve bioacoustics (sound production) and habitat-induced sound-degradation problems (attenuation). In the first case, student teams could research and experiment with the size of the sound box and the amplitude of the sound produced. Some animals even choose an object in the environment that increases the amplitude of the signal (e.g., tree frogs that call in hollow plant stems and woodpeckers that tap on hollow trees and take advantage of metal transformer cases on telephone poles). Sound degradation is a problem that a vocalizing animal encounters in the environment. Students can play recordings of different pitches and other sound qualities through a speaker out of doors and record the sounds received in different habitats and at calling locations within habitats.

Exercise 3: Aerodynamics & Dispersal

Dispersal is one of the key characteristics of life. It has consequences for fitness, the individual's ability to pass its genes on to the next generation. It also affects population dynamics, population genetic structure, and species distribution. The seeds of many plants are dispersed by air currents. It is particularly important that seeds that drop from trees land out of range of potential competition with the parent trees while remaining within the local area of favorable habitat. The mechanics of dispersal in wind-dispersed seeds is critical to achieving this goal. This is also true for ballooning spiders, which release silk parachutes as a mechanism of dispersal via air currents. The passive dispersal of plant seeds and spiders by air currents relies on a parameter called *drag*, which can be defined as any force that opposes the direction of motion. Through a simple form of projectile motion called *free fall*, a seed dropping from a tree branch will fall in a straight path to the ground below. Drag, however, interferes with free fall, causing the seed to deviate in its vertical path. Drag must often be mediated for the sake of energy conservation in engineering systems, but it is often beneficial in biological systems. It is also important in airplane flight.

In Exercise 3a, the class will explore variation in the effects of drag with respect to the mass and cross-sectional area of objects. Pairs of volunteers will simultaneously drop two different items from a group provided (e.g., flat copy paper, flat cardstock, coffee filters in stacks vs. interconnected into a parachute shape, and books of different weights) from a standard height as other volunteers time the fall of each item with stopwatches. The goal is to complete the number of trials necessary to have all items paired with each other. Before starting the tests, the class will make predictions about which item will hit the floor first and the manner in which each will fall. A class poll will be taken on the board at the front of the room. Each trial's outcome should be discussed upon its completion. For example, the fall of a crumpled sheet of paper will be compared with that of a flat sheet of paper of the same linear dimensions. In discussing these results, we will introduce the concept of drag and Newton's second law of motion, and students will gain an understanding of the parameters in the equations that describe them.

Exercise 3b involves a design challenge that will be completed by student teams. A basic template for building a simple paper helicopter that will spin when dropped to the ground will be given to all teams. Their challenge is to modify the design, using only paper and paper clips, to maximize the drag and, thus, the time it takes for their paper helicopter to fall to the ground in competitive trials. In the process of experimenting with these simple paper devices, students will come to understand the principles (e.g., mass and blade length) that govern the parameter, drag.

Exercise 3c involves exploration of seed design and flight/dispersal characteristics in a variety of propeller seeds produced by maple, ash, and sycamore tree species. After examining the seeds and predicting the fall pattern of each, the students will complete drop experiments from a balcony or a similar height. In addition to comparing drop times, the students will be asked to examine the lateral distance from each seed type's landing to the location of the drop. This parameter should be discussed when comparing the dispersal distances that the seeds would achieve from their parent trees.

The open-ended exercises associated with the biology of dispersal focus on comparison of the morphological adaptations that are involved in different types of seed dispersal strategies. In this exercise, we focus on the short-distance dispersal of propeller seeds. There are also numerous seeds that exhibit long-range dispersal strategies via air currents, seeds that use animals in dispersal through hitchhiking or consumption, and seeds designed for dispersal via water currents. Student teams might research one of these types of dispersal and compare the morphology of the seeds with that of the propeller seeds investigated in this exercise. They might also design their own "seeds" based on a given strategy and assess the design's performance in competitive trials. For instance, after researching the traits associated with water dispersal, student teams might each design a water-dispersing seedpod. Trials could be completed at a local creek to compare the distances traveled per unit time or float time among the designs.

○ Concluding Remarks

The exercises and materials planned for our first engineering unit tied to biological systems address a major goal of the STEM Education Initiative: making science a multidisciplinary learning experience. Also, the exercises are designed such that no prior knowledge of the subject matter is needed. Sufficient background information is provided at the beginning of each exercise for students to understand the concept and follow the inquiry-based exploration of it. The teacher is free to learn with the students in the spirit of community learning.

While many of the *Biology in a Box* units incorporate mathematical equations and computations, this is the first unit that emphasizes a multidisciplinary approach to science education. Elements of physics, math, engineering, technology, and biology are present in each unit and there is the opportunity for engineering or biology students to explore their particular interests further in the completion of suggested open-ended activities that are based on the physical principles presented in the formal exercises.

We have mentioned biological inquiry at the end of each exercise here, but student teams could just as easily select a technological application to research. These latter applications are included in actual exercises for this *Biology in a Box* unit. Combined, the exercises described here give students experience with the following math applications and skills: algebra, geometry, trigonometry, unit conversions, weights and measures, ratios, square roots, coefficients, vectors, rates of change, equilibrium, scales, approximation, direct and inverse relations, linear equations, trigonometric functions, constrained optimization, expression of physical laws as mathematical equations, solving of equations, experimental techniques, data collection, quantitative analyses, graphic representations, and tables.

Biology, math, physics, and technology teachers might use one or more of these and the additional exercises presented in our Engineering Unit to reinforce curriculum content in their particular disciplines. Our hope, however, is that the exercises will be used in a multidisciplinary learning context.

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