Bridging the Gap: Connecting Biology and Engineering in the High School Curriculum

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Abstract - The STEM (Science, Technology, Engineering, Math) education initiative has developed out of an interest in increasing student pursuit of careers in the sciences and math. One of its approaches has been to integrate science, math and technology in US high school and college curricula. While physics and chemistry are the sciences most often targeted by this initiative, engineering frequently draws inspiration from biological systems. Here we, discuss the merits of offering an 'Engineering Box' consisting of inquiry-based materials and exercises to high school biology, physics and math classes as a STEM curriculum enrichment opportunity. We provide brief descriptions of exercises on projectile motion, aerodynamics, sound amplification and construction that demonstrate the interrelatedness of physics, math, biology and technology.

Keywords: STEM, *Biology in a Box*, inquiry-based learning, multidisciplinary educational experience

The Science, Technology, Engineering and Math (STEM) education initiative has developed out of a need to correct two perceived deficiencies in the US educational system. First, comparative evidence suggests that the United States is producing fewer practitioners in the sciences than other developed countries [Kuenzi 6, NCEE 9]. Secondly, science literacy test results suggest that the average US citizen lacks the understanding of science necessary to make informed decisions in our high-tech world [Nelson 10]. STEM solutions to these problems have largely focused on the areas of teacher performance and curriculum content.

Teacher Performance. In a series of papers, Goldhaber and Brewer analyzed student performance in classes that varied with respect to teacher knowledge of the subject matter. They found that students significantly perform at a higher level in science and math classes, when their teachers have degrees in the subject [Goldhaber 7,8]. Yet, it is difficult for teachers to major in math or one of the sciences while they are pursuing a degree in education. A number of initiatives have been developed to provide practicing teachers this additional training. A teacher, for instance, might intern with a university scientist in a summer research program. Other grant programs fund teacher pursuit of graduate work in science, math and engineering departments. There are even special graduate programs that combine training in math or science with teaching strategies relevant to these subjects.

Providing outside expertise in the classroom is an alternative approach to offering teachers this advanced training. Colleges and universities, for instance, obtain grant programs that place graduate students or advanced undergraduates in the schools to work with science teachers and their classes, one example of which is the STEP (Student Teacher Experience Program) at the Georgia Institute of Technology. Typically, the student spends one day a week over the course of the school year, providing enrichment activities to classes at the school he/she is assigned to. Similar programs bring retiree scientists, engineers and other specialists into high school classrooms.

Curriculum Content. The STEM education initiative also favors a curriculum shift from the compartmentalization of math and science classes into discrete subject areas to an integrated, multidisciplinary experience. To borrow an analogy, the typical K-12 core curriculum offers students knowledge about the individual trees (subjects), but fails to show them how the trees combine to make a forest. Students need to know that math, for instance, is not just an isolated exercise. Rather, it is a way of presenting natural phenomena in a form that can be quantitatively compared to other phenomena, as well as applied to solve problems of interest to humans.

Many states are currently implementing programs in high schools that provide greater integration of math, the physics or chemistry, and technology. Students are engaged in team projects in these programs that require knowledge and skills in all three subjects. Program evaluation results indicate that students participating in the multidisciplinary programs exhibit significantly higher levels of motivation and develop higher cognitive skill levels compared to students in the traditional compartmentalized curriculum [Ross 12] and [Venville 16].

The focus of much of this integration of science, math and technology has been on the physical sciences, chemistry and physics. These sciences have a more direct link to math and engineering than biology. However, modern biological constructs also have an underlying quantitative framework. Likewise, technological advances often stem from investigations of biological systems. In fact, the engineering discipline, biomimicry, quantitatively examines adaptive solutions organisms exhibit to various problems they face in nature. The goal of these investigations is to adapt these solutions to human problems [Benyus 3]. Examples of some of the technological contributions made by the field of biomimicry are presented in Table 1. Similar ties between biology, physics and engineering exist in all of 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, a subject people have a natural curiosity about [Crain 4].

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

Technology Application	Biological Source	Citation
Swim suit materials	Dermal denticles of shark skin	[Benjanuvatra 2]
Inexpensive solar cells	Light capture & transfer processes in leaf chloroplasts	[Ball 1]
Velcro fasteners	Hitch hiking seed (bur) design	[Paul 11]
Bioactive coronary stents	Internal artery wall function	[Schwartz 13]
Dry adhesive applications	Gecko foot hairs	[Sitti 14]
Walking robots	Kinematic configurations of a stick insect	[Frantsevich 5] & [Cruse 4]

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

One method of integrating elements of biology, physics, math and engineering principles into the respective classrooms or into a multidisciplinary program is through the addition of an Engineering Unit to the *Biology in a Box* science education project (http://eeb.bio.utk.edu/biologyinbox/default.htm). Riechert has developed this outreach project to enrich curriculum content in biology and math in K-12 classrooms. *Biology in a Box* exercises employ inquiry methodology in teaching science. These methods emphasize higher-order thinking, concepts rather than facts, and collaborative problem-solving skills in which teachers act as facilitators and students as the collaborators. Materials needed for completion of the exercises contained in the units are completely reusable and generally not commercially available. Sets of the thematic units are donated to school systems throughout the State of Tennessee (67 partnering school systems in 47 counties to date). Units are also loaned out to other school systems on request and all exercises are available at the project's website.

The *Biology in a Box* program addresses the noted problem of a lack of depth in teacher knowledge of the subject matter. Though specialists in a subject are not physically brought into the classroom, they provide the background introduction to a particular concept, and the blueprint and materials necessary to exploring it. In simulating the scientist's method of discovery, students learn through direct experience with materials, by consulting additional sources and experts, and through argument and debate among themselves. Most importantly, they respond eagerly to the experiential learning and tend to learn more quickly because of their enthusiasm.

Ten themes with grade-level appropriate exercises, Fossils, Of Skulls and Teeth, Fur Feathers, Scales: Insulation, Simple Measures, It's in Your Genes, Animal Kingdom, Backyard Naturalist, Everything Varies, Forestry and Animal Behavior are currently available. The development of an "engineering box" to complement these themes, affords an excellent curriculum enrichment opportunity that interconnects math, physics, biology and technology. The topic of biomimicry is so broad that we could conceivably develop a number of 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. The materials needs are also more appropriate to *Biology in a Box*, as all materials need to be reusable and of a size that they can fit into a wooden trunk. The merits of developing the connection between biology, physics and its engineering applications are clear from the successes of STEM education initiatives we have mentioned earlier. Below, we provide brief summaries of a few of the exercises that will be included in this unit, following a summary of the general format of *Biology in a Box* themes and exercises under them.

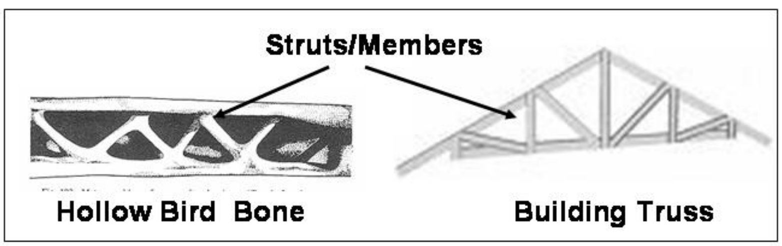
Basics of Exercise Design. We begin each *Biology in a Box* theme with an explanation of the problem or concept. A brief background section in which the concept is placed in a broader context and terms are defined follows this opening statement. The exercises available in the unit are then listed and the rationale for their placement in the order shown presented. The general goal of each exercise is delineated here also, along with indication of the skill level required to complete it.

A specific introduction to the subject of each exercise is provided under its heading. State science and math framework standards are presented under the exercise headings as well. Math faculty and graduate students from the National Institute for Mathematical and Biological Synthesis (NIMBioS) collaborate with the project in incorporating math elements where appropriate in the exercises. Just as the science presented is designed to meet grade appropriate State and Federal Standards, all mathematical computations are presented in a didactic format that reinforces fundamentals taught in K-12 math classes.

We try to design all exercises to be completed by teams of three to four students. A team may work independently on an exercise, using the bound book included in the wooden trunk housing the materials. Alternatively, a teacher acting as a facilitator may lead the entire class divided into teams through the exercise. If an LCD projector is available, the teacher may use the animated PowerPoint presentation provided on an accompanying CD. Overhead projection sheets can also be made from the pdf file also available on the CD. The facilitator typically compiles team results on the board at the front of the room for class summary of the results and discussion. Links to pertinent websites and journal article references are presented at the end of each exercise within a given unit. Suggestions are also made here for extension of the exercise just completed to open-ended inquiries.

Example Engineering Unit Exercises

1 From Skeletons to Bridges. D'Arcy Thompson, 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 15], he provided example after example of correlations between biological forms and mechanical phenomena. For example, he compared the internal supporting structures in the hollow bones of birds to the engineering truss shown in the figure below. One of the most famous comparisons he made was between the skeletons of four-legged animals and bridges. He proposed that bridges are simply well designed skeletons. In his analogy, the front and hind legs of a mammal are the supporting piers of the bridge, while the 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 this set of exercises, we introduce students to the principles of bridge construction by investigating tension, compression and bending as it applies equally to bridges and other engineering structures as well as animal bones and spinal columns.



After the forces are defined for the students, in Exercise 1a volunteers will apply the three forces in a class demonstration to a series of materials supplied in the trunk to determine the forces most limiting to each material, if any.

In Exercise 1b, teams consisting of three to four students, will be given the same set of materials (plastic connectors etc) from which to design a suspension bridge of specified length and width. The roadway of the bridge will need to have a hole through which a cord can be extended to a bucket. Once each team has completed their bridge, they will draw a picture of it showing the elements of the design in appropriate scale. They will also measure the mass of the bridge by setting it on a kitchen scale, and record this on their scale 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 the bucket suspended below it with weights until the structure breaks (collapses).

In subsequent exercises, bridge design will be modified to more closely resemble the vertebral columns of quadrupeds. The teams will be asked in Exercise 1c to build bridges that vary in span between the two pairs of supporting piers in one exercise. In Exercise 1c they will test the effects of degree of curvature (arch) of the spine. A series of pictures of the skeletons of different mammals will be available for them to examine in planning the design of these bridges. Following a discussion of their design results, the students will be asked to read D'Arcy Thompson's chapter on the vertebral column as a double-cantilever bridge. They can then revisit the results they obtained in their experiments in a concluding discussion.

The From Skeletons to Bridges exercises reinforce the following math skills: geometry, trigonometry, unit conversions, algebra, weights and measures, ratios, and constrained optimization. The following technological applications involving building construction principles are discussed under the open inquiry section at the end of the formal exercises: bridges, towers, buildings, skyscrapers, structures, cables, beams, vehicle frameworks and airplane body and wing structures. Each student team will select one application to research. They will present written and verbal reports to the class on the development of this technology.

Other open-ended exercises will require the students to examine additional mechanical properties of organism design discussed by D'Arcy Thompson or that they think of themselves.. For instance, they may choose to examine tree shape relative to their magnitude (tower construction), the jumping ability of fleas (springs), walking (pendulums), Millipede and centipede gaits- power generation versus speed (gears).

2 Sound and Animal Communication. Sound is simply the vibration of molecules, whether in air, water or through the ground. Sound communication is extremely important in the animal world because it has many advantages over olfactory (chemical) and visual communication systems. These include the fact that sound wave transmission can go around obstacles such as a cluster of trees, can be accomplished in the dark and it is much faster than chemical communication. This form of communication is also more flexible than other forms of communication: a single sound-producing organ can vary frequency, amplitude, pitch, tone and intensity in producing 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

Under Exercise 2a, students will be introduced to the basic mechanics of sound production. They will then complete our audio-guided exercise that shows how various sound parameters can be translated into a two dimensional graphical representation (audiospectrogram/sonogram) for quantitative examination. We will expose them 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 in the Power Point presentation version of the exercise. The challenge at the end of this exercise is for students to correctly assign each of the songs played to them of five species of courting male frogs and toads to the five sonograms displayed.

In Exercise 2b the student will examine sound production mechanisms in different animal systems and compare and contrast these mechanisms to engineered speakers used in cars, computers, televisions, public announcing systems etc). To do this, each team of three to four students will examine the sound generating mechanism in the working model provided 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: playing 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 Sound and Animal Communication exercises give students experience with the following math applications/skills: expression of physical laws as mathematical equations, direct and inverse relations, linear equations, trigonometric functions, graphical representations, quantitative analyses and square roots. The following technological applications involving sound production are discussed under the open inquiry section at the end of the formal exercises: loud speakers, car, radio, computer and television speakers, home sound systems, sound stages, microphones, musical instruments, synthesizers, and amphitheater acoustics.

Open-ended exercises in biology might involve bioacoustics (sound production) and habitat-induced sound degradation problems. 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 amplitude of the signal (e.g., tree frogs that call in hollow plant stems and woodpeckers that tap on hollow trees and even take advantage of metal transformer cases on telephone poles). The environment an animal is vocalizing in also influences the frequency of the signal it calls or the signal an animals calls at determines what environment it can best call in. This is because sound tends to be habitat attenuated or degraded. With a boom box, recorded sounds at different pitches, and a tape recorder, students can experiment with the problem of sound attenuation in different habitats and calling locations within habitats

3 Projectile Motion. Projectile Motion is a physical principle that assumes that once an object drops or is thrown or projected, it continues in motion and is influenced only by the downward force of gravity. Projectile motion falls under the physic discipline of kinematics (the study of motion). Three initial inquiry-based exercises have been developed for this theme. In Exercise 3a Free Fall, students explore projectile motion in mammals such as squirrels and monkeys or insects that drop from tree branches to the ground when disturbed by predators. Exercise 3b explores the phenomenon of launching. Launching behavior is characteristic of a number of temperate and tropical plant and tree species that have exploding seed pods as a seed dispersal mechanism [Vogel 17]. There are also animals that launch venoms, silk and blood at enemies and potential prey through spitting, squirting or the expulsion of darts maintained under pressure. Elephants and monkeys also engage in launching behavior. In Exercise 3c we combine the two types of projectile motion in the more complex context of a hunter launching a projectile at a prey that is dropping from a perch. Although exhibited by many predators, humans represent the best biological example of this complex behavior. Note that the projectile motion theme is one in which exercises form a logical progression. Each new exercise utilizes the results of the previous exercise.

Under the free fall exercise (3a), students are challenged to define the parameters that determine how long it will take an animal to reach the ground when it drops from a branch to chase a competitor, escape from a predator or when it is leaving a tree in search of a new foraging site. Balls that are identical size, but that differ in material composition and thus mass, will be dropped from different heights in this exercise.

The goal of the launching exercise (3b) is to learn how this form of projectile motion differs from free fall. A slingshot outfitted with a ruler and protractor with weighted string serves as the launch mechanism in this exercise and plastic beads simulate seeds. In respective trials, the angle of projection will remain constant while modifying the force applied (stretch length of the sling) and vice versa. The influence of each parameter on the distance the seed travels will be examined.

The final exercise (3c) combines free fall and launch projectile motion problems in a single context and thus tests what students have learned under the first two exercises. The context simulates the decision a hunter has to make when launching a projectile at a prey that is about to drop in free fall from a branch. The students must calculate where the projectile should be aimed to hit the prey in the midst of its freefall. (We actually pose this problem in the framework of a zookeeper attempting to hit an escaping monkey with a tranquilizer dart.) The materials used in the exercise include a stuffed monkey hanging from an electromagnet and a Nerf gun. The monkey is electronically connected to the trigger of the Nerf gun, so that it will drop from the rod it is hanging on simultaneously with the pull on the trigger of the gun and subsequent release of the dart.

The Projectile Motion exercises reinforce the following math skills: unit conversion, identification of linear and quadratic equations, solving quadratic equations, trig functions, optimization, the importance of initial conditions, direct and inverse relations and the solving of word problems. The following technological applications involving projectile motion principles are discussed under the open inquiry section at the end of the formal exercises: artillery, no line of sight cannons (like modern tanks), bombs, missile defense shields, extinguishing fires from long distances with hoses, aid drops (as in disaster relief zones, Antarctic missions), other weaponry including guns, spears, arrows and sports (e.g., baseball and football). Each student team will research one application and present written and verbal reports to the class on the development of this technology.

Other open-ended exercises are designed to explore the principles of projectile motion in biological contexts. For instance, we suggest that teams each build a plant designed to maximize seed launch. There will be a class competition with trials completed to determine which design performs best. Discussions will focus on the success of the designs in terms of the physics of projectile motion. In a second exercise, students are expected to search the literature on horny toads, spitting cobras and spiders to obtain any relevant parameters available for predicting launch distance. Students are expected to be able to calculate missing parameter values and to be able to explain the limits of the particular projectile system.

4 Aerodynamics and Dispersal. Dispersal is one of the key characteristics of life. It has fitness consequences, which are defined as the individual's ability to pass its genes on to the next generation. It also affects population dynamics, population genetic structure and species distribution. In the free Fall experiment under the Projectile Motion exercise, students made the assumption that drag is negligible. Yet, in real world applications, this assumption is rarely validated. In engineering systems drag is a parameter that often must be mediated for the sake of energy conservation. But in biological systems it is often a beneficial effect. Of particular importance is for seeds dropping from trees to land out of range of potential competition with their parent trees, while remaining within the local area of favorable habitat. The mechanics of dispersal in wind-dispersed seeds and even ballooning spiders is critical to achieving this goal. (Spiders release silk thread parachutes as a mechanism of dispersal via air currents.)

The initial experiment (4a) entails class exploration of the ways in which objects fall by presenting them with flat copy paper, flat cardstock, coffee filters in stacks versus interconnected into a parachute shape, and books of different weights. Pairs of volunteers will drop pairs of these items at the same time from a standard height and the speed with which each falls timed with a stopwatch. The goal is to complete the number of trials necessary to have all items paired with each other. Individuals in 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 made on the board at the front of the room as well. Each trial's outcome should be discussed upon its completion. For example, the fall of a crumpled sheet of paper will be compared to 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. Students will also gain an understanding of the parameters in the equations that describe them. The second exercise (4b) involves a design challenge that will be completed by teams of three-four students. A basic template for building a simple paper helicopter that will spin when dropped from to the ground will be given to all teams. They will be expected to modify the design, using only paper and paper clips, to maximize the drag and thus the length of the time it will take in the competitive trials to fall to the ground. The students will need to fully understand the principles (e.g., mass and blade length) that govern how their 'helicopter' performs.

The final formal exercise involves exploration of the seed design and flight characteristics in a variety of propeller seeds produced by maples, ash and sycamore trees. Following examination of the seeds and predictions made as to the fall pattern of each, the students will complete free fall experiments from a balcony or its equivalent. In addition to comparing the drop time, the students will be asked to examine the lateral distance each seed morphological type lands from the location of the drop. This parameter should be discussed when comparing the dispersal distances the respective seeds achieve.

The Aerodynamics and Dispersal exercises give students experience with the following math applications/skills: unit conversions, geometry, experimental techniques, data collection, data display, algebra, coefficients, tables, the expression of physical laws as mathematical equations, solving equations, vectors, rates of change, equilibrium, scales, approximation. The following technological applications involving aerodynamic principles are discussed under the open inquiry section at the end of the formal exercises: helicopters, airplanes, boats, submarines, parachutes, cars, fuel efficiency, turbines, wind mills, kites, and the control surfaces of flying objects. In an open-ended inquiry exercise, each student team will select one application to research and will subsequently present written and verbal reports to the class on the development of this technology.

The open-ended exercises associated with the biology of dispersal will focus on comparison of the morphological adaptations that are involved in different types of seed dispersal strategies. In this exercise, we focused 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 hitch hiking or consumption, seeds designed for dispersal via water currents. Student teams might research one of these types of dispersal and compare the morphology to the propeller seeds investigated in these activities. They might also be expected to design their own seeds of a given strategy with the design function assessed 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 where distance traveled per unit time or float time compared among the designs.

Concluding Remarks

The exercises and materials planned for our first engineering unit tied to biological systems addresses the two major goals of the STEM education initiative: overcoming a lack of depth of teacher knowledge in the subject matter and making science a multidisciplinary learning experience. 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 her class 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 the engineering or biology student 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.

Teachers from any of the subjects might use one or more of these exercises to reinforce curriculum content in their particular discipline. Our hope, however, is that the exercises would be used in a multidisciplinary learning context. To that end, we plan to offer a special *Biology in a Box* workshop on this unit under the sponsorship of NIMBioS. Math, biology, physics and technology teachers the same high school will compose each team of participating teachers. There will be a maximum of 4 teachers per team, but there could be fewer team members if individuals teach more than one discipline. We will work with our teacher teams in developing strategies for joining their classes in inquiry-based learning experiences. The *Biology in a Box* Engineering unit will be used as the model enrichment opportunity.

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