MODEL IMMERSIVE PROJECTS FOR HIGH SCHOOL CLASSES

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Sound Investigations

The study of sound is important in biological science, physical science, and engineering contexts. Many animals use sound to detect prey, to avoid predators, to communicate with each other, and even to eavesdrop on others. These factors provide the impetus for innumerable engineering applications in acoustics, which may be directed towards sound dampening, amplification, or detection. The fundamental physics of sound involves sound wave creation, the analysis of the speed of sound through various media, the pitch or frequency of sound, and how the loudness or intensity of sound is measured. We list some of the many research applications that can be conducted in this area below. Note that each one could easily (and should) draw from elements of others, reinforcing an integrative STEM approach.

Sound Production and Propagation

In analyzing sounds, a recording is typically converted to its graphical representation (sonogram/spectrogram). Periods, amplitudes, and frequencies of sound waves can be quantitatively measured and compared in these visual displays translated using an oscilloscope or its equivalent. The relationships of these parameters to loudness and pitch can also be specified. Through such analyses, students can examine and make numerous comparisons between natural and engineered sounds. A few examples follow.

- Hypothesize the evolutionary relationships among closely related organisms by analyzing the sounds that the organisms produce.
- Investigate the mechanical production of animal sounds and build models to replicate various types of animal sounds.
- Compare the acoustic properties of musical instruments that vary in classification, quality, or the materials from which they are constructed, and determine the influence of each factor on the sounds that are produced.
- Investigate questions about the propagation of sound by mapping the acoustic properties of industrial, educational, entertainment, and residential spaces. Is the propagation of sound truly omni-directional? Why is it so difficult to locate the position of an electronic beeper? What characteristics of sound make a sound difficult to locate?

<u>Mathematical Model:</u> The physical structure of the sound production mechanism is adaptable to simple physical models, which can be described mathematically and tested experimentally. In theory, the fundamental frequencies of natural or manmade sounds are predictable based on geometry, as are the higher-frequency harmonics that would be expected in complex sounds. Oscillators can be modeled mathematically using differential equations. Fourier transform analysis would yield frequency distributions present in natural and manmade sounds.

<u>Experimentation:</u> Sound spectrograms are widely available in the literature and in web-based data banks, and such available graphical depictions of sound could be used to supplement or take the place of student-collected data in some projects. Both PASCO and Vernier produce probeware that allow for the collection and analysis of sound. Apps for mobile devices can also be used for

sound analysis. The high-speed acquisition hardware produced by PASCO provides reasonably accurate Fourier transform and oscilloscope functions. Raven is popular interactive sound analysis software. Raven is a software program that can be used to analyze sounds within the classroom. Schools can receive discounts on the software when they apply. Students could spend $50 for a full semester license to use Raven Pro. Teachers may purchase an instructional license for four instructional machines for $400. Finally, there is a limited version of Raven Lite, which allows for students to perform basic functions like recording, saving, and visualizing sounds as spectrograms and waveforms. Oscilloscopes can be obtained as software from various software companies including Onyx Apps, Dog Park Software Ltd., and BitScope. Software prices range between 0 – $10. However, hardware oscilloscopes are another option if far more expensive then their software counterparts. The trade-off with using hardware oscilloscopes is their robust build and more accurate analysis of audio waveforms. The downside to using software packages is they are less accurate at acquiring data and often require frequent updates from the software company in order to remain up to date with changing technology. Tektronix is a leading manufacture of hardware oscilloscopes whose most basic model starts at a price of $1,290. Rohde and Schwarz is another manufacture that takes quotes for various software and R&S oscilloscope models. Cheaper hardware oscilloscopes can be bought from Link Instruments like the MSO-19 analyzer, which costs $250.

To explore sound production from an engineering perspective, students can build speakers. In an engineered speaker magnets are vibrated by electricity running through a coil of wire, and this vibration is transmitted through some medium (the cone). Speaker kits and parts can all be purchased at www.parts-express.com in various configurations. Prices range between $50-$500 for a complete speaker assembly kit. Individual speaker components can also be purchased from the above mentioned website. Students may have access to a variety of materials purchased from this website. Teachers may purchase multiple different speakers to demonstrate their how their varied constructions suite different functions for customers.

Sound Attenuation

One problem animals face with regard to sound communication is that of attenuation, or the apparent decrease in intensity of the sound over distance, as sound waves are dispersed differentially or absorbed by various transmission media. Students can determine how sounds produced by particular organisms are attenuated in different habitats and relate this to the ecology of the organism (e.g., habitat selection; adaptations to reduce, or in some cases, increase attenuation in varying ways). Students could also investigate how animals use particular pitches or amplitudes to avoid eavesdropping by their prey or potential competitors or predators.

Attenuation is also important in an engineering context, such as in trying to avoid the loss of sound quality and projection in classrooms and auditoriums. There are also natural and engineering applications in which the attenuation of sound is desirable. Students might identify soundproofing materials that selectively dampen sounds of particular pitches or amplitudes. Students can evaluate the absorption/reflection behavior of different materials and design solutions for real world applications. An excellent company to purchase acoustic absorptive/reflective materials would be Acoustical Solutions, Inc.

Students may examine how space is often artificially engineered within popular music by analyzing the tools used in music production applications. Reverb plugins, utilized within Digital Audio Workstations (Garageband, Audacity, Pro Tools), use parameters that include dampening, diffusion, decay, and equalization. Sound parameters that could be explored within this context would include frequency, amplitude, dampening, and resonance.

Mathematical Model: Sound intensity is measured using a logarithmic (decibel) scale. Intensity, or loudness, is quantitatively related to the energy transferred in a sound wave. As with all energy transfers, the Law of Conservation of Energy must be obeyed, although verifying this experimentally with statistical validity could be challenging to demonstrate. Sound attenuation from a point source could follow various geometric models depending on whether the sound travels outward spherically, travels outward along a planar surface, or travels down a rod. Are the geometric models accurate in the natural world? Do living organisms send sound out in a cone of a certain solid angle? Are they capable of producing another geometric shape? How does this affect attenuation? An exponential model is often proposed when sound travels through materials, but what is the theoretical underpinning of this? Is that model solely empirical? Does the frequency composition of the sound change in a predictable way as it attenuates, based on different attenuation of the sound frequencies based on material?

Patterns of constructive and destructive interference as a function of location in a room, speaker number and position, diffraction of sound around barriers, sound frequency and wavelength, air temperature, and the relative amplitudes of harmonics in the sound, involve much in the way of geometric thinking and analysis. The shape of the walls of the room, and the material on the walls, is also involved. Mathematics can be used to predict the location of “dead spots” in an auditorium. These predictions can be easily tested with the human ear or a sound intensity meter. The shape of the room can be analyzed with regard to sound reflection and its contribution toward constructive and destructive sound interference. Sounds of different frequencies undergo diffraction and interference differently. There are many opportunities for mathematical prediction and experimental testing in this area.

Experimentation: Using an inexpensive sound intensity meter or qualitative measures, students might compare the attenuation of sounds over varying distances and through different media. Example sources of sounds include: a standard tone generator program, actual sound recordings produced by animals, by musical instruments, or by appliances and other equipment. Quotes for sound intensity systems may be obtained from companies like Bruel &Kjaer, whereas some companies such as Gracy & Associates allow for equipment to be rented for approximately $50/day. Tone generators can be obtained for free online from various sources including www.softonic.com and the NCH company. PASCO and Vernier probe ware provides the ability to measure sound amplitude, which can be compared with sound intensity as measured by other devices. Using an oscilloscope, students may examine the how various sound quality parameters such as amplitude and frequency affect how the sounds themselves are attenuated. There is an oscilloscope app (plus external gear) that may be purchased in a set for prices between $300-$400. The webpage where the oscilloscopes may be purchased is www.oscium.com. PASCO and Vernier probe ware provides an oscilloscope function, although it is not as sensitive as that provided by an actual oscilloscope.

In the acoustics and music industries a major goal is often to improve the distance at which sounds can be detected as well as maintaining sound quality. Students can test speakers with the aim of defining factors that improve frequency spectrum transmission, overall sound quality and or projection distance in innumerable environmental contexts. Students might compare speaker structure to the morphological adaptations possessed by animals to project sound as well as behavioral use of features of the environment. Students may deconstruct cheap speakers. For example, speakers like the Arion-Soundstage 2.0 channel can be purchased in pairs for 15$. Comparisons may be made between cheap and expensive speakers in the materials that were used between each speaker model. Students may then alter their own speakers with materials that will change certain aspects of their speaker's sound attenuation. Students will alter their speakers to not only play louder, but also to sound with a higher dynamic range, better bass, and natural timbre. For example, students may alter the distance the speaker may vibrate to strengthen the speaker's bass power. This parallels with adaptations seen within amphibians that allow for calls to be exhibited at lower frequencies via more space for vocal cords to vibrate.

Modeling the Human Ear

Hearing is largely a mechanical process. Sound is detected within our ears as vibrations and transmitted via various mechanical structures. The vibrations are eventually converted into electrical signals, which are sent to the brain. In this project, students will first research the ways by which the ear can pick up and interpret sound. After gaining an understanding of the underlying functions of the ear, students will design an artificial ear. This artificial ear must detect sound and send an electrical signal that can be measured by a computer.

Mathematical Model: Oscillations involve frequency, amplitude, and wavelength. The physical model for sound is a compression, or longitudinal, wave. Areas of alternating high and low pressure cause physical vibration of mechanical structures that can resonate at the frequency of the sound. The frequencies at which a mechanical structure can oscillate depend on its geometry.

Experimentation: Students can use the 3D printer to aid in construction of the model ear. They can also deconstruct speakers and microphones to aid in the development of their model. Sources to aid in the investigation include the URLs below:

http://health.howstuffworks.com/medicine/modern-technology/hearing-aid.htm

http://health.howstuffworks.com/mental-health/human-nature/perception/hearing1.htm

Light Investigations

Light impacts daily life in almost every way, yet the transmission and behavior of light are largely taken for granted. However, our buildings are now being designed to maximize light quality while minimizing costs. The use of lenses and mirrors to form optical images is an important technology, as is the development and use of laser technology. Fiber optics cables are essential for high-efficiency signal transmission.

Comparison of Commercial Lighting Sources

In recent years, engineers have been hard at work reinventing the light bulb. While we typically describe light bulbs in terms of the amount of electrical power used, these metrics have become outdated with the introduction of more energy efficient bulbs. Manufactures now list the power equivalence of newer light sources by comparing them to an incandescent light bulb; e.g., a 40 W incandescent is comparable in light production to a 5W compact fluorescent bulb. This simple comparison does not take into account the color of the light, which affects human perception of its brightness as well as its desirability. In time, as the incandescent bulb becomes less common, it is anticipated that a new methodology will be developed.

Mathematical Model: Students can compare various light sources in terms of their power and brightness. There are several units that are used to report light intensity that can be applied in such an investigation. Students can select the most appropriate unit and justify its selection, or they can develop their own metrics for comparison of lighting sources. Aspects to consider are light intensity, coverage area, frequency profile, etc. As part of the investigation, students can evaluate the claims made by the manufacturers for accuracy.

Experimentation: Light bulbs can be purchased at www.1000bulbs.com in various shapes, power output, electrical requirements, and brands. Prices for most bulbs range between 1-5 each. Light intensity measurements can be made with light meters. PASCO and Vernier supply probeware that can be used for this purpose.

Light and Other Wave Phenomena

Studying the wave nature of light can be based in the study of general wave behavior. Such a study helps us understand various general wave phenomena, such as constructive and destructive interference, polarization, and diffraction. Sound and water waves are useful models to use, although these mechanical waves require a medium in which to travel. Diffraction is a useful phenomenon that is invaluable in the study of materials, as diffraction patterns give us important information about molecular structure. Polarization of light results in glare, which is helpfully removed by polarizing filters in sunglasses. The creation of 3D movies depends on an understanding of polarization as well.

Mathematical Model: How oscillations work, in terms of amplitude, frequency, and wavelength, is a necessary mathematical starting point. The difference between models of light that are coherent (such as produced by a laser) and incoherent (such as natural light) is important to understand. Creation of a 3D effect requires the interplay between the geometry of polarization and the spacing between the human eyes. Finally, reflection off of a planar surface, such as a lake or a wet roadway, partially polarizes light. How sunglasses are constructed depends upon the predictability of the plane of polarization.

Experimentation: Lasers and other light sources, diffraction gratings, and polarizing filters are readily available supplies that can be used to study light. Models using water waves can be created with ripple tanks. Sunglasses can be modeled using polarizing filters, or by purchasing inexpensive sunglasses directly. Light intensity can be readily measured using light meters, or with probeware from PASCO and Vernier.

Optical Instruments Based On Lenses and Mirrors

From eyeglasses to bathroom mirrors, optical instruments are an important part of our everyday life. Some optical instruments, such as plane mirrors, create images that are the same size as the source object, while other instruments, such as the side mirror on an automobile, create images that are intentionally distorted. Images can be as complex as a hologram, or as simple as the bright spot made by focusing the energy of the sun in a very small area.

Mathematical Model: The study and design of optical instruments make heavy use of geometry and trigonometry. Conic sections (parabolas and hyperbolas) are essential mathematical ideas that are used with certain optical instruments, especially focusing devices such as concave mirrors.

Experimentation: Inexpensive mirrors and lenses are widely available from scientific supply companies, and an assortment of mirrors and lenses are already available in the VolsTeach Materials Library. Low-power lasers and incandescent light sources are also inexpensive and readily available.

Building a Microscope from a Smartphone

Modern smartphones have highly sensitive cameras. In addition to clicking photos, the smartphone camera can be used to build an easy-to-use optical microscope. However, the smartphone-based microscopes that have been built so far have a modest resolution allowing only visualization large eukaryotic cells. The aim of this project is to build a smartphone based microscope with a better resolution that will enable imaging of bacterial cells. Once students develop a lens they want to incorporate within their smartphones, they may send their designs to Diverse Optics, a company that specializes in injection molding, which is a process from which optic lenses are created.

The smartphone based microscopes truly open up whole range of interesting experiments for science classroom, but they could also possibly used for environmental monitoring and in medicine. This is an excellent project to learn about optics, microfluidics, smartphones and bacteria.

Mathematical Model: Geometric optics would be involved, along with the mathematics required to build the stand, calculate the magnification, and build the microfluidic device. This is a very good general application for both mathematics and biology. Mathematical methods would span several different areas of mathematics.

Experimentation: The project goals are to build an optical lens system and a stand that together with a cell phone camera forms a digital microscope. It will also be necessary to build a microfluidic device that can be loaded with bacterial samples from the environment for imaging in this microscope. The tool should be usable in middle and high school classrooms.

Modeling the Human Eye

Building a model of the human eye is an excellent way for studying how the lens and pupil structure can impact how light is refracted within the eye.

Mathematical Model: The eye is essentially a dual-lens optical instrument, with the cornea providing the majority of the focusing power and the crystalline lens doing the fine-tuning. Visual correction can be provided with additional lenses in glasses or contact lenses. The thin lens equation and Snell's Law of refraction serve as valuable calculation tools for this project.

Experimentation: Students can build a model eye to demonstrate and conduct experiments by altering various aspects of the eye structure (lens shape, size, or type) and noting the consequences on how images are projected. This model may be constructed using two clear plastic bowls stacked together to make a complete sphere. A soldering iron can be used to melt a hole big enough for a lens to fit within it. Post-it notes within the bowls can serve as a screen, or retina. Lenses and lens holders can be purchased from the Diverse Optics Company and Thor Labs webpage. Students may experiment with a variety of lens types to investigate how lens combinations may help focus light to the desired location.

Forces and Newton's Laws

Anything larger than a subatomic particle that moves or remains at rest obeys Newton's laws of motion. Newton's 1st Law states that an object will not change its motion unless acted upon by a net external force; the 2nd Law states that acceleration of an object is proportional to the net external force exerted on it and inversely proportional to its mass, and the 3rd Law states that objects exert forces of equal magnitude but opposite directions on each other. Biological systems must also obey these laws, leading to amazing evolutionary adaptations. Investigation of these adaptations often leads to elegant and efficient solutions to real world problems.

Statics and the Strength of Natural and Manmade Materials

Statics is a subset of mechanics in which all external forces on an object are balanced and as such represents an important field of study in mechanical and civil engineering. Keeping systems at rest (e.g. keeping a building standing or bridge from collapsing) often depends on the characteristic properties of the materials used in construction. For thousands of years engineered materials have built civilizations and enabled new technologies. However many modern materials are designed to recreate the successes of the natural world to achieve lighter weight, higher strength composite materials.

Mathematical Model: Materials that can be compressed or extended exhibit various mathematical relationships between the force exerted and the extension or compression. Leonhard Euler, the Swiss mathematician and physicist, first developed the idea of the elastic modulus that was later named Young's modulus after Thomas Young. How does the characterization of a material using Young's modulus determine its dimensional stability under different load conditions? How does the shape of the material affect its ability to bear a load? There are many areas for mathematical analysis in this topic.

Experimentation: Students can test samples of engineered materials (metals, polymers, etc.) and natural materials (woods, spider silk, etc.) to determine their characteristic material properties. Metal materials can be purchased from Metals Depot at www.metalsdepot.com in varying types, shapes, and sizes. Home Depot's lumber department carries a vast array of wood to purchase that students may use within the classroom to investigate statics. Boards of Cedar, Pine, and Oak can be purchased for prices that range between $2-$15 in various dimensions.

Friction

Friction is a force that occurs when two different materials move against one another. Friction opposes the movement of the materials, causing resistance, which slows the movement of the materials relative to the input of force. Friction also releases additional energy in the form of heat, which also increases the amount of force needed to move the materials across each other. The coefficient of friction relates to the amount of resistance when two particular materials come into contact. The higher the coefficient of friction the greater the resistance. In addition, there are two kinds of friction: kinetic and static. Static friction refers to the amount of force that is required to being movement of one material across the surface of another, while kinetic friction refers to the amount of force required to maintain movement of one material across the surface of another.

Mathematical Model: Students can easily model friction using the equation for frictional force. Students should consider how friction affects and should be included in other force models, such as how friction would affect a car's ability to stay on the road when making a turn. Under what scenarios is friction beneficial, and when is it detrimental?

Experimentation: Students can find the coefficient of friction for various different materials by measuring the amount of force that is required to move one material against another. In these experiments students can use spring scales to measure force. The student can attach one end of the scale to the material and grasp the other end of the scale. When the student pulls the scale will then provide a measure that can be converted to newtons or, in the case of a Newton scale, simply used straight. Students should consider which materials would cause the highest levels of friction and which the lowest when formulation hypotheses and crafting their experiments. Students should also observe the difference between the kinetic and static friction of different materials. Students can build upon their classmates and previous classes' work by using different materials. Materials such as wood boards, sandpaper, cloth, and ice can be acquired for these experiments at relatively little cost.

The Dynamics of Hopping and Jumping Animals

Hopping and jumping are useful locomotion strategies used by some animals that have aroused the interest of engineers working on robots for difficult terrain. Storing energy and releasing it quickly to propel objects into the air is the fundamental mechanism.

Mathematical Model: Can the derivation of the mechanical energy stored in a spring or rubber band when stretched or compressed be adapted as a model for a muscle pair associated with limb movement? Is there a biologically optimal design for hopping as opposed to running? What are the advantages and disadvantages in terms of limb function and stability for animals who have limb muscles largely located in the torso (horses, antelopes) as opposed to in the limb itself (humans, frogs)? In addition to force and torque, there are thermodynamic (heating and cooling) considerations as well. Conservation of energy and energy flow would be important quantities to model.

Experimentation: Students can investigate and build models for the hopping mechanisms of natural systems, and determine the energy, force, and acceleration requirements for these actions. Amphibians would be an excellent group to focus upon for relating the physics of hopping and jumping to the biological world. Recent studies suggest that jump performance is not affected by just muscle performance, but by other factors including hind limb length, mass of jumping muscles, and skeletal structure. All of these factors may be tested within a classroom using amphibians. Frogs like the spring peeper and green tree frog can be purchased for 9$ apiece from websites like http://www.backwaterreptiles.com/tree-frogs-for-sale.html.

Gravity, Projectile Motion, and Flight

A subset of mechanics, projectile motion plays an important role in many applications. Anything that flies through the air under only the influence of gravity can be classified as a projectile, many engineered and natural systems use projectile motion to accomplish tasks.

Gravity and Elevation

While all objects are pulled toward the each other in proportion to their mass, the relationship is also dependent on the distance between the objects. Therefore, as elevation changes, the rate at which objects are accelerated by gravity varies.

Mathematical Model: Students can use established measurement techniques, or mine data bases, to investigate the variation in gravity at different points on earth. For example, students may use the formula below to calculate gravitation force at varying altitudes above sea level.

$$g_h = g_0 \left(\frac{r_e}{r_e + h} \right)^2$$

It is critical that students understand where this formula comes from, and how it is derived.

Experimentation: Schools that are located near areas of higher elevation could take a field trip to these areas and perform basic experiments to test for any changes in Earth's gravitation force that are measurable. Students may choose to assemble a laser trigger for more accurate data collection when testing acceleration due to the earth's gravitational force. Many instructions are available online for how to build the configuration for this method. One such site can be found at http://www.instructables.com/id/Laser-Sensor-Timer/. A related device from PASCO is also available. The gravitational field does not change measurably near the surface of the earth, but at what point does the non-constancy of *g* become noticeable? Can an experiment be performed in Knoxville and repeated in the Smoky Mountains that is so sensitive it shows the non-constancy of g? This would involve calculus and very careful attention to the statistics.

Magnetism

Magnetism is a particular kind of force that arises naturally in certain types of metals and artificially in electromagnets. In magnetism there are always two poles, the "north" and "south" pole, with the two like poles (north-north and south-south) repelling each other and the two opposite poles (north-south) attracting each other. In an active magnet there is a constant magnetic force in the direction from one pole (north) to the other pole (south) in what is called the magnetic flux. The strength of magnets can vary greatly, from relatively weak magnets that are able to be pulled apart by human hands to relatively strong magnets that can pick up entire cars.

Mathematical Model: The strength of a magnet can be calculated in a number of different ways. Magnetic flux density refers to the amount of magnetic flux, or amount of magnetic field, concentrated in a particular volume and can be calculated with a formula. Magnetic strength can also be measured with pull force, or the amount of force required to detach a magnet, which may be calculated by normal force equations. Magnetomotive force is another measure of the strength of a magnet measured in amperes rather than the conventional force unit of newtons. Magnetomotive force is particularly easy to calculate in electromagnets but also occurs in naturally occurring magnets.

Experimentation: The strength of magnets can be directly measured using a flux meter or Gaussmeter. These meters come in at around $100-130 on the cheap end. However, students can measure the relative strength of magnets in other ways, such as the pull force of a magnet. Students can measure the pull force of a magnet by attaching a scale to a magnet and measuring the amount of force required to pull the magnet free. This force can be measured directly with a newton scale or indirectly with an ordinary spring scale. For experiments in the lab it is likely that only magnets with relatively weak pull forces will be able to be measured this way.

Electromagnets

Electromagnets are magnets creating by running an electric current through wire wrapped around a core. Unlike natural magnets electromagnets only function as long as there is an electric current moving through them. When the electric current is shut off the electromagnetic will no longer act as a magnet. Note that there may be a delay and some residual magnetism may remain after the current has stopped, but the full strength of the electromagnet will only be present so long as the current is running.

Mathematical Model: The magnetomotive force of an electromagnet is relatively easy to calculate using the right formula. Unlike natural magnets the materials that make up an electromagnet can also affect the strength of the magnet. The permeability of an electromagnet, or the relative ease with which magnetic flux can pass through the central material of the electromagnet, can also be calculated by formula.

Experimentation: Students can create cheap electromagnets using simple materials like an iron nail, some copper wire, and a battery. Students can calculate and/or measure the strength of an electromagnet the same way the strength of a natural magnet can be calculated or measured. Students should create experiments to measure the strength of their electromagnets and observe how to increase and decrease them, either by using the materials they possess in different ways or varying the materials.

The Flight of Projectiles in Sport

Throwing, shooting, and falling all involve projectile motion. In first-semester physics, only gravitational acceleration and launch velocity are used to characterize the motion of a projectile; however, in practice other factors are important as well and can dominate the behavior of the projectile. Describing and compensating for these other influences, such as lift and drag, is imperative to understanding projectiles in flight through the atmosphere.

Of course, many sports involve objects in flight. The long pass in football often must travel over fifty yards in the air, forcing the quarterback to adjust the release speed and angle to achieve the necessary distance and hang time. Similarly, the ball leaves the bat of a professional baseball player very differently than it does for the amateur. Consultants for pro sports teams are often paid handsomely to analyze the technique of players to improve the trajectories of their projectiles. Students can use measurement and analysis techniques to describe the difference between a professional and amateur athlete and determine the requisite performance characteristics necessary to achieve pro status. They can also analyze how the characteristics of projectiles, such as the dimples on a golf ball or the laces on a baseball, affect their motion.

Mathematical Model: Students must consider the gravitational force that influences objects in free fall, and then extend their knowledge to include lift and drag forces. The spinning of projectiles about an axis is another important consideration, especially for non-spherical projectiles such as footballs. Sports projectiles often rotate to provide stable orientation, and that involves calculation of rotational inertia and angular momentum. Students can derive spatial domain trajectories incorporating various components that go beyond simple gravitation acceleration, and use their understanding of parametric equations to develop and analyze time-domain functions in two or three dimensions.

Experimentation: Projectile launchers are available that can vary the force used to launch a projectile as well as the launch angle. Human beings can also be used to throw, hit, kick, or otherwise launch projectiles. The shape and mass of projectiles can be varied, along with their surface composition. The trajectories can be recorded using a high-speed camera, and videoanalysis can be performed on the recorded video using Logger Pro by Vernier or Capstone by PASCO.

Trebuchets

A trebuchet is a type of machine that throws a projectile using a swinging arm. Historically, trebuchets were used for war by lobbing large objects at an enemy's forces. In physics courses, however, trebuchets are interesting because they combine a variety of different concepts. Trebuchets store potential energy to convert into kinetic energy, the trebuchet tosses a projectile, a trebuchet combines several different simple machines such as the lever and axle. Understanding how a trebuchet works requires first understanding several other simple concepts.

Mathematical Model: Students should use the concepts they have learned in their physics course to design the optimal trebuchet. Students will need to consider the conversion of potential energy to kinetic energy and how best to create potential energy. Gravity is often used when constructing trebuchets, but students should also consider the potential energy of a spring, for example. Students will also need to consider projectile motion. How might students reduce the forces of drag and gravity on their projectile so that it might fly further? Students will also need to know how to calculate the different forces on the simple machines within their trebuchet and consider the release time and angle of their trebuchet. Students should also consider how the relative size of their trebuchet and their projectile might affect lobbing distance.

Experimentation: Students will physically develop their modeled trebuchets and observe the distance the projectiles are thrown. Students should pay careful attention to the differences between their model and the actual thrown distance and attempt to reconcile the two. Students should also compare their trebuchet to that of other students and previous classes to see how their trebuchet might be improved. Students might also research historical trebuchets. Students can also record the trajectories of their trebuchet's lobbed object and analyze it in a similar manner to the "The Flight of Projectiles in Sport" in project.

Flight Involving Wings

Flight mechanisms may be specifically related to the varying wing designs of diverse avian species. Flight is a costly mode of locomotion. Many adaptations in species function specifically to minimize the cost of flight. Furthermore, the body structure of an organism that enables flight can be related to that organism's ecology..

Mathematical Model: Bernoulli's principal can be used to calculate the pressure differential due to airflow around a wing of a specific shape. The pressure differential, along with the wing area, can be used to calculate lift. Drag forces are also involved, and these follow a different mathematical model. For a fixed winged craft to stay aloft, the calculations are more straightforward. Can models for lift and drag forces be combined into a mathematical model that describes how birds fly? Flying involves high energy expenditure, so birds must gather fat reserves that will be used up as fuel for their seasonal migration events. Is it possible to calculate the food requirements of a migratory bird?

Experimentation: Students can investigate the elements of wing design that determine lift and drag forces and experiment with different wing shapes for maximum lift and efficiency. Differences between hawk, songbird, and bat species wing structures could be compared and contrasted on how their unique adaptations enable stable flight specifically within their respective habitats. Also, variation in wing structure can be correlated with different flight modes and speeds. Foraging tactics may also be compared and contrasted between avian species with their adaptations that allow them to obtain that specific food source. For example, sometimes bats and birds fly continuously during foraging while others will perch between foraging bouts.

A solid printer can be used to construct model wings, and a wind tunnel can be made or purchased to analyze the airflow around the wing to test predictions made mathematically. Laboratory mini wind tunnels can be purchased from the Omega Company for $3,500. Slow motion video of insect or avian wing motion during flight can be analyzed in an attempt to understand the forces involved.

Flight Involving Rockets and Propulsion

A direct application of Newton's 3rd Law, rocketry in the 20th century propelled humans into space. Students can experiment with using model rockets or CO_2 cars and compare these devices with similar locomotion strategies in the natural world (e.g. octopuses). Model rockets can be purchased at www.estesrockets.com for prices that range between $15-$65.

Mathematical Model: Impulse, or force integrated over a time interval, is equal to the momentum change of an object over that time interval. Various measurable parameters of a rocket or CO_2 car can be used to calculate their drag coefficients, which can then be used to calculate drag forces that affect acceleration. Predicting the maximum altitude of a toy rocket, or the top speed of a CO_2 car, in a mathematically rigorous model that is then tested experimentally makes for effective integration of science, engineering and mathematics. Powered flight involving thrust would involve calculus and differential equations.

Experimentation: Force as a function of time can be measured using probe ware from PASCO or Vernier. The force and impulse provided by Estes rocket engines is reported on the Estes site, but also can be measured using PASCO probe ware equipped with a rocket engine test bracket. CO_2 cars can be purchased in kits or just components from companies such as AC Supply. Entire classroom packages (50 CO2 car kits) can be purchased from the Midwest Technology Products company for prices ranging between $300-$600.

Collisions

Cars collide sometimes, usually by accident. Football players collide as well, usually intentionally. The Law of Conservation of Momentum and the Impulse-Momentum Theorem, which both derive from Newton's Laws, are most often used to analyze collisions as well as the inverse of collisions, namely explosions.

Collisions in Sport

Conservation of momentum can explain why a larger football player is less likely to be sped up, slowed down, or diverted by an opponent in a football collision. Impulse and momentum changes can be used explain how a football or soccer player launches a ball by skillfully colliding into it with his or her foot.

With collisions comes the risk of injury. For example, the concussion is becoming a prominent injury in high impact sports such as soccer, football, baseball, and basketball. Students should understand the physics behind concussion injuries, such as rapid acceleration, torque, and rebound forces. In soccer, leg injuries can result with kicks to the shin, and heading the ball in certain ways can jar the brain. In baseball, getting hit with a major league pitch can cause life-threatening injury.

As part of their study, students may investigate how protective sports gear works. For example, football helmets serve to help prevent concussions by increasing the distance of deceleration and the surface area across which the force is absorbed. The shin guard was developed to help prevent injuries to the shin when collisions with it occur. Baseball players wear protective gear when batting and when catching the ball. If a collision can be made to occur over a longer time frame, the magnitude of injury-causing forces can be reduced. Football pads, helmets, and shin guards are designed with this in mind.

Mathematical Model**:** Momentum, which is a vector quantity, is conserved in collisions. If the mass and speed of athletes is known, momentum conservation can be applied to tackles, blocks, and other types of collisions. The idea of impulse (integration of force over time) and momentum change can be applied to other collision situations, such as punting, batting, and placekicking.

Experimentation: Students can find videos to analyze for the momentum change in sports collisions, and estimate the forces that were involved. Students can also examine safety gear, such as helmets, pads, and shin guards, for evidence of how they reduce forces by lengthening the time of a collision. An extension would be to design and build protective gear and analyze it for effectiveness. Plastics can be brought from home or purchased from Metro Plastics Inc. Other materials can be purchased from local hardware stores or Universal Foam Products Inc. Students can test safety equipment by dropping masses from set heights. The deceleration can be measured using an accelerometer attached to the dropped mass. Forces can be measured using probeware from PASCO and Vernier. Video analysis can be performed using Logger Pro from Vernier, and the Capstone video analysis feature from PASCO..

Collisions Involving Automobiles

Not surprisingly, the same physics that is used to explain collisions in sports can also be used to explain automobile collisions. The concept of impulse can be used to explain how airbags in automobiles work to prevent injury in a collision. The construction of guardrails and breakaway light poles is done with safety of the driver in mind. In Formula 1 auto racing, cars are designed to fly apart during collisions in order to cause a drop in kinetic energy in a way that can actually protect the racecar driver.

Mathematical Model**:** Momentum is of course conserved in automobile collisions. Accident investigators use tire skid marks to estimate the speed of and angle of collisions in order to determine liability. The idea of impulse and momentum change can be applied to airbags, guardrails, and crumple zones that are designed into automobiles. Calculations will rely on an understanding of vectors, as well as the ability to calculate average and maximum force over a certain time period, which may involve integral calculus. Kinetic energy can also be estimated before and after a collision, to see how much of an energy change the driver has experienced in an accident.

Experimentation: Video of racecar collisions can be analyzed, and the momentum and kinetic energy change estimated over the time frame of the collision. Auto safety gear for ordinary drivers, such as airbags and seatbelts, can be investigated. Models of airbags and seatbelts can be built and tested using similar methods as the investigations defined above for collisions in sport.

Fluids

The physics of fluids encompass many phenomena experienced within science and engineering, including pressure, buoyancy, and surface tension. Fluids encompass liquids and gases, as well as many non-crystalline solids such as butter or wax. The concept of pressure, or force per unit area, is more important for fluids than it is for solid objects.

Non-Moving Fluids and Pressure

The relationship between pressure and water depth must be considered when designing and constructing dams, submarines, and scuba diving gear. In the study of marine creatures that live at, or dive to, great depths in the ocean, one must fully understand the absolute pressure, as well as the pressure changes, these animals must withstand. Because air is a fluid, albeit a compressible one, studying the variation of air pressure with depth is important if one is to fully understand how our atmosphere works. Hot air balloon pilots and meteorologists must fully understand atmospheric pressure as it varies with altitude.

Mathematical Model: The dependence of fluid pressure on depth can be modeled using Bernoulli's equation, although for static fluids one of the simpler derivative equations may be used as a more convenient mathematical model. In the case of gases, the more complex barometric distribution law must be used to calculate pressure. The barometric distribution law requires the use of integral calculus.

Experimentation: Pressure can be measured in the laboratory using probeware from PASCO or Vernier. Atmospheric pressure variation with depth (or elevation) as determined by GPS can be obtained from databases (for an example see http://www.xcmag.com/2011/07/gps-versus-barometric-altitude-the-definitive-answer/).

Moving Fluids and Circulation

Fluid dynamics is the study of moving fluids and addresses velocity, acceleration, and the forces exerted by or upon fluids in motion. Systems and components such as valves, mixers, and pumps are engineered specifically to control fluids; their design requires a thorough understanding of the forces exhibited on and by fluids. The circulatory systems of biological organisms are examples of natural systems involving fluid flow. Cardiologists and other physicians working with the human circulatory system must know something about fluid flow in this natural system.

Mathematical Model: The dependence of fluid pressure on speed can be modeled using Bernoulli's equation. When fluid flows through a pipe, mass conservation and its mathematical expression in the fluid flow continuity equation must be considered. The materials with which a pipe is made also affect the flow of fluid, as friction with pipe walls can cause mechanical energy loss. How well do different materials model the human circulatory system? What does the elasticity of blood vessels have to do with blood pressure? Will more rigid blood vessels result in higher overall blood pressure, a higher differential between systolic and diastolic pressures, or both? How can mathematics be used to model pressure at the walls of the vessels as opposed to the center of the vessel?

Experimentation: Pressure can be measured in the laboratory using probeware from PASCO or Vernier, as described above. Flow rate can be measured using a variety of instruments that may be acquired from the Omega Company. The instruments Omega sells are costly, ranging between $500-$1000. However, students can measure the flow rate in a variety of cheaper ways using only a bucket and stopwatch.

Renewable Energy Technology

Finding and developing affordable and environmentally friendly sources of energy is important for energy independence and combating anthropogenic climate change. While nearly all energy sources originate from the sun, the different methods of capturing, storing, and deploying it vary greatly, as do the associated efficiencies of the energy capture method. Solar, wind, and biomass approaches to solving the environmental crisis associated with our energy use have been proposed, but each type of alternative energy has strengths and weaknesses associated with it.

New Advances In Energy Production

Alternative energy forms, such as solar, wind, and biofuels, have much lower energy densities than traditional forms such as fossil fuel or nuclear, and some alternative energy forms have the additional challenge of requiring storage of energy in batteries. Understanding the mechanism of energy production from alternative sources is important if they are to be improved over time.

Mathematical Model: Students can mathematically model the energy provided by alternative sources, and then test their calculated values experimentally. The mathematical model would vary greatly according to energy source. For solar energy, integration of light intensity over time and area will indicate how much energy is theoretically available, but the actual energy that can be delivered depends on the efficiency of solar cells and storage batteries. Wind energy would involve averaging wind speed over long periods of time, and determining which fraction of this energy could be harvested.

Experimentation: Students can disassemble solar panels or small model wind turbines to study the mechanism by which they generate electricity. For solar and wind energy, which generate electricity directly, measurement of energy output can be done using simple electrical meters, such as the digital multi-meters readily available in the VolsTeach library. Recording voltage or current over long periods of time can be done using PASCO and Vernier probeware.

Calorimetry is a technique that can be used to determine energy that is released as heat, which is often considered wasted energy unless the heat energy is being used in a thermodynamic heat engine. A dual-purpose calorimeter may be purchased from www.hometrainingtools.com/calorimeter for $11 each. However, a cheaper option would be to have the students build their own with a Styrofoam cup, stirring rod, and thermometer.

Alternative Energy Conversion Efficiency

The efficiency of conversion of energy to useful work has a large impact on the applicability of the energy source. For example, internal combustion engines convert approximately 20-35% of the stored chemical energy in fossil fuels into useful work. Students can research methods of energy conversion and perform small-scale experiments to quantify the energy lost to extraneous light, sound, and heat.

Mathematical Model: The First Law of Thermodynamics can be used to model the maximum available mechanical energy a source can theoretically provide. The Second Law of

Thermodynamics describes why the theoretical upper limit can never be attained, and is generally invoked to explain efficiency of thermodynamic heat engines such as those found in fossil fuel powered automobiles. The Second Law can also be used to explain the loss of usable energy as thermal energy when batteries are used as a storage medium for wind and solar power. The mechanical energy dissipated by nonconservative forces, such as friction, is a factor when electrical energy is generated by mechanical means. Geometric thinking is required for solar energy, as the angle at which a solar panel is placed relative to the sun is of importance. Calculations of solar flux involve understanding the mathematical representations of solar intensity, angle, and integration over surfaces. Likewise, the shape, size, and orientation of fan blades in a wind turbine affect the amount of electrical energy that is generated from wind.

Experimentation: Students might operate the solar panel under various conditions to investigate how efficiency varies. Students can build model wind turbines using the 3D printer to construct blades of various shapes that can be mounted on an electric motor. Multi-speed fans can be used to generate wind that turns the turbines, and energy output can be measured and recorded. Merely calculating the amount of harvestable energy in a given source, whether it be sun, wind, or biofuel, will be a challenge in any efficiency investigation.

Energy Transfer and Storage in Biological Systems

Energy storage mechanisms seen in nature are often complex, unique, and well adapted to that organism's specific ecology. Students can explore these mechanisms, relate them to our current energy technology, and recognize the parallels between our and other species' mechanisms for efficient energy storage. For example, some organisms hibernate as a means for conserving energy, and others develop certain types of body coverings to control the exchange of heat energy with the environment.

Mathematical Model: The First Law and Second Laws of Thermodynamics are integral in studying energy transfer in biological systems; see the descriptions in ***Part B*** above. The size and shape of an animal can be an important factor. The closer an animal is to a sphere, the smaller the surface area to volume ratio, which reduces heat exchange with the environment. The color and thickness of fur can affect how a mammal is able to absorb or reflect solar energy.

Experimentation: Developing solid geometry models for animals could be a part of the study. Comparison of the average temperature of an animal species' natural environment with its mass or its surface area to volume ratio would involve careful statistical analysis as well as function pattern analysis. Data for such a study should be available in online or printed reference materials. Heat transfer rates could be modeled in the laboratory for typical animal shapes or exterior coverings using PASCO or Vernier probeware.

Human-Powered Energy Sources

Kinetics recently has become a major field of research for finding new ways to facilitate renewable energy transfer and storage. Physicists and engineers have recently capitalized upon human motion as a source for renewable energy, for example in hand-operated generators that power flashlights. Students can develop ways to create and store energy from their own kinetic motion. One such way is to use two copper wire coils through which a generator magnet can move freely. The change within the magnetic field induces a voltage across copper coils thus creating energy from a motion as simple as walking.

Mathematical Model: Generation of alternating current through the use of coils and magnets depends upon many factors, including the relative speed of the motion of the magnet and/or coil, coil winding density, magnet strength and size, and dissipative factors such as wire resistance. These are all straightforward to model mathematically. Efficiency should be an interesting and essential part of any investigation of human-generated electrical energy.

Experimentation: Apex Magnets is a company that sells a variety of magnets that can be used by students when creating their own energy harvesters. Copper wires may be acquired at any hardware store whereas plastic housing for electronics can be purchased from the Hammond Manufacturing Company on websites like http://www.alliedelec.com. In order to store the energy generated in this manner, the alternating current must be rectified to charge a battery. Students will gain some knowledge of semiconductors as they develop a method to store the electrical energy.

Microbiology

Each human being carries more bacterial cells than is the number of his/her own cells. Moreover, bacteria constitute a large fraction of Earth's biomass. These microorganisms are important for our health and for the health of the planet. To be able to control and make use of these tiny organisms we need to know how they are built and how they function. While there is plenty of information on the individual components of the cell (DNA, proteins, lipids, etc.) there is still very little understanding how these components come together and make a functional cell.

Working with bacteria takes instruction and practice, particularly if quantitative results are being obtained. All work with bacteria will be done under the direction of Dr. Jaan Mannik, who is a biological physicist. His laboratory and expertise are well equipped to support investigations with bacteria.

Yeast Ecology and Evolution with Kombucha

The varied names of the fermented tea beverage known as "mushroom tea", "tea kvasse", the "Immortal Health Elixir", or "kombucha", reflects its varied uses through history and across cultures. More recently, it has become a trendy lifestyle beverage in western countries, touted for its health benefits, although these largely remain unsubstantiated (Dufresne and Farnsworth, 2000).

Kombucha is easily created by adding sugar and a symbiotic colony of bacteria and yeast (also known by its acronym, "scoby") to tea. The scoby is comprised of yeast, which consume and ferment the sugar, as well as acetic acid bacteria, which create acetic acid by oxidizing those products. The acetic acid bacteria also create a cellulose network, which further facilitates their association with the yeast (Balentine et al., 1997). Caffeine and other tea compounds stimulates the growth of this cellulose network, promoting the overall growth of the scoby. Kombucha generally requires 7-14 days before the sugar and tea products are consumed. The resulting growth is often a new scoby layer that can be peeled and added to a new batch of tea and sugar. The resulting drink is characterized by acidity, which may contribute to its antimicrobial and antifungal properties.

Despite its recent popularity as a health drink and the increasing production and consumption in the western world, few studies have formally investigated how various factors affect the development of the scoby, and by association, the characteristics contributing to the overall taste. Students can investigate yeast ecology and evolution by one or more of the following experiments.

<u>Scoby growth:</u>

Questions: How do varying environmental factors affect the growth of kombucha scobies?
What combination of these factors will optimize scoby growth?

Instructors can begin by first describing the basic protocol/recipe associated with making kombucha. They can then encourage students to consider the different environmental factors that can affect the resulting growth of the scobies to identify the research projects of interest. Potential factors include: Light exposure (full sun, partial light, full darkness), sugar concentration, sugar type (brown vs. white), sugar granule size (coarse vs. fine vs. powdered), temperature regime, tea concentration (# of tea bags/ grams of loose leaf tea; steeping time), tea type (black, green, flavored versions of black tea, etc.), tea brand (generic vs. Lipton's vs. name/organic brands), tea form (loose leaf vs. tea bag), air exposure (varying mesh sizes or layering), initial scoby properties (size, shape, etc.), etc.

Kombucha properties:

Questions: How do kombucha properties change by varying environmental conditions? Besides growth of the scobies, students can measure other kombucha properties throughout the experiment, including ethanol concentration, tannin concentration, acetic acid concentration, pH, etc.

Scoby adaptation:

For longer-term projects, students can explore whether extreme conditions may lead to rapid selection for adaptive traits. This will require multiple generations of scobies maintained under different conditions, a control and at least one treatment group. The control group will consist of the standard kombucha recipe (or the optimum conditions that students previously determined from the ecology component of this unit). The treatment group can consist of scobies that undergo some environmental extreme. Students can help brainstorm what such conditions may be, but generally these can include: low temperatures, high light exposure, or long fermentation periods before moving the scobies into a new sugary tea environment.

Multiple generations (at least 3-5) grown in these conditions will result in two lineages of kombucha scobies, a control and extreme line. Each time, students should move the newest layer of kombucha scoby into the newest tea batch. Given the importance of creating identical treatment conditions over time to avoid confounding factors, this could provide an opportunity to discuss human error associated with setting up experiments.

When the two (or more) treatement lines have been established after multiple generations, students can answer a variety of questions relating to potential adaptation of these scobies to their environment.

Questions: How will these two lines of scobies compare when exposed to both control and extreme conditions? (This question is ideally answered by having four resulting treatment groups: Control line in control conditions, control line in extreme conditions, extreme line in control conditions, and extreme line in extreme conditions.)
Does the extreme line exhibit different antimicrobial properties than the control line?
Does the extreme line exhibit higher tolerance to low pH/high ethanol content/etc. Compared to the control line?

Suggested materials: Mason or pasta jars, measuring cups/spoons, black tea, sugar, water, scoby culture, coffee filters/napkins/cheese cloths, rubber bands, water boiler, thermometer

Suggested Reading:

Dufresne, C., & Farnworth, E. (2000). Tea, Kombucha, and health: a review. *Food research international*, *33*(6), 409-421.
Teoh, A. L., Heard, G., & Cox, J. (2004). Yeast ecology of Kombucha fermentation. *International journal of food microbiology*, *95*(2), 119-126.

References:

Balentine, D. A., Wiseman, S. A., & Bouwens, L. C. (1997). The chemistry of tea flavonoids. Critical Reviews in Food Science & Nutrition, 37(8), 693-704.

Growth of Bacteria

The growth of bacteria follows well-known mathematics; however, culturing and quantifying bacteria requires excellent experimental technique, lots of patience, and long hours in the laboratory. Students studying bacterial growth will need to be prepared to attend laboratory during night-time and weekend hours.

Mathematical Model: Bacterial growth in a broth medium follows a classic S-curve, which can be mathematically derived using integral calculus. The population will then crash as toxins build up. The shape of the function depends on many factors, including the concentration of nutrients, the type of cell, the temperature, and other chemicals that are introduced. A strong understanding of statistics is required, as the quantitative results will have large inherent uncertainty and error.

Experimentation: Students would need to know how to identify known species such as *E. coli* and *P. aeruginosa* using colony color and shape, bacterium shape, Gram stains, oxidase test (to see if the bacteria has cytochrome c), catalase test (apply a drop of hydrogen peroxide to see if the bacteria can break down peroxides) and plating on different selective media. After incubation of a culture, students can plate out bacteria. Students will sometimes need to choose one to several different colonies on a plate and culture each colony separately. Students can make monocultures of one species of bacteria and perform the above tests to make an educated guess as to how they would classify the bacteria based on their results. Students can swab the same surface to culture different colonies and then swab the same surface or various surfaces nearby to make an inventory of how many bacterial species they found right in their own classroom. Quantitative estimates will need to be made using colony counts.

Bacterial Cell Division

This interdisciplinary project, which combines physics, biology and computer science aims to build better understanding how bacterial cell divides. Cell division is a key event in bacterial lives in which two daughter cells emerge from a single mother cell. This process starts with an assembly of protein scaffold, called the Z-ring, in the middle of the cell. How this filamentous protein scaffold assembles and is positioned in the center of the cell is not yet well understood.

The goal of the project is to find if the experiment and the model agree. If they do then you may have unraveled one of the most fundamental molecular processes that happens essentially in all bacteria (each of us carries about 10 trillion of them). Of course, in a research project like this the agreement is not at all guaranteed. If it turns out that the model and experiment do not agree then how would you modify the model to achieve a better agreement?

Mathematical Model: In this project, students will model the process of assembly and positioning of the Z-rings using Ising model. Ising model was originally proposed to describe magnetism in physics but it turns out to be capable of describing a wide variety of processes in which molecules self-organize themselves into ordered patterns. Students will develop a Monte Carlo based calculation program in MatLab to study formation of protein pattern during bacterial cell division. Time permitting you can convert this program also to a faster C++ code. Both codes can be used in teaching in high school settings to introduce students to an exciting modern topic of self-organizing systems. With slight modifications one can use these programs to model variety of interesting phenomena in very different fields.

Experimentation: The modeling results will be compared to experiments. To experimentally measure the assembly and dynamics of Z-ring, bacteria with fluorescently labelled Z-ring will be imaged in the state-of-the-art fluorescent microscope setup. Time-lapse sequence of Z-rings will be recorded and analyzed. Students will analyze the position of the Z-ring within the cell, and how the ring condenses over the time. Condensation of the ring can be described by its root-mean-square width. For analysis students will further develop image analysis algorithms and adapt them to the needs of the project. Fluorescent labelling of Z-ring will be carried out using fusion proteins. These are already present in Mannik's lab. They consists of three amino acid sequences – 1) protein of interest, which in present case is FtsZ protein, 2) a short amino acid linker, and 3) fluorescent protein such as GFP (green fluorescent protein).

How Thermal Fluctuations Organize DNA in Living Cells

DNA is the carrier of genetic code. Physically it is a long molecule, which length exceeds 100-1000 times the cell length. To fit into a cell it needs to be highly packed. The packing influences all processes in the cell via its effect on gene transcription, DNA replication and repair. Interestingly, thermal motion significantly decreases the volume DNA occupies in the cell and acts as one mechanism of packing.

How can thermal fluctuations reduce the volume DNA occupies? DNA in the cell is in aqueous solution. Water, ions, proteins and other molecules constantly collide with it. The net effect of these collisions is such that DNA takes shape of a loosely coiled ball of yarn. The diameter of this ball is much smaller than the length of the DNA. DNA in this ball is not standing still but fluctuating strongly; thus the shape of the ball is not fixed but always changing.

The aim of this project is to study compaction of DNA by thermal fluctuations both experimentally and by computer modelling. It is possible to compare the some experimental and modelling results also with the theoretical results.

Mathematical Model: The method of choice to model molecular motion is Molecular Dynamics (MD). In MD simulation Newton's equations are integrated for each atom or group of atoms. To model DNA in aqueous solution one typically cannot rely on brute force MD simulations that accounts for motion of all atoms in DNA and water molecules that surround DNA. Even for a short piece of DNA, say from a virus, the number of atoms is just simply too large even for the largest supercomputers. Instead of trying to calculate the trajectory of each atom in DNA one can define larger segments of DNA that behave like rigid rods. These segments are called Kuhn's segments and their length is approximately 100 nanometers (10^{-9} m). Also, one does not need to include all water molecules in the simulations but model their effect using concept of random thermal force. The random thermal force is called also Langevin force and its magnitude is determined by temperature. Altogether, this approach is called course-grained modelling and it uses Netwon's equations to calculate the trajectory of each Kuhn segment to which thermal forces are applied. To integrate Netwons's equation simple Euler algorithm suffices. The Euler algorithm can be coded in any programming language but there are also free packages that can solve these equations very effectively for longer molecules.

Experimentation: The experimental investigation of DNA will be carried out in Mannik's lab. As mentioned before, a bacterial DNA will be studied. To visualize DNA fluorescent proteins that bind to DNA will be used. Time-lapse sequences of DNA will be measured that show the fluctuating nature of DNA. From these measurements you will find measurable quantities that can be compared in experiments and models. Do they qualitatively agree? If not what factors may be responsible for the discrepancy?

Statistics of Gene Expression

How genes are expressed determines most traits in living organisms. Genes are turned on and off as a result of environmental conditions, by progression of cell cycle and developmental stage or it can also happen seemingly spontaneously. The periods when genes are turned on and off are subject to large fluctuations that obey statistical laws.

Mathematical Model: Students will propose a model that captures the distribution of protein expression. They must understand how the mathematical model is derived so they can explain the model as part of the project. They will test one or more chosen models experimentally.

Experimentation: To experimentally determine how genes are expressed and proteins are synthesized you can use fluorescent proteins. Fluorescence means that when you shine blue light on a molecule it glows green. Most proteins do not fluoresce when irradiated by visible light but some, such as GFP (green fluorescent protein), do. It is possible to insert the sequence of GFP into genome of bacteria (or any other organism). Once this sequence is inserted into genome, bacteria will synthesize fluorescent proteins themselves. One can measure fluorescence intensity of these proteins from microscope images. Each fluorescent protein gives out about the same amount of light. Knowing how much light a single protein emits allows to convert fluorescent signal to number of proteins in the cell. The recording can be sensitive enough to capture individual molecules. Some proteins in bacterial cells are present only in one or two copies while the number of some can exceed 10,000.

The aim is to study how some gene of interest is expressed and not fluorescent proteins. For that purpose, the DNA sequence of the fluorescent protein needs to be inserted next to the gene of interest so that bacteria synthesizes the product of the gene of interest and fluorescent protein together. In this case the numbers of fluorescent proteins and the gene products will be the same. Moreover, the insertion of sequence of fluorescent protein must be done so that it does not affect the rate of synthesis of that protein. All this can be done. Mannik's lab has many strains with fluorescent fusion proteins that can be used in this work. One of these fluorescently labeled *E. coli* strains has been made by the previous team of VolsTeach students.

Knowing how proteins numbers fluctuate in different cells sheds light on how they are synthesized. The research has shown that protein synthesis happens not continuously in time but in bursts meaning that there are long periods of time when no protein is synthesized and then short period when many new proteins appear. The burst-like synthesis gives rise to distributions that can be approximated by Gamma distributions (see Y. Tanigushi et al Science 329 (2010) 533). Derive this distribution following the above mentioned paper and compare to distributions that you measured experimentally. Do they agree? What can you conclude about the protein synthesis from the parameters of the distribution?

Mutation and Mutagens

Mutation occurs when a mistake is made in the copying of DNA (or in some cases, RNA) resulting in a difference between the original strand of DNA and the copied strand of DNA. There are a great number of proofreading methods in cells that attempt to find and repair mutations, but even so there are still mutations that are missed and go on to be reproduced in future cells of the cell line. While mutation will occur naturally without the presence of any unusual chemicals or radiation there are certain things that increase the mutation rate of DNA, referred to as “mutagens.” Mutations are the foundation of evolution and without them populations would never change. However, the vast majority of mutations are harmful rather than helpful, and as a result mutagens are of great concern to organisms.

Mathematical Model: Students can model the results of their data and compare how the mutation rates of different chemicals compare against others. A variety of statistical methods will be required in order to perform the analysis.

Experimentation: Students can use the Ames test to compare the mutagenicity of different compounds. Ames test kits are available for purchase from companies such as EBPI for $200 for 6 groups. Students should consider what substances might be the most mutagenic when conducting their tests. Testing common household substances should be considered. Students can work with each other and build upon the research of previous classes by using different substances and building a profile of common (and uncommon) mutagens over time.

Evolution

“Evolution” means the change in genes and other inherited traits within a population over time. Individuals do not evolve, populations evolve. Evolution acts on genetic differences within the population by either increasing or decreasing the proportions of certain traits which may or may not be beneficial to the population’s survival. Four factors contribute to evolution of a population: selection, be it natural, artificial, or sexual, genetic drift, mutation, and immigration/emigration. Selection is the only one of these factors that drives evolution in a particular direction.

Mathematical Model: Students can model the evolution of a simple population. It is important that students first understand Hardy-Weinberg equilibrium, where no evolution occurs. Students can then build on this model to show how genes or other heritable traits might change in a population over time. Students should be encouraged to think creatively about all of the potential factors that could contribute to the evolution of a population and how these different factors might interact and contribute to one another. Particularly advanced projects might include the rate of mutation in the population and the chance that any given mutation will be beneficial, detrimental, or neutral. How might changes in the mutation rate, such as the increase around the site of Chernobyl, affect the rate of evolution? Would sudden catastrophic events change the rate of evolution in the model population? Students could build upon previous years by progressively building more and more complex models of evolution using previous students' models as reference.

Experimentation: Students should research evolution in different population, especially if growth of cultures in the lab is infeasible. If growth of cell cultures in the lab is possible students may use a modified version of the above "Statistics of Gene Expression" experiment to explore evolution. Students could adjust the environmental conditions of their cultures and see how this affects the gene expression of their cultures. Students could also observe how the gene expression differs without changes in environment through genetic drift and mutation alone.

Sexual Selection

Sexual selection is a form of natural selection where preference in mate choice leads to changes in the allelic frequency of a population. That is, as individuals selectively choose to reproduce with others of the population heritable traits associated with the preferred trait tend to increase in prevalence with progressive generations. For example, cardinal females prefer cardinal males with bright red feathers. As a result bright red feathers in male cardinals has increased in cardinal populations because males with bright red feathers tend to father more children. Students should be encouraged to consider why sexual selection has importance distinct from other forms of natural selection.

Articles to start with:

Mead, L. S., & Arnold, S. J. (2004). Quantitative genetic models of sexual selection. *Trends in Ecology & Evolution*, *19*(5), 264-271.
Kirkpatrick, M. (1982). Sexual selection and the evolution of female choice. *Evolution*, 1-12.
Kodric-Brown, A. (1985). Female preference and sexual selection for male coloration in the guppy (Poecilia reticulata). *Behavioral Ecology and Sociobiology*, *17*(3), 199-205.

Mathematical Model: After acquiring an understanding of Hardy-Weinberg equilibrium students can begin creating models of sexual selection. Unlike in the basic Hardy-Weinberg model, however, students will need to create a model that keeps track of males in females. There are many different possible models depending on the type of species the student wishes to replicate. For instance, which sex is the "choosy" sex? Is the trait being chosen by the choosy sex only physically evident in one sex or both? Is the trait dominant, recessive, or does it exhibit some other form of inheritance? Students might also consider how other forms of natural selection, such as predation, might counteract sexual selection. Could there be a situation where sexual selection overpowers other forms of natural selection, leading to high rates of an otherwise detrimental trait?

Experimentation: Students could observe whether a short-lived, rapidly reproducing species such as *Drosophila melanogaster* exhibits sexual selection in its populations. To conduct this experiment it would be necessary to acquire at least two different strains of flies homozygous for some easily identifiable trait, such as eye color. In order to explore specifically sexual selection the trait in question must be one that has minimal effect on the individual's survival and only one on mate choice. Students would then cross breed the two strains and, over successive generations, observe whether or not one trait’s prevalence increases over the other. Students could also experiment with sexual selection on a shorter scale using a force mate choice experiment. In such an experiment students would place a focal individual equidistant between two (or more) potential mate choices which differ in some selected trait but are otherwise similar and then observed for choice. One common example is that of the Y-maze, where the focal individual can see or otherwise sense (but is physically separated from) two potential mates. Whichever individual the focal individual then moves toward first is considered the focal individual’s “choice.” This experiment could be conducted with a wide variety of species using relatively cheap materials. Students could build upon the work of other students and previous classes by comparing different traits within a species or different species altogether and observing any differences.

Morphology and Phylogenetics

Morphology and phylogenetics can be used to elucidate evolutionary relationships and can be compared to phylogenies produced from molecular data to produce composite evolutionary relationships.

Morphological Classification Based on Patterns

Using skeletons and other models of plants and animals, students can identify patterns in morphological traits in order to construct a family tree using a pre-determined set of characteristics, such as whether an organism has radial or bilateral symmetry, whether the dermal layers are diploblastic or triploblastic, and whether or not an animal possesses an internal skeleton.

Mathematical Model: Patterns and symmetry characteristics of animals could be identified and used in construction of a hierarchical classification tree. Measurements of bone lengths, and the calculation of the ratios of various bone lengths within a skeleton, can be made to verify or refute claims made in the literature about the prevalence of the Fibonacci sequence or golden ratio in skeletons. Other claims about patterns can be investigated in both plants and animals. Careful measurement and sound statistical analysis must be an integral part of these investigations.

Experimentation: Dissections and/or examination of models could form the experimental component of this project. Measurements of skeletons from closely related species can made to draw comparisons based on identified patterns. Samples from natural history museums could be examined and measured. Published data could also be examined.

Biomechanics, Force and Torque

Students can examine skeletons, teeth, and other biological models to identify how form fits function, and how natural selection has produced adaptations. In specific, students could investigate how much force or torque an animal limb or jaw can exert based on its physical structure. Students can identify how the specific biomechanical characteristics make various organisms fit for some environments, and unfit for others. They can identify how animal limbs and beaks can be modeled using various classes of lever systems. Likewise, they can see how another simple machine, the wedge, can be used as a model for the functioning of animal teeth.

Mathematical Model: Using concepts of force and torque, as well as their numeric calculation, biomechanical models can be developed. The strength of bones and how they resist breaking under a different magnitudes and directions of force can be investigated. How does the magnitude of torque differ when limbs are bent and straightened? When animals use their jaws to apply torque, how do different jaw and tooth structures provide different advantages? What is the maximum force and torque with which a specific animal can bite? Why can animals typically exert more force when closing their jaws than they can when opening their jaws? These are just a few biomechanical questions that could be answered in this investigation area.

Experimentation: Students can measure the length, thickness, and mass of bones and the articulation of joints to explain the physics of animal movement. They can also carefully measure animal teeth. Based on these measurements, the 3D printer can be used to build models of biological structures for testing in the laboratory. Actual animal bones, teeth, and beaks can be tested if they are available, although well-constructed models might be better for comparative studies since their construction can be carefully controlled. Force measurements can be made with PASCO and Vernier probeware.

Acids and Bases

Acids and bases are important in the natural world. There are many different definitions of acids and bases, including Lewis, Arrhenius, and BrØnsted-Lowry. Each definition has different aspects that may be explored within a natural environment. Typically students investigate acid and base reactions within only a controlled laboratory setting. The following examples provide opportunities for students to experience acids and bases firsthand within nature and to understand chemistry's relevance to biology.

General Acid-Base Reactions

Nearly every aqueous solution we encounter is acidic or basic, with pure water being the exception. The simplest acid-base reactions involve excess hydrogen ions (H^+) combining with hydroxide ions (OH^-) to form water molecules. Other ions are generally also present in solution and, if all the water is evaporated, form a salt.

Mathematical Models: Models for acid-base neutralization, like all chemical reactions, are inherently mathematical. Stoichiometry is involved, and if weak acids and bases in a buffered solution are involved, an understanding of the mathematics of equilibrium is required. The pH scale used to define acidity is requires an understanding of logarithms. Concentration models involve an understanding of ratios. Finally, acid-base reactions generally release predictable quantities of heat, as the products are generally more chemically stable than the reactants.

Experimentation: The amount of heat released in chemical reactions is generally measured using calorimetry. It would be interesting to see if an infrared camera can be used to detect exothermic reactions such as these, and under what conditions such a method would be reliable. The measurement of pH can be made in a variety of ways, including the use of pH paper, pH indicator solutions, and probeware from PASCO and Vernier.

Lewis Structures

Lewis structures were essential in developing the understanding that acids and bases went beyond considering H^+ and OH^- ions, and could encompass other compounds and ions that function as either electron acceptors or donors. For example, ammonia, with its free electron pair, functions as a Lewis base because it is an electron donor. Naturally occurring coordination compounds are vital to living organisms and the biological systems they live in. Catalase, a catalyst for hydrogen peroxide decomposition, contains iron-porphyrin complexes and is found in all living organisms. The bombardier beetle utilizes catalase via mixing catalase with hydrogen peroxide and hydroquinones to activate a noxious spray from the tip of their abdomen. Over 40 species of bombardier beetles reside within the United States.

Mathematical Model: In addition to the general mathematical models described above, the population genetics of the bombardier beetle and the mathematics of diffusion could be a part of this study.

Experimentation: Unfortunately, because bombardier beetles cannot be shipped, only high schools that are located in areas where the bombardier beetle can be found will be able to engage in this experiment. Experiments can be as short as three days to an entire school year. After students learn the bombardier beetles' chemistry, they can then investigate their biology addressing topics such as population genetics, behavioral ecology, selection, etc.

Arrhenius Model

Svante August Arrhenius classified acids as any substance that increases the H^+ ion concentration within a solution, whereas bases increase the OH^- concentration within a solution. For example, one common base is Ammonia. Ammonia, when placed into water, yields ammonium and hydroxide ions. Ammonia is an important source of nitrogen for biological systems. Plants utilize ammonia from decaying matter within the soil as a source for nitrogen.

Mathematical Model: In addition to the general mathematical models described above, the growth rate of plants fertilized by varying quantities of nitrogen fertilizer can be measured and compared.

Experimentation: Students can synthesize their own nitric acid (HNO_3) in a laboratory setting via choosing from an array of reaction paths with either ammonia or an ammonium salt being a required starting reagent. The heat released can be measured using calorimetry. Students can then use their newly synthesized nitric acid for a biological experiment observing nitrogen's effects on plant growth. This experiment could be done by either using the school's garden or by individually raising potted plants within the classroom. Students will grow various samples of the same plant species using fertilizer with different amounts of nitric acid added within the soul. Each plant's growth rate will be recorded and compared then to the ratios of nitric acid supplement added to each batch of plant fertilizer to see if there is any relationship between the two variables.

BrØnsted-Lowry Model

This model that states that any compound that can transfer a proton to another compound is an acid; the compound that receives the proton is the base. The BrØnsted-Lowry Theory includes certain atoms and molecules that function as cations and anions, which the Arrhenius and Lewis theories fail to incorporate. An example for how the BrØnsted-Lowry Theory could be applied in the classroom or field setting is utilizing a reaction case between boric acid and water. Boric acid does not dissociate but donates a proton to the base (proton acceptor) that is water, thus being a prime example for a reaction that can only be described as an acid/base reaction using the BrØnsted-Lowry Theory. Students may find boric acid in fruit.

Mathematical Model: In addition to the general mathematical models described above, percent yield of boric acid would involve careful measurement and calculation..

Experimentation: The process involves first burning the fruit until ash. Next, students will acidify the ash of the sample with hydrochloric acid and then dip a piece of yellow turmeric paper into the solution. If the boric acid is present the turmeric paper becomes red on drying. The length of coloration of the turmeric paper is directly proportional to the quantity of boric acid present.

Students can bring in their own fruit from home to investigate any presence of boric acid as a preservative within their food.

Population and Growth Studies

Growth of organisms and populations is fundamental to the understanding of biology.

Demographic Study

The health of a population depends upon age- and stage-specific growth rates. Whether a population increases or decreases in size is heavily influenced by the population's overall growth as well as by the growth rate of specific demographic groups within the population.

Mathematical Model: Students may investigate a group of age classes within a matrix (such as a Leslie matrix) and determine which classes offer the biggest contribution to the population's growth rate (eigenvalue) via their use of first and second derivatives. Students may also explore the sensitivity of stochastic growth rates by the product of various population matrices. Logistic growth functions can be a focus in the presentation. Students should have basic knowledge on how to perform matrix algebra before attempting this project.

The project may touch upon demographic groups to target in advertising. An example would be to identify the target demographic for advertising for a rock concert by a particular artist. Students may construct an imaginary matrix generated by concert attendees over time. How many 15 year olds return to the artist's concerts when they are twenty? Thirty? Forty? Students would then identify which demographic contributes most to the success of the artist.

Papers that teachers may choose to give to students for helping them get started on their initial research:
Caswell, H. (1996). Second Derivatives of Population Growth Rate: Calculation and Applications. *Ecological Society of America*, 77, 870-879.
Lefkovitch, L. P. (1965). The Study of Population Growth in Organism Grouped by Stages. *Biometrics*. 21, 1-18.

Experimentation: Students would need to identify published sources of population statistics with which to test the validity of their mathematical models. It is important that data sources be identified prior to embarking on this project, as laboratory investigation will not in general be possible.

Carrying Capacity

Carrying capacity refers to the maximum number of individuals in a population a particular area or habitat can support with its limited resources. The growth of a population when a few individuals arrive into a previously un-colonized area often follows that of an S-shape, mathematically reproducible using integrals in the same manner referenced during the "Growth of Bacteria" section. Like in the lab-grown bacteria a population growing in this manner will have slowed growth as it begins to reach the maximum number of supportable individuals and then growth will hover around zero. Unlike in lab grown bacteria, however, once a wild population reaches carrying capacity the number of individuals tends to stay around that value instead of an entire population crash. (In reality the population will experience fluctuations where the population grows above carrying capacity, then falls below it, then increases above it, and so on.)

Mathematical Model: Students should calculate the S-curve use integral calculus. Students should also be able to calculate the k-value for a given population. Students can manipulate this model to represent higher levels of nutrients, droughts, and so on.

Experimentation: Students would research existing population data as long-term experiments would be difficult to conduct in the lab. The first stage of bacterial growth could be used for this experiment before the population crash occurs, though this information should still be supplemented with published population data.

Reproductive Strategies

There are two primary reproductive strategies employed by living organisms: r-reproduction and k-reproduction. The “r” in r-reproduction represents the strategy of a high reproductive rate. Species that implement r-reproduction include many insects, such as locusts or mosquitoes. Most of the offspring produced through an r-strategy are not expected to survive, but rather by producing so many offspring at least a few are statistically expected to make it to adulthood. In this manner parents put relatively little resources into each individual offspring. This strategy is best for situations where the environment is relatively unstable or offspring are in general expected to have low survival rates. On the other hand, k-reproduction involves producing fewer, more resource intensive offspring. Examples include species such as the elephant or human. A much higher proportion of k-strategy offspring are expected to survive due to the higher resource expenditure. The k-reproductive strategy is generally better for more stable environments.

An article to start with:
Pianka, E. R. (1970). On r-and K-selection. *The American Naturalist*, *104*(940), 592-597.

Mathematical Model: Students could model the reproduction of k- and r-reproductive populations. How does this change the growth curve of the population? Students could also add complexity to their models by including various factors associated with population growth, for example, predation. Using these models students could explore the various factors that lend toward species being more r- or k-strategy. Is it ever optimum for a species to be somewhere in the middle? Is it better for a species to be more r-strategy during certain situations and k-strategy during others? Students should also consider how animals might shift between strategies, if possible. For example, some birds will selectively feed a single offspring rather than feed all offspring in order to increase the chances that at least one chick will survive.

Experimentation: Students should research existing population data, as experimentation in the lab will be infeasible for k-reproductive strategy species. Other experimentation options include using two quickly reproducing species where one reproduces marginally faster than the other and manipulating environmental conditions to see under which each species fairs better. However, existing population data should still be explored for scale and reference.

The Cancer Phenomenon

When doctors design a treatment plan for a patient who has been diagnosed with cancer, one imperative point of data to know is the rate at which the cancerous tumor spreads within the patient.

Mathematical Models: Students will investigate the research done by William DeWys (1972), where a tumor's growth rate was examined using calculus application along with possible outside factors that may have been responsible for inhibiting tumor growth. Avner Friedman and Fernando Reitich (2000) developed a unique calculus application to model non-spherical tumor growth that students may analyze and discuss during their demonstration.

Relevant references:

DeWys, W. D. (1972). Studies Correlating the Growth Rate of a Tumor and Its Metastases and Providing Evidence for Tumor-related Systemic Growth-retarding Factors. *Cancer Research*. 32. 374-379.

Friedman A., Reitich F. (2000). Symmetry-breaking Bifurcation of Analytic Solutions to Free Boundary Problems: An Application To A Model Of Tumor Growth. Transactions Of The American Mathematical Society. 353. 1587-1634.

Experimentation: Students would need to identify published sources of tumor growth rate statistics with which to test the validity of the mathematical models. It is important that data sources be identified prior to embarking on this project, as laboratory investigation will not be possible.

Disease Spread And Prevention

The prevention of virulent diseases from spreading has accrued great research interest over time. Farming is one business for example that depends on a successful crop yield each season in order to operate successfully within an economy. Researchers are now focusing their efforts towards new ways for preventing diseases from spreading.

Articles of Interest:

Gray, A., Greenhalgh, D., Hu, L., Mao, X., & Pan, J. (2011). A stochastic differential equation SIS epidemic model. *SIAM Journal on Applied Mathematics*, *71*(3), 876-902.

Munz, P., Hudea, I., Imad, J., & Smith, R. J. (2009). When zombies attack!: mathematical modelling of an outbreak of zombie infection. *Infectious Disease Modelling Research Progress*, *4*, 133-150.

Mathematical Models: Students should investigate the popular disease models that have been developed and understand the calculus behind each model. How students decide to present this information to the class is completely up to the students. One example might be that students who are giving the demonstration develop a fictitious scenario involving a zombie apocalypse in which they must develop a disease model to characterize the behavior of the outbreak and create a response plan to the outbreak. A basic understanding of matrix algebra may be helpful but not required in developing disease models.

Experimentation: Students would need to identify published sources of statistics for the spread of disease with which to test the validity of the mathematical models. It is important that data sources be identified prior to embarking on this project, as laboratory investigation will not be possible.

Virulence

Virulence refers to the strength or relative health risk a disease poses. This means that diseases with a high virulence have a higher rate of death when they infect an individual. Diseases are caused by parasites such as bacteria or viruses, and the level of virulence a particular disease possesses is acted upon by evolution. A dead host can no longer provide nutrients or a breeding ground for a parasite, so why, then, do parasites kill their hosts at all?

Articles of Interest:

Baalen, M. V. (1998). Coevolution of recovery ability and virulence. *Proceedings of the Royal Society of London B: Biological Sciences*, *265*(1393), 317-325.

Bremermann, H. J., & Pickering, J. (1983). A game-theoretical model of parasite virulence. *Journal of Theoretical Biology*, *100*(3), 411-426.

Choo, K., Williams, P. D., & Day, T. (2003). Host mortality, predation and the evolution of parasite virulence. *Ecology letters*, *6*(4), 310-315.

Mathematical Model: Students might begin by exploring previously created virulence models. Calculus will likely be required for this project, and a basic understanding of matrix algebra would be helpful. Students might begin by creating models where different levels of virulence can exist in equilibrium within a population without killing off all of the hosts. This would require measures of birth rates as well as natural death rates. Students might then expand their models to include a greater number of factors, such as migration of individuals, spread to other populations, or even the use of vaccines or culling activity. Students can build upon previous classes by creating more complex or complete models or modeling different diseases.

Experimentation: Experimentation with virulence in the lab will be infeasible in a high school setting, so students would need to research already published data on virulence. Students should examine across different diseases and note differences in virulence as well as think about what factors contribute to different levels of virulence in different populations or species.

Ecology and Environment

Ecosystem Modeling

An ecosystem is a network of connecting and interacting biological and non-biological factors. Ecosystems can be defined at many different levels of complexity and size, such as the ecosystem of a drop of swamp water or the ecosystem that sprawls across the entire globe. Ecosystems that exist in total isolation are rare on Earth, but an ecosystem can be pictured as everything that occurs and interacts within a particular area and everything that enter or leaves that area. Ecosystem interactions are not always straight-forward or intuitive and one seemingly minor change in an ecosystem process can have a dramatic effect on all other processes.

<u>Some articles</u> to start with:

Fulton, E. A., Smith, A. D., & Johnson, C. R. (2003). Effect of complexity on marine ecosystem models. *Marine Ecology Progress Series*, *253*, 1-16.

Fulton, E. A. (2010). Approaches to end-to-end ecosystem models. *Journal of Marine Systems*, *81*(1), 171-183.

McGuire, K. L., & Treseder, K. K. (2010). Microbial communities and their relevance for ecosystem models: decomposition as a case study. *Soil Biology and Biochemistry*, *42*(4), 529-535.

Laundré, J. W., Hernández, L., & Altendorf, K. B. (2001). Wolves, elk, and bison: reestablishing the" landscape of fear" in Yellowstone National Park, USA. *Canadian Journal of Zoology*, *79*(8), 1401-1409.

<u>Mathematical Model:</u> Students may model a simple ecosystem. Though matrix algebra is not required for this model it would be helpful and would allow for more complex models to be explored. On a fine scale students might simply look at resources into and out of an ecosystem, such as the energy that goes into the system as sunlight and leaves as leached nutrients downstream. More advanced models would explore how the different nutrients or energy move around within an ecosystem as well as into and out of the ecosystem. Students could explore how specific nutrients, such as nitrogen, move around an ecosystem or could generalize more broadly about ecosystem processes. Students could build upon previous years by making increasingly complex models, starting with the simpler models of previous students, or also by making models of processes not considered by previous classes.

Students should also note that there are many different processes that occur within an ecosystem. Movement of carbon or water through a system are examples of ecosystem processes, but so are parasite and patch movement. Students should also be encouraged to explore ecosystems with unusual processes, such as ecosystems that frequently experience fires that are required for certain seeds to germinate. Consideration should also be paid to how different processes interact, and how changes in one part of the system might affect other parts of the system As with all models, students should consider the trade-offs between complexity and practicality or usefulness in their models.

<u>Experimentation:</u> Students should research existing models of ecosystem processes and studies observing them as experimentation in the lab will be difficult for most schools. Ecosystem

processes can occur over various different time scales, so students should be sure to look at both short-term studies and long-term studies when researching ecosystem processes.

Decomposition

Decomposition is the process whereby organic materials are broken down into component parts. Decomposition is a vital part of any ecosystem because without it all the materials used to construct an individual's bodily structures would become lost to the system forever. With decomposition, however, these components are recycled and returned to the system for use. Some particularly valuable nutrients in an ecosystem can be recycled nearly completely due to their value. Furthermore, some materials are easier to recycle than others. Pine needles, for example, have a higher amount of tannins, which make decomposition more difficult.

Some articles of interest:

Cornelissen, J. H., PÉREZ- HARGUINDEGUY, N. A. T. A. L. I. A., Díaz, S., Grime, J. P., Marzano, B., Cabido, M., ... & Cerabolini, B. (1999). Leaf structure and defence control litter decomposition rate across species and life forms in regional floras on two continents. *New Phytologist*, *143*(1), 191-200.

Deans, J. R., Molina, J. A. E., & Clapp, C. E. (1986). Models for predicting potentially mineralizable nitrogen and decomposition rate constants. *Soil Science Society of America Journal*, *50*(2), 323-326.

Lovett, G.M., Weathers, K.C., Arthur, M.A., & Schultz, J.C. (2004). Nitrogen cycling in a northern hardwood forest: Do species matter? *Biogeochemistry 67*, 289-308.

Melillo, J. M., Aber, J. D., & Muratore, J. F. (1982). Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. *Ecology*, *63*(3), 621-626.

Mathematical Model: Students can model decomposition. There are various ways to measure decomposition rates, and students can model different components of decomposition. Students should research existing models of decomposition and consider them when creating their own models. Students should also model decomposition of their own samples as decomposition studies will be relatively easy to conduct in a classroom setting. Students should also be advised to use statistical techniques to appropriately compare and understand sample data.

Experimentation: Students can easily create their own decomposition experiments. There are a great number of ways to measure decomposition that can easily be accomplished by high school students. One common method involves tying a string to a stick being observed for decomposition. The student would first weigh the stick, and then return days, weeks, or months later, pick up the stick by the attached string, and weigh it again for mass lost. Other methods include the litter bag, which is a mesh bag into which the student places a certain amount of litter. The bag can then be weighed again for mass lost. The advantage of a litter bag is that the mesh size can be changed to allow or prevent the entry of different size decomposers. A fine mesh, for example, would exclude larger arthropods from contributing to decomposition but would freely allow fungal contribution. Using certain chemical test kits students might also be able to measure the loss of different nutrients in litter over time. Once a method of measuring decomposition is determined students can create experiments to compare different factors that might contribute to decomposition rates, such as habitat, moisture, type of leaf litter, or so on. Students can easily work with each other and data from previous classes to create a more complete image of decomposition.

Relative Soil Fertility

There are a number of factors that contribute to relative soil fertility. The most obvious of these include the levels of different nutrients in the soil, such as nitrogen, but can also include things such as the ability of the soil to retain or drain water or even the microbial community within the soil. Many land-based ecosystems rely on plants as their primary producers, and without appropriately fertile soil plant growth is stunted or even halted altogether, making it an extremely important subject of ecosystem study.

Mathematical Modeling: Students should learn and understand CLORPT, the equation for soil formation created by Hans Jenny. Students might consider mathematical models that relate to each of the specific factors in CLORPT and might attempt to propose additional factors if possible. Furthermore, students should use statistical methods to analyze the results of the experimentation section, and mathematically summarize the results.

Experimentation: Students can experimentally compare the relative fertility of different soils within their area. Students might take trips to different places within their area, preferably to different habitats, and harvest soil samples. Within the soil samples students can grow plants and compare relative growth or productivity. Students should hypothesize which soils will be the most fertile and why. Variations on this experiment might include trying to identify the limiting nutrient in different areas, observing which soils are most receptive to which fertilizers, and even comparing how different plants grow in the different soils. Is one soil sample equally fertile to different species of plants? What about native versus non-native species? Students might also consider how the soil community of their sample affects fertility and could remove various components of the soil community to observe how that affects soil fertility. Baking the soil in the oven could be used to create a completely sterile soil for instance, while sifting the dirt at different mesh levels could be used to remove macroinvertebrates or fungal hyphae. Students could additionally observe the fertility of the different soils under different conditions. Do some of their samples out-perform others at low levels of moisture, for example? If it is impossible or otherwise difficult for students to acquire soil samples from their area they might instead consider testing different soil samples that can be ordered or bought from local stores.

Students can build upon each other's work and that of previous classes by exploring soils from different areas, or testing the same soils for different conditions. Also, classes could build upon each other to observe how soil fertility varies with time. If one soil sample displays a certain level of fertility in the first year, if plants are grown in it again the second year with no additional nutrients added will it be equally as fertile the second year, third year, and so on? Does this vary with plant species?

Water Quality

Water is vital to life on Earth and as a consequence water quality is important to almost every organism within the area. For humans water quality can determine whether or not a water source would make good drinking water or how it might affect our crops. For wildlife low quality water can reduce fitness or even result in death. Aquatic and amphibious organisms are particularly vulnerable to pollutants or nutrients in the water.

Mathematical Model: Students can use statistical methods to compare observational data of water quality across different habitats with reference to various factors, such as urbanization or level of canopy cover.

Experimentation: There are a wide variety of affordable water quality test kits available for students, such as Lamotte kits, which can be purchases for around $40 and include tests for pH, dissolved oxygen, nitrate, phosphate, E. coli, temperature, and turbidity. Using a water quality test kit students can analyze various aspects of water quality in their area, such as the amount of nitrogen in the water, the levels of dissolved oxygen, and the presence of E. coli. When designing the studies students should consider what may lead to different water qualities. For example, what would lead to the presence of E. coli in the water, and what might increase the levels of dissolved oxygen (vital for aquatic organisms)? Water quality data can be used in isolation to explore things like the health of a water source or in combination with other studies, such as biodiversity studies.

Biodiversity

Biodiversity refers to the diversity, or range of variation, of life within a particular area. It can be measured in several different ways at any given scale, though one of the simplest methods is simply to count the number of different species in the sample area. Biodiversity is generally considered beneficial for the environment and has been correlated with several different effects, including heightened productivity of an area, greater resistance against invasion, and generally greater stability, and is therefore of great concern to environmentalists and conservationists.

Mathematical Model: Using experimental data students can calculate the biodiversity of a given area. One commonly used measure of biodiversity is the Simpson's Diversity Index, which can easily be used by students in high school. In addition, students can use various statistical techniques to compare biodiversity from different areas in reference to different variables.

Experimentation: Students can formulate many different observational studies to investigate the biodiversity of across areas. One example would be the biodiversity of urban areas compared to more rural areas, or forested to more open habitats. Students should keep in mind when investigating biodiversity how best to randomize their collection in an area. Examples include dividing an area into quadrats and using a random number generator to decide which area to analyze. When analyzing biodiversity students don't need to know the exact species each of individual they identify so long as there is a way for all students to recognize and compare their counts. However, it would also be advisable to have several field guides on hand. Students should also be sure to keep track not only of the number of species found but of the number of individuals found within each species. Students might also compare different categories of individuals, such as non-native versus native or different families.

Soil biodiversity is an important but often under-studied aspect of environmental research. One way students can explore soil biodiversity is to collect a certain volume of soil from focal areas and then sift through the dirt by hand. The use of trowels and sieves would be particularly helpful for this type of work. Though this method will only reveal macrofauna visible to the human eye it will still provide valuable data. Students might also employ the use of a dissecting scope or a hand lens to assist in the effort. Students might also explore the biodiversity of an area's litter (such as leaf litter) rather than or in addition to the soil diversity.

Plant biodiversity can be studied relatively easily by designating an area to use for sampling and then identifying all of the visible plants in the area. This can be accomplished easily and cheaply by outlining a quadrat using PVC square frame or yarn and stakes and with the accompaniment of an area appropriate field guide. Students should ensure that the quadrats are always equal in size and randomly determined. Plant biodiversity is particularly convenient because plants are stationary, giving students time to identify them or photographically record the data as necessary.

Aquatic biodiversity can be studied in two easy ways. The first is simple to take a set volume of water from a chosen area of the aquatic habitat and inspect the water for different species. This method will work particularly well for smaller organisms. For ease of identification the container of water can first be emptied into a shallow tray or bowl. If students expect to find larger organisms in the water they might instead employ a netting method. Students would scoop the water using the net and then empty it into a shallow tray or bowl with a small amount of water. The netting method is particularly good for catching macroinvertebrates such as dragonfly larvae or water scorpions, but will be unlikely to catch larger, faster moving organisms like tadpoles or large fish.

Avian or other larger-scale vertebrate biodiversity can be measured visually and from a greater distance. Binoculars would likely be helpful. Students might set up bait stations, such as bird feeders, to attract a general category of organisms and then observe in person at set points in the day. Other possibilities include leaving camera traps or observing animal tracks. Students should be encouraged to consider how their presence might alter the behavior of these larger animals, such as birds, which could skew their results.

Students should be advised that when working with live animals sometimes unexpected interactions can occur. If a sample contains carnivorous organisms, for example, they may prey upon other individuals in the sample before the students can properly identify them. Students should further be encouraged to consider a wide range of factors that might affect biodiversity when designing their studies. For example, what environmental conditions might lead to heightened or lowered biodiversity? What is the best way to measure urbanization in reference to biodiversity? Students can build upon each other and on previous classes by investigating different habitats, target species, time of day or year, or other factors that might contribute to a particular level of biodiversity.

Effects of Climate Change

Climate change is becoming an ever more relevant problem in modern day society and is a constant focus of research. Though the term "global warming" is technically correct, as there is a trend toward a warmer Earth, there is more to climate change than simply warmer weather. Higher temperatures can change air currents, resulting in huge snowstorms in locations unprepared for them, as well as increased rain in areas that previously had relatively little, leading to floods, and decreased rain in others, leading to droughts. Ocean currents can change, and how bacteria decompose dead matter can even be affected, which in turn has an effect on the amount of CO_2 released into the atmosphere, which affects the overall temperature again. Because of all of these different factors scientists are almost constantly discovering new and important things about climate change.

Articles of interest:

Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, *440*(7081), 165.

Malcolm, J. R., Liu, C., Neilson, R. P., Hansen, L., & Hannah, L. E. E. (2006). Global warming and extinctions of endemic species from biodiversity hotspots. *Conservation biology*, *20*(2), 538-548.

Peng, S., Huang, J., Sheehy, J. E., Laza, R. C., Visperas, R. M., Zhong, X., ... & Cassman, K. G. (2004). Rice yields decline with higher night temperature from global warming. *Proceedings of the National academy of Sciences of the United States of America*, *101*(27), 9971-9975.

Mathematical Modeling: Students can attempt to model climate change. Students should first research existing models of climate change and consider what factors to include in their own models. Changes in temperature could be one model, but so could changes in precipitation, humidity, or even plant density. When making their models students should consider whether specificity or generalizability is most important for their model. Students can also run statistical tests on the results of the experimentation below and model their results.

Experimentation: There are many different experiments students can run to test the effects of global warming. One example might be to grow plants at various temperatures and observe how those grown at higher temperatures compare to those at lower temperatures. Students could also observe how decomposition is affected by global warming in the same manner. Students could also find projections of expected changes in climate beyond simply temperature. For example, some areas would become drier, and students could create experiments to observe how the native plants of the area would react to a drier climate. Students don't necessarily need to be limited to plants: students could also investigate using simple animals, such as pill bugs or ants. In addition to experiments students could also establish an observational study, where every year students observe how the ecosystem in their area is reacting to changes in the climate locally. This would allow students to build upon previous years' work and feel a sense of continuity and context.

Pollution

Pollution is a common problem in urbanized areas, and even often in more rural ones. Pollution can take many forms, from air pollution such as smog to ground pollution which can be as varied as fertilizer runoff, pesticides, or oil spills. Pollution is generally assumed to have a negative effect on the environment it touches, though the extent and effects of pollution can be greatly varied. Pollution should always be a concern to students because their own actions affect the levels of pollution in an environment. Researchers are always on the lookout for ways to not only reduce pollution but counteract what has already been released.

Articles of interest:

Lanctôt, C., Navarro-Martín, L., Robertson, C., Park, B., Jackman, P., Pauli, B. D., & Trudeau, V. L. (2014). Effects of glyphosate-based herbicides on survival, development, growth and sex ratios of wood frog (Lithobates sylvaticus) tadpoles. II: agriculturally relevant exposures to Roundup WeatherMax® and Vision® under laboratory conditions. *Aquatic toxicology*, *154*, 291-303Relyea, R. A. (2005). The lethal impact of Roundup on aquatic and terrestrial amphibians. *Ecological applications*, *15*(4), 1118-1124.

McBride, J., Semion, V., & Miller, P. (1975). Impact of Air Pollution on the Growth of Ponde Rosa Pine. *California Agriculture*, *29*(12), 8-9.

Nowak, D. J., Crane, D. E., & Stevens, J. C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban forestry & urban greening*, *4*(3), 115-123.

Relyea, R. A. (2005). The lethal impact of Roundup on aquatic and terrestrial amphibians. *Ecological applications*, *15*(4), 1118-1124.

Mathematical Modeling: Students can model pollution and the effects it has on the environment. Students should spend some time researching existing models of pollution before starting their own. Student models could be as simple as modeling the pollution of an individual to larger, such as modelling the pollution from an entire city. Students might consider modelling their own pollution or the pollution from their families by doing things like monitoring how much they use their cars and finding out how much pollution that model of car produces. Students could also model the effects of pollution on an environment. In addition, statistical tests and modeling can be used on the results of the experimentation below.

Experimentation: Students can experiment with the effects of pollution on species or even an ecosystem as a whole. For instance, students might take water samples from local streams and observe the biodiversity of the micro invertebrates under the microscope. Students could then expose the samples to pollutants such as pesticides or fertilizers and observe the difference in biodiversity. Similar experiments can be conducted with plants or simple animals such as brine shrimp, though students should be very careful if experimenting with higher order organisms. Students can also do observational studies where they measure the amount of pollution in their area and observe the effects on the health of native species or the levels of biodiversity. Students might consider taking measurements from areas with high pollution versus low pollution. Pollution can be measured using a variety of reasonably priced test kits, such as Lamotte kits, which can be purchases for around $40 and include tests for pH, dissolved oxygen, nitrate, phosphate, E. coli, temperature, and turbidity. Students can also experiment with ways to counteract pollution. For example, students could add plants to the water samples taken from local streams and observe whether or not this buffers the effects of the added pollution. Students should think about many different sources and types of pollution when creating their experiments. CO_2 released from cars might be an obvious air pollutant, but students should also consider things like acid rain or even noise or light pollution. More long-term experiments can be repeated across years, with classroom building upon the work of previous classes, or students could attempt different scenarios to increase the breadth of research. Is pollution ever beneficial? Are there situations where pollution appears beneficial at first glance, but has deeper and more damaging effects than they appear on the surface? Students might consider experiments that observe the long-term effects of pollution. If pesticide runoff only entered an experimental area once, for example, would it only affect the first generation or would later generations also be affected? Species with short generation times would be particularly useful here.

Invasive Species Spread

Invasive species (or, more neutrally, non-native species) have begun to appear in a wide range of habitats across the globe. In most cases invasive species fail to establish themselves and die, but a few manage to not only succeed in their new habitat but actively thrive. In several cases invasive species disrupt the pre-existing ecosystem of the area and cause a wide range of problems, including extinction of native species and overall decreases in biodiversity.

One iconic example is that of the chestnut blight, the result of an invasive pathogenic fungus. In its native habitat, chestnut blight is not fatal to its hosts due largely to the long history of co-evolution between the parasite and its host species of chestnut. However, when the blight was introduced to the United States, the native species of chestnut had none of the evolutionary adaptations to protect them from the blight as did the original hosts, and as a result the American chestnut was largely extirpated. The American chestnut was a keystone species in its ecosystem and its destruction had wide-ranging effects that are still evident today.

Articles of Interest:
Ellison, A.M. *et al*. (2005) Loss of foundation species: Consequences for the structure and dynamics of forested ecosystems. *The Ecological Society of America* 3, 479-486.
Neubert, M. G., & Parker, I. M. (2004). Projecting rates of spread for invasive species. *Risk Analysis*, *24*(4), 817-831.

Mathematical Model: Students can create a basic model for the invasion of a non-native species. The simplest of these models would simply be a function of the spread of the invasive species over time. Students should research other invasion models currently in use and attempt to understand them to the best of their abilities to help develop their own models. More complicated models might take in other factors aside from just measured spread so far, such as environmental or habitat conditions. For example, how long does it take for the invasive species to spread if the invaded patches are far apart versus very close together? Is there a difference in invasion time between habitats that have a lot of native biodiversity versus those that have minimal biodiversity? Students might work with each other to create models of different invasion fronts or invasions under different circumstances, and can use the models of past classes to either create more accurate models or models that cover different categories of invasion.

For cross-disciplinary models students might consider the economic effects of the non-native species spread. For example, invasive species can reduce concentrations of economically beneficial plants, such as trees that produce quality wood. Students could model how the increases in the non-native plant affect wood production from the native trees. Other examples might include the zebra mussel, which kills native mussels, clogs up pipes, and attach to boat motors or hydroelectric turbines and impede functioning. Students might also investigate populational health risks or other non-obvious impacts of invasive species.

Experimentation: If students attend school or live near an area with some plant growth they can likely conduct their own invasive species observational study. These could be longer-term studies, that occur over the course of a season, for instance, or cross-sectional studies, where students observe the amount of non-native species across several different study sites that represent the invasion front. For long-term studies the research could extend from class to class so that the research done by previous classes contributes to the research done by the current class. In the cross-sectional studies students would have to be careful when picking their locations to ensure that they aren't simply exhibiting confirmation bias, and should also have some way of measuring how different plots represent different amounts of time or distance from the initial invasion point. Students could also consider observing how invasive species spread differs across habitats or any number of other factors.

Students can also create experiments rather than merely observational studies. An invasive species experiment would necessarily be a longer-term study, and would include different treatments intended to determine factors that increase or decrease the spread of invasive species. An example would be observing how manual removal of invasive individuals at certain intervals affects the spread of the invasive species versus a control of no removal (or comparison treatments of different removal intervals). Students can build upon their fellow classmates and previous classes by attempting different variations of others' experiments or different treatments to create a wider pool of data.

Behavior

Behavior Modeling

Time and effort are valuable commodities for organisms. Things such as number of hours of daylight or nighttime or number of hours that can be spent until rest are required constrain the ability of individuals to accomplish important tasks for survival, and how an individual budgets its time can be the difference between survival and death.

Mathematical Model: Students can model the time budget of an individual organism through various activities, such as rest, foraging, mate seeking, and territorial behavior. Matrix algebra is not required but could provide additional depth to models. Particularly advanced projects might include the relative importance of various behaviors to overall survival, such as hunger's importance to the number of hours spent foraging. Students might also compare how time budgeting differs with age class, such that young animals might spend more time playing, for example, while adult animals might spend more time seeking a mate.

Experimentation: Students may record their own behavior throughout the day or that of their friends, family, and/or classmates. This will allow them a personal example of time budgeting. Students can further compare their data against that of others. Students can use data from different age groups to compare how time budgeting changes in humans over time.

Students could also conduct observational studies on other species, such as observing birds or squirrel behavior in the schoolyard. Using statistical methods students could come up with an average time budget behavioral schedule of the observed population. Students could further observe the behavior over different circumstances, such as morning and noon or spring and summer.

Classical Conditioning

When presented to an organism there are certain stimuli that result in an inherent, automatic response. For example, in scary movies when someone jumps out at the screen a human being's normal response is to flinch and experience and increase in heart rate. Any such stimulus that causes such an automatic response is called an unconditioned stimulus (UC), because it causes no training for the body to respond, and the physiological reaction is the unconditioned response (UR) for the same reason. Sometimes a different stimulus can become associated with an unconditioned stimulus. For example, in a scary movie certain creepy piano music might play before someone jumps out at the screen. Throughout the movie the music and the jump scare become associated. This second stimulus, or the conditioned stimulus (CS), by being related to the unconditioned stimulus, will begin to elicit a response similar to that of the unconditioned response. The response to the conditioned stimulus is therefore called the conditioned response (CR). The conditioned response is not always exactly like the unconditioned response, and is generally weaker than the unconditioned response. This process of associating an unconditioned stimulus with a conditioned stimulus so that a conditioned response is elicited similar to the unconditioned response is called classical conditioning.

Some stimuli are easier to associate with an unconditioned stimulus than others. The strongest conditioned stimuli tend to be ones that are directly related to the unconditioned stimulus or are stimuli that would have been relevant in an evolutionary context. For example, the sight of black and yellow stripes on a wasp is directly relevant to the pain of a wasp sting and is likely something our human ancestors experienced throughout evolution. However, the smell of chocolate chip cookies is not directly relevant to the pain of wasp stings and is not something humans likely evolved experiencing together. As a result, even if you frequently smelled chocolate chip cookies when you received wasp stings it is unlikely that the smell of wasp stings would immediately instill in you a fear of stings.

A conditioned stimulus can also become dissociated from the unconditioned stimulus through time. A person who has been conditioned to have the conditioned response of fear in response to the conditioned stimulus of yellow and black wasps might, through time, lose their fear of yellow and black wasps if they are around a great many yellow and black wasps and then not stung. The process by which a conditioned stimulus and conditioned response fade and are lost is called extinction.

Generalization and Discrimination

"Generalization" in classical conditioning is when stimuli similar to the conditioned stimulus but not exactly the same also elicit a conditioned response. For example, a human who is afraid of black and yellow wasps might also react with fear toward black and yellow bees and black and yellow flies even though neither of these are black and yellow wasps. "Discrimination," on the other hand, is when an individual selectively responds to the conditioned stimulus but not other, similar stimuli. In this case the human would respond with fear to black and yellow wasps but *not* bees or flies.

Mathematical Model: Students might model the development of a conditioned response to a conditioned stimulus. Students might include as factors how often the conditioned and unconditioned stimulus are paired, how relevant the conditioned stimulus is to the unconditioned stimulus, and how strong a conditioned response a certain conditioned stimulus garners. After gathering data from experimentation the students could continue to develop their models and include what they think might be relevant factors in a conditioned stimulus eliciting a conditioned response, such as the strength of the stimulus. Students might also model the extinction period of the conditioned response and predict how the strength of the conditioned response, the speed with which the conditioned stimulus was conditioned, and the length of conditioning relates to the rate of extinction. Students might also explore the differences between responses in generalized conditioned stimuli and whether or not reactions are stronger when there is a high level of discrimination. Both the tendency for discrimination and generalization can be increased through classical conditioning. For example, if the person afraid of black and yellow wasps is later stung by a black and yellow bee then they are more likely to also be scared of black and yellow flies in the future. However, if instead the person is never stung by a black and yellow bee and has only pleasant experiences with bees then they may be less likely to be afraid of black and yellow flies.

Experimentation: Students can practice classical conditioning on each other. Examples might include associating a noise with a puff of air to the eye, which automatically results in a person to blink, or measuring heart rate when a bell is associated with being made to do jumping jacks. Students should think creatively about what stimuli would make the best conditioned stimulus for a particular unconditioned stimulus. In doing so students should consider the relevance of the potential conditioned stimulus to the unconditioned stimulus and the evolutionary context of human beings. Students could also explore what conditioned stimulus garner the longest extinction period. Students could also experiment with the extent to which a conditioned stimulus is generalized or discriminated. Does this vary from stimulus to stimulus? For example, are auditory stimuli generalized more often than visual stimuli? What can the students do to increase generalization or discrimination?

Students could also experiment on simple animals in the classroom, such as fish. This would provide the additional challenge of thinking about which stimuli would be most relevant to another species. Not all species can see in the same color spectrum as humans, for instance, and some species place a greater importance on certain senses, such as smell. Students should research the biological and evolutionary contexts of any animals they plan to study. It would also be interesting to explore generalization and discrimination in non-human animals and to compare the tendency for discrimination versus generalization between species.

Operant Conditioning

In operant conditioning actions taken by an organism either increase in rate through reinforcement or decrease in rate through punishment. Unlike classical conditioning the actions being controlled in operant conditioning are deliberate actions that an individual can choose to do or not to do. Operant conditioning is vital to the learning process for many different species of animals, including humans, and helps shape many of the behaviors that occur on a daily basis. Operant conditioning is different from classical conditioning because in classical conditioning the responses are physiological responses. That is, they are not actions, they are unconscious responses of the body, such as an increase in heart rate or breathing. In operant conditioning behaviors and actions are altered to be more or less frequent rather than physiological actions.

Generalization and Discrimination

Generalization and discrimination are a little different in operant conditioning than in classical conditioning. In operant conditioning they refer to how much the changes in behavior generalize or discriminate across different settings. For example, if a dog is trained to be less destructive inside one person's house will the dog still remain less destructive if the dog goes to another person's house for a few days? Alternatively, if the dog is trained to be less destructive in the morning will the dog be destructive again at night?

A scientific article to start with:
Jager, W. (2003). Breaking bad habits: a dynamical perspective on habit formation and change. *Human Decision-Making and Environmental Perception–Understanding and Assisting Human*

Decision-Making in Real Life Settings. Libor Amicorum for Charles Vlek, Groningen: University of Groningen.

Mathematical Model: Students can create a mathematical model of increases or decreases in a subject's behavior based on the application of reinforcement or punishment. How does changing the strength of the reward/punishment affect the rate of the behavior at different time periods? After experimenting the students could then compare how their data compares to their models.

Experimentation: Students could experiment on themselves using a within subject design. Students would start by identifying a behavior they want to change, either by increasing it or decreasing it. (An example might be to increase studying.) Students would start by measuring how often they perform the behavior normally over an appropriate period of time. (Are there any confounds present with observing one's own behavior?) Students would then identify an appropriate punishment or reinforcement they believe might change the rate of the behavior. They would then begin to either punish or reinforce themselves for the specific behavior. (Are there any confounds associated with punishing/reinforcing one's own behavior? They might want to enlist family or friends to help them.) Students would measure the new rate of the behavior after implementing the reinforcement/punishment regime. Students could also observe the extinction period, or the length of time it takes for a behavior to return to baseline after the removal of reinforcement/punishment. An indefinite extinction period is one where baseline behavior never recurs. The extinction period is one measure of reinforcement/punishment's effectiveness that can be directly compared to other students as a ratio of before and after instances of the behavior.

Students might also explore generalization and discrimination. If the operant conditioning only occurs while the student is at school, for example, will the changes in behavior also be found at home? Alternatively, students might look for ways to increase discrimination, such as being quiet and attentive in class but friendly and outgoing when doing a group project in the hallway.

Students could also experiment with groups of simple animals. Examples of possible subjects include Madagascar hissing cockroaches or zebrafish, both of which are relatively simple animals that are relatively easy to care for. Cichlid fish would also be good choices due to their relatively high intelligence for fish and their ease of purchase, though due to their aggressive nature they can be difficult to keep in groups in fish tanks. (Peacock cichlids are an example of a relatively unaggressive and easy to care for cichlid.) Students would pick a behavior commonly seen in their subject and either try to increase or reduce the behavior through reinforcement or punishment. (For example, a punishment for a cockroach might be shining a light into the enclosure.) Treatment and control groups could be used more easily than in the student groups.

Statistics: Descriptive statistics such as means, ranges, and standard deviations could be used in analysis of data for each within subject or whole group analysis. Ratios of behavioral changes could also be used to compare against other groups or other students, and could additionally be used to compare results to that of previous years.

Positive and Negative Reinforcement and Punishment

Reinforcement and punishment come in two different forms: positive and negative. In positive reinforcement or punishment something is provided to either punish or reinforce. For example, a positive reinforcement might be giving a child candy, and a positive punishment might be playing a loud noise to a dog. In negative reinforcement or punishment something is taken away. For example, a negative reinforcement might be turning off an annoying noise, and a negative punishment might be taking away a favorite toy.

Related scientific article:
Lalli, J. S., Vollmer, T. R., Progar, P. R., Wright, C., Borrero, J., Daniel, D., ... & May, W. (1999). Competition between positive and negative reinforcement in the treatment of escape behavior. *Journal of Applied Behavior Analysis*, *32*(3), 285-296.

Mathematical Model: Students could research whether positive or negative reinforcement/punishment is more effective and/or make models of how effective they believe the different types of reinforcement/punishment would be. After experimentation students could then model their data and see how it compares to their initial models. Students could also reach across disciplines and look at whether or not positive or negative reinforcement/punishment would be more cost-effective. For example, would it be cheaper to give a child a piece of candy every time the child does the desired behavior or would it be cheaper to give the child a bowl of candy and take the bowl away when the child does the undesired behavior?

Experimentation: Students could use the same basic procedure as the above (operant conditioning) project but this time examine the difference between positive and negative treatments. For a within subject design students can test both positive and negative treatments by using an observation-treatment-observation-treatment-observation design. The first observation period would be used as the baseline for the first treatment period, either the positive or negative reinforcement/punishment. The middle observation period would serve both as the post-observation period for the first treatment, to observe how effective the treatment was, and the pre-observation period for the next treatment to use as a baseline. The final observation period would be used only as the post-observation period for the final treatment. Students should also be encouraged to think of creative examples of positive and negative reinforcement/punishment that can be used in everyday life. One example might be the use of happy and pleasant music to encourage shoppers to stay longer in a store versus using unpleasant music to encourage them to leave around closing time. How might the students test this? If using simple animals the students could compare positive and negative reinforcement/punishment groups directly, without the need to use both on the same group.

Reinforcement Schedules

How often and in what manner reinforcement/punishment is provided can also vary. In a continuous reinforcement schedule the target behavior is always rewarded/punished every time the behavior occurs. A non-contingent reinforcement schedule is when reinforcement/punishment is provided regardless of the occurrence of the behavior. There are four other basic types of reinforcement schedule: fixed-ratio, variable-ratio, fixed-interval, and variable-interval.

In a fixed-ratio reinforcement schedule the behavior is reinforced/punished after a certain number of occurrences. For example, say someone was teaching their dog how to “sit.” In a fixed-ratio 5 schedule (or FR 5) the dog would be rewarded every fifth time it sat. In a fixed-interval reinforcement schedule the first behavior is reinforced/punished after a set period has occurred. For example, when making pancakes the pancakes must cook for a certain amount of time before that side is done and needs to be flipped. Say it take exactly one minute for each side of a pancake to be cooked. This would be a fixed-interval 1 minute schedule (FI 1 minute). If a person flips before the minute then the pancake isn't done yet and they aren't rewarded by the sight of a golden-brown pancake.

In a variable-ratio reinforcement schedule the behavior is not reinforced/punished after a specific number of occurrences but rather a random or unpredictable but average number of occurrences. For example, a slot machine might pay out a prize on average every 100 spins, or a variable-ratio 100 schedule (VR 100). This means that the slot machine might pay out after 10 spins, or 110 spins, or exactly 100 spins, but on average it pays out after 100. In a variable-interval reinforcement schedule the first behavior after a variable or random but average amount of time is reinforced/punished. For example, say a mother only rewards her child with a hug when asked on a variable-interval schedule of 2 minutes (VI 2 minutes). This means that, on average, she will reward the child with a hug when asked on average after 2 minutes, but the exact time could be after 1 minute, or 3 minutes, or so on, as long as the average is 2.

The effectiveness of reinforcement/punishment on a behavior and how long the behavior will remain after reinforcement/punishment has been removed depends at least partly on the reinforcement schedule.

<u>Mathematical Model:</u> Students might model the expected rates of behavior on each of these reinforcement schedules, and how long they expect the behavior to persist after the reinforcement/punishment has been removed. After experimentation the students could model their data and compare them to their earlier models. Students could also reach across disciplines by examining the cost effectiveness of different reinforcement schedules. Which reinforcement schedule produces the best results for the least amount of money? How does gambling work? What is the trade-off between costs and effectiveness of a particular schedule?

<u>Experimentation:</u> Students could design experiments to compare the effectiveness of different reinforcement schedules. For fixed-ratio schedules, for example, students might try to find the optimum number of instances before reward, or in fixed-interval the optimum amount of time before a reward. Students should also observe the pattern of the occurrences of the behavior associated with the different reinforcement schedules and graph them to see how behavior varies with schedule type. Students should keep in mind that what might be considered "effective" on a ratio schedule is different to the "effectiveness" of an interval schedule, as a ratio schedule rewards number of occurrences and an interval schedule rewards behavior that occurs after a certain time. Students should also observe the extinction period of different reinforcement schedules. Which type of reinforcement schedule has the longest extinction period? Which the shortest? Which reinforcement schedule increases/decreases the target behavior the most? Which the least? Students could also examine how positive versus negative rewards interact with reinforcement schedule.

Decision Making

Animals have to make a great number of decisions every day, many of them with high risks and relative survival importance. A zebra during the dry months, for example, must make the decision of whether or not to drink from a watering hole. On the one hand, the zebra is thirsty, and if it doesn't get enough water to drink it will die. On the other hand, there may be a crocodile in the watering hole that could kill the zebra. The zebra could make the decision randomly, but in reality most decisions are made by weighing the different costs and benefits of each decision and the probabilities of the different risks. Note that the mathematical modeling of decision making is game theory if at least one other individual's decision making is also involved.

Decisions without Prior Knowledge

There are many situations where an animal will be forced to make a decision with no relevant experience for how decisions like this one have occurred in the past. In these situations the individual can only use the information readily available for decision making. For the zebra at the watering hole the zebra might use information such as how many other animals are drinking at the watering hole, which could indicate safety or lower the risk of the zebra being targeted, how thirsty the zebra is, and the muddiness of the water. By combining all the information concerning risk the zebra can calculate the likelihood that there is a crocodile and that the crocodile will eat the zebra. The zebra would also need to calculate an acceptable risk value. If there is a 75% chance that there is a crocodile in the watering hole, for example, the zebra might consider this risk too high and leave. However, if the zebra is severely dehydrated and unlikely to find a new watering hold before it dies of thirst then a 75% chance of a crocodile might actually be worth the risk.

<u>Mathematical Model:</u> Students can model simple decisions using probabilities. For students with a basic understanding of matrices conditional probability models are also possible. Students should start by considering the simplest decisions that an animal might make in a day. From there the student should carefully consider all of the different factors that lead into that decision. It is important to note that factors that affect one individual might not affect another. A mouse, for example, would be concerned about the presence of an owl when foraging, while a larger animal like a ground hog would likely be less concerned. Students should be encourage to think about the uncertainty of the decision making animal when creating their models. Students can work with others by creating related but different decision models and can build on previous classes models by either expanding on them or exploring different types of decisions. Students should consider across disciplines when making their models; for example, these sorts of models are frequently used in economics to determine whether or not to make certain business decisions as well as being relevant to biology. Students should also consider how biases might play into decision making when formulating their models.

<u>Experimentation:</u> Students can use experiments to see how well their models hold up in the real world. For example, using classmates or friends students might observe how individuals make decisions when all of the probability values are known. For instance, there is a 75% chance of winning a bouncy ball but a 20% chance of losing $5 from option A but a 20% chance of winning a bouncy ball and a 2% chance of losing $5 from option B which decision would the average person make? Students might also use simple animals that can be kept in a lab setting, such as fish or

insects, for these experiments. Students could even work together to compare the results of human vs. non-human animal trials. Students should keep in mind the biases of their subjects when formulating the experiments. Students might also consider exploring evolutionary-based biases in their experiments.

Decisions with Prior Knowledge

Often times when an animal is making a decision the animal has experience to back up its choice. In these cases the animal must take in the information available to it from the environment itself but also calculate in previous experience. If a zebra was deciding whether or not to drink at a watering hole, for instance, and the zebra had previously seen a crocodile in the watering hole the zebra would probably consider there to be a higher risk of a crocodile than if the zebra had never seen one. Time might also play a factor. The zebra would probably consider there to be less of a risk of a crocodile if it had seen a crocodile in the watering hole a year ago versus a month ago.

Mathematical Model: Students can use Bayes' theorem to create simple decision models. Students should first research other decision models to gain a fuller perspective of all of the components that go into a decision before crafting their own models. Students should again start by considering the simplest decisions that an animal might make and how experience would play into that decision. Students can work with other classmates and build upon previous classes by expanding upon the decision models of others or creating models for different types of decisions. Students might explore across disciplines in their models, looking at both ecology and economics for instance. As with decision models involving no prior experience students should also consider the role of biases in decisions, but also consider when and how these biases might be based on prior experience. Students might also consider how the proximity of the experience affects the decision. Are fresher experiences more influential?

Experimentation: Students can create experiments to observe how prior experience changes the decisions of subjects. For example, students might have subjects run several trials where A was always the correct choice and B always the incorrect choice. On the fifth trial students could then observe what percentage of participants then choose A or B. Experiments like these can be conducted on classmates or on simple animals that can be kept in a lab setting. Students could even work together to compare the results. Do simple animals place a different emphasis on experience than do humans? Students might compare evolutionary-based biases in their experiments.

Game Theory

Game theory is a mathematical way of representing the rational deliberation between different choices, where two (or potentially more) participants in the choice (or game) depend on choices made by the other player(s) for different favorable outcomes.

An article to start with:

Kuhlman, D. M., & Marshello, A. F. (1975). Individual differences in game motivation as moderators of preprogrammed strategy effects in prisoner's dilemma. *Journal of personality and social psychology*, *32*(5), 922.

Mathematical Model: Students can model various game theory examples. Matrix algebra would be optimal for such models. The Prisoner's Dilemma is a particularly common scenario used when teaching game theory and is relatively easy to model. Students could then build upon this and other models by exploring what changes in the conditions would also change the optimum choices. Students could build on each other and on the work of previous students' work by creating increasingly complex game theory models with interacting factors. Models of real-world decisions should be encouraged.

Experimentation: Students can study how well game theory models replicate reality. Students could take either game theory scenarios already in existence or ones they have created and survey other individuals as to how they would respond in these scenarios. Particularly well-designed studies might involve finding answers to several different game theory scenarios and seeing how they compare. Students should pay careful attention to how they phrase the scenario. Do they receive different responses for the same scenario when it is asked in different ways? When are the mathematical models the most accurate, and when are they the least? Students should consider the fact that individuals don't always react rationally and why.

Agonistic Behavior

Agonistic Behavior is any and all behavior related to being aggressive, including but not limited to threat displays, actual fights, and surrender. Agonistic behavior is costly to an individual because it involves the use of time, is generally highly energetic behavior, and in the case of actual aggression can be dangerous. In order to balance out the costs of agonistic behavior the rewards must be sufficiently high.

Articles to start with:

Hurd, P. L. (2006). Resource holding potential, subjective resource value, and game theoretical models of aggressiveness signalling. *Journal of Theoretical Biology*, *241*(3), 639-648.

Neugebauer, T., Poulsen, A., & Schram, A. (2008). Fairness and reciprocity in the hawk–dove game. *Journal of Economic Behavior & Organization*, *66*(2), 243-250.

Mathematical Model: Students can model agonistic behavior in a game theory structure, using previously created simple models as reference. The classic example is that of the hawk-dove game. Students should be encouraged to consider in what ways the hawk-dove game is accurate and in what ways it does not truly reflect real-life situations. Students can build upon previous simple models of agonistic behavior by adding additional factors to be considered, such as the number of resources being guarded and how strong the challenger appears. In addition, what are the particular costs and benefits of different agonistic behaviors, and under what circumstances do the costs or benefits outweigh the other? What is the evolutionary benefit of threat and display behaviors that counteract their energetic costs when individuals could instead immediately attack their opponent? Particularly thoughtful and complex models could also include state-dependent factors that might alter an individual's decision (such as level of hunger when fighting over food). Is there one optimal solution when it comes to agonistic behavior? Should all individuals fight? Should all individuals surrender? Or is it better for there to be a mix of strategies in a population? Students could also make models with a mind toward economics or politics.

Experimentation: Students can run computer simulations to see how effective their models are and how perfectly rational individuals might act. Students could compare these results to responses by actual humans by surveying others and seeing how they would respond to different situations. In some classes students could run experiments using live animals placed in situations that will result in agonistic behavior. One economic lab using convict cichlids was designed by Jennifer Templeton and is cited below. Other examples might include territorial or aggressive insects. Even when students are unable to conduct experiments using live animals students could potentially use footage of agonistic interaction between individuals available on the internet in a pseudo-experiment. Students should consider what role evolution plays in agonistic behavior and why some species are more aggressive than others.

Cichlid Lab:

Templeton, J. (2017). Exploring animal behavior in the laboratory: Territoriality in cichlids. *The American Biology Teacher 79*(1), 41-48. DOI: 10.1525/abt.2017.79.1.41

Sociality

Over the course of the Earth's history many different species of animal have evolved the tendency to regularly interact and even cooperate with other individuals. The development of sociality is interesting because it is inherently costly. The development and maintenance of social bonds takes time, there is often conflict required in the creation of hierarchies, individuals in social groups are often expected to share food, large groups are more obvious to predators, and so on. Considering all of the many costs to sociality the benefits must be sufficiently strong to outweigh them for it to have been maintained throughout the course of evolution.

Articles to start with:

Van Cleve, J., & Akcay, E. (2014). Pathways to social evolution: reciprocity, relatedness, and synergy. *Evolution*, *68*(8), 2245-2258.

Riolo, R. L., Cohen, M. D., & Axelrod, R. (2001). Evolution of cooperation without reciprocity. *Nature*, *414*(6862), 441-443.

Mathematical Model: Students can model the costs and benefits of sociality. Models should include variables for different costs and benefits to calculate in which situations sociality is evolutionarily viable and when it is detrimental. Students should consider a wide range of species and habitats when making their models. Students can further build upon each other and previous classes by either expanding upon existing models or creating new ones that explore different contexts. Particularly advanced models could include consideration for the scale of sociality that is viable.

Other potential models students could create include how quickly sociality should evolve in different contexts. What factors would lead to particularly quick development of sociality and which would slow down its development? For example, would higher levels of predation encourage sociality? Would it depend on the type of predation? Furthermore, what factors are required to maintain sociality in different contexts? For instance, is it necessary to have a system in place that punishes liars or cheats?

Experimentation: It will be largely infeasible for students to explore the development of sociality in the lab setting, so students should be encouraged to research sociality in different species. In particular, students should pay attention to related species that express different degrees of sociality, such as the various lemur species. What makes one species more social than another? Are there ever situations where sociality arises and then proves detrimental to the species?

Students could also explore sociality in humans. For instance, students might design a difficult puzzle or problem and then observe how quickly the problem is solved by a single person versus a group of people. Students should consider in such experiments what extraneous factors might influence the results. Would a group of people who are already familiar with each other solve a problem faster than a group of strangers? Does the size of the group matter? Students might also consider observing how individuals and groups budget their time when solving a problem. How much time do individuals in a group setting spend simply establishing social roles, for example? Students can build upon the work of their classmates and previous classes by exploring different aspects of human sociality and testing if the results are the same across different types of problems or puzzles.

Recognition of Conspecifics

A “conspecific” is the scientific term used to refer to another individual of the same species. For example, a conspecific of a Carolina chickadee would be another Carolina chickadee, and the conspecific of a desert cottontail would be another desert cottontail. For many species, both animal and otherwise, it is very important for an individual to recognize other individuals of its same species. This might be for breeding purposes, such as finding a mate, to know when a conspecific is infringing on an individual’s territory, or even just to know the risk of predation. However, recognition of conspecifics isn’t always easy, and different species have different recognition techniques.

Project inspired by:

http://sciencing.com/science-projects-using-betta-fish-7968901.html

Mathematical Model: Students can attempt to model the process of deciding whether or not another entity is a conspecific. Students would have to consider what an individual looks for in another entity to determine if it is of the same species or something else. Students should be encouraged to research previous research on conspecific recognition, such as in Tinbergen’s classic stickleback experiments. Students should start their models by considering very simple organisms that need only one or two cues to identify a conspecific and then progress to make more complicated models. Students can build upon their classmates or previous classes by building more complicated models or models for different scenarios. Students might also consider how different settings, such as different levels of lighting, might change how a conspecific is identified, and when an individual might make a false positive or false negative selection. Students should also use statistical tests to analyze the results of the experiments below.

Experimentation: Students can test how individuals identify conspecifics through the use of simple lab animals and models. For a betta fish, for example, students could create model betta fish and experimentally test what feature or features eventually lead to the live betta fish identifying the model as a real fish. Betta fish are a good model animal for this sort of experiment because they have very obvious aggressive displays that students can use to identify when they recognize the model as a real fish, but other animals should also be considered. Students should think about the evolutionary history of any organism they are working with when conducting their experiments. Students might also consider how to best obscure a conspecific so that it is no longer properly identified. For example, if the light is made dim can a betta fish still identify another betta fish? What if a one-way mirror is used, so that one betta fish can see the other but the other will not respond to the first? Students should also remember that not all species use visual cues as their primary way of identifying conspecifics. Ants, for instance, are more likely to use smell than shape, and so a successful ant model would likely employ olfactory cues.

Schooling Behavior in Fish

Schooling behavior is common in many prey species of fish. Examples include guppies, herring, and many species of tetra. Schooling is thought to be used as a method of protection from predatory fish, making it difficult for a predator to identify a single fish to catch in a school and potentially to appear bigger than a single fish really is. As discussed earlier in the sociality section interaction between individuals is costly for a number of reasons that depend on the social interaction, with the same being true of schooling. However, it is found in a wide range of species of fish and is a relatively common behavior, so it must have a distinct evolutionary advantage.

Mathematical Modeling: Students can attempt to model the different costs and benefits of schooling behavior in fish. Students might also consider models of the communication or observation required for schooling. For example, the focal fish notices flashes of fins moving toward the left, does the fish follow? Are there trade-offs for larger versus smaller schools? Students should spend some time researching schooling behavior to see if there are alternative factors they didn't initially consider. Students can also run statistical tests on the experiments below and model their results.

Experimentation: Students can observe schooling behavior in the lab. Many common hobbyist aquarium fish species are schooling fish, and therefore are easily acquired and cared for in a lab. Examples of easily cared-for species include the zebrafish (often called a "zebra danio" in stores), neon tetras, and fancy guppies. Students can formulate a number of different experiments to observe differences in schooling behavior. One simple experiment, for example, might be how schooling behavior changes as the number of fish in the tank changes. Another example might include how schooling behavior changes when there are multiple species presence, or schools of other species of fish. Does schooling behavior change if the fish feel threatened or when they're relaxed? What if the environmental conditions of the tank change? Students might also consider observing changes in water conditions of an aquarium in relation to schooling. For example, do ammonium levels increase with fish numbers in a manner other than linearly? Water condition test kits for aquariums can be easily and cheaply acquired from local fish stores.

Cooperation versus Competition

Even in highly social species cooperation and competition are facts of everyday life. For wild animals cooperation and competition can mean the difference between survival and death, whereas in human society it tends to have much less dire stakes. Even friendly relationships between individuals, in both the wild and human society, tends to involve both cooperation and competition.

Mathematical Model: Students might model the trade-offs between cooperation and competition. Are they always necessarily mutually exclusive? Students might also consider modelling the considerations required in different types of cooperation or competition, and the factors that must be weighed to decide which one should be chosen in a particular situation. Students might work with each other or build upon previous classes by creating models of different situations or scenarios, or by building upon previous models. Students can also run statistical tests on the below experimentation and model the results.

Experimentation: It will be relatively difficult to experiment with cooperation and competition in most species in the lab, though it may be possible with simple animals such as social fish or insects. It will likely be far easier to experiment with the differences in fellow human beings. Students might create experiments to determine under which scenarios or conditions individuals choose to compete versus cooperate, which will likely have a great relationship with game theory. Students might also choose to observe physiological changes of individuals when they compete versus cooperate. For example, when individuals are playing a competitive board game, such as checkers or chess, are there pulse rates different than when they play a cooperative board game, such as Pandemic? Do any physiological differences vary with the conditions surrounding play? Are there differences between individuals with different personalities? How do individuals react when they attempt to play cooperatively and their partner instead plays competitively?

Video Games and People

Video games have become a heated topic in our society. Some people say that video games inspire violence or are an overall depersonalizing experience. But are video games themselves inherently bad, and do they have effects that are distinct to video games compared to other forms of play?

Mathematical Modeling: Students might model the different factors that go into playing a game in real life versus in a video game and how that would determine behavior. For example, would playing chess with a physical person in front of you have different factors leading to behavior than if the game of chess was virtual, with no person in front of you? Students can also run statistical tests on the experimentation below and model their results.

Experimentation: Students can create experiments to determine the effects of video games on people. These experiments might be comparative by, for example, comparing a person’s physiological responses to playing a physical version of a game versus a digital one. Students might also observe how different levels of personalization within a game affect a person’s behavior. For example, does being able to hear your opponents voice elicit a different response than only text-based communication? What if your avatar is pre-determined versus customization? What if your avatar is designed to look like you versus a complete stranger? These experiments could tie into the cooperation versus competition experiments above. Students might also consider situations where there isn't a clear distinction between video games and physical games, such as a pinball game that has a digital score screen with animations.

Metabolic Processes of Plants

Plants, like all organisms, require nutrients and energy with which to build and maintain their structure. Plants are vital to many ecosystems and as such it is important to understand their basic functioning.

Transpiration

Transpiration is the process through which water moves through plants. Liquid water is taken up by the roots of the plant, moves through the stem to the leaves, and is released through the stomata of the leaves as water vapor. Transpiration is necessary for the plant to survive because not only for hydration but also because nutrients are drawn into the roots along with the water. The loss of water vapor through the leaves is necessary to draw new water into the plant because transpiration is driven by water potential differences. This means that when there is less water in the roots of the plant than in the soil surrounding it water will naturally diffuse into the roots. However, without evaporation of the water through the leaves then the water content in the roots and the water content in the soil would be equal and the water could not move. A module to help learn about transpiration is available at http://oregonstate.edu/instruct/oer/Transpiration%20Module%20Sound/story.html .

Mathematical Model: Students can model transpiration. What factors would increase transpiration rates? What factors would decrease transpiration rates? What are the limiting factors in transpiration? What are the tradeoffs associated with transpiration? After experimentation students could model their data and see how well it compares to their original models. Students should explore current published transpiration models. While many of them will be too complicated for high school students they will give the students insight into transpiration processes and current theories of transpiration. Do the students see anything they disagree with? Are there any additions they would make? Are there ways to simplify these models so that the factors used are more easily measurable?

Experimentation: Students can experiment to discover what factors affect the rates of transpiration. A module that examines this experimentation is available at http://www.mhhe.com/biosci/genbio/virtual_labs/BL_10/BL_10.html . Small potted plants could be used for these experiments. Students would start by weighing the plants and then putting them in various conditions, such as a high humidity condition, a high heat condition, or so on, with at least one group kept as a control. Without adding additional water to the pots the plants would be weighed over the treatment period the plants would then be weighed periodically, with the loss in weight being attributed to water loss through transpiration. Students could build on previous years by experimenting with different plants and different conditions. Creativity in potential transpiration factors should be considered, such as the surface area of the leaves and the content of the soil. Students could further explore the differences in transpiration between different species of plants at the same conditions. Does one species of plant have higher transpiration rates because of broader leaves or for some other factor? Other experiments might include comparing related species from different habitats, or the same species across seasons or even time of day. Students should research how photosynthesis affects transpiration rates and hypothesize treatments accordingly.

Students could also consider the interaction between different individuals in transpiration. Does having several plants in the same pot change transpiration rates? What if different species are kept together? Are there parasites that can increase transpiration rates? Are there symbiotes, such as fungal species, that affect transpiration rates?

Plant Pigment Chromatography

Chromatography is a method whereby a solution is separated into component parts in a gradient, allowing observation of the different molecules. In pigment chromatography the pigments of a solution are separated, resulting in a visually distinct chromatography that can be observed by the human eye. Pigments are very important to plants, as they allow plants to absorb light for use in photosynthesis. While green pigment is one of the most obvious colors in plants there are several others present which provide a variety of services for a leaf.

Reference for experimental method:

http://www.phschool.com/science/biology_place/labbench/lab4/concepts1.html

Mathematical Model: Students should research the pigmentation of plants before they start the experiment. Using this knowledge students can then make basic models of what they believe will be their chromatography results. Students can also run statistical tests on the below experimentation and model their results. If teachers keep the results from previous classes students can use this data to make models as well, and to compare results across experiments.

Experimentation: Students can run their own plant pigment chromatographies using relatively cheap supplies. One method for creating these chromatographies can be found in the above link. Another option is to grind up the leaf of the plant being observed and place a dot of the solution at the top of the paper. In either case a relatively long piece of filter paper needs to be used for optimal results. It might be best to allow the students to run an initial trial to get used to the methods. Then, students can create their own experiments to compare chromatography results. Examples might include comparing the chromatography of different parts of the same plant, or leaves from different plants across latitudes, or different habitats, or so on. Students might also experiment with the chromatography results of samples from the same portions of the same species of plants where the subjects have been kept in different conditions, such as high light or low light conditions. Students should also think about how best to measure their chromatographies so that they can compare results and how to standardize the methods so that the results are directly comparable. For example, does it matter how long the chromatography is left to run? What about how much solution is used, or the length of paper? How can students standardize the amount of plant solution being used in the experiment? Students can build upon their classmates' and previous classes works by creating variations of similar experiments or exploring alternatives to what has already been proposed. Students might also consider how to improve the designs of previous classes.

Statistical Analysis

In addition to other types of mathematics, all projects will be expected to include appropriate statistical analysis. Here are some types of statistical analyses, although this is not an exhaustive test.

Chi Square Test

A Chi Squared test is used to determine if whether the distributions of categorical data differ from one another or the expected frequencies. In other words, this test is great for seeing whether two independent categorical variables are linked or if there is no statistically significant difference between the two variables. Teachers can use something as simple as a bag of Skittles to demonstrate how a Chi Square test may be implemented for seeing if there is any statistically significant difference between the numbers of each colored Skittle and the expected number if no color was favored more within each bag. Students will then perform an experiment using the Chi Squared test to analyze their data set. An example biological experiment would be to compare the food preferences of a population of Drosophila. Using four different food sources, students could see if there is any significant preference for one food source over all others by comparing the counts of fruit flies that remain on each source for an extended period of time and then relating these counts to the expected counts if their was no preference.

ANOVA Test

The ANOVA test is used primarily for comparing the variation between means of three variables to see if the variation between each variable is statistically significant. This test can be conducted as either a “balanced” ANOVA test in which each variable’s mean has been calculated via an identical sample size. However, students will likely have to conduct an “unbalanced” ANOVA test whereas each variable’s mean has been calculated from samples that differ in size. Students will learn to calculate things such as the standard deviation for each mean and solve for that ANOVA’s test statistic. Wolf Spiders can be the model organism that students can use for running experiments that require running an ANOVA test for data analysis. An example experiment would be to investigate a wolf spider population to see if there is any statistically significant size variation amongst a diverse environmental correlates. In fact, any species may be used for this field study of relating size to an ecological feature(s).

T-Test

This simple test is commonly used to determine if two data sets are significantly different from one another. There are a variety of t-tests that compare things such as two sample means or an observation to a sample. Despite the t-test test being used similarly to the ANOVA test, it is important that students recognize each popular statistical test used as these tests potentially will be encountered again within the literature. An interesting example experiment would be to use the t-test for investigating any significantly different “chill-coma” tolerances between two populations of fruit flies that were fed different diets. Students will first freeze each fruit fly group for fifteen minutes and then remove and record each fruit fly's recovery time. Students may choose their own unique diet to feed the fruit flies, however, media can be purchased from the websites www.rakuten.com or www.flycafe.net.

Regression Analysis

The principle use of regression analysis is to investigate whether two variables co-vary. This variance may be classified as being either of a positive or negative correlation. This analysis can test the validity of whether a particular variable actually "causes" another variable to change. Students will learn to recognize when it is proper to use either a correlate or linear regression when running their own experiments that involves analysis via a regression function. Students may design an experiment that investigates for example whether different levels of water exposure has an effect on cricket growth rate. Crickets may be obtained from the website www.flukerfarms.com/Crickets.