Unit 11: Biomechanics

Biology in a Box

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Unit 11: Biomechanics
Materials List

Exercise 1:
- Workbook

Exercise 2:
- K'Nex Middle School Math Kit
- Rat skeleton
- Digital scale with calibration mass (100 g)
- Wood block with hook
- Mini pail with chain
- Plastic beaker (100 ml)
- Spring scale (5 N/500 g)
- 12" rulers (6)
- Protractors (6)

Exercise 3:
- Demonstration lever with attached accessories and BB 'coins'
- Set of six pliers with bite force device
- Lever examples
- Bird food examples
- Fish food examples
- Set of bird cups (6) and food bowls (2)

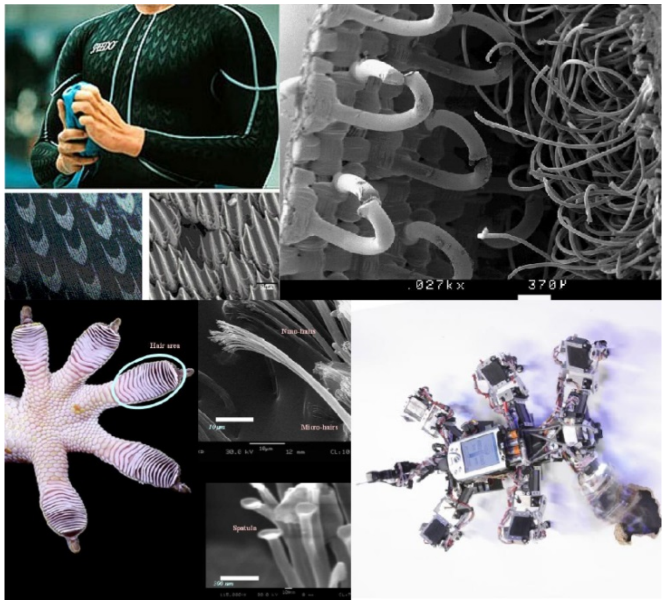
Exercise 4:
- Ball set (5) with stopwatch
- 10 m tape
- Straw Rocket launcher with accessories

Exercise 5:
- Set of Silver Maple samaras
- Set of Sugar Maple samaras
- Set of Box Elder samaras
- Mass sheet for samaras
- Set of Elm samara models
- Stopwatch

Exercise 6:
- Set of instruments (4)
- Sound meter with batteries
- Bone conduction transducer
- Speaker example
- Boostaroo signal amplifier with batteries
- Set of speaker diaphragms (4)
- Mini amplifier speaker and cable
- Slinky spring
- CD with audio and video

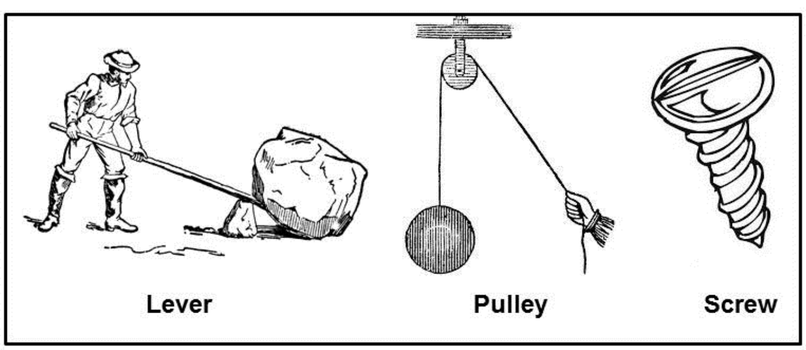
Unit 11: Biomechanics
Table of Contents

Unit 11: STEM I. Biomechanics



Introduction

When you hear the word “mechanics,” you probably immediately think of people who work on automobiles. The word is a good descriptor for such individuals, as it comes from the ancient Greek prefix *mekhane*-, which means “machine,” or “tool,” and the suffix –*ikos*, meaning “pertaining to.” So, literally translated, the job of a mechanic is one pertaining to tools or machines. The ancient Greeks didn’t have automobiles, however, so their definition of a “machine” was anything created to take advantage of forces and physics to accomplish tasks. The first simple machines formally described were the lever, the pulley and the screw shown in the figure below.



In science, the term mechanics refers to the branch of physics that deals with the motion of objects as well as the forces on them. As physical objects with mass, living organisms are also subject to the effects of applied forces. Further, many organisms move and often in complex ways! Therefore, an understanding of mechanics can help us not only better understand the physical world, but the biotic world, as well!

In this unit, you will learn about a number of physical principles, while also thinking about them in a biological context. You will also play the roles of engineers, using the principles of biomimetics to draw from biological examples to inspire your designs. In **Exercise 1: Borrowing Designs from Nature**, you will learn about the field of biomimetics where structural features of plants and animals, or those produced by animals, have served as blueprints for manmade products. In **Exercise 2: From Skeletons to Bridges**, you will examine the physics of bridge-building and how this structure mimics elements of skeletons and bones. In **Exercise 3: Jaws are Levers**, you will learn about a simple machine, the lever, and how the structure of the double class one lever (pair of pliers) in animal jaws influences what they feed on. In **Exercise 4: Drop, Squirt, Throw: Projectile Motion**, you will learn about trajectories of falling/dropping and thrown or propelled objects, and how organisms and mankind make use of such motions. **Exercise 5: Similar Things to Wings: Drag** is an extension of Exercise 4 in which you will learn about how the force of drag affects the descent of falling objects through the air and how it is utilized by trees in dispersing seeds. Finally, in **Exercise 6: Bioacoustics**, you will examine the phenomenon of sound, and learn about acoustic communication in animals, as well as practical technological applications related to the science of sound.

Exercise 1. Introduction to Biomimetics

Biomechanics is a particular scientific discipline at the interface of physics and biology that involves the study of the structure and function of organisms through the application of the principles of mechanics. As such, it falls under the engineering field of biomimetics or biomimicry, where *bio* refers to life and *mimicry* to imitate. We use biomimetics here to avoid confusion with the biomimicry that occurs in nature *(See Unit 10 Animal Behavior Exercise 3: Slap Snack Mimic, a series of exercises dealing with biomimicry in nature).* It is not surprising that engineers look to nature for insight into designs that might be applied to solve problems of interest to humans. The structures and processes organisms possess are, after all, the end product of testing through the process of natural selection over extensive periods of time. If a solution exists naturally, one should be able to utilize it in designing products and devices that can be put to practical use by man to inspire an engineering solution.

This is not as simple as it may seem because one has to fully understand the multiple systems that might be involved in the trait of interest. Take, for instance, the recent interest in geckos, small lizards that are unique for their ability to climb slippery surfaces, given their large size. They are, in fact, small as lizards go, but very large for an animal capable of moving across a surface upside down, Spiderman-like. The toes of the Gecko have inspired the potential for invention of a reusable dry adhesive that can be put down, taken up and reused, just as geckos pick up their feet and put them down again while moving across a slippery substrate (Figure 1). Close examination of the underside of the gecko toe indicates that it has hundreds of thousands of tiny hairs/bristles. These bristles are approximately 5 microns (0.005 mm) in diameter and 100 microns (0.1 mm in length). When pushed forward onto a surface the bristles attach, and when pulled back they detach, a function of their angle and shape. A UC Berkeley team (Chary et. al., 2013) reported that their silicon-based fibers modeled after gecko bristles successfully attach and detach making a decent dry adhesive, albeit a very small one that does function as well as nature's model.

Figure 1. The gecko lizard, close up of the foot showing treads similar to that of an automobile tire, and EM image of stiff bristles with surface-conforming tips.

Another group (Bartlett et al., 2012) from the University of Massachusetts has approached the same problem of how to mimic the geckos and other animals' unique climbing abilities in producing dry adhesive materials. The U Mass researchers point to the fact that some insects even climb with smooth attachment pads that lack the minute bristles seen on gecko toes altogether. What is it about the structure of the seta (bristle) that gives it its adhesive properties on a gecko toe or insect tarsus (foot)? It is stiff in the direction of load (weight-bearing), while being flexible (conforming) at the tip permitting it to have maximum surface area in contact with the surface. These researchers used simple scale-up theory to produce a large pad made of a stiff fabric in the direction of load onto which a layer of rubber is poured (conforming material that maximizes contact with the surface being traversed). The result is a reversible synthetic adhesive pad capable of holding up a large, wide-screen television. A comparison of the synthetic adhesive produced by scaling up compared to the natural adhesive properties of the gecko toe is shown in Figure 2 below.

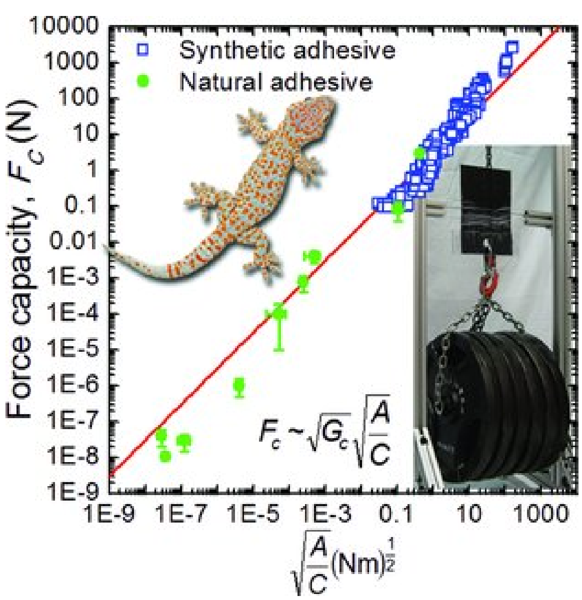
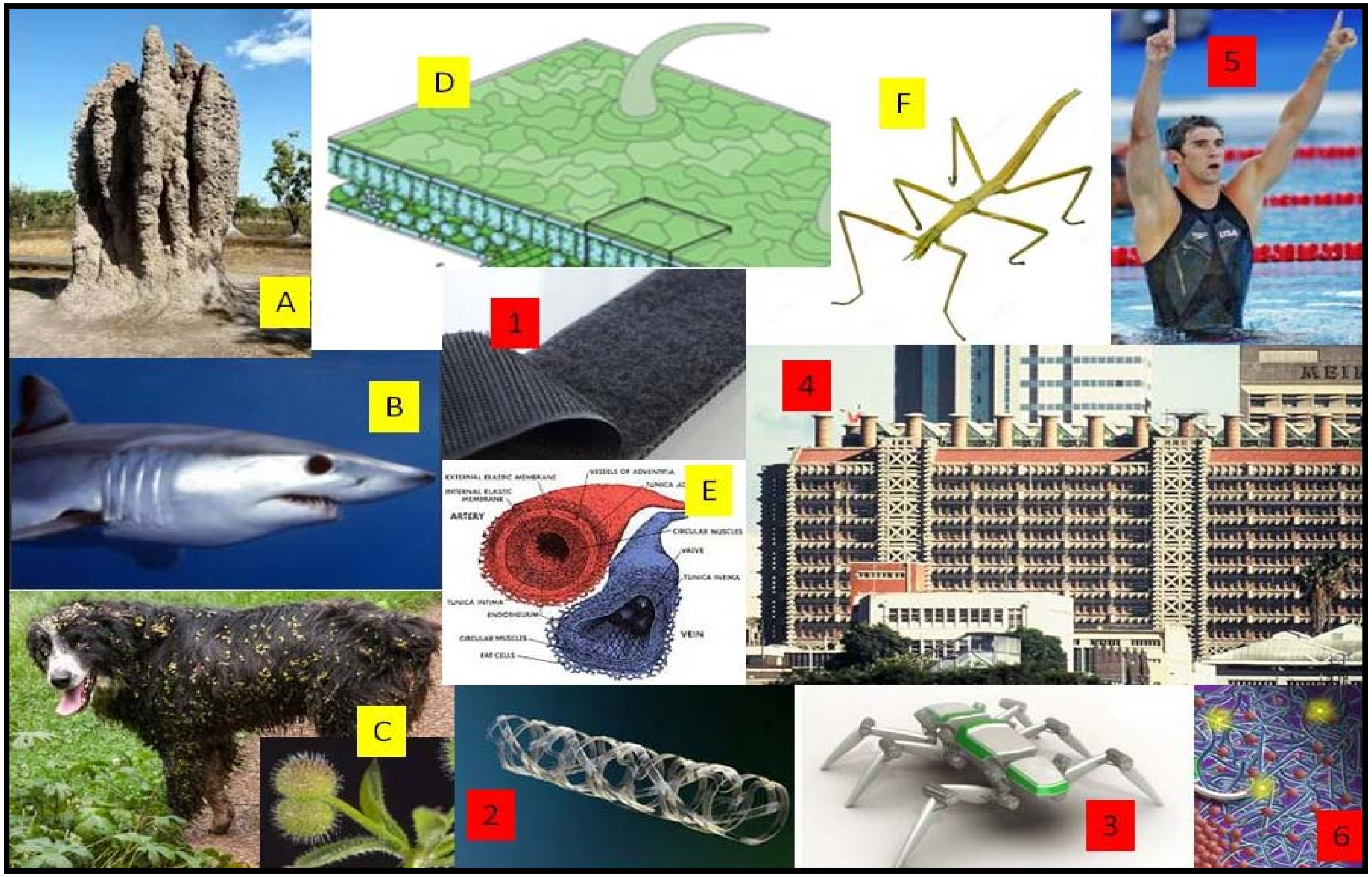


Figure 2. A 100 cm^2 reversible synthetic adhesive pad was able to hold a hanging mass of 135 kg. (After Bartlett et al., 2012)

Biomimetics has resulted in many advances in engineering. A few of these are pictured in the collage below.



Complete the following <u>Biomimetics Challenge</u>:

- Attempt to match the biological example (letter) with the correct technological advance that mimics it (number) in the collage above.
- Check your matches under Exercise 1 in the answer section of this unit.

Exercise 2. From Skeletons to Bridges

Many animals besides humans are accomplished builders. Animals can create structures that act as nests and shelters. In developing such structures, animals alter their surrounding habitats, shaping the world around them. Notable examples include giant termite mound "cities" in Africa, weaver bird "apartment" nests that may house hundreds of individuals, bee honeycombs, wasp nest chambers, spider webs, and even a huge beaver dam in Canada that can be seen from space! Humans have long been fascinated and inspired by such structures, and many modern architectural principles were derived from observations of animal building behavior.

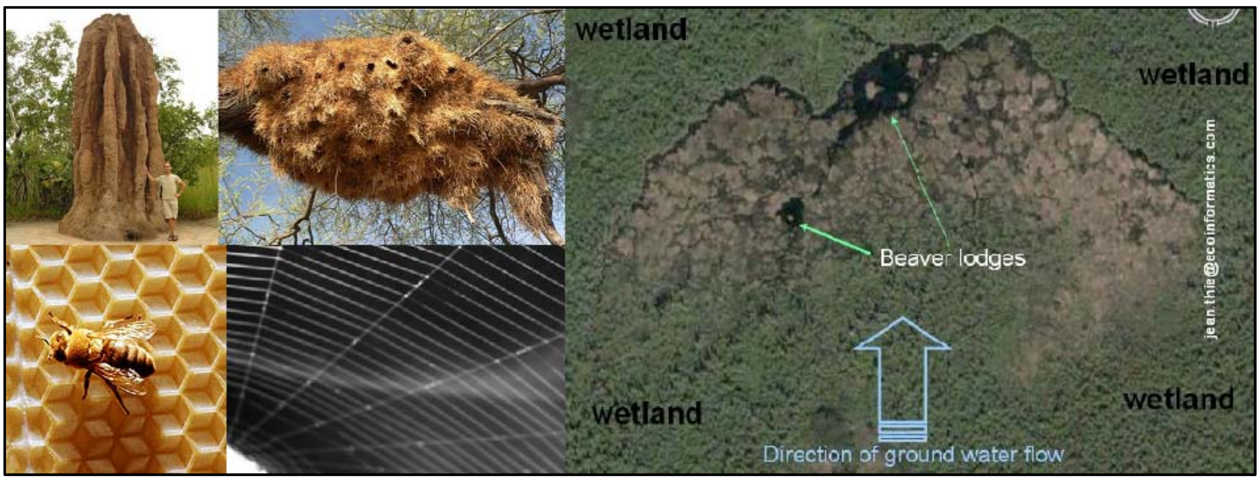


Figure 1. Examples of animal architecture. Clockwise from upper left: termite mound in Africa, weaver bird apartment nest, Google satellite view of the world's largest beaver dam in Alberta, Canada (2,790 feet long – over half a mile!), close-up views of sections of an orb web, and the honeycomb composing a bee nest.

Structures built by animals may show remarkable precision, structural integrity, and even geometric regularity. In this set of exercises, however, we are less interested in the structures animals build and more interested in the fact that an animal's body itself offers examples of geometric structures that provide structural support. Structures such as the vertebrate skeleton and the bones that they are made of have provided the inspiration for human-built structures such as bridges, towers, and more.

Figure 2 shows some examples of existing bridges, including one that has failed (collapsed). In this series of exercises, you will experiment with bridge design and gain a greater understanding of the factors involved in bridge weight-bearing capacity and stability.

Exercise 2a. Spaghetti Spans: Trial 1. Initial Competition

"As you head out for summer vacation, ponder this: There's a 1 in 9 chance that the bridge you're crossing has been deemed structurally deficient or basically in bad shape by the federal government." (Naylor, 2013). Part of the problem is associated with bridge age; but the design of a bridge is very important to its strength and the load (mass) it will bear. In these exercises, you will learn the elements that are important to bridge strength. In the first step towards reaching this goal, each student team will develop a bridge design plan using K'Nex building pieces and then construct a trial bridge out of dry spaghetti noodles that spans a distance of 25.4 cm (10 inches) between two student desks. Load bearing trials will determine the rank order of designs from least to greatest strength (has the greatest load bearing capacity).

Figure 2. Some examples of bridge design.

Materials Needed:

- Small block of wood with hook
- Pail (with chain segment)
- Set of K'Nex building pieces
- Digital scale
- Mechanical scale (hanging)
- Rulers (6)
- Protractors (6)
- *2 two-pound boxes of dry spaghetti noodles **

- *Water or sand* *
- *Tacky glue* (available in the craft sections of stores) or glue guns and sticks*
- *Graph paper* (optional) *
- *Pencils (that will possibly be broken)**

*** Consumable materials to be provided by teacher**

Procedure:

- Divide into groups of 4 students each.
- Use the K'Nex building elements to experiment with the way you will put elements together in producing a bridge. This is called a prototype or model that you will follow in building your bridge of spaghetti noodles for the competition.
- When you are satisfied with the design, sketch out a rough drawing of it on paper.
- **NOTE: It is important that you NOT use the K'Nex pieces for strength testing. These sets are expensive to replace, and are intended ONLY for prototype design.**
- Once your group has completed its basic design, your teacher will provide the building materials you will use in the strength trial competition (dry spaghetti noodles), as well as tacky glue or its equivalent. You will use these materials to construct your bridges, conforming to the following rules:
  1. The bridges must be at least 30.5 cm (12”) in length.
  2. Bundles of more than five strands of spaghetti are not allowed.
  3. There must be a hole at the center of the bridge’s span to support the testing apparatus.
  4. Comparison of bridges will be done on a strength-to-mass ratio (strength/mass) basis. In other words, the bridge that supports the most mass, relative to the bridge’s mass, will be declared the winner. This ratio would correspond to cost effectiveness of the bridge, as greater strength/mass values indicate stronger bridges using less building materials.
- Work together to construct your team’s bridge using only the dry spaghetti and glue provided.
- Take pictures or make a scale drawing of each bridge, using rulers and graph paper.

- Use the provided digital scale to obtain the mass in grams (g) of each team's completed bridge. Record the mass on the drawing or picture.
- You will now test the strength of each team's design using the following procedure:
    - Set up the bridge to span the space between two desks placed 25.4 cm or 10" apart. Mark the positions of the desks on the floor with tape, or measure this distance, so that if the desks get moved between trials, this distance can be reestablished between each trial.
    - Place the wooden block with the hook on the center of the "roadbed" of your bridge, with the hook passing through the hole at the center of your bridge.
    - Hang the provided pail from the hook on the wooden block. See Figure 3 for an example.

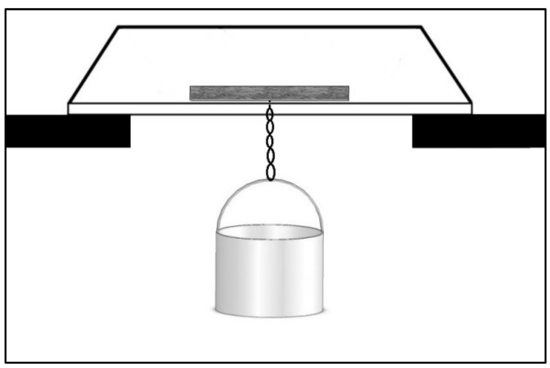


Figure 3. Example setup for bridge strength testing.

- Slowly add water, sand, or other weights (such as marbles, beans, etc.) into the suspended bucket until the bridge falls.
- Upon failure of the bridge, hang the bucket (with its contents) from the hook on the provided mechanical scale. Place the wooden block with the hook into the bucket as well, as the bridge was also supporting its mass. Record the total mass (in kg) of these items on the drawing or picture of that bridge. This is the mass at which bridge failure occurred.
- Repeat these steps for each team's entry in the competition.
- All teams should now calculate the strength-to-mass ratios for their bridges as shown below.

$$\textbf{\textit{Strength to mass ratio}} = \frac{\textbf{\textit{Failure mass of bridge}}}{\textbf{\textit{mass of bridge}}}$$

- Record this value on the picture or drawing of the team's bridge.
- After all groups have calculated the strength-to-mass ratios of their bridges, place these values on the board for comparison.
- Rank each team's bridge based on its strength-to-mass ratio from greatest to least. The team with the greatest strength-to-mass ratio for their bridge is the winner.
- As a class, compare your scale drawings or pictures of each team's bridge. Observe and discuss any trends in bridge strength related to bridge design.
- Discuss as a class what types of designs worked well and why particular design aspects worked better than others.

Exercise 2b. Under Stress!

Let's see what we can learn about bridge structure from examining the structural elements of animal skeletons before completing a second bridge building competition. In 1866, Karl Culmann, a Swiss mechanical engineer, attended a scientific meeting. At the same meeting, Hermann von Meyer, an anatomist, was presenting his findings on the internal structure of the human thigh bone. Von Meyer noted that the interior of a healthy bone consisted of a complex **truss**, or framework of tiny ridges called **trabeculae**. Take a look at Figure 4 below, showing cross sections of healthy and unhealthy bone. Note that in the healthy bone, the framework of trabeculae is much more extensive than that in the unhealthy bone (in this case, affected by osteoporosis).

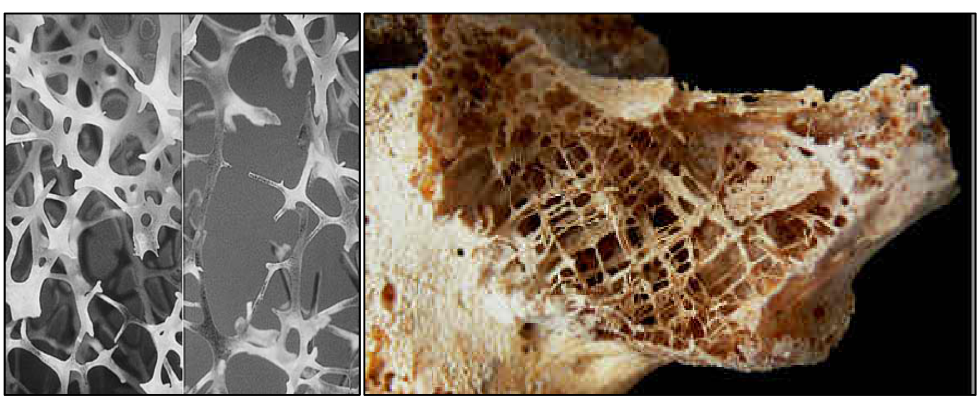


Figure 4. Images of cross sections of healthy bone (left) and osteoporotic bone (center) and exposed internal structure of a hip bone showing osteoporosis (right).

Cullmann noted that the framework of trabeculae within a healthy thigh bone shown in von Meyer's drawings was very similar to the patterns of stress experienced in a type of steam crane known as a Fairbairn crane (see Figure 5).

Figure 5. Left: cross section of human femur, showing trabeculae; Center: Fairbairn crane; Right: Cullmann's and von Meyer's drawings of stress patterns in a Fairbairn crane and trabecular alignment in the femur.

Working together, Cullmann and von Meyer developed a theory that trabeculae help give bones additional stiffness and strength, as they seemed to be aligned as braces against the directions of principle stresses experienced by the bone. In fact, weight-bearing exercises such as walking and running actually increase the density of this structural web, making the bones stronger and less likely to fracture.

What sorts of stresses affect bones, as well as animal-built and manmade structures? There are three main types of stress that are important to consider when thinking about various anatomical and manmade structures (Figure 6):

Tension is a type of stress in which forces pull on an object or structure in opposite directions parallel to the object's longitudinal axis.

Compression is a type of stress experienced when forces push on an object from opposite directions parallel to the object's longitudinal axis.

Bending is a type of stress experienced when force is applied perpendicular (at a right angle) to the object's longitudinal axis.

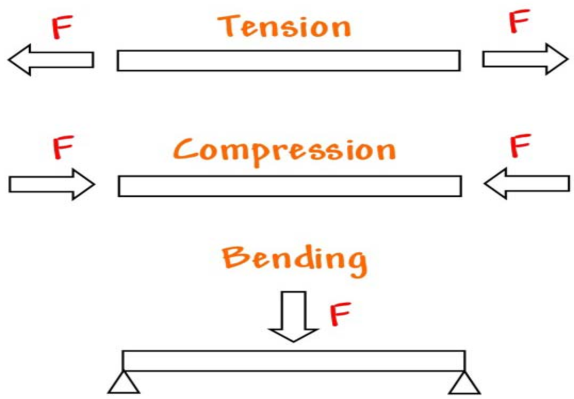


Figure 6. Illustration of various kinds of mechanical stress: tension, compression, and bending.

How do these types of stress affect a structure? Truss bridges can help provide insights as models.

Truss bridges (see Figure 7 left) are a mainstay of the civil engineering field. These relatively simple structures are built on some very fundamental principles that are found in numerous examples in both the natural world and in manmade structures (Figure 7 right).

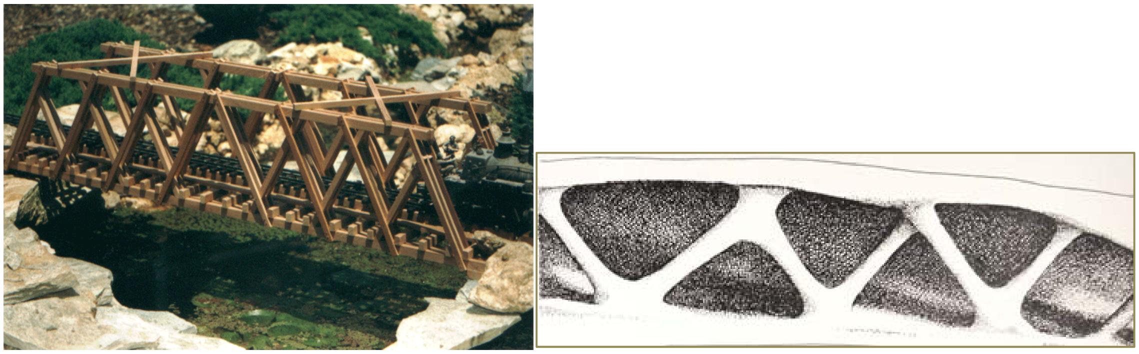


Figure 7. (left) Typical truss bridge; **(right)** long section of a vulture wing showing internal bone struts similar to those seen in mechanical bridge structures (after D'Arcy Thompson 1942).

In Exercise 2b, you will examine one of the main principles underlying truss bridge construction, namely the relative effects of each of the three main types of stresses on the various materials used in building them.

Materials Needed:

- *Several unsharpened pencils* *

*** Consumable materials to be provided by teacher**

Procedure:

- The teacher asks several volunteers to come up to the front of the classroom.
- Each volunteer is given an unsharpened pencil.
- Upon instruction by the teacher, each volunteer attempts to make their pencil longer by applying tension (pulling on each end of the pencil in opposite directions).
- Next, volunteers are instructed to attempt to make their pencils shorter by applying compression (by pushing inward on each end of the pencil from opposite directions).
- Finally, volunteers are asked to attempt to bend but not break their pencils by applying bending stress (force applied perpendicular to the length of the pencil).
- As a class, discuss the following questions:

Q1. Which types of stress(es) did the pencil most effectively withstand? Which type of stress(es) would have made it easiest to break the pencil?

Q2. Think about the different types of materials used in building bridges. Do you think that each of these materials responds to the different main types of stresses in the same way?

- Check your answers in the answer section for Exercise 2 at the end of this unit before moving on.

Exercise 2c: Bridge Competition Trial 2

Given what you've now learned about the various stresses experienced by elements of truss bridges, the design of such bridges should make a little more sense. Let's see if you can apply the understanding you have gained of the three stresses, compression, bending and tension, to produce a stronger bridge in a second trial.

Basically, the members of a truss are arranged in such a way as to distribute the load to minimize the bending stresses applied to each individual member while maintaining a stiff, strong, and lightweight structure. To do so, the members are commonly distributed in triangular groupings, as in Figure 8 below.

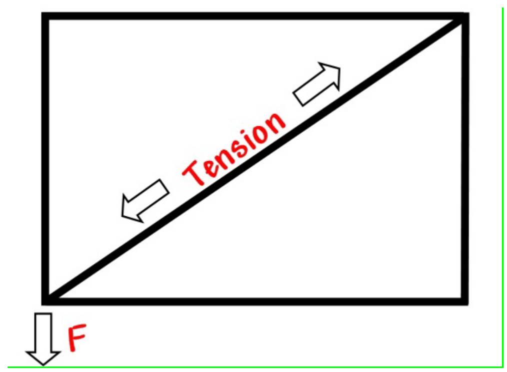


Figure 8. Arrangement of elements of a truss in a triangular configuration.

When this pattern is repeated, a structure suitable for use in bridges is obtained, as shown in Figure 9.

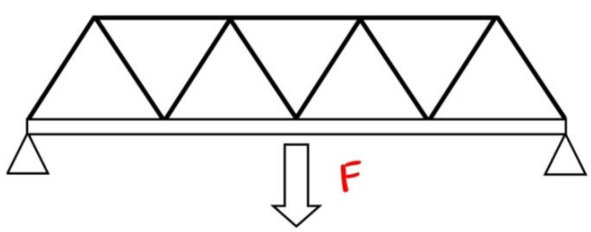


Figure 9. Repetition of triangular arrangement of elements in a truss bridge.

- Examine the bridges each team has developed under Trial 1 and determine which designs provided the best strength-to-mass ratios. There are many types of truss constructions you could have used. Compare your bridge designs to the picture of a truss bridge in Figure 9 above.

- Can you think of any anatomical structures in animals that look similar to the bridges? If your answer was "a backbone," then you are very clever! In fact, in 1917, D'Arcy Thompson, a Scottish biologist and mathematician proposed the very same analogy in his most famous work, *On Growth and Form*, in which he compared the front and hind limbs of a vertebrate to the piers of a bridge, and the spinal column to the bridge's span. In truss bridges, the materials used and their arrangement are very important to the strength and integrity of the bridge. Likewise, the shapes and arrangements of bones in an animal's body are important in supporting the animal. Take a look at the internal structure of a bird wing bone compared to that of a building truss, shown in Figure 10. Bird wings are designed for maximum strength and minimum mass.

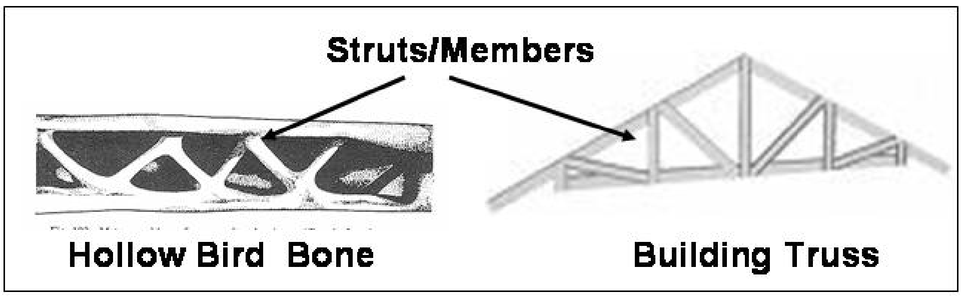


Figure 10. Cross section a bird ulna (arm bone) compared to a building truss used in construction (from D'Arcy Thompson 1917).

- Find the rat skeleton included in the materials for this unit, and examine it carefully. Can you see the similarities to the structures of truss bridges?
- Also, note the arched structure of the rat's spine.

The prominent upward arch of the rat's spine, as well as the arch seen in the spines of apes (see Figure 11) is typical of that seen in **quadrupeds** (animals that walk on four legs). The arch shape results in compression on each of the vertebrae of the backbone which reduces stresses due to tension and bending. This leads to a strong and stable structure. Manmade arches are some of the strongest structures in the world. A great illustration of this principle in human architecture is the structure of the ancient Roman aqueducts which transported water from distant sources to towns and cities (Figure 11). These aqueducts still stand today after over 2000 years of exposure to the elements.

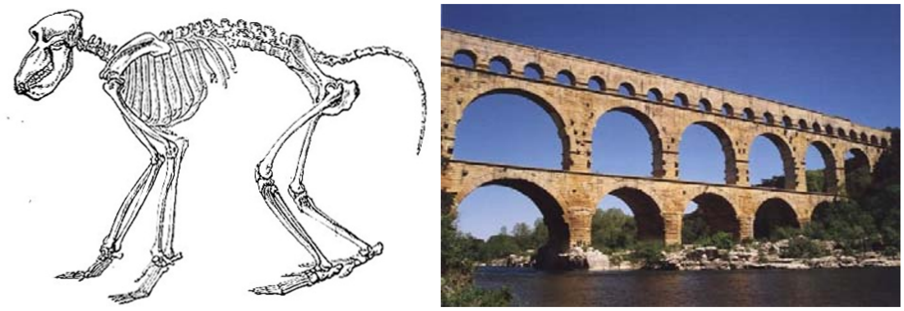


Figure 11. Arches: (left) ape skeleton; (right) Ancient Roman aqueducts.

In this second trial, each team will have the opportunity to design a bridge that better mimics the design features demonstrated by quadrupeds.

Procedure:

- Each team should research using the web to examine the structure of vertebrate skeletons, paying particular attention to the backbones as well as the hip and support limbs of more massive species such as buffalo and elephants.
- Review the characteristics of the most successful bridge designs from bridge building trial 1. Discuss: How do these characteristics compare to quadruped skeleton of the small rat and to those found on the web?
- Examine Figure 12 below for some examples of truss designs. Feel free to incorporate any combinations of these truss styles and any of your own, as well.
- Repeat the steps of Exercise 3a in designing and testing a second bridge, this one having two pairs of supporting piers equivalent to the front and rear pairs of legs of a quadruped mammal.
- Answer the following questions.

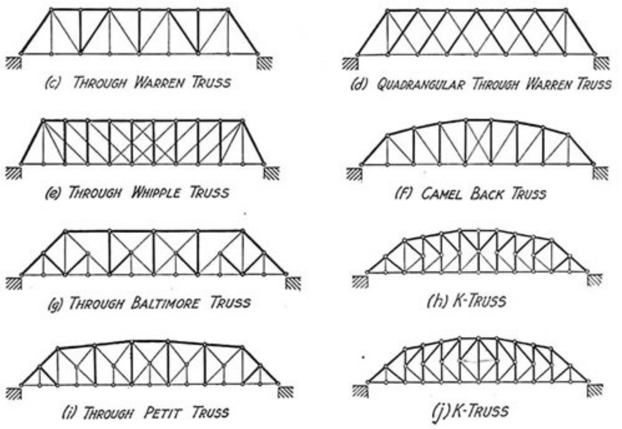


Figure 12. Examples of various bridge truss types.

Q3. Consider the forces of tension, compression, and bending in the case of bipedal animals (animals that walk on two hind legs) like the human shown in Figure 13:

a) Which force is most limiting/important in the case of the bipedal mammal?
b) Does the curvature of the spine help to minimize the effects of that force?
c) If not, why does curvature exist?

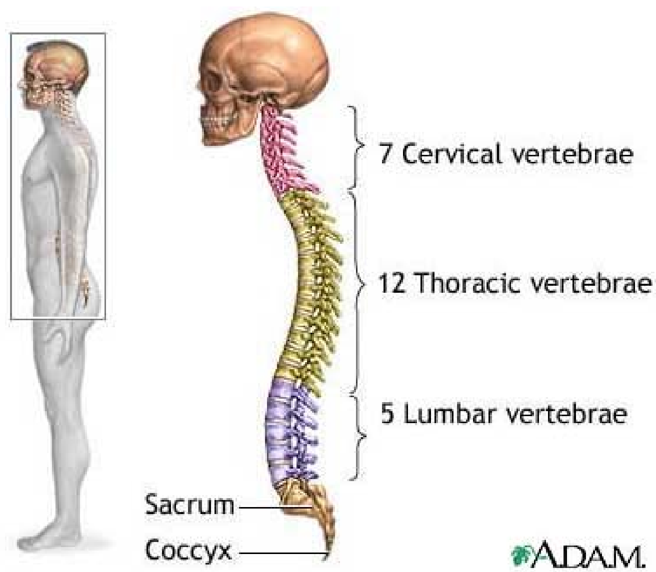


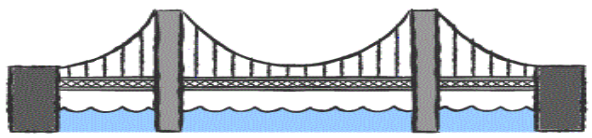
Figure 13. The human spine as characteristic of a bipedal organism.

Q4. In one of the most spectacular bridge collapses in history, the Tacoma Narrows Bridge fell into the Puget Sound in 1940, shortly after it opened. At the time, it was the third longest suspension bridge, 5939 ft. The deck of the bridge fell 195 feet into the water and the splash it created was 100 feet high.

a) Convert all measurements to metric equivalents and show these.

b) Determine the ratio of the spray height to the drop distance?
c) How much larger was the drop distance to the spray height?

Q5. Compression and tension are the major forces that apply to suspension bridges like the one shown here.



Bridge span is the distance between bridge supports which might be land edges or piers anchored in the water body below the bridge. Where do compression and tension forces apply to this bridge and why would having a tower with support wires strengthen a bridge, permitting a longer span?

Open-ended Exploration:

- Students might test the effect of bridge arch on bridge strength in an open-ended competition where the goal is to span the greatest distance.
- Individual students could research using the web to find bridges for which type and span distance information is available. They might develop a bar graph showing bridges by type on the X axis and span distance on the Y axis, labeling each bridge and its distance within the bar itself as well as the axes.
- Students might examine additional mechanical properties of organism design discussed by Thompson, or suggested by themselves. For example, they might choose to examine tree shape as a function of size (tower construction), the jumping ability of fleas (springs), the process of walking (pendulums), or power generation versus speed in millipede and centipede gaits (gears). Students might also investigate technological advances in the construction of bridges, towers, buildings, skyscrapers, cables, beams, vehicle frames, and airplane body and wing structures, all of which follow the basic engineering principles observed in animal skeletons.

Exercise 3. Jaws are Levers

This set of exercises integrates hands-on use of simple tools with measurements and biomechanical models to understand how the jaw of a fish and beak of a bird work. Both in form and function, jaws resemble a pair of mechanical pliers. Like a pair of pliers, jaws grasp and hold items for handling. Fish and birds rely primarily on their jaws to handle food, as their forelimbs have become specialized for locomotion. The modified forelimbs of fish form fins for swimming, and those of birds form wings for flight.
Pairs of pliers are levers that gain a mechanical advantage in the application of a force to an object. The lever is a simple machine first used by the ancient Greeks in the 3rd Century BC to lift or move heavy objects. As shown in Fig. 1 below, a lever consists of:

1) A stiff length of wood, metal or some other material (beam) that rests on a point (fulcrum) on which it can rotate.

2) A load to be moved or repositioned.

3) A force (effort) to be applied in overcoming the load.

Figure 1 shows the three types, called “classes,” of levers. Each class of lever differs in the relative positioning of the fulcrum, load, and effort elements along the horizontal rod. Note that many tools combine two of the simple lever types shown in Fig. 1. In this case, two levers of the same class work together. These are referred to as double levers of the class type they belong to. For example, pliers consist of two Class 1 levers that work together in grasping and holding objects. Pliers are an example of a Double Class 1 lever.

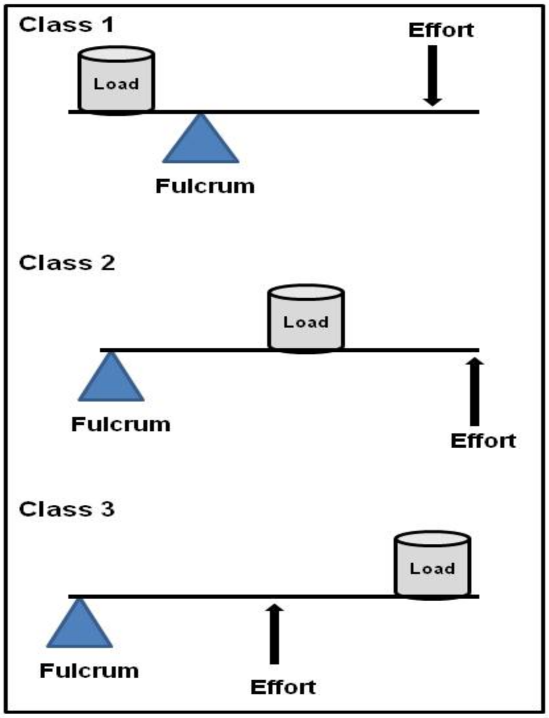


Figure 1. Three classes of levers, showing the different relative positions of effort exerted, fulcrum or pivot point, and load to be overcome. All are the single form of the lever.

We will experiment with Class 1 levers in this series of exercises. In Exercise 1, you will explore the Law of the Lever as you experiment with the simplest form of lever, a teeter-totter (wood beam in our case that pivots on a fulcrum) to understand the relationship between the position of the three elements relative to each other and the magnification of force (mechanical advantage) obtained. You will learn what tools commonly used by us are based on the principles of the Class 1 lever.

Animals need to grip food to tear, manipulate, and prepare it for consumption. In Exercise 2, you will relate different types of Double Class 1 levers to the food preferences of fish possessing particular jaw structures. In Exercise 3, you will examine the efficiency of bird beaks or bills of different shapes and sizes in handling different food types. And in Exercise 4, you will compete with classmates in a role-playing game that has parent birds using pliers of different shapes and sizes to gather seeds for their nestlings. You will quantify the fitness benefits of possessing a bill that provides the greatest mechanical advantage in completing this task, examining the effect of natural selection on bill size and shape.

Learning outcomes:

Student teams will:

- *Gain an understanding of the function of a Class 1 lever to deliver mechanical advantage versus speed of movement, depending on the position of the fulcrum along a beam.*
- *Contribute to setting up the test apparatus and establishing what measurements will be made.*
- *Calculate the mechanical advantage of a simple Class 1 lever by measuring effort force relative to effort and load beam distances.*
- *Present the results of mechanical advantage as it relates to fulcrum position graphically.*
- *Understand the relationship between jaw structure and function.*
- *Be able to explain how selection pressures can link structure and function.*
- *Be able to quantify absolute and relative fitness.*

Exercise 3a. The Lever: A Simple Machine to Lift or Move Objects

Lever systems are typically a solid beam or bar that can rotate on a support called a fulcrum (Figure 2). *Note that a fulcrum in the case of animal mechanics is an anatomical structure that may be a support or a hinge.* A lever is used for the transfer and modification of force and motion in doing work. Power (*P*) is defined as the rate of doing work and is the product of the force (*F*) on an object and the object's velocity (*v*):

$$\boldsymbol{P} = \boldsymbol{F} \times \boldsymbol{v}$$

The fact that power is always conserved underlies the mechanical transformations achieved through the operation of a lever. As long as no energy is lost from friction, for example, power input will equal power output. This means that the force that goes into a lever (also called effort) times the velocity the lever is moved will always equal the force times the velocity transferred to the load on the other end of the lever:

$$\boldsymbol{F_{input}} \times \boldsymbol{v_{input}} = \boldsymbol{F_{output}} \times \boldsymbol{v_{output}}$$

If there is a Mechanical Advantage (increase in force output) obtained from a lever, it is at the cost (decrease) of velocity of movement. Conversely, if there is increased velocity of movement in the output of lever action, then there is a corresponding cost decrease in the force of the action.

Exercise 3a1. Structure and Function of the Class 1 Lever in Terms of Mechanical Advantage

Let's assume that the Class 1 lever shown in Figure 2 does not scatter/disperse energy nor store it. This means no friction is generated by the beam rotating on the fulcrum. The force applied to the lever then equals the force output, and the ratio of output to input force is given by the ratio of the distances from the fulcrum to the points of application of these forces.
This relationship is known as the **Law of the Lever**:

$$\frac{F_L}{F_E} = \frac{E}{L}$$

F_E is the effort force
E is the length of the effort arm
F_L is the load force
L is the length of the load arm

(Equation 1)

The above equation can be read as**:** the ratio of the force of the load to the force of the effort is equal to the length of the effort arm divided by the length of the load arm.

When the effort applied to a lever comes from the weight of an object, this law may be represented in terms of the weights involved using $F = Mg$ with M as mass and g representing acceleration due to gravity:

$$\frac{M_L g}{M_E g} = \frac{E}{L}$$

or equivalently by reducing to:

$$\frac{M_L}{M_E} = \frac{E}{L} \qquad \text{(Equation 2)}$$

This last equation can be read as: the ratio of the mass of the load to the mass of the effort is equal to length of the effort arm divided by the length of the load arm.

Let's solve the following problem using the second version of the **Law of the Lever** (Equation 2).

If the length of the effort arm (E) of a Class 1 lever (Figure 2) is 1 meter, the length of the load arm (L) is 0.5 meters, and you add a mass of 0.5 kilograms to the effort arm, then how many kilograms of load will the lever be able to lift?

$M_L/M_E = E/L$ becomes $M_L/0.5 = 1/0.5$

Then $M_L = 1$ kilogram, which means that you can lift up 2 times the force that you push down ($F_L/F_E = 1$ kg/0.5 kg = 2).

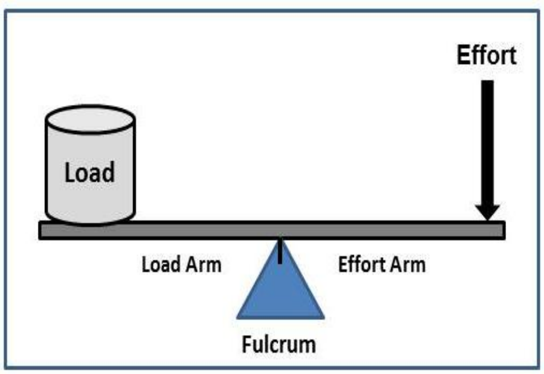


Figure 2. A simple Class 1 lever showing that the effort force transmitted through a beam positioned on a fulcrum can cause the movement of a load in the opposite direction to it. (The fulcrum on which the beam rotates divides the beam into effort and load arms.)*If effort is applied in the direction of the arrow, in which direction do you expect the load to move?*

Your goal in this exercise is to perform an experiment to physically explore how changes in the position of the fulcrum in a Class 1 lever offer different advantages in moving a load. You will use a real lever to find out how much effort it takes to move a load at six different test fulcrum positions. Where you place the fulcrum will determine the lengths of the load and effort arms. You will compare the results you obtain with calculations of the **Mechanical Advantage** (the ratio of force achieved to force exerted to lift a load) that are offered by the different fulcrum positions you test.

You may complete this exercise in teams of three or four students taking turns using the Class 1 lever system provided in this unit as the rest of the class works on other activities. Alternatively, this can be a teacher led exploration using this apparatus.

Setting up the Class 1 lever test apparatus

- Find the following lever system materials shown in **Figure 3**: fulcrum pin, balance support, and a 50-cm-long wooden beam (with pictured attached spring scale, bucket for BB 'coins' and bubble level), and BB 'coins'.

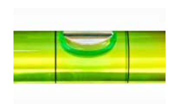
Fulcrum pin	Balance support	Spring scale	Metal bucket + BB 'coins'	Bubble Level
			 	 (beam is level when bubble is between lines)

Figure 3. Materials needed for examination of the Mechanical Advantage of a Class 1 lever as a function of fulcrum position.

- Place the balance support on the corner of a table or on a stack of books to make room for the bucket and spring scale.
- Slide the fulcrum pin into the center hole of the beam and rest on the balance support as shown in Figure 3 above. This fulcrum pin will later be moved from place to place to adjust the relative lengths of load and effort arms.
- Load the bucket with approximately 300–310 grams of BB 'coins'.

Your set up should resemble the one pictured in Figure 4.

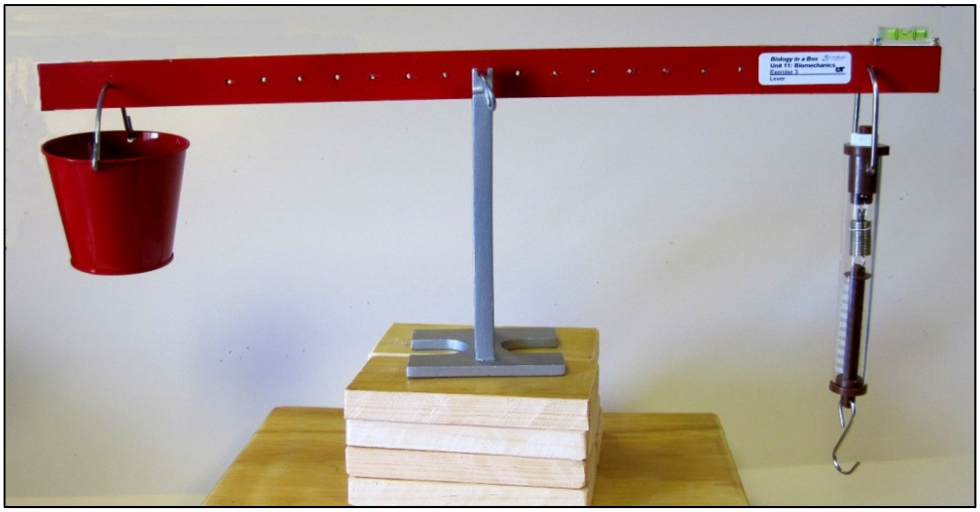


Figure 4. Apparatus for testing the mechanical advantage of a Class 1 lever.

- Each student should have a pencil and notebook paper for recording results and making calculations.

Team Exploration

- The teacher divides the class into teams of 3–4 students.
- Before starting the experiment, each student will copy Table 1 onto a sheet of notebook paper.
- Note that in this experiment, measurements of weight are proxies for force (see Equation 2 previously).

Table 1. Mechanical Advantage Experiment Data: *Remember the Law of the Lever:* $F_L = F_E E/L$*, where* F_E *is the effort force, E is the length of the effort arm,* F_L *is the load force and L is the length of the load arm*

Trial (and position letter)	Effort Arm Length (E)	Load Arm Length (L)	Effort Force (F_E) (spring scale reading)	Load Force (F_L) $F_E \times E/L = F_L$	Mechanical Advantage F_L/F_E
1					
2					
3					
4					
5					
6					

- As can be seen from Table 1, the students on a team will record data for six fulcrum positions in all (out of fifteen options).
- Team members should decide among themselves which effort arm versus load arm distances they will use in each of the six trials and list these positions in the first column of Table 1. Record the distance from the position to the bucket handle (load) and to the spring scale handle (effort) in centimeters for each trial. For example, at the central fulcrum position (H), the load and effort arms are each 20 cm in length.
- Move the fulcrum pin to the Trial 1 position and pull down on the spring scale hook until the bubble level indicates that the lever bar is horizontal. Record the effort measurement shown on the spring scale in grams.

(On a Class 1 lever, the force applied has to equal the weight of the object for the beam to be perfectly level. You will use the bubble level provided (Figure 4) to determine at what spring scale reading the effort force matches the load force.

- Repeat the above step for the remaining five trials. Partition the tasks among group members (e.g., setting up the apparatus for each trial, pulling down on the spring scale to match the force of the load, reading the measurement of force on the spring scale, determining when the beam is level, acting as scribe to fill in elements that need to be recorded in the table.)
- <u>Each team member should separately calculate the mechanical advantage obtained for each of the trials</u>.
- When finished compare the results and make sure that all team members agree on them.
- Report your results in a class discussion.

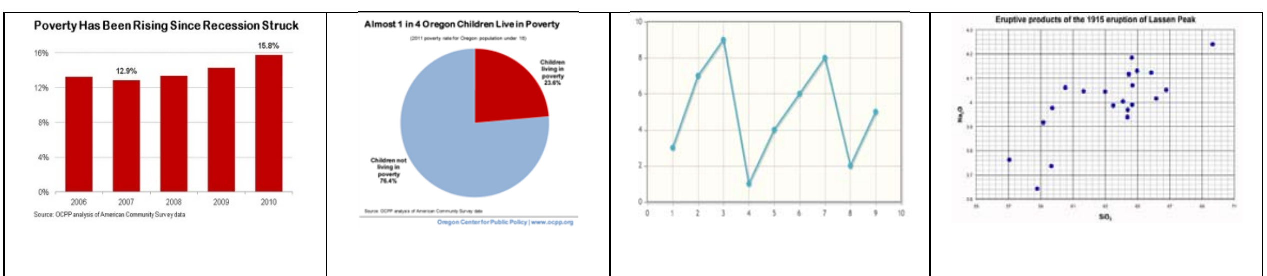
Teacher Led Experiment

- Each student will write his or her name on a small sheet of paper along with a suggested fulcrum position for one trial of the experiment you will be completing.
- The teacher will draw a student's entry from the container, and that student will select two others to assist in completing the trial (i.e., set the fulcrum position, measure the load (L) and effort (E) arm lengths, and determine how much force is needed to balance the load provided for that fulcrum position).

- Each student should record the data for the trial in their own copy of Table 1.
- Repeat the process an additional five times, each trial involving a new fulcrum position and new set of assistants.
- Calculate F_L using the formula ($F_L = F_E$ E/L), and calculate the mechanical advantage of each fulcrum position. Record the answers in the table.
- Discuss the results of your trials. For example, which effort arm length relative to load arm length offered the greatest Mechanical Advantage and why?

Variations on this basic experiment might include: 1) establishing whether different load masses; or 2) the fact that the beam has mass itself will affect the mechanical balance relationships you have established in the initial trial experiment. Before completing the above variations, discuss whether variation in load mass, or beam mass will affect Mechanical Advantage.

Scientists summarize their results in the form of graphs/plots (Fig. 5). They use many different types of graphs to organize data because graphs provide a *visual display of information* so that changes or trends can be easily determined. The kind of graph we choose for our data depends on the type of experiment we conduct, and what we want the collected data to explain. If you want to compare different items within a group, you might use a *bar graph*. You can use a *pie chart* (the sections look like slices of pie!) to show the size of different elements within a group. A *line graph* uses points connected by segments to show how something changes in value (such as distance or time). A *scatter plot* is similar to a line graph but the data points are not connected by segments. A scatter plot is frequently used when one has many subjects or different trials that have been completed. For example, do frogs call more in warmer weather or cooler weather? A scatter plot can give you a visual representation of that information for many frogs by using temperature for one axis and number of call notes exhibited by each frog recorded at a given temperature for the other axis.



Bar graph	Pie Chart	Line Graph	Scatter Plot

Figure 5. Examples of various types of graphs.

Table 2 presents a chart with sample data that are used to make the line graph shown in Fig.5.

Table 2. Example data chart: Rates of Snack Consumption during a Party

Hour	M&Ms consumed per minute	Marshmallows consumed per minute	Peanuts consumed per minute
1	10	10	10
2	10	5	9
3	8	4	7
4	7	3	5

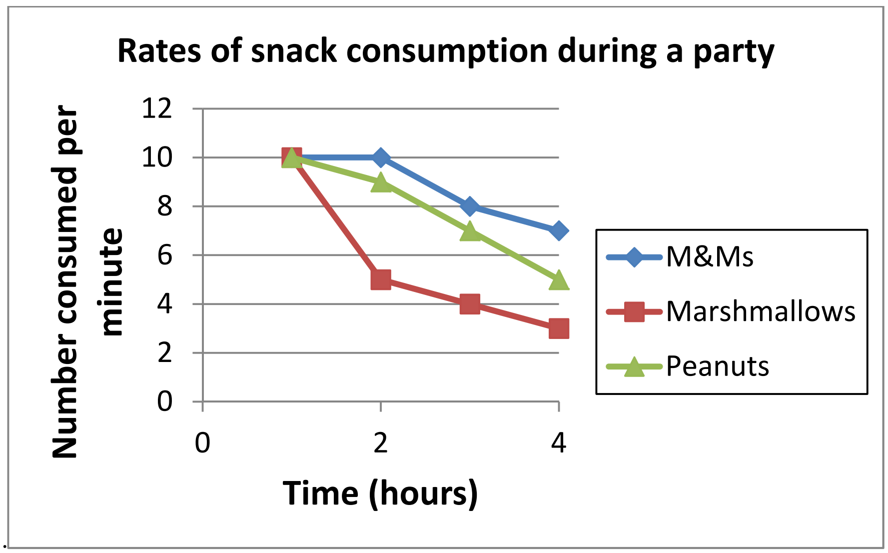


Figure 6. Line graph based on the rates of consumption of different snack types at a party presented in Table 2.

- Examine Table 2 and Figure 6.
- Using the snack consumption graph as an example, create a line graph comparing the lengths of the respective load and effort arms you recorded in Table 1 for your experiment to the Mechanical Advantage produced.
- Summarize in words the relationship you observe between the position of the fulcrum on your beam and the effort required to lift your load. Hint: Which arm should be longer to maximize the mechanical advantage of the lever and minimize the effort you need to exert to counteract the load?
- In your own words – what is meant by Mechanical Advantage?

Supersolver Question for Exercise 3a1

Given a lever of fixed total length T, let L =length of the load arm. Note that this implies that the length of the effort arm E = T – L. Express the Mechanical Advantage as a function of L when T = 1 meter, and draw a line graph for this function choosing a few L values between 0 and 1.Then, express Mechanical Advantage as a function of E and draw the corresponding line on the same graph. Compare your two lines and record your conclusions about the relationship between the two functions (L and E). Check your graphs and summary conclusions under the answer section of Exercise 3a1.

Exercise 3a2. Levers We Use Every Day

Now that you understand the relationship between the position of the fulcrum on the beam and the Mechanical Advantage achieved, we can consider the many tools that take advantage of this relationship.

- Your teacher will provide each team or individual with a copy of Figure 7.
- Examine each picture and name describing the everyday tool or implement presented in the figure.
- Using the lever class description presented in Figure 1, find and mark the fulcrum, effort location and direction, and load on your figure for each lever system shown.
- Note to which lever class each of these simple implements belongs.

  (Hint: Look first for the fulcrum. Then, figure out which is in the center: F (fulcrum),L (load) or E(effort)?If F, the lever is Class 1; if L, the lever is Class 2; if E, the lever is Class 3).

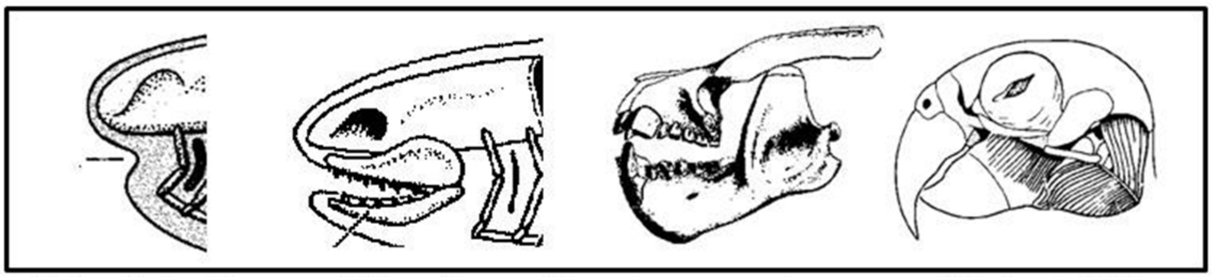
  Some of these examples are double levers - two copies of a lever working together.
- Find the double levers of each class on your sheet and note each by initialing the box with a DL (double lever) designation. While double levers share the same fulcrum, you may need to identify two positions for load and/or effort in these cases. Do so.
- Finally, circle the double Class 1 levers that you identify in Figure 7.

- Consult Exercise 3a2 in the answer sheet for classification of the various items shown in Figure 3 as well as notation of where the fulcrum, effort force and load are located for each. Correct your worksheet accordingly.

Figure 7. Common manufactured items that are examples of one of the three classes of levers.

Exercise 3b. The Vertebrate Jaw (Figure 8)

Early vertebrates lacked a jaw and hence, the Agnatha (Greek for "no jaws) were jawless fishes that also lacked paired appendages. The lampreys and hagfish are modern representatives of this ancient group of early vertebrates, which feed through an oral cavity bounded by lips, cheeks and gums (Figure 8a). The jaw appeared in later fishes, and is considered by biologists to be one of the greatest advances in the history of the vertebrates. Upper and lower jaws apparently formed from gill arches that supported the breathing apparatus of fishes (Figure 8b). Evidence for this shift in function from supporting gas exchange through gills to grasping jaws comes from examination of the gill apparatus in primitive versus more advanced fishes. The primitive jawless vertebrates, Agnatha (hagfish), possess nine gill arches, while the jawed vertebrates (Gnathostome fish) have only seven arches. The two missing gill arches in the Gnathostomes are assumed to have been modified to form the jaw itself with an anchor or brace beside the brain case. The gill arches, then, were not lost but persist in their new function as jaws.



a) Mouth lacking jaw in 1st fishes

b) Jaw from gill arches in later fishes

c) Mammalian jaw with teeth & muscle surface attachment

d) Avian bill & jaw musculature

Figure 8. Evolution of the vertebrate jaw.

The vertebrate jaw is composed of opposing lower and upper structures made of cartilage or bone that are used to grasp and manipulate food. The analogous mechanical device to the vertebrate jaw is a pair of pliers, a double Class 1 lever. Examine the pair of pliers in Figure 9. Note that the effort (force) is applied from two directions in the closing of the pliers handles (effort arms) through force applied by human hands. This serves to grasp and grip objects between the two load arms (jaws) of the pair of pliers through which the force is augmented. In the case of this tool, the Mechanical Advantage offered is equal to the following ratio:

$$\frac{\textit{Force Applied BY the Mechanism} \; [\textit{Jaws of Pliers}]}{\textit{Force Applied TO the Mechanism} \; [\textit{Handles of Pliers}]}$$

For example, if we apply 3 grams of force to the handles and the pliers applied 15 grams of force to the object they are gripping, then the Mechanical Advantage is (15/3) = 5. In the case of the pliers, the effort arms (E) are far longer than the load arms (L), since E > L, (E/L > 1).

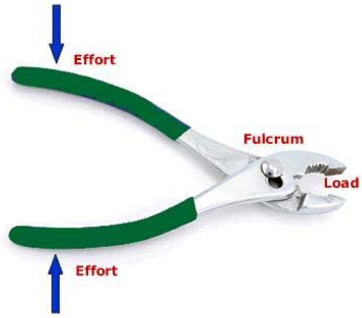


Figure 9. Drawing of a pair of pliers showing its relationship to a single Class 1 lever. Here two single Class 1 levers share the same fulcrum.

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Our joints, (think of your shoulder or elbow joint) typically offer a low mechanical advantage relative to that achieved through the use of a tool. This is because the muscles that provide the effort force to our joints are close to the fulcrum. Thus, the Mechanical Advantage is generally less than 1, since the lengths satisfy $E < L$ ($E/L < 1$). Unlike most of the muscles in the vertebrate body, the masseter muscle (Figure 10), which provides the effort force (In-force*), in the mammalian jaw is attached relatively far from the joint. This enables large forces to be exerted by the rear teeth in mammals. (For example, the human jaw has a Mechanical Advantage of 1.43.)

***Note the change in terminology used in animal mechanics:**
***effort force* = In-force (I) and *load force* = Out-force (O)**
***effort arm* = In-lever and *load arm* = Out-lever**

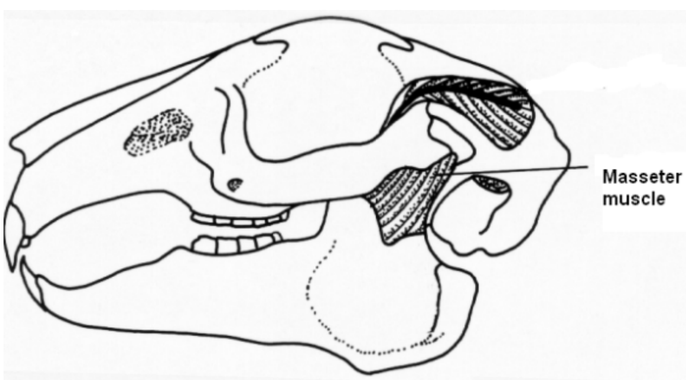
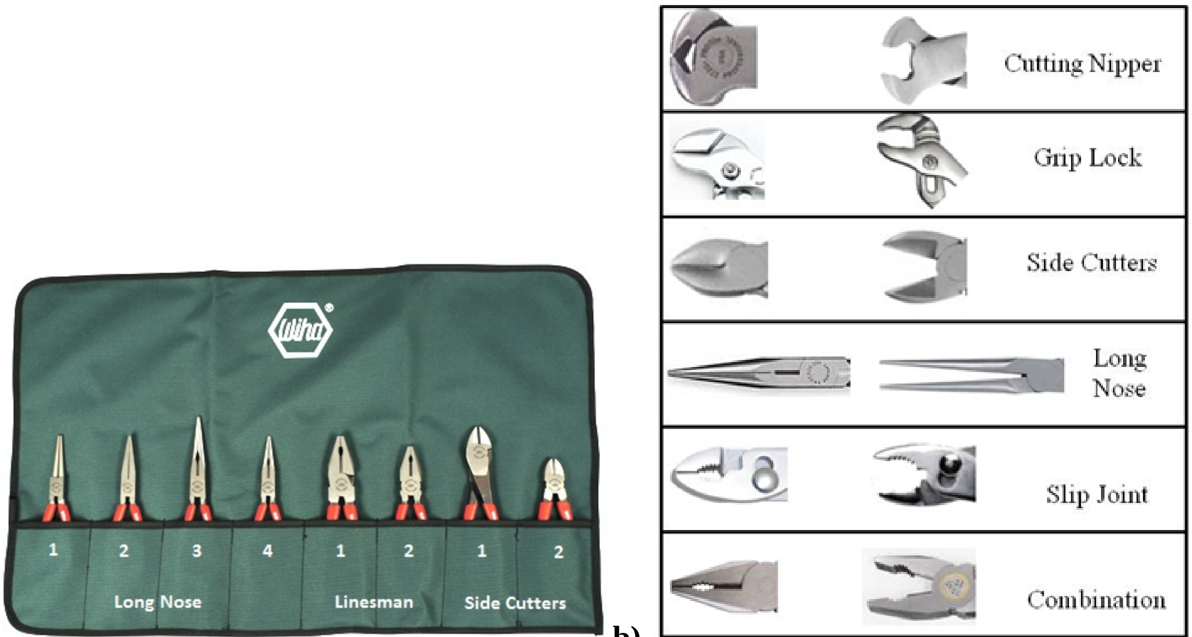


Figure 10. Image of the skull of a rabbit showing posterior location of the left side masseter muscle. Left and right masseter muscles provide the In-force in this lever system.

We will be using pliers of different types and sizes in this set of exercises to explore the relationship between diet and jaw shape in fishes' mouths and birds' beaks. Unlike humans who can choose different pliers from their toolkits (Figure 11a) in completing different tasks, animals must make the most of a single type. This leads to diet specialization, with mouth structure perhaps resembling one of the plier types shown in Figure 11b. We will assume that similar structure indicates similar function here.



a) b)

Figure 11. Pliers vary in function and size: **a)** workmen's tool kit showing different sizes of three pliers types; **b)** pliers types showing closed and open positions. (*Note the similarity between linesman pliers pictured in 11a and combination pliers in 11b. Combination pliers are linesmen pliers with a cutting edge added close to the fulcrum*.)

In the following exercises, you will use the images and descriptive names presented in Figure 11 in exploring the relationship between the diets that fish with different mouth morphologies and birds with different beak shapes exhibit. You will also examine feeding performance in a role playing competition involving birds with different beak shapes represented by various types of pliers. The feeding performance trial demonstrates the fitness consequences of possessing a feeding apparatus of appropriate shape and size for a given food type.

Exercise 3b1. Mouth Shape and Size Predicts Feeding Habits in Fish

Part I. Think-Pair-Share: Examining Fish Mouth Morphology

	a) Longnose Gar
	b) Blue-spotted Sunfish

- Examine the images of the Longnose Gar and Blue-spotted Sunfish above.
- Divide a piece of paper in half and use one side for the Gar and the other for the Sunfish.
- Write down 2–3 observations for each about the structure of their heads and mouths and how they are different.
- Do you think these fish must eat different things?
- What do you think they eat?
- Make your best guesses, and be prepared to justify your thinking.
- Now, draw a model of what the jaw structure looks like of these two different fish.
- Imagine the jaws are like two levers working together. Label on your model: (A) Where is the effort force applied? (B) Where is the load force? (C) Where is the fulcrum? (D)Where is the Effort arm and Load arm? *It does not matter if you are wrong or right. Just be prepared to justify your thinking.*
- Get together with a partner and discuss your observations and inferences – feel free to change your answers and modify your drawings based on sharing with your partner.
- Each group should share an observation they have made or an inference from their exploration. The teacher will list the unique ideas on the board.
- Next, your teacher will select some of the groups to draw their jaw models on the board.
- The class will discuss the differences observed among the drawings and which they think are more correct and why.

Part II. Class Observation and Discussion: Fish Feeding in Action!

Let's see some fish feeding strategies in action.

- Watch the two You Tube videos and write down your observations.
- Describe the feeding behavior that you see.
- First, let's check out a fish similar to the long-nosed gar:
- https://www.youtube.com/watch?v=f9JMgTxQrC4
- Next, let's look at some examples of different sunfish feeding: https://www.youtube.com/watch?v=WxzVqIxgd2Q.
- Pay special attention to how fast the different fish feed, how their jaws work, and what they are eating. How are these fish feeding behaviors different?
- Which of your class predictions from Part I were true? Which were not? Explain.

Part III. The Mechanics of Fish Feeding

As you have observed, the shape and size of a fish's mouth may limit the food types that a fish can consume as well as influence its efficiency in the capture and manipulation of food items. Three aspects, shape, size and lever structure, of the fish mouth should influence what food different species will feed on. Species differences in mouth morphology have developed in response to competition among fish for food. More species can coexist in the same area if they target different foods. You will have the opportunity to explore this idea first hand with fish and birds shortly, but first we need to discuss the mechanics of the animal jaw in a bit more detail.

Remember from our initial discussion of the lever that it is used for the transfer and modification of both force and motion, but that power is always conserved in these mechanical transformations. Thus, if there is a Mechanical Advantage obtained from a lever in the case of a long in-lever, it is at the cost to velocity or speed of the movement load arm (Figure 12b). Conversely, if the output of lever action is increased velocity of movement (long Out-Lever), it is at a corresponding cost to the force of the action (Figure 12a).

As a class, verify the relationship between In-Lever and Out-Lever speed versus force:

- Find the following materials in your unit box:
    - pliers with a short handle and long jaws (e.g. long-nose),
    - pliers with long handles and short jaws (e.g. linesman or slip-joint),
    - the bite force measurement device, and
    - a ruler.
- Test the force applied by each type of pliers by closing the jaws on the bite force measurement device and record the forces by lever type: longer In-Lever versus longer Out-Lever. Which provided greater compression?
- With the ruler, measure the distance between the tip of the jaws when spread open maximally and record these distances by lever type.
- Discuss your results. Why, for instance, can we equate greater distance between spread jaws with greater speed or velocity of tip closure in this case? (Hint: speed is the rate at which an object covers distance and velocity is speed with a direction.)

We mentioned earlier that vertebrate jaws tend to have the In-Force of the double Class 1 lever much closer to the fulcrum than is characteristic of mechanical pliers. As the lever pivots on the fulcrum, points further from this pivot move faster than points closer to the pivot. Force is lost but speed (velocity) is increased when the fulcrum of a Class 1 lever is positioned such that the In-Lever is short in length relative to the Out-Lever. This leads to lower force production, but higher speed of jaw opening and closure in fish (Fig. 12a vs. 12b). Thus, if the ratio of In-Lever to Out-Lever equals 0.1 in a fish species, the speed of jaw opening will be 10 times greater than its biting force.

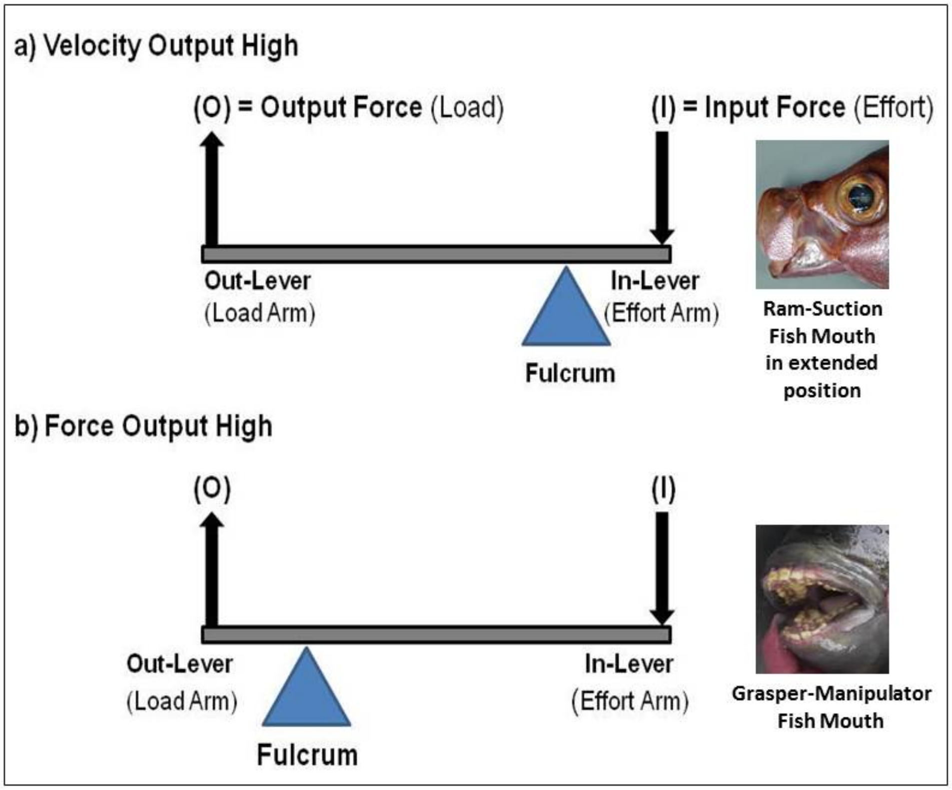


Figure 12. Relationship between fulcrum position and velocity versus force outputs in Class 1 lever systems in vertebrate jaws.12a) The Ram-Suction fish species and 12b) the Grasper-Manipulator fish species shown with the analogous lever design.

Although fish jaw morphology is far more complex than the simple lever depictions above, biologists have found that fish exhibit two main attack strategies depending on the ratio of In-Lever to Out-Lever lengths. The attack strategies are Ram-Suction and Grasper-Manipulator. *Remember from our earlier discussion that Power of a mechanical device is the product of force and velocity (speed) and that Power is always conserved. Thus, if force (Mechanical Advantage) is higher, speed of mouth opening and closing is lower and vice versa.* The jaws of Ram-Suction species exhibit lower In-Lever to Out-Lever ratios (approximately 0.1 to 0.2) (Figure 12a). This does not favor the crushing and chewing of prey, but produces the necessary high speed of jaw movement to capture and swallow whole swimming prey. This fish type thrusts or rams its closed mouth into a prey item and then rapidly extends the mouth forward to suck the prey in.

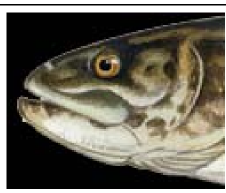
Figure 12a shows the extended mouth of a Ram-Suction fish in the suction phase of capturing a prey. Which pliers types shown in Figure 11 allow this latter action? On the other hand, Grasper-Manipulators utilize jaw force in securing prey that they bite. They have long In-Lever relative to Out-Lever) ratios (approximately 0.3 to 0.5) (Figure 12b). A fish with this jaw type applies a strong bite force so that it can grip the food item in its jaws for subsequent ripping, shredding or crushing. Teeth similar to our molars are present in many of the Grasper-Manipulator species. The lever mechanics differ between the two foraging strategies as shown in Figure 12 above along with an image of the mouth of a fish exhibiting the respective foraging strategy.

In this exercise, each team will examine images of fish mouths provided in Figure 13 and make decisions about this species as to: 1) whether it exhibits a Ram-Suction or Grasper-Manipulator feeding strategy; 2) what pliers pictured in Figure 11 its mouth most resembles and 3) what it feeds on. (Examine the diet items provided with this exercise and consult the web for making diet decisions for the various species.)

- The teacher will find the box labeled *Exercise 3: Fish Food Examples* and will spread the contents of the box out on a desk at the front of the room.
- The teacher will then divide the class into teams of 3–4 students.
- The teacher will provide each team with a copy of Figure 11 showing the potential pliers types, Figure 12 depicting the lever action of the respective foraging strategies, Figure 13 showing the fish species images and Figure 14 showing the potential food types.
- Students visit the spread of potential diet items and take notes on these prior to making decisions about diet type. They may also search the web to gain information about the diets of each fish, which will help them in deciding whether the particular fish is a Grasper-Manipulator as opposed to a Ram-Suction type.
- As a class, discuss the decisions made by each team. Attempt to reach a consensus as to attack strategy, pliers type and diet of the various species.
- Are you able to predict a species' diet by the shape of its mouth? What is the difference between the outward appearances of a Ram-Suction feeding apparatus versus that of a Grasper-Manipulator?
- Check your predictions for feeding strategy and diet against the observations of fish biologists under *Answers for Exercise 3b1* at the end of this unit.

See Figure 13 below, and on the following two pages.

	***Chromiscyanea* (Blue chromis)** **Attack Strategy:** **Pliers Type:** **Diet:**

	*Archosargusprobatocephalus* **(Sheepshead)** **Attack Strategy:** **Pliers Type:** **Diet:**
	*Cephalopholisfulva* **(Coney)** **Attack Strategy:** **Pliers Type:** **Diet:**
	*Hypoplectrus indigo* **(Indigo hamlet)** **Attack Strategy:** **Pliers Type:** **Diet:**
	*Ocyuruschrysurus* **(Yellowtail snapper)** **Attack Strategy:** **Pliers Type:** **Diet:**
	*Labidesthessicculus* **(Brook Silverside)** **Attack Strategy:** **Pliers Type:** **Diet:**
	*Amia calva* **(Bowfin)** **Attack Strategy:** **Pliers Type:** **Diet:**
	*Pomoxis annularis* **(Crappie)** **Attack Strategy:** **Pliers Type:** **Diet:**
	*Esoxamericanus* **(Redfin pickerel)** **Attack Strategy:** **Pliers Type:** **Diet:**
	*Lepisosteusoculatus* **(Spotted gar)** **Attack Strategy:** **Pliers Type:** **Diet:**

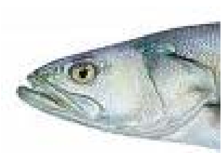
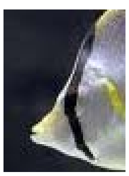
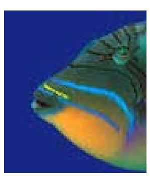
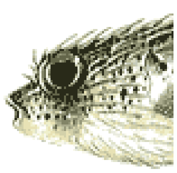
	***Percinasquamata* (Olive darter)** **Attack Strategy:** **Pliers Type:** **Diet:**
	***Melichthysniger* (Black triggerfish)** **Attack Strategy:** **Pliers Type:** **Diet:**
	***Cynoscion nebulosus* (Spotted seatrout)Attack Strategy:** **Pliers Type:** **Diet:**
	***Sparisomarubripinne* (Redfin parrotfish)** **Attack Strategy:** **Pliers Type:** **Diet:**
	***Chaetodonocellatus* (Spotfin butterflyfish)** **Attack Strategy:** **Pliers Type:** **Diet:**
	***Balistesvetula* (Queen triggerfish)** **Attack Strategy:** **Pliers Type:** **Diet:**
	***Diodonhystrix* (Spotfin porcupine fish)** **Attack Strategy:** **Pliers Type:** **Diet:**

Figure 13. Fish Species Table. Attack strategy potentially is Ram-Suction or Grasper-Manipulator. Potential diet items include fish, jellyfish, crabs, shrimp, crayfish, copepods and other crustaceans, algae, aquatic insects, coral, snails, clams, polychaete worms and sea squirts (tunicates). See Figure 14 for images of the food types and examine the physical examples available in the box. You may also look up the diet of each species on the web. Diet type will help you to identify the attack strategy.

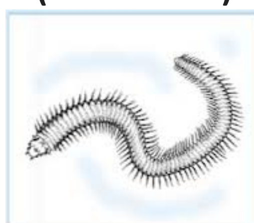
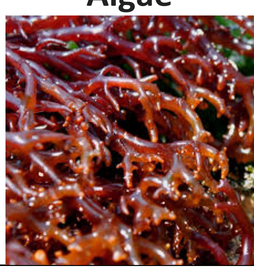
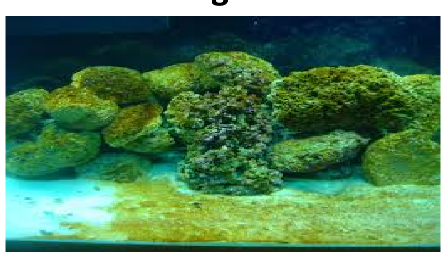
Jellyfish (Cnidarians) 	**Coral (Cnidarians)** 	**Coral (Cnidarians)** 
Clams (Molluscans) 	**Polychaete worms (Annelidans)** 	**Sea Squirts (Urochordates)** 
Aquatic Insects (Arthropodans) 	**Aquatic Insects (Arthropodans)** 	**Crustaceans (Arthropodans)** 
Algae 	**Algae** 	**Fish (Vertebrates)** 

Figure 14. Examples of the prey of different fish species exhibiting Ram-Suction vs. Grasper-Manipulator mouth types.

Exercise 3b2. Bird Beaks (Bills) as Simple Machines: From Feeding Niches to Individual Fitness

All organisms compete for resources that are important to their survival such as food, water, and a suitable place to live. Competition for food has been shown to lead to changes in the feeding apparatus of species because individuals inheriting variations on a trait that permit them to use a different resource will be favored by natural selection. In feeding on foods that are not used by other species, individuals may grow more quickly and produce more young than they would if they competed with other species for the same food source. They occupy a different niche. The dictionary's definition of a niche is that it is "a job, activity, etc., that is very suitable for someone."

In birds, the size, shape and strength of an individual's bill (scientists refer to a bird's beak as its bill) determines what it can grab and eat. The birds' bill is particularly critical for obtaining food because its front limbs have been modified for flight and cannot assist in grasping food. An excellent example of changes in morphology to avoid competition is seen in the shape and size of bills of birds inhabiting island systems such as the Hawaiian Island chain. Because the Hawaiian Islands are 4,000 kilometers from the nearest mainland, birds rarely reached them. Evidently a finch (Family: Fringillidae) was a successful immigrant to the Hawaiian Island chain because, with the exception of recent introductions, all 84 documented bird species on the islands are honeycreepers belonging to the finch subfamily *Drepanididae*. The finch is typically a seed-eater and has a bill designed for cutting or crushing the seed covering (Figure 15). That first finch gave rise to the wide variety of bill types seen in the Hawaiian honeycreepers (Figure 16). Biologists conclude that a single finch species that arrived on the island has undergone changes in bill structure through time to fill the available feeding niches on each of the islands in this chain. The Hawaiian birds have diverged sufficiently in structure and in the feeding niches they occupy to merit subfamily status.

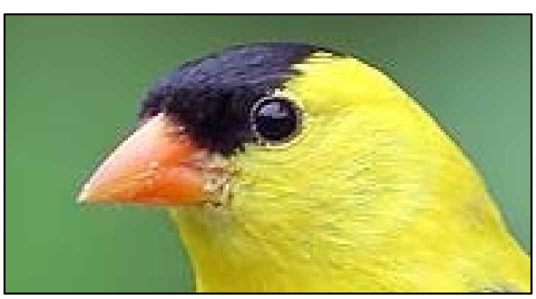


Figure 15. The American Goldfinch, showing beak adapted for feeding on seeds characteristic of the finch family, Fringillidae.

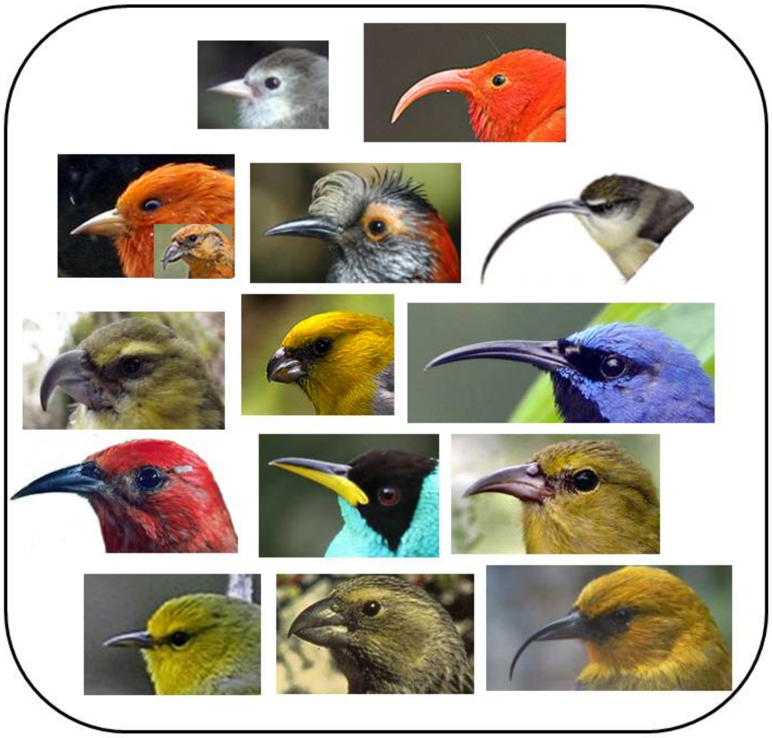


Figure 16. Examples of the species of Hawaiian honeycreepers showing the diversity of bills exhibited among them in Hawaii.

Your goal in this exercise is to partition the Hawaiian honeycreeper bird species pictured in Figure 16 into diet type (fruit, seed, insect and nectar) based on examining the double Class 1 lever tools provided that resemble the range of bills present and the different classes of food types available.

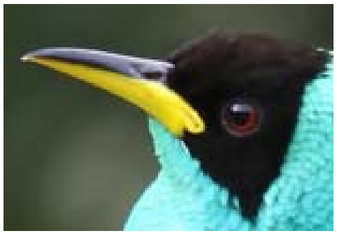
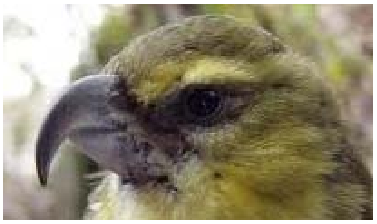
Procedure:

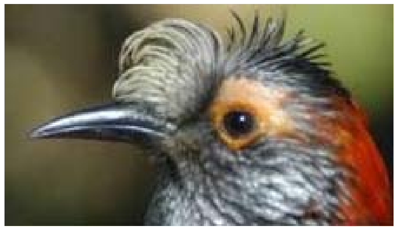
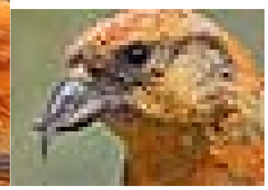
- The teacher divides the class into teams of 3–4 students.
- Each team should have a chart showing the bird species images labeled A, B, C, etc., with space to record your decision as to what the diet of that species is.
- The teacher locates the container labeled *Exercise 3: Pliers* which contains tools that mimic beak types, as well as the bag labeled *Exercise 3: Bird Food Examples* for examples of the food items birds might need to manipulate to obtain the nutrients they seek. **Note that these food items are permanent materials that many classes will be using; please do not attempt to use the tools to procure or manipulate them as they could be damaged.** Your teacher might supply nuts, seeds, etc. for actual manipulation. If so, be sure to clean the tools before returning them to the container at the end of the exercise.
- Once teams are through filling in the chart, examine the group of species as a whole and label G for those that you feel may be feeding generalists (i.e.,

switch to feeding on three or more of the food types depending on the abundance of particular foods at the time).

- Do the same for feeding specialists using an S. The bills of the specialists may limit them to feeding on a particular food type.
- Once all teams have filled in their charts, record the results on the board at the front of the room and through discussion, attempt to reach a consensus as to what each bird species diet is and which species might be considered feeding generalists versus specialists.
- Check your results under *Answers for Exercise 3b2* at the end of this unit.

A		**DIET**
B		**DIET**
C		**DIET**
D		**DIET**
E		**DIET**

F		**DIET**
G		**DIET**
H		**DIET**
I		**DIET**
J		**DIET**
K		**DIET**
L		**DIET**

M		**DIET**
N	 	**DIET**

Exercise 3b3. Pliers and Finch Fitness: Natural Selection

Under Exercises 3b1 and 3b2, you considered fish and bird species adaptations in mouth structure that correspond to particular feeding strategies. However, the strongest competition for limited resources occurs among individuals within populations. Natural selection is a process that operates within each generation through differential reproductive success. That is, individuals possessing inherited traits that favor their survival and subsequent production of offspring pass these traits on to their offspring. The proportion of individuals in a population that possess a favorable trait will thus increase over evolutionary time (multiple generations). In this exercise, individuals possessing a successful pliers type will become more prevalent in the class through repetitions of the experiment you will be completing.

You may recall from Exercise 3b2 that the Finch family from which the honeycreepers are derived are seed feeders. Let's assume that we started with a population of *Pliers finch*, a finch species that had the same basic 'pliers' bill type. However, genetic mutations through time have produced several novel hinge joints (pliers types), each of which is best suited for feeding on a particular type seed. Today, we have a single, variable population of the *Pliers finch* possessing variation in pliers shape and size (i.e., slip joint, needle nose, mini and larger diagonal, long nose, and mini and larger linesman pliers).

In this exercise, you will quantitatively determine the relative contribution of individuals possessing the various pliers morphologies to the next generation of your *Pliers finch* population. You will be determining the fitness of each trait variant of the pliers present.

- Divide the class into groups of 5 individuals: two parents and three chicks in each family group.
- The chicks will stand around a desk (the parent's nest) begging for food. Each will have a cup of the same color, but with a different number (1, 2, or 3).
- The parents will be given a pair of pliers, reflecting their bill phenotype. (We assume that the population exhibits assortative mating. This means that females choose male mates that have the same bill type as theirs.)
- Place the plastic bin that matches the nest color along the wall in the hall outside of the classroom or some equivalent distant location. This bin will be filled with dried beans provided by the teacher.
- The male and female parent will take turns collecting food for their chicks.Parents alternate flying out to the feeding grounds (hall) and picking up one bean with their pliers to carry in the pliers back to their offspring. ***The foraging parent bird must have one arm behind his/her back when collecting and delivering a bean to offspring.***
- The parent "feeds" this bean to one of its begging chicks. *(Beans do not need to be equally distributed among the chicks in a nest. Better beggars may obtain more food! Chicks should compete for the beans their parents bring to the nest!)*
- Repeat trips by alternate parents to the feeding ground until the teacher ends the feeding session.
- Each family group then counts the number of beans in each of their chick's cups and writes these values on a piece of paper for transfer to the board at the front of the room.
- Fill in a table recreated on the board at the front of the room that looks similar to the one shown below.
- Some chicks may have received too little food to have survived. (Those that receive less than the average for the class.) They will have failed to survive to reproduction and offer 0 fitness points to the parents. The parents will receive one fitness point for each successful offspring (those that received the number of beans equal to or greater than the average).

Below is the summary table to reproduce and fill in.

Pliers Type	A. # Beans Chick 1 Obtains	B. # Beans Chick 2 Obtains	C. # Beans Chick 3 Obtains	D. # chicks offering 0 fitness to parents[1]	E. Parent Fitness 0-3	F. Relative Fitness[2] Pliers Types
Slip joint						
Needle nose						
Mini diagonal						
Larger diagonal						
Mini linesman						
Larger linesman						
Sum # of beans						

[1]To determine column D, first find the class mean number of beans/offspring = Sum of columns A, B, C divided by total number of chicks (21) in this example. All offspring that obtained more beans than this mean value give the parents an extra point for fitness.
[2]Relative fitness of the respective pliers types = Fitness score from column E/Number of Plier Types (6in this example).

The fitness data you have collected for pliers type above (Column E) permits you to determine the relative representation of the different pliers types in the next generation. Stabilizing selection will have occurred, if pliers type representation is not expected to change because all phenotypes (pliers types) offered equal fitness to the parents. The status quo is maintained if that is the case.

- Discuss factors besides pliers type that may have influenced the foraging success of particular nests.

Exercise 3b4. Supersolver Questions

Find answers to these questions under **Exercise 3b4** at the end of this unit.

Q1. Where in the beak should a bird grip a seed to break it open most easily?

Q2. If an input of 0.6 N is required to lift a rock of 36 N, what is the actual Mechanical Advantage? Show your calculations.

Q3. What is the correlation between lifestyles of animals and their jaw Mechanical Advantage and velocity ratios?

Q4. Would you expect to find a high Mechanical Advantage and a high velocity ratio in the same animal jaw? Explain

Q5. Does a generalist feeder seem to have any advantages over a specialist? Justify your answer.

Exercise 4: Drop, Squirt, Throw: Projectile Motion

Projectile motion is a physical principle that assumes that once an object drops, or is thrown or projected, it continues in motion and is influenced only by the downward force of gravity. Projectile motion falls under the discipline of physics known as kinematics (the study of motion). It is an important branch of mechanical engineering as it has applications to ballistics and, in fact, ballistics is often referred to as the study of projectile motion. Nevertheless, organisms that drop from trees or plants to escape predators, jump as a form of locomotion (including fleas), or throw or project materials (monkeys, elephants, spitting cobras and blood squirting horned lizards) do so under the physical principles controlling vertical and horizontal motion. Projectile motion assumes that air resistance is negligible as objects drop from rest (referred to as free falling) or are thrown, or projected, in a path (called a trajectory) such as a golf ball in flight or a pitched or hit baseball. This latter form of projectile motion is referred to as launching. An object in free fall undergoes vertical motion only, while a launched object experiences both vertical and horizontal components of motion.

In **Exercise 4a. Free Fallin'**, we will explore how projectile motion relates to animals that drop from tree branches to the ground when disturbed by predators or in pursuit of prey or competitors. In **Exercise 4b. Launching**, we will examine angular projectile motion as it relates to plants and animals that project or launch seeds and fluids. In **Exercise 4c. Stop the Monkey's Escape**, we will combine the two types of projectile motion examined in Exercises 4a and 4b in a complex context that combines elements of both dropping at rest and launching. Finally, students will examine technological applications that use the principles underlying projectile motion in open-ended exploration.

Exercise 4a. Free Fallin'



In this exercise, you will explore the parameters that determine how long it will take an animal to reach the ground as it drops from a branch or ledge for any number of reasons (e.g., to escape from a predator, chase a competitor, join a mate or other social group members, to leave a resting perch to seek food). From the images above, you can see that people free fall for pleasure. Clearly, the most important of the above activities is dropping off of a plant, tree, or perch to escape predation, which occurs in animals lacking wings that are preyed on by arboreal predators. For example, a defensive tactic that caterpillars of many species exhibit on detecting the presence of a predator such as a spider, wasp, bird, or lizard is to drop off the plant or tree onto the ground. Once there, they seek shelter in the litter.

Procedure:

- Divide into teams of 4 students. Each team should receive a measuring tape, a stopwatch, and one each of the balls of various materials available in the bag labeled Exercise 4: Free Fallin' in the Unit 11 materials box.
- Discuss locations where you can drop each ball from different heights. These will need to be sufficiently high for drop times of seconds, say a stairwell offering different heights, a balcony, or bleachers in a stadium or gymnasium.
- Measure and record each of the heights used for the groups' trials on a table you make similar to the one shown below.
- Before completing the experiment, each team should discuss among themselves what they expect the outcome of their experiment will be and why they should complete three trials at each height for each ball type.
- The teams should share their opinions about these two questions with the class.

Height (m) Distance of Free Fall				
	Ball #1 mass			
	Trial 1	Trial 2	Trial 3	Mean Secs
1				
2				
3				

Height (m) Distance of Free Fall				
	Ball #2 mass			
	Trial 1	Trial 2	Trial 3	Mean Secs
1				
2				
3				

Height (m) Distance of Free Fall				
	Ball #3 mass			
	Trial 1	Trial 2	Trial 3	Mean Secs
1				
2				
3				

- For each trial, drop the balls one at a time from each height, starting the stopwatch at the instant the ball is released and stopping the watch at the instant the ball hits the substrate. Record this time and retrieve the ball.
- Present your data in a line graph with distance on the X axis and time of falling on the Y axis for each of the means of the three trials. (Read the following section on graphical presentation of data if you are unfamiliar with how to produce line graphs.)

On Graphical Presentation of Data

Scientists summarize their results in the form of graphs and plots (Figure 1). They use many different types of graphs to organize data because graphs provide a *visual display of information* so that changes or trends can be easily determined. The kind of graph we choose for our data depends on the type of experiment we conduct and what we want the collected data to explain. If you want to compare different items within a group, you might use a *bar graph*. You can use a *pie chart* (the sections look like slices of pie!) to show the size of different elements within a group. A *line graph* uses points connected by segments to show how something changes in value (such as distance or time). A *scatter plot* is similar to a line graph but the data points are not connected by segments. A scatter plot is frequently used when one has many subjects or different trials that have been completed. For example, do frogs call more in warmer weather or cooler weather? A scatter plot can give you a visual representation of that information for many frogs by using temperature for one axis and number of call notes exhibited by frogs recorded at a given temperature for the other axis.

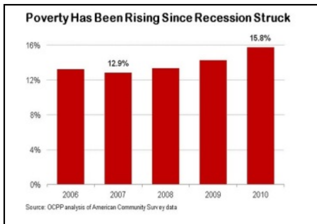
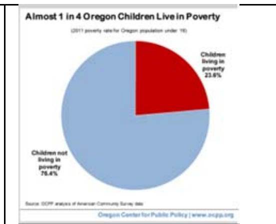
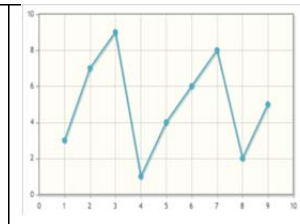
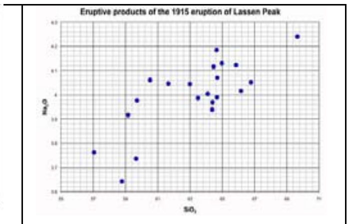
			
Bar graph	Pie Chart	Line Graph	Scatter Plot

Figure 1. Examples of various types of graphs.

Table 1 presents a chart with sample data that are used to make the line graph shown in Figure 1.

Table 1. Example data chart: Rates of Snack Consumption during a Party

Hour	M&Ms consumed per minute	Marshmallows consumed per minute	Peanuts consumed per minute
1	10	10	10
2	10	5	9
3	8	4	7
4	7	3	5

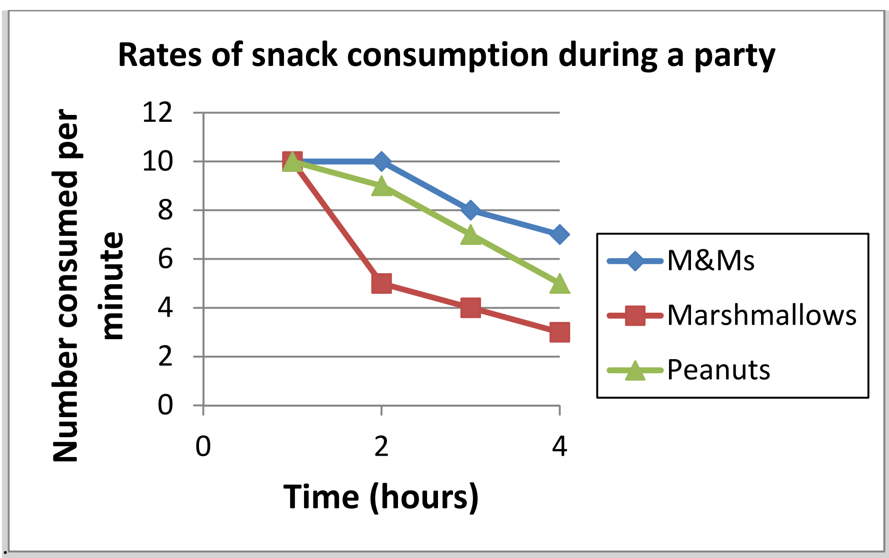


Figure 2. Line graph based on the rates of consumption of different snack types at a party presented in Table 1.

- Based on your observations of the free falling of the balls and experimental data, answer the following questions:

Q1. What influence does height from which an object is dropped have on the amount of time it takes for an object to hit the ground?

Q2. Does the material/mass of an object influence its free fall?
Thus, would an organism that has less mass be able to fall faster to escape an organism dropping after it with greater mass?

Q3. Which object do you think hits the ground with the highest speed/velocity?

Q4. If you were to throw an object downward, would it take more or less time for it to reach the ground than if you dropped it? (*You might repeat the experiment to answer this question.)*

Q5. Besides mass and distance, what other factors could affect how much time it takes for a falling object to reach the ground?

Q6. We have learned from this exercise on free fall that all objects regardless of their mass accelerate downwards at the same rate due to gravity. Why then, may a leaf swirl downwards in a glide-like matter?

- Check your answers at the end of this workbook, and then, as a class, discuss the physics and equations involved in the motion of falling objects.

Exercise 4a1. The Numbers Behind Free Falling (For grades 9-12)

As you have seen from your trials and graphical presentation of your results, there are relationships between the height from which an object falls and how long it takes to hit the ground. You have also seen that mass doesn't have much of an effect. Luckily for engineers and everyone else, the 16th Century Italian physicist, mathematician, engineer, astronomer and philosopher Galileo recognized that free-fall motion is the key to understanding all motions of bodies (Fig. 3). Through experiments he established that in the absence of air or other resistance, an object will accelerate downward at a certain rate regardless of its composition, shape, weight, surface size etc. The mathematical relationship between free falling objects and acceleration due to gravity was subsequently established so that one does not need to complete experiments such as the one you completed over and over again. At a given location on the Earth and in the absence of air resistance, all objects fall with the same uniform acceleration. We call this the acceleration due to gravity on Earth or *g* (approximately 9.8 m/s^2, or 9.8 m/s/s [meters per second per second]).

Figure 3. Free fall shown through time lapse photography. Photograph shows a falling weight captured on film by a strobe light which is flashing thirty times/second. Observe that the distance traveled by the falling weight in each successive interval is increasing at a regular rate.

Velocity is the rate at which an object changes its position. For example, a ball rolled straight across the floor that moves two meters in one second would have a velocity of two meters per second (2 m/s). Note that velocity is not equivalent to speed. If the same ball moved forward 1m and then backward 1m in a second, it would have speed (rate at which an object covers distance) but not velocity since there was no resulting change in position.

From many more experiments, physicists came up with an equation to represent the relationship between the time an object has been falling and its relative position. The height *h* above the ground of an object released at starting height h_0 and with the initial velocity v_0 (in the vertical direction) is

$$h = -\frac{1}{2}gt^2 + v_0 t + h_0$$

Where *g* is the acceleration due to gravity (9.8 m/s^2). If the object starts out with zero initial velocity (dropped, $v_0 = 0$), the equation becomes

$$h = -\frac{1}{2}gt^2 + h_0$$

.

And, if we solve for the time t when the object hits the ground (when $h = 0$) we obtain

$$0 = -\frac{1}{2}gt^2 + h_0$$

and

$$h_0 = \frac{1}{2}gt^2$$

.

Solving for t gives

$$t = \sqrt{\frac{2h_0}{g}}$$

.

Notice that if the starting height is increased, then the time t (to hit the ground) is increased.

Q1. If h_0 is doubled, how does t change?

Q2. Do the trial data your team collected under Exercise 4a support this? Explain.

The equation for the velocity v of an object falling under the influence of gravity is negative because gravity is pulling down and thus is in the minus direction. (Note that speed would be positive as it is scalar and is direction independent).

$$v = -gt + v_0$$

Withv_0 being the starting velocity. If the object starts out with zero initial velocity (dropped, v_0= 0), then the equation becomes

$$v = -gt$$

.

Q3. Think about your trials where you dropped objects with different mass and from different heights. Did the objects sometimes hit the ground at a greater velocity during certain trials? Justify your answer using the equation above.

For all of the previous questions the object started out with zero initial velocity (dropped, $v_0 = 0$). What if the object is thrown down (*i.e.* $v_0 \neq 0$)? If we solve

$$\boldsymbol{h = -\frac{1}{2}gt^2 + v_0 t + h_0}$$

for the time t when the object hits the ground (when $h = 0$), we obtain

$$\boldsymbol{0 = -\frac{1}{2}gt^2 + v_0 t + h_0}$$

Then

$$\boldsymbol{-v_0 t + \frac{1}{2}gt^2 = h_0}$$

.

Q4. Revise your answers to Q4 and Q5 under Exercise 4a to incorporate what you've learned about the mathematics of falling. Do the mathematics support or change your initial answers?

Exercise 4b. Launching

In Exercise 4a, you learned that the projectile motion of simply falling or being thrown in a strictly vertical direction towards the ground is influenced by the acceleration due to gravity, the height from which the object is dropped, and the initial velocity at which the object is released. The second form of projectile motion, object launching, has both the vertical component important to free fall and a horizontal component. It is, thus, further influenced by the angle at which the object is thrown.

While humans are best known for their ability to throw or launch objects like arrows or baseballs, there are other animals as well as plants that engage in launching actions important to their wellbeing. Figure 4 shows images of some of the examples presented here. See if you can find the picture that matches the description of the animal and its launching behavior. In animals, launching is most often used in defense. Liquid projectiles are used for defense in a number of organisms. This includes vertebrates such as spitting cobras of the genus *Naja* and the Mangshan pitviper of the genus *Ermia.* These snakes squirt a stream of neurotoxic venom from their fangs at the eyes of potential predators. Horned toads, which are actually lizards of the genus *Phrynosoma,* squirt a jet of blood from their eyes into the face of potential predators. Horned toad blood has a high concentration of formic acid that the lizards take in from their diet of ants. Some Gecko lizards of the family *Dipodactlidae* shoot out a nasty fluid from glands in the tail region for a distance of as much as a meter and the southern giant petrel (*Macronectesgiganteus*) is a bird that sprays stomach fluid vomit at predators. This petrel is known as "the stinker" for this defensive behavior, which has a strong odor associated with it. Let's not forget camels (stomach contents and saliva), elephants (water), and skunks (noxious fluid from glands near the anus). All of these animals are well known for their propensity for launching fluids, respectively from the mouth, trunk and anus. Also, numerous insects launch acid chemical sprays at attackers, including ants, beetles and even walking sticks. The most famous example is the bombardier beetle, a southwestern US desert inhabitant. It uses a chemical reaction between two compounds to send bursts of boiling noxious spray out of glands in its abdomen.

While we have been discussing the projection of liquids, animals also launch solids in defense. For example monkeys throw fruit and poop to deter predators from approaching and using a flicking action of the hind legs, tarantulas project urticating hairs off the dorsum of their abdomens into the faces of potential mammalian predators. The hairs are barbed and cause respiratory irritation. If you see a tarantula with a bald spot such as the one shown in Figure 4, it is because the spider has recently engaged in this defensive behavior. It must molt (shed its skin) to replace the lost urticating hairs.

Some animals use the launching of fluids in the capture of prey. The archer fish, for instance, squirts water out of its mouth to dislodge insect prey from branches overhanging the water (Figure 4). Another example comes from the spider family *Scytodidae*. These spiders spit silk and venom at potential prey. The silk glues the prey item to substrate allowing the venom to act. And then there is the nematocyst of the jellyfish and its relatives, the cnidarians. Anyone who has brushed up against a jellyfish knows how painful the encounter can be. The cnidarians have specialized cells called nematocysts that have a hollow thread coiled up in a spring mechanism. The coil is packed up at 180 atm, such that when released the barbed string travels out at high speeds delivering poison. (The conversion rate between atmospheres and psi (pounds per square inch) is 1 atm = 14.7 psi). The nematocysts are fired both in defense and in the capture of prey.

This brings to mind the fact that animals launch themselves in locomotion. Take a leaping mountain goat or a flea, for that matter. Even some plants, which are typically stationary, use projectile motion in dispersing seeds from the parent plant. Common North American plants such as Jewelweed or Touch Me Not (*Impatiens* sp.), Dwarf Mistletoe (*Arceuthobium* sp.), Creeping Woodsorrel (*Oxalis corniculata*), and Squirting Cucumber (*Ecballium elaterium*) launch their seeds to disperse them. The launching of seeds can be particularly impressive. For instance, maturing seed pods of the Caribbean Sandbox Tree (*Huracrepitans*, also known as the Dynamite Tree for the loud explosions of its fruits), shoot out seeds at speeds of up to150 mph (Vogel 2005). This tree can potentially injure passers-by with its shrapnel of seeds and flying fruit segments. See Figure 5 for some examples of projectile motion observed in "explosive" seed dispersal. (Jewell weed and its flying seeds are pictured in Figure 4.)

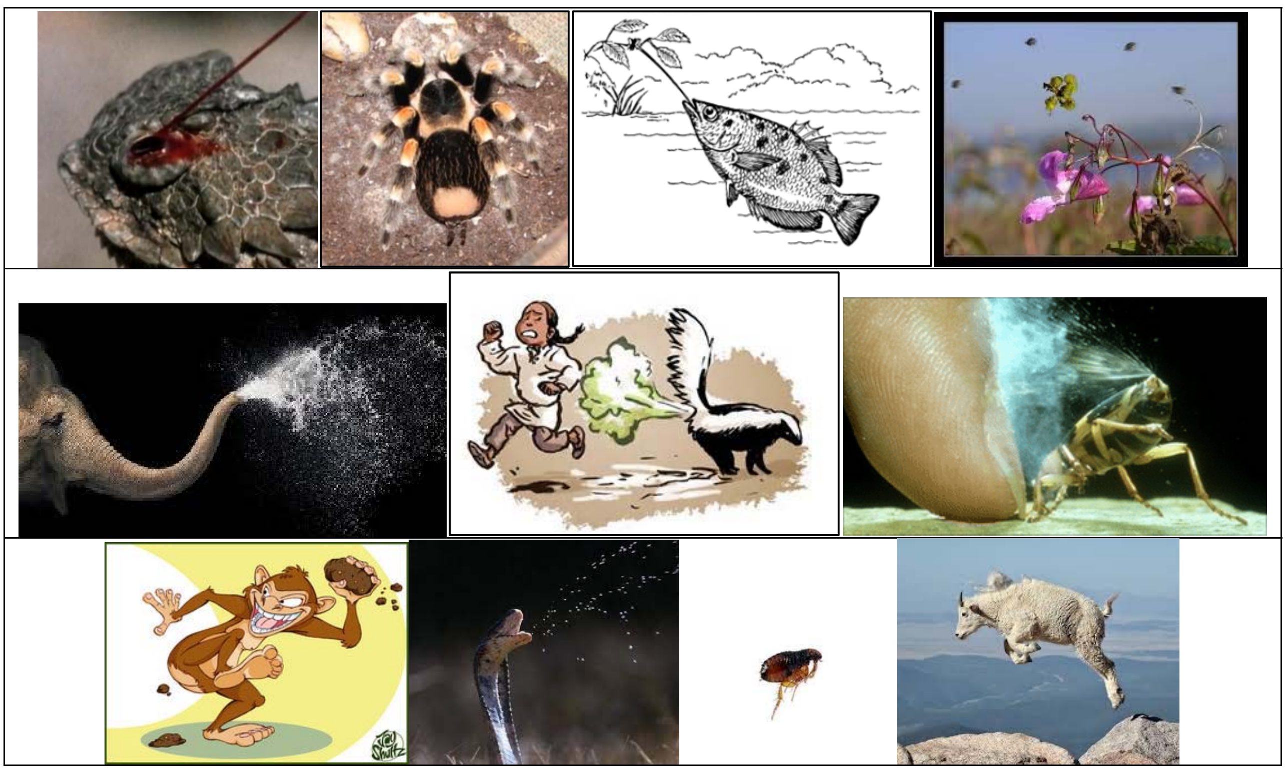


Figure 4. Examples of organisms that use projectile motion.

Figure 5. *Left:* The flower and fruit of the Sandbox Tree (*Huracrepitans*), along with “shrapnel” pieces of exploded fruit. *Right:* Dwarf Mistletoe discharging a seed.

In this exercise, you will examine the parameters associated with launching, and learn how this form of projectile motion differs from free fall.

Materials Needed:

- Straw rocket launcher assembly
- Straws with rubber caps
- Bicycle pump
- Tape measure
- Stopwatch
- Extension cord

- For this exercise, you will use the included model launcher to fire straw projectiles with rubber tips. Examine the image of the rocket launcher in Figure 6 and familiarize yourself with the labeled parts of the launcher before continuing with the rest of this exercise.

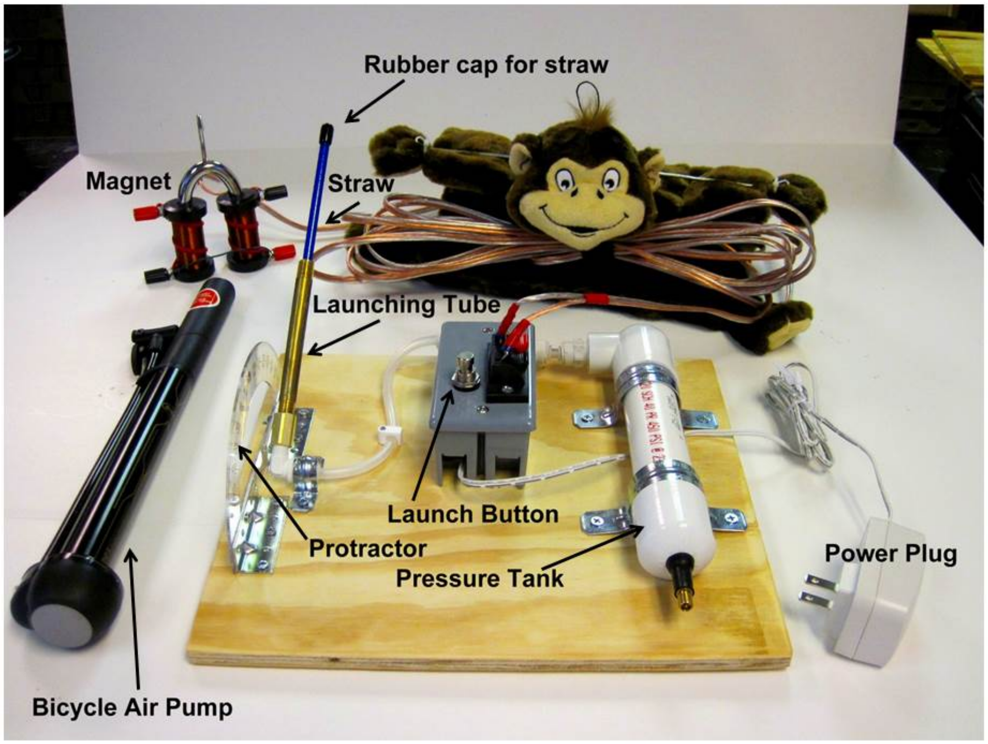


Figure 6. The straw rocket launcher included in this unit (tank safety valve not shown).

- This exercise will use the straw rocket launcher shown along with the air pump in Figure 6. The monkey, cable and magnet may be set aside as they will be used in a later exercise. The exercise is best completed in a room or hallway with a high ceiling. Read the instructions on operating the straw rocket launcher outlined in the box below to ensure that you know how to properly use the apparatus to avoid its damage. Be especially careful when attaching and removing the air pump from the valve on the compressed air tank and filling the tank.

Using the Straw Rocket Launcher:
1. Place a rubber cap on the end of a straw, and place the uncapped end of the straw into the launching tube. Make sure the straw goes all the way into the tube.
2. Adjust the angle of your launch by lining up the launching tube with the appropriate angle measurement on the protractor.
3. Attach the bicycle pump to the valve on the pressure tank. Fill the tank to the desired pressure. Leave the pump attached for the entire experiment. A safety valve on the tank will release excess pressure.
4. Ensure that the potential path of the rocket is clear of people!
5. Insert the power plug into an outlet. Use the extension cord provided, if needed.
6. Assign someone to work the stopwatch and confirm that the person is familiar with its use and is ready to depress the start button on it.
7. Depress the launch button, start the stopwatch and watch the rocket fly!
8. Stop the stopwatch and record the flight time and distance.

- In the first set of trials, you will hold the angle of projection constant (at 0°) while modifying the pressure applied to the rocket. The rocket launcher assembly should be directly on the floor or ground with someone holding it in place from the rear.
- Launch a rocket at each of the following pressure values: 10, 15, 20, and 25 psi, while keeping the angle of projection at 0° for each trial. (You may want to assign different psi data points depending on the style of the pressure gauge of your bicycle pump.)
- Repeat the test for 3 trials at each pressure. Make sure the pressure to which the assembly is inflated is as exact as possible.
- For each trial, record the distance traveled -- the linear distance from the base of the launching tube to the uncapped end of the straw where it lands-- and time elapsed from launch to landing in a table similar to the one below:

Pressure (psi)	Distance (m)				Time (s)			
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
10								
15								
20								
25								

- Repeat the above procedure at different angles. Complete a table just like the one above for the three angles you choose which should be below 90°. Record the distance traveled and the time to landing for each trial. The angles you test in your experiment will be somewhat dependent on the height of the ceiling. If the straw hits the ceiling during its flight, you will obtain an inaccurate result. Make sure you label each of your tables with the angle used for each!
- Construct a scatter plot of the average distance traveled on the y-axis against pressure on the x-axis. Use different symbols for the data points from each of the different angular data sets. You may wish to fill in a summary table similar to the one below to help you organize all of this data into one place:

Pressure (psi)	Average Distance Traveled (m)			
	Angle 1°	*Angle 2°*	*Angle 3°*	*Angle 4°*
10				
15				
20				
25				

- Based on your observations and experimental data, answer the following questions:

Q6. What is the relationship between the pressure to which the assembly is inflated and the distance the projectile travels?

Q7. For the same pressure reading, which launch angle results in the greatest distance?

Q8. If a flea wishes to reach a larger height to jump on an animal what would be the best launch angle to take? Would it use the same launch angle to range further horizontally as it tries to catch up with an animal it wishes to feed on? Explain your answer.

Q9. We mentioned that many seeds are launched by plants and trees to disperse them away from the parent tree. Seeds vary a great deal in size. Would you expect seeds of any size to fit the predictions of projectile motion? Might there be size constraints on the predictions of dispersal distance, for example, as a function of launch angle and velocity?

Exercise 4b1. The Numbers Behind Launching (for grades 11-12)

Teacher Note: The following information and questions pertain to the mathematics underlying motion. These enrichment sections are designed for students with some knowledge of trigonometry and/or calculus.

If you had described your launcher to a physicist or mathematician, she could have figured out for you the best angle without ever touching the device! You too can use mathematics to describe or model a projectile's travels, and to predict the optimal angle. Just follow the approach outlined below to represent the distance traveled of the projectile in the horizontal direction in terms of the angle Θ after Figure 7.

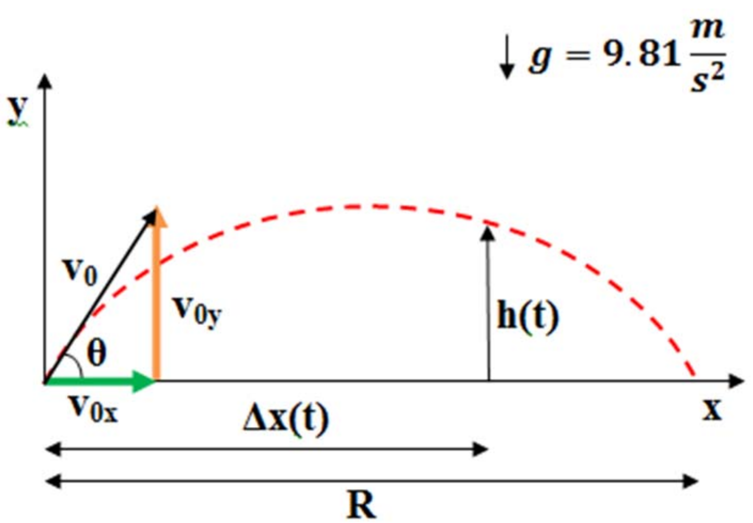


Figure 7. General diagram of projectile motion involving both vertical and horizontal components

Imagine that the projectile moves through a coordinate plane like in Figure 7, where x is the horizontal direction and y is the vertical. Assume the initial position is at the origin (0,0) and the initial velocity $\overrightarrow{v_0}$ is a vector with horizontal and vertical components $\overrightarrow{\boldsymbol{v_0}} = < \boldsymbol{v_{0x}}, \boldsymbol{v_{0y}} >$. Also recall that g represents acceleration due to gravity, or 9.8 m/s^2.

In the vertical direction, the acceleration is:

$$\boldsymbol{a_y(t) = -g}$$

The velocity in the vertical direction is:

$$\boldsymbol{v_y(t) = v_{0y} - gt}$$

with v_{0y} being the vertical component of the initial velocity vector $\overrightarrow{\boldsymbol{v_0}}$.

The vertical height is prescribed as:

$$\boldsymbol{h(t) = v_{0y}t - \frac{1}{2}gt^2}$$

with initial height, $h(0) = 0$.

In the horizontal direction, there is a zero acceleration component, giving the velocity

$$\boldsymbol{v_x(t) = v_{0x}}$$

where v_{0x} is the horizontal component of the initial velocity.

The horizontal position with respect to t is:

$$\boldsymbol{x(t) = v_{0x}t}$$

To find when the projectile returns to its original height (0), solve the vertical height equation for $h(t_{end})=0$ when t is a positive number:

$$\boldsymbol{0 = v_{0y}t - \frac{1}{2}gt^2}$$

$$\boldsymbol{0 = t\left(v_{0y} - \frac{1}{2}gt\right)}$$

$$\mathbf{0} = \boldsymbol{v_{0y}} - \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{gt}$$

$$\frac{\mathbf{2}\boldsymbol{v_{0y}}}{\boldsymbol{g}} = \boldsymbol{t_{end}}$$

Then, we can use this to find the horizontal position x*(t)* at time $t_{end,}$ called R:

$$\boldsymbol{R} = \boldsymbol{x}(\boldsymbol{t_{end}}) = \boldsymbol{v_{0x}}\frac{\mathbf{2}\boldsymbol{v_{0y}}}{\boldsymbol{g}}$$

Using trigonometry,

$$\frac{\boldsymbol{v_{0y}}}{\|\boldsymbol{v_0}\|} = \mathbf{sin}\,\boldsymbol{\Theta}\,\mathbf{and}\frac{\boldsymbol{v_{0x}}}{\|\boldsymbol{v_0}\|} = \mathbf{cos}\,\boldsymbol{\Theta}$$

where, $\|\boldsymbol{v_0}\|$ is the speed of vector $\overrightarrow{\boldsymbol{v_0}}$.

Substituting for v_{0x} and v_{0y} we obtain

$$\boldsymbol{R}(\boldsymbol{range}) = \|\boldsymbol{v_0}\|\,\mathbf{cos}\,\boldsymbol{\Theta}\,\frac{2\|\boldsymbol{v_0}\|}{\boldsymbol{g}}\,\mathbf{sin}\,\boldsymbol{\Theta}$$

$$= \frac{\mathbf{2}}{\boldsymbol{g}}\|\boldsymbol{v_0}\|^2\,\mathbf{cos}\,\boldsymbol{\Theta}\,\mathbf{sin}\,\boldsymbol{\Theta}$$

$$= \frac{\|\boldsymbol{v_0}\|^2}{\boldsymbol{g}}\,\mathbf{sin}\,\mathbf{2}\boldsymbol{\Theta}$$

(using the trig. identity $\mathbf{2}\,\mathbf{cos}\,\boldsymbol{\Theta}\,\mathbf{sin}\,\boldsymbol{\Theta} = \mathbf{sin}\,\mathbf{2}\boldsymbol{\Theta}$).

(*Note: Non calculus students may look at* $\boldsymbol{sin}\,\mathbf{2}\boldsymbol{\Theta}$ *and see where it is at maximum.*)

Keeping $\|\boldsymbol{v_0}\|$ and *g* fixed, we find where *R* is maximized as a function of *Θ*:

$$\frac{\boldsymbol{dR}}{\boldsymbol{d\theta}} = \frac{\mathbf{2}\|\boldsymbol{v_o}\|^2\mathbf{cos}(\mathbf{2}\boldsymbol{\Theta})}{\boldsymbol{g}}$$

This implies that the derivative is zero and the function achieves its maximum when

$$\cos(2\,\boldsymbol{\Theta}) = \mathbf{0}$$

and then

$$\mathbf{2}\boldsymbol{\Theta} = \frac{\pi}{2}\ (90^{\circ})$$

and

$$\boldsymbol{\Theta} = \frac{\pi}{4}\ (45^{\circ})$$

.

This gives a maximum instead of a minimum because

$$\frac{d^2R}{d\Theta^2} = \frac{-4\|v_0\|^2}{g}\sin 2\Theta \le 0$$

for $0 \le \Theta \le \frac{\pi}{2}, \sin(2\Theta) \ge 0$.

Exercise 4c. Stop the Monkey's Escape

This exercise combines free fall and launching projectile motion problems in a single context, applying what you have learned under Exercises 4a and 4b. In this exercise, you will play the role of a zookeeper attempting to capture a monkey that has escaped its enclosure (Figure 8). The monkey has climbed a tree next to a boundary fence and is hanging from a limb, about to drop to freedom. You are armed with a tranquilizer gun and only one dart. Assuming that the monkey drops at the exact moment the dart leaves the gun (straw rocket), your job is to determine where to aim in order to hit the monkey in the midst of its free fall in order to capture it before it escapes. In this exercise, you will use the straw rocket launcher from the previous exercise to simulate the tranquilizer dart gun.

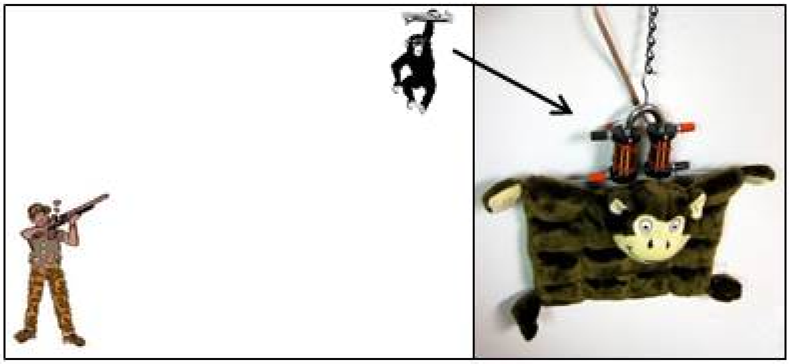


Figure 8. Monkey and zookeeper scenario and setup: electromagnet hanger-metal rod on monkey, hanging on wall.

Materials Needed:

- Straw rocket launcher assembly
- Straws with rubber caps
- Bicycle pump
- Stuffed monkey on hanger wire
- Electromagnet assembly (magnet with 20-foot electrical wire)
- Cable for hanging electromagnet from the ceiling or top of the blackboard. (Teacher to provide.)

Procedure:

- Find a suitable location to hang the electromagnet from the ceiling, wall, or blackboard in the room using the provided hanger hook and/or cable on the electromagnet. The location should allow the flight trajectories of the dart and the monkey to be visible by all students (e.g. in the front of the classroom with the monkey at one end and the zookeeper's straw rocket launcher at the other.
- Plug the cables from the electromagnet into the two receptacles on the launch pad at the power supply box in Figure6 to adapt the unit for this exercise. The monkey can be hung from the electromagnet as shown in Figure 8 after the power cord is plugged in. Wait to do this until you are ready to begin the trials.
- Decide what three distances the zookeeper might be standing at relative to the monkey (close, mid-range and far). Mark these locations with tape on the floor and record the distances on the board at the front of the room.
- Divide the class into teams of 3–4 students.
- Each team should attempt to determine at what angle the zookeeper should aim to catch the monkey with the tranquilizer dart before it reaches the ground and runs off, based on the results the class obtained in the experiments completed under Exercise 4a and 4b. Teams should make three predictions, one for each distance.

- Discuss each team’s predictions as a class and organize what trials would be performed by teams and in what order.
- Each team should list on the board at the front of the room their predicted solution to each of the three distances the zookeeper is from the monkey. Predict what combination of forces (psi and vertical angle of the straw rocket launch) should be used.
- The class should set up a list of the trials they will run, given that there may be some overlap in the settings each team proposed to apply.
- Teams will take turns running the trials chosen.
- Successful trial runs will be starred on the board as to the parameters used.
- A class discussion should follow to ascertain what relationship between free fall and launch satisfies the goal to hit the monkey with a dart before it has landed on the ground and escaped.
- Answer the following questions:

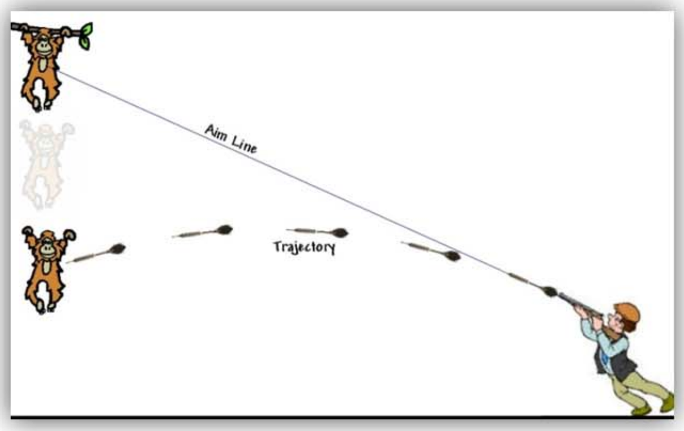
Q1. What equations (from the answers to Exercise 4b) apply to the motion of the monkey and the dart? Consider both horizontal and vertical directions.

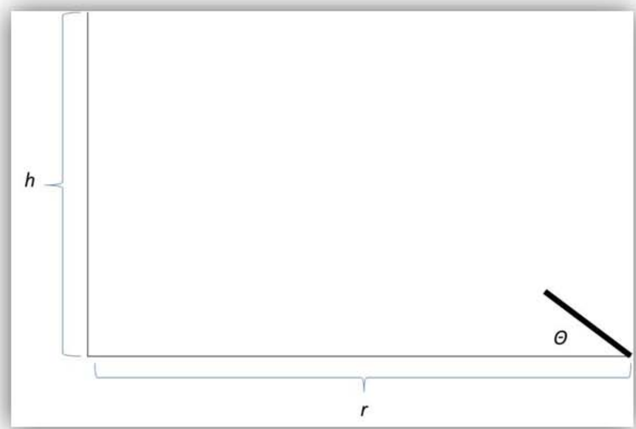
Q2. Is there a useful trick for determining where one should aim the straw rocket to hit the monkey before it escapes?

Check the answer section at the end of this workbook under Exercise 4c for answers to the above questions.

Exercise 4c1. The Math Behind Stopping the Monkey (for grades 11-12, with algebra and trigonometry knowledge. The derivative material can be reviewed by calculus students.)

Teacher Note: The following information and questions pertain to the mathematics underlying motion. These enrichment sections are designed for students with some knowledge of trigonometry and/or calculus.





The dart is propelled with velocity $(\boldsymbol{v}\cos\boldsymbol{\Theta}, \boldsymbol{v}\sin\boldsymbol{\Theta})$ and angle Θ. Let:

$$\boldsymbol{y_m(t) = h - \frac{1}{2}gt^2}$$

be the position of the monkey at time t.

The x_d and y_d positions of the dart at time t are

$$\boldsymbol{x_d(t) = (v\cos\Theta)t}$$
$$\boldsymbol{y_d(t) = (v\sin\Theta)t - \frac{1}{2}gt^2}$$

Find t_*, the time when x_d trajectory of the dart covers the distance r.

$$\boldsymbol{r = x_d(t_*) = (v\cos\Theta)t_*}$$

$$\boldsymbol{t_* = \frac{r}{v\cos\Theta}}$$

Then the y position of the dart at time t_* is

$$\boldsymbol{y_d(t_*) = \frac{v\sin\Theta\, r}{v\cos\Theta} - \frac{1}{2}g{t_*}^2}$$
$$\boldsymbol{= r\tan\Theta - \frac{1}{2}g{t_*}^2}$$

The position of the monkey at time t_* is

$$y_m(t_*) = h - \frac{1}{2}gt_*^2$$

We find the Θ value so that the y positions meet at time t_*,

$$y_d(t_*) = y_m(t_*)$$

$$r\tan\Theta - \frac{1}{2}gt_*^2 = h - \frac{1}{2}gt_*^2$$

$$\tan\Theta = \frac{r}{h}$$

The above calculations indicate where the dart needs to be pointed at the start. Consult the answer key under Q1 of Exercise 4c2 to check your answer.

<u>Open-ended Exploration:</u>

- Working in groups, design and build a plant that maximizes seed launch. Conduct trials to determine which design performs best. Discuss this success in terms of the physics of projectile motion.
- Do an internet and/or library search on a particular organism that uses projectile motion. See if you can obtain parameters (velocity, distance, etc.) relative to the principles of projectile motion, and see if you can use this information to determine other parameters. For example, if you are given the maximum velocity of a projectile (such as a seed, or an animal's projectile defense), you can calculate the maximum distance the seed can be dispersed, or at which the animal can strike a predator or prey organism.
- Do some internet and/or library research on technological applications involving the principles of projectile motion. For example, pick a particular device or specific usage of projectile motion, and prepare a brief report that you can share with the rest of your class.

Exercise 5: Similar Things to Wings: Drag

Introduction

In all living organisms, an important part of the life cycle is dispersal, the movement of organisms away from parents or a dense cluster of individuals competing for the same resources. Dispersal can have very important consequences not only on the dispersing organism, but on populations and species as a whole. At the individual level, an animal may move from one patch of habitat to another to find food or mates, or to avoid competition, all of which can affect the animal's fitness, its ability to survive and pass on its genes.

On a larger scale, dispersal can positively affect the genetic structure of a population through its effects on the degrees of relatedness among individuals within it. By dispersing away from locations where close relatives are likely to be clustered, for example, an organism reduces its chances of inbreeding (breeding with a closely-related individual). Inbreeding is harmful because parents who are closely related may share the same deleterious recessive gene in common. If each parent donates this deleterious recessive allele to an offspring, the trait would be expressed in the offspring with harmful consequences. Offspring dispersal leads to population mixing under which deleterious recessive copies of a gene are masked by the more common dominant allele of the same gene that does not have deleterious effects. Finally, dispersal may lead to the occupation of new habitats permitting the spread of a species as well as survival under environmental change.

While all organisms disperse, some are restricted to dispersal during particular stages of the life cycle. Take plants for example. It is quite obvious that trees do not move from place to place but their seeds, containing embryos, have numerous dispersal strategies. Though there are a number of different dispersal strategies exhibited by plants, they all involve several important factors. In particular, in close proximity to the parent plant, competition for light from larger parent plants reduces the fitness of both the parent and germinating seed, so it is advantageous for seeds to be capable of dispersal to land out of this range. However, if seeds are dispersed *too* far, they could land in an area of unfavorable habitat, where germination might not occur, or in which growth of the new plant would be poor, also reducing fitness. The various mechanisms of seed dispersal, then, reflect adaptations that are responses to each of these (and other) pressures, which will vary in intensity among species. Three seed dispersal mechanisms used by plants that are associated with the laws of physics are briefly described below.

Free Fall/Gravity dispersal: Plants that produce large, round, heavy fruits that drop straight off the parent tree are classified as having a gravity dispersal strategy. If they have a hard shell, they may roll some distance from the parent plant, depending on height from which they dropped. Others may break open on hitting the ground, scattering the seeds. The apple, coconut and passion fruit are examples of the gravity seed dispersal strategy.

Launch dispersal: Under Exercise 4b, several plants were mentioned for their launch dispersal strategies. In the genus *Impatiens, s*eeds are flung out of seed pods when touched by a passing animal. These plants have been given the common name “touch me not” reflecting this behavior. (*Yes, behavior is not limited to animals*). More typically, seed launch occurs as a result of differential drying of one side of the mature pod in the sun. The euphorb and geranium families exhibit this latter strategy as does the squirting cucumber, *Ecballium elaterium,* shown in Figure 1 below. On drying of the pod, this species shoots out a sticky stream of fluid containing its seeds.

.

Figure 1. Examples of plants that exhibit a launch seed dispersal strategy: *left*, euphorb with ripening seed pods; *right,* cluster of squirting cucumber plants showing seed pods on stalks extending up from the plant base.

Drag/Wind dispersal: Many plants produce seeds with adaptations that allow them to disperse by wind, such as tuft-like structures that help seeds float on the breeze. Elms, maples and ashes produce a dry fruit called a samara, each encompassing one seed. As the wind blows, this papery fruit helps to carry the seed away from the parent tree. Examples of seeds that use wind dispersal are shown in Figure 2 below.

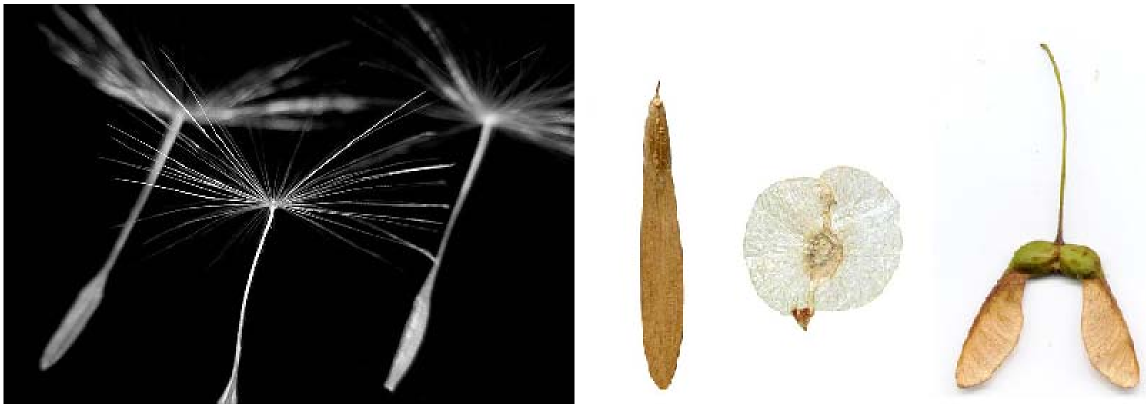


Figure 2. Fruits (with seeds) dispersed by wind: *left*, the tuft-like pappus of dandelion fruits allows them to float on even very light breezes; *right*, samaras (winged fruits) from various trees (from left to right: ash, elm, and maple).

Exercise 5a. Forces and Falling Objects

In Exercise 4a, you examined the physical principle of free fall under which all objects, regardless of their mass, drop with the same acceleration. This is the acceleration of gravity (*g*), which is approximately equal to 9.8 m/s/s (also written as 9.8 m/s^2). In this set of exercises you will learn about the influences of air resistance (drag) on the vertical and horizontal movement of seeds through the air which limits the velocity of objects falling through the air.

Air resistance is a physical phenomenon which creates a frictional force on objects that are moving through air or which air is moving around. Drag may also occur in water. Air resistance results from collision of an object's leading surface with air molecules. Two factors increase the amount of air resistance: an object's speed of movement and its surface area. As an object such as a pine cone falls, it initially picks up speed which leads eventually to an air resistance that is equal to the speed at which the object is falling. At this point the object has reached its **terminal velocity** and no longer continues to increase in velocity.

Seeds designed to be dispersed by wind take advantage of the physical phenomenon of air resistance (drag). In this series of exercises, you will experiment with drag. In the end you will design your own wind-dispersed propagules. The focus propagule will be the **samara** described and pictured in Figure 3. Biologically speaking, fruits are seed-containing structures that are formed from the ovaries of a flower. Within a flower's ovary (or ovaries, as some flowers have more than one), there are small round structures known as ovules. When these ovules are fertilized by male gametes (sperm) produced by pollen grains, the ovule then becomes a seed containing a newly-developing plant embryo and food for the embryo. After ovules are fertilized and become seeds, the pericarp, or ovary wall of the flower, may begin to change in terms of size, shape, and texture, becoming either fleshy, hard (as seen in nuts), or, in the case of samaras, papery. See images of family-level samara types in Figure 2 as well as labeled diagrams of the samara structure in Figure 3.

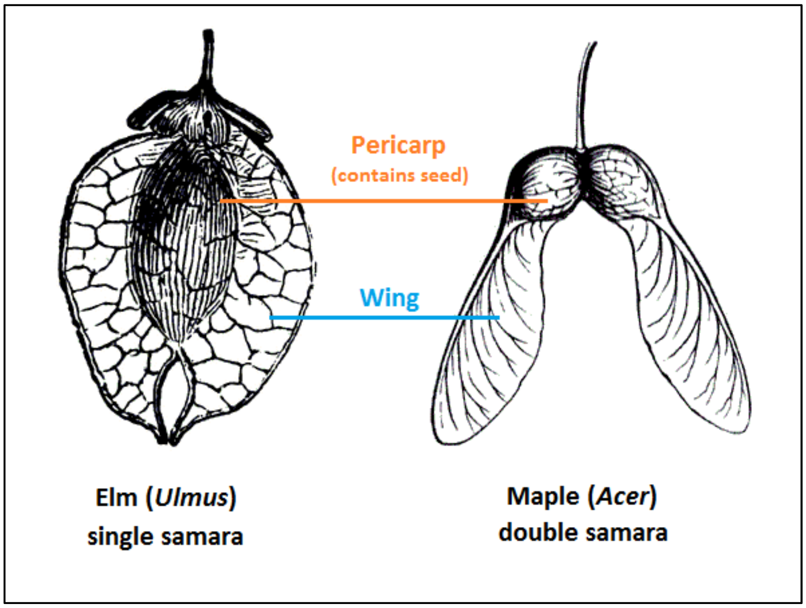


Figure 3. Two samara types with component parts labeled.

You have been provided with several samaras from different species of maple trees (genus *Acer)*.

- Examine these fruits and take note of their anatomy. You should be able to clearly distinguish the wing, the large bulge that marks the location of the seed, and the papery pericarp that surrounds the seed and also forms the wing.

- Take one of these samaras and drop it towards the floor from a distance about as high as your head or higher. What do you notice as the samara falls?

You should have noticed that the samara spins or at least rotates as it falls. This particular phenomenon is known as <u>autorotation</u>. Autorotation is the process of generation of rotation and lift purely due to aerodynamic forces of pressure and friction of air acting on a wing's surface. Samara design is such that resistance or drag and air pressure influence both the direction and timing of the fruits fall from the tree to the ground. A time lapse image of samara autorotation is presented in Figure 4.

Figure 4. High speed photograph showing autorotation in a maple (*Acer* sp.) samara.

Before you explore the phenomenon of autorotation in samaras, it is important for you to gain an understanding of the factors that influence the degree to which drag affects an objects drop or fall through air. Completion of the following five simple experiments will provide this understanding. Each experiment will be completed as a class demonstration. The last experiment will have two trials with the class deciding variations on the elm samara design.

Materials Needed:

- Stopwatch
- Tape measure
- Model giant elm samaras paper plates
- 2 each of two different sized button magnets
- Several sheets of standard 8.5 × 11” copy paper *
- Several sheets of standard 8.5 × 11” cardstock*
- Coffee filters (around 20 should suffice) *
- Scissors *

***To be provided by the teacher**

Procedure

- Divide the class into teams of 3–4 students each.
- Each team should construct a data sheet similar to the one on the following page, or your teacher may provide you with copies.

Experiment	Object	Prediction	Reasoning	Results	Notes
1					
2					
3					
4					
5a					
5b					

- Your teacher will now ask for two to three volunteers to come to the front of the classroom to conduct the first of the five experiments. One student will perform the experiment and the others will record important parameters such as the distance of the fall (shoulder height of experimenter to floor) and time of the fall, in seconds, of the object(s) and report these measures to the class. *Note that two timekeepers will be needed when two items are dropped to watch each object.*

Figure 5. Position of volunteer in initiating drag experiment involving two objects. (*Open mouth not required*). (http://article.wn.com/view/2015/01/09/When_Does_the_Air_Resistance_Force_Make_a_Difference/)

- Be sure each student serving as a timekeeper has tested his/her understanding of the workings of a stopwatch and has practiced timing some event students suggest as a test (*e.g*., how long it takes the class to sing a chorus of the school song).
- Also, a discussion question or questions will be posed for consideration by the class before each experiment. Each team will discuss the question(s) and record their answers in the prediction column on their data sheet. There will be one or two post-experiment questions to address as well.

<u>Experiment #1</u>

- Your teacher will give the volunteer a piece of paper and instruct the student to hold it, parallel to the floor, at about shoulder height when the experiment is initiated.

- A second student uses the tape measure found in the STEM box to measure the distance that the item will fall .The second student will also prepare to use a stopwatch to time the fall.
- Before proceeding, however, the student teams should take a few minutes to discuss and answer the following pre-experiment questions on their data sheet:

Pre-experiment #1 questions:
What motion do you predict the paper will exhibit when dropped from this height? Why?

- Teams should then discuss their predictions and reasoning with the rest of the class. On the teacher's command, the volunteer drops the sheet of paper. Each team should record the results of the experiment on their data sheet. Discuss the following question as a class.

Post-experiment #1 question:
Q1. What force(s) do you think were acting on the paper as it fell?

- Check your answer under Q1 of this exercise (5a) at the end of this unit.

Experiment #2

- Your teacher will give the next volunteer two sheets of paper that are equal in area and shape (e.g., printer paper).
- The volunteer should crumple one of the sheets of paper into a ball.
- For this experiment, the volunteer will hold the flat sheet of paper in one hand, again parallel to the floor at shoulder height, and the crumpled sheet in the other hand at the same height.
- A second volunteer will measure the fall distance as well as time the fall in seconds and report the values of the respective measures to the class.
- Before proceeding, the student teams should take a few minutes to discuss and record their answers to the following pre-experiment #2 questions on their data sheet:

Pre-experiment #2 questions:

If the flat sheet and crumpled sheet of paper are dropped at the same time, do you predict that one will hit the floor before the other, and if so, which one? Alternatively, do you think that the pieces of paper will hit the floor at the same time?

- Teams should then discuss their predictions and reasoning with the rest of the class.
- On the teacher's command, the volunteer drops the two sheets of paper.
- Each team should record the results of the experiment on their data sheet.
- Discuss the following questions as a class.

Post-experiment #2 questions:

Q2. Were the gravitational forces acting on the pieces of paper different? Why or why not? And if not, what was happening?

Hint: First, think about the forces acting on each sheet of paper as it falls. Of course, there is gravitational force, which is independent of the mass of the paper and is responsible for the behavior of objects under free fall (See Exercise 4a Free Fallin' of this Unit for a full treatment). If you are not familiar with the equation for the force of gravity acting on a falling object, it is given as follows

$$\boldsymbol{F_g = mg}$$

In this equation, F_g is the gravitational force (in Newtons) that is pulling an object towards the Earth, m is the mass of the object (in kg), and g is the acceleration due to gravity in meters per second squared (m/s^2), where g = 9.81 m/s^2. If the gravitational forces acting on both pieces of paper were the same, then why did one hit the floor before the other? This is because gravity is not the only force acting on each sheet of paper. Each piece of paper was also affected by a force known as drag, which is also sometimes referred to as air resistance (or fluid resistance if motion is in a fluid other than air). Drag is a force that acts on an object in the opposite direction in which the object is moving through the medium, in this case air. The magnitude of the force of drag on a low density object that is moving fairly rapidly is given by the following equation:

$$F_d = \frac{\rho v^2 A C_d}{2}$$

Note that objects not meeting the low density, fast moving criteria have a drag force dependent on the first order of velocity (v).

In the drag force equation, F_d is the drag force, the symbol ρ (the lower case Greek letter “rho”) is the density of the fluid through which the object is traveling, v is the velocity of the object, and A is the surface area of the object. If we are considering motion in one direction, the velocity has only one non-zero component. In this case, drag force is proportional to the velocity *squared.*

Q3. Consider this scenario: You are completing a comparison study of lizard energetics in the desert. You use a stopwatch to record the speed with which two equal-sized fence lizards run distance X after you present them with a predatory cue, a shadow of a bird passing overhead. You find that subject A ran the distance twice as fast as subject B.As a result, test subject A experienced how many times as much drag as subject B and how much more energetic cost? Note that both lizards were of the same size and shape, so the variable C_d was not relevant to the cost in this case. C_d is the drag coefficient, which depends on an object’s shape. An illustration of the range of drag coefficients is shown below in Figure6.

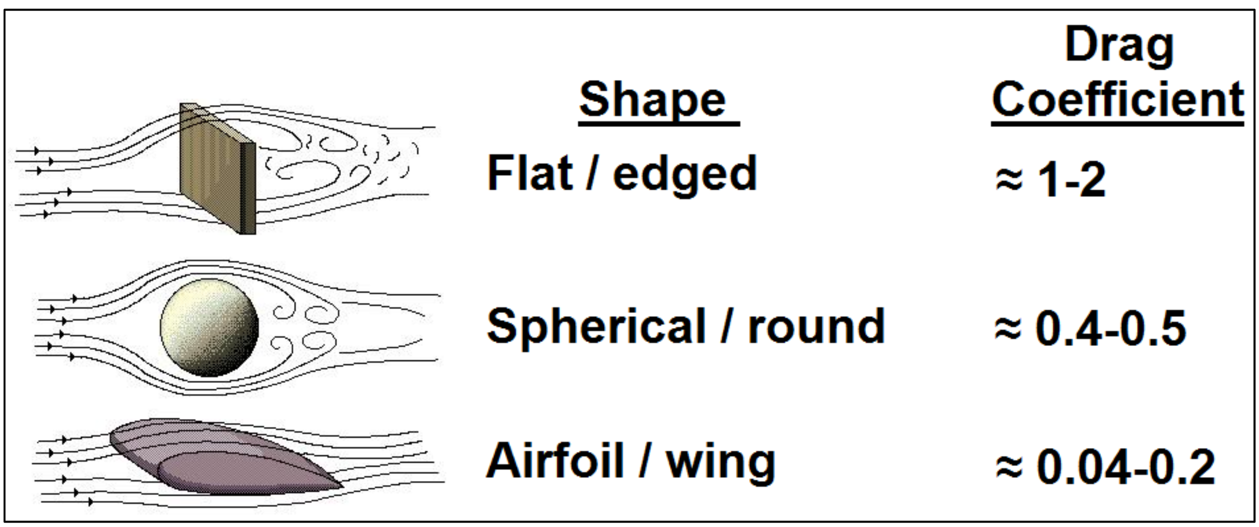


Figure 6. Drag coefficients of various shapes.

- Check your answers under Q2 and Q3 of this exercise (5a) at the end of this unit.

Remember that we are considering motion in one dimension. Now that you know a little more about the force of drag, let's think about the two sheets of paper for a moment while considering the net force acting on each piece of paper. It is often helpful when solving these kinds of problems to draw a free-body diagram, which is a picture showing an object or objects of interest, as well as illustrations of the forces acting on them. Figure 7 below presents an example of a free-body diagram for the flat sheet of paper.

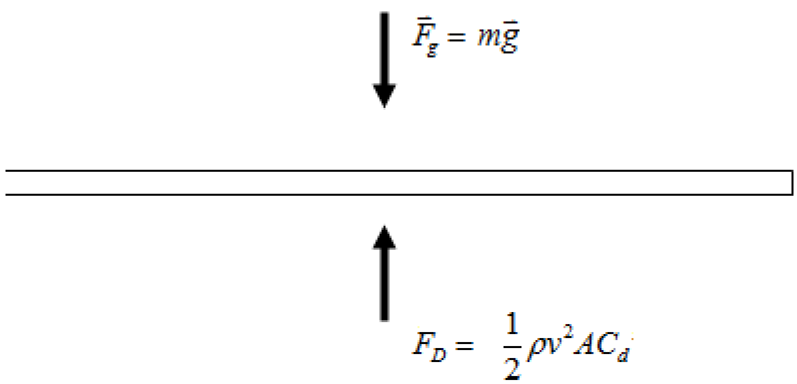


Figure 7. Diagram illustrating gravity and drag acting on a falling sheet of paper.

When considering free-body diagrams, we are often concerned with calculation of the net force, or *sum of all forces acting on an object*. In this case, the net force is calculated as follows:

$$\boldsymbol{F_{net} = F_g - F_d}$$

$$\Rightarrow \boldsymbol{F_{net} = mg - \frac{\rho v^2 A C_d}{2}}$$

Notice that the drag force is *subtracted* from gravitational force in this equation for net force, since it is acting in the opposite direction.

By looking at the part of the equation that represents drag force, you should be able to see that drag force is directly proportional to surface area *A* of the object. The flat sheet has a larger surface area than the crumpled sheet. This is because, by crumpling the sheet, some of the area that was on the surface before the sheet was crumpled is actually now on the inside of the ball of paper and no longer on the surface. Also, notice that a flat sheet of paper has a higher drag coefficient C_d (Figure 6) than the crumpled ball of paper. Because of these factors, the flat sheet of paper experiences a larger drag force than the crumpled ball of paper.

Thus the net force acting on each sheet is different, with the crumpled ball experiencing a larger net force in a downward direction.

Newton's Second Law states that an object subject to a net force undergoes an acceleration that has the same direction as the force, and a magnitude that is directly proportional to the force and inversely proportional to the mass, or stated mathematically,

$$\boldsymbol{F_{net} = ma}$$

Alternatively, we can solve this equation for acceleration by dividing both sides by *m*:

$$\Rightarrow \boldsymbol{a} = \frac{\boldsymbol{F_{net}}}{\boldsymbol{m}} = \frac{\boldsymbol{F_g - F_d}}{\boldsymbol{m}} = \frac{\boldsymbol{mg - \frac{1}{2}\rho v^2 A C_d}}{\boldsymbol{m}} = \boldsymbol{g} - \frac{\boldsymbol{\rho v^2 A C_d}}{\boldsymbol{2m}}$$

Since crumpled ball of paper thus has a greater acceleration (because of a greater net downward force due to less surface area and a lower drag coefficient), this explains why it hits the floor first!

<u>Experiment #3</u>

- Your teacher will give the next volunteer a piece of copy paper and a piece of cardstock of the same size.
- In completing the experiment, the volunteer will hold each sheet, one in each hand, parallel to the floor at shoulder height.
- A second volunteer will measure the fall distance as well as time the fall in seconds and report the values of the respective measures to the class.
- Before proceeding, the student teams should take a few minutes to discuss and answer the following pre-experiment #3 question on their data sheet.

Pre-experiment #3 questions:
If the two pieces of paper are dropped at the same time, do you predict that one will hit the floor before the other, and if so, which one? Alternatively, do you think that the pieces of paper will hit the floor at the same time?

- Before proceeding, the student teams should discuss their answers with the rest of the class.
- On your teacher's command, the volunteer should drop the pieces of paper at the same time.
- Each team should record the results in the data sheet.
- Discuss the following question as a class:

Post-experiment #3 question:
Q4. What explanation can you give for the observed results?

- Check your answer under Q4 of this exercise (5a) at the end of this unit.

Experiment #4

- Your teacher will give the next volunteer nine coffee filters taped together in a 3×3 array as shown below in Figure 8 along with nine coffee filters stacked with an equivalent amount of tape attached.

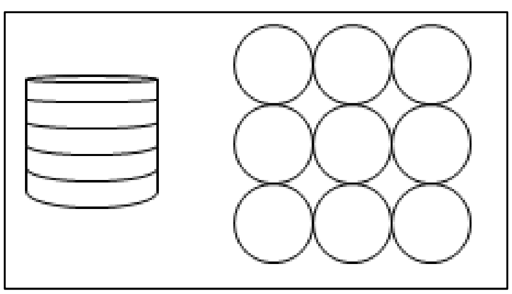


Figure 8. Two different formations of nine coffee filters: stacked on the left and as an array on the right. Note that the stacked formation has the same quantity of tape added as present in holding the array in position. Thus the mass of the two formations of the nine filters is equivalent.

- In completing the experiment, the volunteer will hold the stack of coffee filters in one hand, and the array of coffee filters in the other hand, with the bottoms of the coffee filters parallel to the floor, at shoulder height. It should be mentioned that the mass of filters and tape is the same in each case.

- A second volunteer will measure the fall distance as well as time the fall in seconds and report the values of the respective measures to the class.
- The student teams should take a few minutes to discuss and answer the following pre-experiment #4 question on their data sheet.

<u>Pre-experiment #4 questions:</u>
If the sets of coffee filters are dropped at the same time, do you predict that both will hit the floor at the same time? If not, which one will hit the floor first and which one last?

- Student teams should discuss their answers with the rest of the class before completing the experiment.
- On the teacher's command, the volunteer should drop the pieces of paper at the same time.
- Each team should record the results in the data sheet.
- Discuss the following question as a class:

<u>Post-experiment #4 question:</u>
Q5. What explanation can you give for the observed results? Hint: What was different about the way in which one set of coffee filters fell?

- Check your answer under Q5 of this exercise (5a) at the end of this unit.

This demonstration also illustrates **terminal velocity**, which is the velocity at which the force due to gravity and the drag force become equal. This means that the net force acting on the array is equal to zero, which means that the acceleration of the array is equal to zero. Remember:

$$\boldsymbol{a} = \frac{\boldsymbol{F}}{\boldsymbol{m}}$$

Keep in mind that acceleration of zero does not mean that the array is not moving. Acceleration is the rate at which an object's velocity is changing. In other words, an acceleration of zero means that as the array falls, it does so at a constant rate, and does not speed up or slow down as it falls. All objects falling through air have a terminal velocity which can be reached if the object is dropped from a sufficient height.Figure7 offers the equation for calculation of terminal velocity and the parameters you would need to measure to perform this calculation.

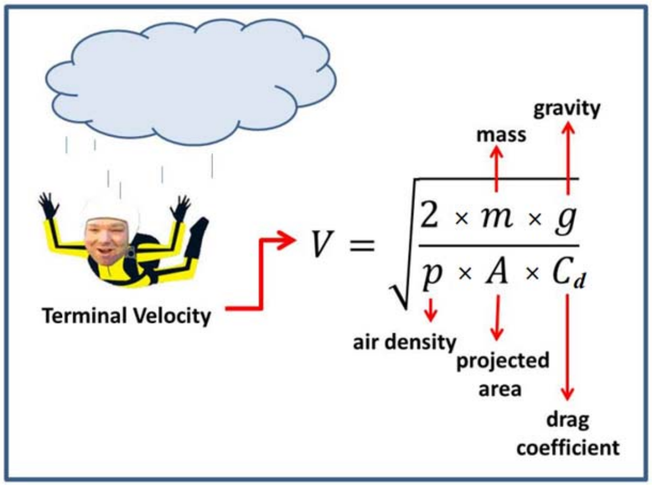


Figure 9. Image depicting terminal velocity which is the velocity at which a falling object is no longer accelerating because the force due to gravity is equal to drag force.

- If you were to attempt to calculate the terminal velocity of your coffee filter array, you would need to plug in the values in this equation:

$$\boldsymbol{V = \sqrt{\frac{2mg}{\rho A C_d}}}$$

One needed parameter in the equation is density.

$$density = \frac{mass}{volume}$$

Density is expressed in units of grams per cubic centimeter (g/cm^3). Density (ρ) in this case refers to the density of the fluid (air) the object is falling through. The density of air changes as a function of air temperature and altitude. The density of air at sea level at 15°C is 1.225kg/m^3.

A in the equation for terminal velocity refers to the projected area of the object (projected onto a plane perpendicular to the direction the object is moving) and C_d is the drag coefficient, a measure of the resistance an object encounters as it moves through a medium (air or liquid). Calculating a drag coefficient for an object such as the array of coffee filters would require a complex series of experiments completed in a wind tunnel! Thus, unless you can find the drag coefficient (C) for an array of coffee filters on the web somewhere, you will not be able to complete the calculation of terminal velocity for your experiment.

Experiment #5

- Find the plastic bag labeled *Exercise 5: Elm Samara Models*.
- After examining the materials in the bag, each team should suggest an experiment they would like to see completed. There will be several possible variations, given the materials available.
- The class should decide which experiment(s) they wish to complete.
- In each case, the primary volunteer should hold the different samaras (one in each hand) parallel to the floor at shoulder height.
- A second volunteer will measure the fall distance as well as time the fall in seconds and report the values of the respective measures to the class.
- Before proceeding, each student team should take a few minutes to decide what questions they wish to address and what their predictions will be for the trial they wish to see completed.
- Teams should then discuss the experiment, their predictions and reasoning with the rest of the class.
- The class decides what experiment(s) to complete and in what order.
- In each experiment, on the teacher's command, the volunteer drops the two samaras.
- Each team should record the results of the chosen experiment on their data sheet.
- The class should discuss what the results of the experiment they have chosen to complete suggest about gravitational force and drag and the dispersal distance an elm samara might achieve relative to the traits it exhibits.

Exercise 5b. Exploring Dispersal in Nature

Now that you have learned about how the forces of gravity and drag affect falling objects, it is time to examine how this applies in biological contexts. We will first experiment with seed dispersal here as it is influenced by the relationship between free fall under projectile motion examined in Exercise series 4 and the parameter that limits the effect of the force of gravity on a falling object, drag. Then, we consider a more complex context involving mammalian gliders.

5b1. Maple Samaras

Trees in the genus *Acer*, known as maples, all produce samaras. The samara is a type of fruit. Each samara contains one seed that is at the top end of a flattened fibrous tissue wing that develops from the ovary wall. The papery wing helps the wind to carry the fruit away from the parent tree. Though maple samaras are similar in terms of overall structure, there are species specific differences in size and shape. See Figure 10 for examples of three common North American maple species.

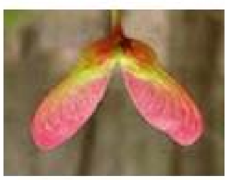
		
Red Maple ½-1” (1.27 - 2.54 cm) *Acer rubrum*	Sugar Maple ¾ - 1¼” (1.91 – 3.18 cm) *Acer saccharum*	Silver Maple 1½-3” (3.81 – 7.62 cm) *Acer saccharinum*

Figure 10. Samaras of three species of maples (genus *Acer*) showing shape and size differences.

Our hypothesis in this exercise is that species-level variation in samara size and shape is linked to dispersal capability. Several studies of wind-dispersed seeds have shown that dispersal ability is closely related to morphological characteristics of the seeds themselves. One characteristic that has been shown to be tightly linked to air current dispersal is **wing loading**, which is defined as the total mass of the fruit divided by the area of the wing (considered as the total area of the entire fruit).Wing loading is also a quantity considered in aerodynamics with regards to planes and other aircraft, in which it is defined as the total loaded mass of the aircraft divided by wing area.

$$\boldsymbol{Wing\ loading} = \frac{\boldsymbol{Total\ fruit\ mass}}{\boldsymbol{Wing\ area}}$$

What exactly does wing loading mean in wind-dispersed fruits and the seeds that they hold, and how/why could it be important? One relationship that has been shown for many wind-dispersed seeds (not just maples) is that the rate of descent of a seed has a linear relationship to the square root of wing loading:

$$\boldsymbol{Descent\ rate} = \boldsymbol{m}\left(\sqrt{\boldsymbol{wing\ loading}}\right) + \boldsymbol{b}$$

$$\Rightarrow \boldsymbol{Descent\ rate} = \boldsymbol{m}\left(\sqrt{\boldsymbol{fruit\ mass/fruit\ area}}\right) + \boldsymbol{b}$$

In the above equations, *m* represents the slope of the line drawn through the species points (e.g., red line in Figure 11) and *b* is the y-intercept of the equation for the line describing the linear relationship between descent rate and wing loading (e.g., dashed arrow in Figure 11). This relationship varies among species. Before we begin experimenting with wing loading in maple samaras, it is important to understand how the relationship between two measurable factors or parameters is established quantitatively. Linear functions help us organize this type of data so that we can identify patterns. Figure 11 is a graphical representation of the relationship between individual seed mass of seventeen species of pine and their respective velocities of descent from the pine cone on the parent tree. What information does this analysis offer that we could not gain from examining a table of the values for mass and descent rate by species examined? A few facts about linear functions and scatter plots are summarized in the **Blue Print** section following Figure 11.If you are already familiar with linear functions and scatter plots, you may skip to the questions posed about the data presented in Figure 11, starting with Q13.

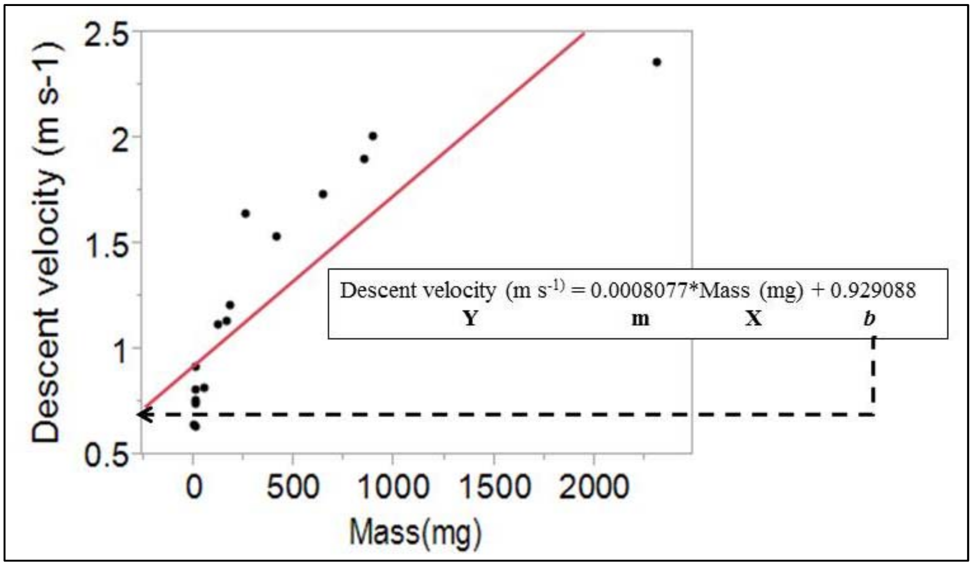


Figure 11. Graphical relationship of velocity of pine seed descent as a function of its mass for 17 species of pine trees. The equation describing the linear relationship between seed mass (mg) and velocity of descent($m\ s^{-1}$) is shown in the box.(Data used in preparing this graph are from a table in D. F. Greene and E. A. Johnson 1993. Seed Mass and Dispersal Capacity in Wind-Dispersed Diaspores. Oikos, Vol. 67, pp. 69-74).

LINEAR FUNCTIONS AND SCATTER PLOTS

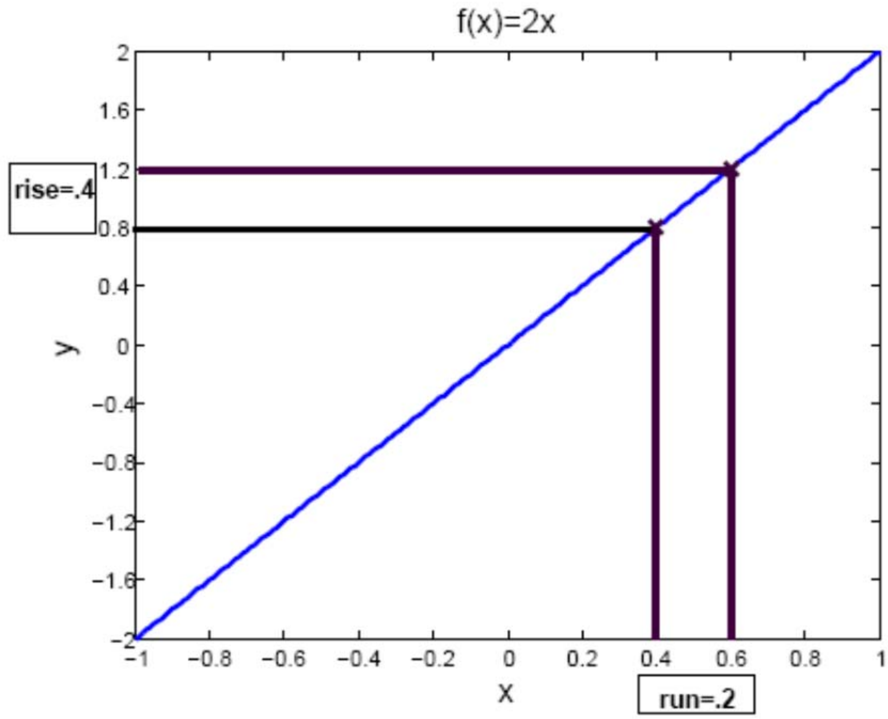
A linear function is a function of the form: $\boldsymbol{y = mx + b}$.where $\boldsymbol{m}$ and $\boldsymbol{b}$ are real numbers. The number $\boldsymbol{m}$ is called the slope of the line. The number $\boldsymbol{b}$ is called the y-intercept of the line. The graph of a linear function is a line. We say that a point $(\boldsymbol{x_1}, \boldsymbol{y_1})$ is on the line if $\boldsymbol{mx_1 + b = y_1}$.

Q6. Check to see if the following points are on the line $\boldsymbol{y = 3x + 4}$:
$(\boldsymbol{1}, \boldsymbol{8})$
$(\boldsymbol{2}, \boldsymbol{10})$

The slope $\boldsymbol{m}$ tells us how the value of $\boldsymbol{y}$ changes with the value of $\boldsymbol{x}$. The slope is equal to the change in $\boldsymbol{y}$ divided by the change in $\boldsymbol{x}$, that is the rise over the run.

$$\boldsymbol{m} = \frac{\textbf{rise}}{\textbf{run}}$$

This definition is illustrated in the figure below that illustrates the slope of a line.



Q7. Find the slope of the line in the figure.

If (x_1, y_1) and (x_2, y_2) are any two points on the line then the slope of the line is:

$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

If m is positive, then as x gets bigger, so does y. If m is negative, then as x gets bigger, y gets smaller.

Because the slope is the quotient of the change in y divided by the change in x , it is measured in $\frac{\text{y units}}{\text{x units}}$. For example, if the y-axis of a plot is measured in miles and the x-axis of the plot is measured in minutes, then the slope of a line on the plot is measured in $\frac{\text{miles}}{\text{min}}$.

The y-intercept b is the value that y takes when x is zero. This means that the point $(0, b)$ is on the line.

Q8. What is the y-intercept of the line $y = 3x + 4$?

The formula $y = mx + b$ is called the slope-intercept formula for the line. If (x_1, y_1) is any fixed point on the line $y = mx + b$, then given any other point (x, y) on the same line gives us:

$$m = \frac{y_1 - y}{x_1 - x}$$

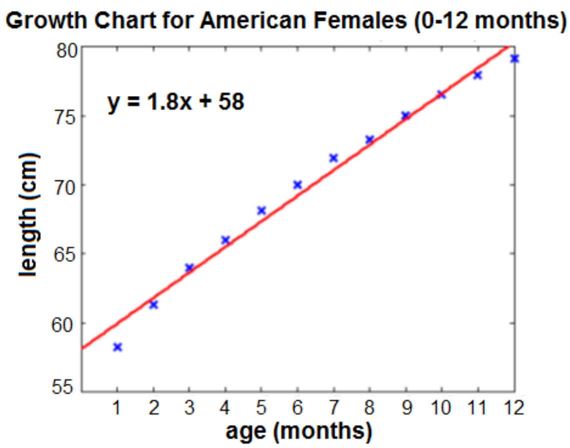
which is called the point-slope formula for the line.

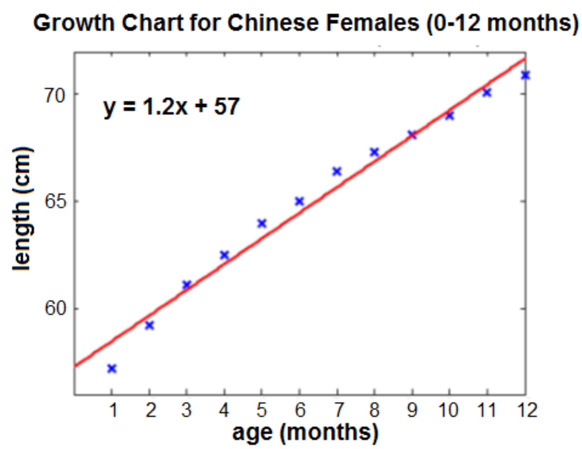
Q9. Suppose that a line has slope $m = 2$ and that the point $(2, 7)$ is on the line. Write down the point-slope formula for the line.

Supersolver Question

Q10. Find the slope-intercept formula for the line in Q4.

The graphs below are examples of scatter plots. Scatter plots are used to explore possible relationships between two variables that both relate to the same phenomenon. By convention, the independent variable (if one is identified as such) is positioned on the x-axis, and the dependent variable (the trait you are questioning) is placed on the y-axis.





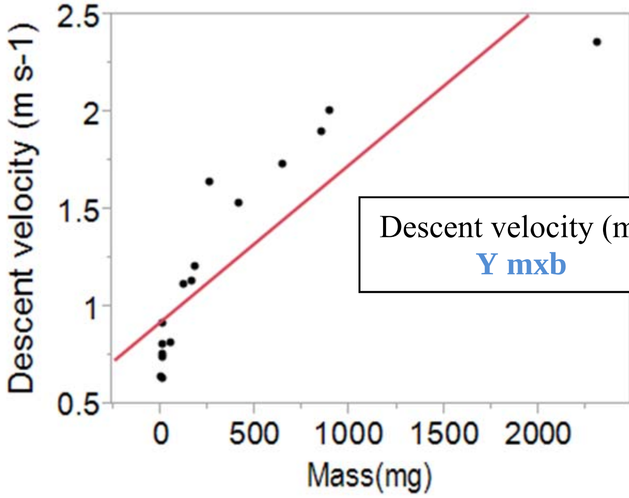
In each figure above, body length is plotted against infant age. We used MATLAB software to draw the ‘best fit’ line through the scatter plots. The equation of the best fit line is also displayed on each plot. The closer the points are to this line, the better the fit, and the stronger the relationship between the two variables. For example, in the scatter plots on the previous page, it looks like the relationship between body length and age is very strong in both Chinese and American infants. If many of the points lie very far from the line there is probably no correlation (relationship) between the traits. If the data points in the figure cluster in a band from upper left down to lower right, then the two traits are negatively correlated (i.e., as age increases, length decreases). In this case the slope of the best fit line is negative. If the points cluster in a band running from lower left to upper right as seen in our figures, the two traits are positively correlated, and the slope of the best fit line is positive. Thus older female infants tend to have longer body lengths than younger female infants.

What else can we see from the figures? Body length in both American and Chinese female infants is correlated with age. However, the data points for American females tend to lie above those for Chinese females. This is reflected in the fact that the best fit line for the American data lies above that for the Chinese data. This suggests that American female infants are, in general, longer than Chinese female infants. Why might this be the case?

Q11. Record the slope of the best fit line for both the American and Chinese infant growth data. Which best fit line has the largest slope? How would you interpret this fact?

Q12. Record the y-intercept of the best fit line for the Chinese and American infant growth data. Which data set has the smallest y-intercept? How would you interpret this fact?

Now that you have reviewed linear functions, let's revisit Figure 11, repeated below.



Descent velocity (m $s^{-1)}$ = 0.0008077*Mass(mg) + 0.929088
Y mxb

Figure 11. Graphical relationship of velocity of pine seed descent as a function of its mass for 17 species of pine trees. The equation describing the linear relationship between seed mass and velocity of descent is shown in the box.

Answer the following questions from examination of Figure 11.

Q13. What does the slope of the line in Figure 11 indicate about the relationship between seed mass and the velocity of that seed type's descent?

Q14. According to Figure 11, when seed mass is at or approximates zero, what is the speed of descent of a seed of that mass according to the linear analysis?

Q15. What can you say about the samara type designated by the point at the top right corner of Figure 11?

Q16. Interpret the relationship between mass and descent velocity for samaras below the best fit line in the lower left corner.

Check your answers to these questions under Exercise 5 at the end of this unit.

Why might tree species have evolved different wing loads? Trees species have evolved to fulfill different niches. The niche of a tree species refers to the physical conditions under which the tree can best exist. Trees that colonize disturbed habitats are fast growing species that make maximum use of the readily available sunlight in growth through photosynthesis. They are poorer competitors however, to the slower growing tree species that come in once a richer soil has built up. Thus, the pioneer species survives by casting its seeds out long distances on the chance that some will land in open areas. On the other hand there is much competition for resources in the climax forest. But the tree species in a climax forest are shade tolerant, grow more slowly and are longer lived. The dispersal strategy in a climax forest is to produce a seed that will stay in the favorable habitat and have qualities that permit it to successfully compete for resources in the environment.

In this exercise, you will examine the samaras of three species of maple and assess their wing loading and associated dispersal capabilities. You will use the data you collect to make inferences about the niches of these maple species.

Materials Needed:

- 90 maple samaras (30 each from 3 species)
- Digital scale
- Tape measure
- Stopwatch
- 1 mm graph paper for each team (Can be copied from sheet at end of this exercise here, or downloaded from the web) *
- A dry spaghetti strand or two for each team in the class *
- Scissors*

**** To be provided by the teacher.***

<u>PLEASE TAKE CARE WHEN HANDLING THE SAMARAS!</u>
The samaras need to be used over and over again by the classes working on this unit. They have been coated with polyurethane, but are nevertheless <u>FRAGILE</u>.

Procedure:

- Divide into groups of 3–4 students.
- Each group will be provided with several samaras from different maple species.
- Note that each of the provided samaras is marked with a number and a colored dot. The dot identifies the species (red = box elder, blue = silver maple, white =

sugar maple). The number allows you to look up the mass of a particular samara (within a species), and it will also be used for tracking and recording the results for that samara in the data table.

- Each team should construct a data table similar to the one that follows.You will use the table to record the data you collect with a new row for each samara.

Species	#	Mass (g)	Area (mm^2)	Wing loading (g/mm^2)	Square root of wing loading	Drop height (m)	Drop time (s)	Horizontal Distance (cm)	Descent rate (m/s)

- For the calculation of wing loading, you will need to record the mass of each samara in your table and an estimate of its wing area. Begin by listing the species and seed number for each of your samaras in your table.

- <u>Record samara mass:</u>
  - The University of Tennessee has made the mass determinations for you as a highly sensitive electronic balance was required. Each team will receive a sheet that has the mass listed for each seed by species and number.
  - Use the laminated sheet provided each team to look up the mass of each of your samaras and record this in milligrams (mg) in your table.

- <u>Determine samara area:</u>
  - Obtain 1 mm square graph paper sheets from your teacher.
  - Carefully trace each samara on 1 mm graph paper. Count the number of *full* squares in the outline of each. You may wish to place a dot in each square

as you count it. If there are any partial squares remaining, try to estimate the total amount of squares represented by each of these fractional parts.
  - Record the areas in square millimeters in your table.

- Determine wing loading and its square root:
  - For each samara, divide its total mass by its area. Record this value in your data table under wing loading for the individual samara.
  - Take the square root of this number and record it in the appropriate column.

- Experimentally determine descent rate:
  NOTE: As maple tree branches are quite high, it would be useful to complete this experiment from a banister, bleachers in a gymnasium or stairwell to get realistic vertical and horizontal drop distances and more accurate drop times. Alternatively, students can get descent results from standing on a sturdy table/lab bench and dropping samaras from a position parallel and adjacent to the ceiling to the floor.

  - During each trial, one student of each team should act as the “dropper”, another as the "timekeeper", a third as the observer "caller", and a fourth as the distance "measurer" (vertical and horizontal from position of drop).
  - Before initiating the trials, the distance (in meters) from drop height to the ground or floor should be measured using the meter tape and recorded. The drop height should include the height of the railing or the shoulder height of the person who will be extending his or her arm out to drop the seed. The tape should be extended down to the ground and the horizontal position of the drop marked with a piece of tape.
  - Once the dropper has the samara held in a repeatable position that has been agreed on by the class, the caller should start the trial by saying “go.” At the caller’s command, the dropper releases the samara and the timekeeper should also start the stopwatch.
  - When the samara hits the floor, the caller should say “stop,” at which point the timekeeper should stop the stopwatch and the measurer mark the landing location.
  - The measurer measures and the group records the distance (in cm) between the horizontal drop point and samara landing point on the data sheet.

- The time (in seconds) that it took for the samara to fall the full distance to the floor should then be recorded in your group's data sheet.
- The samara's descent rate, in m/s, can then be calculated by dividing the total distance of the descent by the total time recorded for the fall. This value should also be recorded in your data sheet.
- Repeat the above procedure for each samara.

- <u>Analyze your data:</u>
  - On the board at the front of the room combine the data by species from all teams. Each team should use these data to develop a scatter plot for the three species similar to that shown in Figure 11. For the figure you create, the x-axis will be the square root of wing loading rather than samara mass like in Figure 11. Note that the y-axis is expressed in meters per second (m sec^{-1}).Make the dots on the graph a unique color for each species.
  - Once each team has prepared their graph and all graphs have been shared with the class, draw a straight line that best represents the data on your scatter plot. This is useful for making predictions about values that may not be displayed on the plot. Called a line of best fit, this line may pass through some of the points, none of the points or all of the points. There are two ways to fit this line to your data: line approximation using a spaghetti strand or, for a more accurate method, you may use computer software for graphing such as Excel or MATLAB. Here we give instructions for how to approximate the line using a spaghetti strand:

    :

    - Lay your scatter plot flat on a desk.
    - Position a strand of spaghetti on the graph and position it so that the plotted points of a given species, denoted by the same color, are as close to the strand as possible as shown in Figure12.
    - Put an X at either end of the spaghetti strand; remove the strand and using a ruler draw a line that reflects the color of that species connecting the X's. This line reflects how quickly descent rate of a samara of the species of interest increases with increases in the square root of its wing loading. (Remember, wing loading equals samara mass divided by its surface area: the greater the mass

relative to surface area, the faster the samara should drop and vice versa).

- Repeat the process by drawing lines for the other two species.

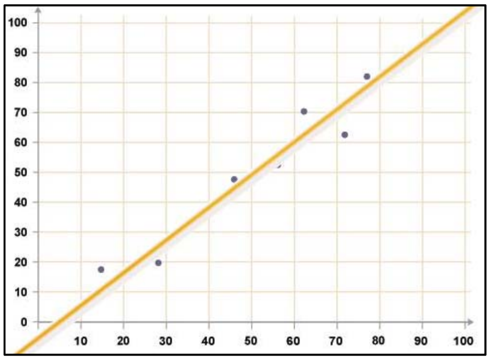


Figure 12. Example of use of a spaghetti strand to find the best fit straight line through a set of data points.

- Next, find the linear function that describes each of the best fit lines. For detailed instructions, check back to the blue section of text titled 'Linear Functions and Scatter Plots' in the introduction to this exercise. This function describes and predicts the relationship between samara mass and surface area and the fruit's rate of descent for each species.

  - Determine the slope and y–intercept of the line for each species.
  - Use the slope and y-intercepts to develop a function for each species that predicts the descent time for a samara given its wing-loading.

- Compare the slopes of the lines for each species. Do they differ? If so, which one has the greatest slope (steepest line)?Which one has the smallest slope (flattest line)?

- Since we are ultimately interested in how the samara dispersal distance varies by species, you also need to compare the horizontal distances that the samaras traveled relative to the position you recorded with a taped spot on the ground.

- Determine the mean horizontal distance traveled for each species. . Visually compare these mean distances from the drop spot among the three maple species.

Answer the following questions:

Q17. You may find the horizontal ranges of your samara types were unexpectedly small and may not show species differences. Why then would the species expend energy to produce a winged fruit? Discuss as a class why you obtained the results you did.

Q18. From your vertical drop results what prediction can you make about the relationship between wing loading ratios and dispersal ability of maple samaras?

Q19. Rank the three maple species from the greatest potential for dispersal distance to the smallest potential. What would be the relationship between the species dispersal capabilities and the niche each of the tree species occupies? Consider the species status as a climax forest or sub-climax forest species versus a pioneer species that invades habitats that have been disturbed (e.g., cleared by a hurricane or landslide or human activity)).

Q20. The traits organisms exhibit represent the trade-offs in selection pressures on species. Think about the characteristics a samara needs to have to disperse the long distances required to settle in habitats where there is less competition for resources, as opposed to the samara that needs to be a good competitor and grow fast in the place it lands in the shade of overhead trees. Discuss the wing-loading characteristic of each of the three maple species with respect to such trade-offs.

Q21.In what types of habitats would you expect to find each of the species from this exercise?

- Check your answers in the answer section at the end of this workbook under Exercise 5.

5b2. Gliding Mammals

The world's smallest monkey, the pygmy marmoset, is a tree dweller that drops from branch to branch. This monkey is only 100 g in weight, similar to the mass of the marsupial sugar glider and the flying squirrel pictured in Figure13 below. The difference between the monkey and the other two tree dwellers is that the monkey lacks the extensive skin membranes called patagia that stretch between fore and hind limbs present in the sugar glider and flying squirrel.

Figure 13. Three adult tree-dwelling mammals of similar mass. From left to right: the marsupial Sugar glider, *Petaurusbrevicups* (115 grams); the Pygmy marmoset monkey, *Callithrixpygmaea* (100 grams); and the Southern flying squirrel, a placental rodent, *Glaucomysvolans* (80 grams).

Monkeys drop from one branch to another, under the conditions of gravitational forces. As a class, answer the following questions. The answers to these questions are posted under Exercise 3b of this unit at the end of the book

Q22. How does the monkey move from tree to tree and what limitations are placed on its movement through the forest?

Q23. What advantage do the gliding mammals pictured in Figure 13 have over the marmoset?

Q24. How is gliding achieved? A third force is involved besides gravitational and drag forces. What is it and what is the nature of their interaction in enabling gliding behavior?

Q25. What difficulty does a glider have to deal with and how might it counter such problems?

Open-ended Exploration:

- **Outdoor trials of horizontal samara dispersal range.** Repeat the experiments you did with maple samaras outside. Use an anemometer, weather reports or a qualitative estimate of your own design to estimate wind speed and direction.

- **Extend the project to other types of wind-dispersed seeds, make within-genus comparisons of ash (*Fraxinus*) or pine (*Pinus*).**

- **Manipulate the weight or area of natural or artificial samaras.**

- **Complete field measurements of seedling distances from mature trees** or compare abundance densities of acorns to maple samaras found under mature trees etc.

  Complete an engineering application - design a whirligig. Imagine that a cereal company has approached your design team and presented you with an interesting challenge. They want to incorporate a whirligig toy template into their box design so that after eating the cereal, children can cut out the template and play with the toy. See Figure 14 below for an example of a whirligig toy.

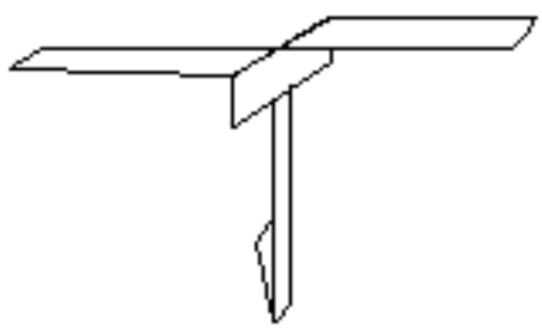


Figure 14. An example whirligig toy.

The cereal company of course wants it to be the best possible whirligig that could be put on the box. Based on their market research, they define "best" as the whirligig that can stay in the air the longest (has the slowest descent rate), while still clearly displaying rotation. Have a class competition for the best cereal box design performance.

Exercise 6: Bioacoustics

Acoustics is an interdisciplinary science that involves the study of mechanical waves, including vibration and sound. The word *acoustic* is derived from the Greek word *akoustikos* which means "of or for hearing" and *akoustos* for "heard or audible".

Hearing is one of the senses that animals use to access external information. Other senses include taste, touch, vision, smell and the perception of magnetic fields, heat, and electricity. The ability to detect and interpret sounds is important for animals to detect of prey and avoid predators and other dangers. Communication through sound is considered the most advanced form of animal signaling in terms of the complexity of information transmitted as well as the distance over which it can be perceived. It can be transmitted through air, water and even the ground. Hence, it is not surprising that 200,000 species of insects have been described as sending signals to each other through vibrational channels. Animal species not only use vibrational channels to communicate with each other, they also eavesdrop on others. The fact that the sense of hearing is so widely used among animal species to detect and interpret sounds, and that there has been corresponding complexity in the production of acoustic information, offers innumerable engineering applications in the area of acoustics. These applications fall into the areas of sound dampening, amplification, and detection**.**

Under the exercises in the acoustic series, you will explore sound communication and acoustics in the ways briefly summarized below.

In **Exercise 6a. Mechanism**, students in grades K–12 will gain an understanding of four main methods of sound wave production used by animals in sound communication. Students will compare the sound characteristics (amplitudes and frequencies) produced by different sound production methods through analysis of recordings of animal signals and by experimenting with musical instruments. They will also learn how sound communication patterns are used by scientists to obtain insight into the taxonomic relationships within an animal group, using call recordings to sort frog species into families.

In **Exercise 6b. Sounds are Waves**, students in grades 4–12 will learn about particle movement in the production of waves and the relationship between wave form and sound properties. They will also learn how sounds are perceived by various organisms and the technological applications of sounds, including those that are outside the range of normal human hearing.

Exercise 6c. Seeing Sound, students in grades 4–12 will learn about graphical representations of sound called sonograms, and why they are useful to scientists. Students will read and try to match sonograms to sounds produced by frogs and birds.

Exercise 6d. Communicating at a Distance, students in grades 4–12 will learn about sound attenuation, the gradual loss of sound intensity over distances, as well as other challenges faced by animals in their auditory communication. Students will measure and compare the attenuation of several different sounds, and will be challenged to think about and simulate various adaptations that animals have to deal with the issue of attenuation in an open-ended exploration. High school students will additionally learn how logarithms and the laws of exponents relate to sound intensity

Exercise 6e. Crank It Up, students in grades 6–12 will learn the basics of how a speaker works. They will assemble simple speakers from common materials under the challenge to improve the sound emanating from an assembled speaker.

Exercise 6f. Stop that Noise, student teams in grades 6–12 will apply what they have learned in Exercises 6a through 6e to competitively develop engineered solutions to the acoustic problem posed. They will be expected to consider both comfort and safety in their solution.

Exercise 6a. Methods of Animal Communication (*grades K-12*)

Sound is simply the vibration of molecules, whether in air, water, or the ground, that produces wave-like patterns (See Figure 1). Sound communication is extremely important in the animal world because it has many advantages over olfactory (chemical) and visual communication systems. This is because sound waves can be transmitted around obstacles such as clusters of trees, achieve communication in the dark, and travel much faster and further than chemical communication. Sound also can produce more complex messages because various **attributes** can change: 1) *pitch or sound wave frequency* - number of cycles of a given wave form per unit time; 2) *amplitude* - degree of change in atmospheric pressure caused by sound waves; 3) *tone* – characteristic frequency or distinctive property of a complex sound; and 4) *intensity* – sound power per unit area (watts/cm^2). All of these attributes can be varied to produce a variety of sounds.

In this exercise, you will learn about four main ways in which animals produce sounds. You will use musical instruments that produce sounds in similar ways.

All sounds, no matter how they are produced, are a result of one overall cause: the vibration of molecules. On land, we are accustomed to sound produced by vibrating molecules of air. However, whales and other aquatic animals produce sound underwater. Sounds in aquatic environments are produced by the vibration of water molecules. There are also innumerable taxa that communicate seismically (earth vibration) by making twigs, leaves, the ground, logs and other substrates vibrate. Whether produced on land, in water, or underground, all sound results from the bumping of molecules into one another. Bumped molecules bump other molecules that bump additional adjacent molecules. In this way, the movement or vibration of molecules moves in the form of a chain reaction. As molecules are bumped towards other molecules, they are brought closer together in a process known as **condensation** or **compression**. Once the molecules collide, they bounce off of each other and are moved further apart, creating regions of lower molecule density. This latter process is referred to as **rarefaction**, the opposite of compression. Rarefaction causes molecules to move closer to molecules further down the direction of movement, again causing condensation/compression. Molecules traveling along the path of multiple cycles of compression and rarefaction create a wave (Figure1). Sounds are thus transmitted through waves consisting of regions of low pressure, or rarefaction of molecules, and regions of high pressure, or compression of molecules. Your ears, and the auditory sensory organs of other animals, are adapted to detect and process these pressure changes.

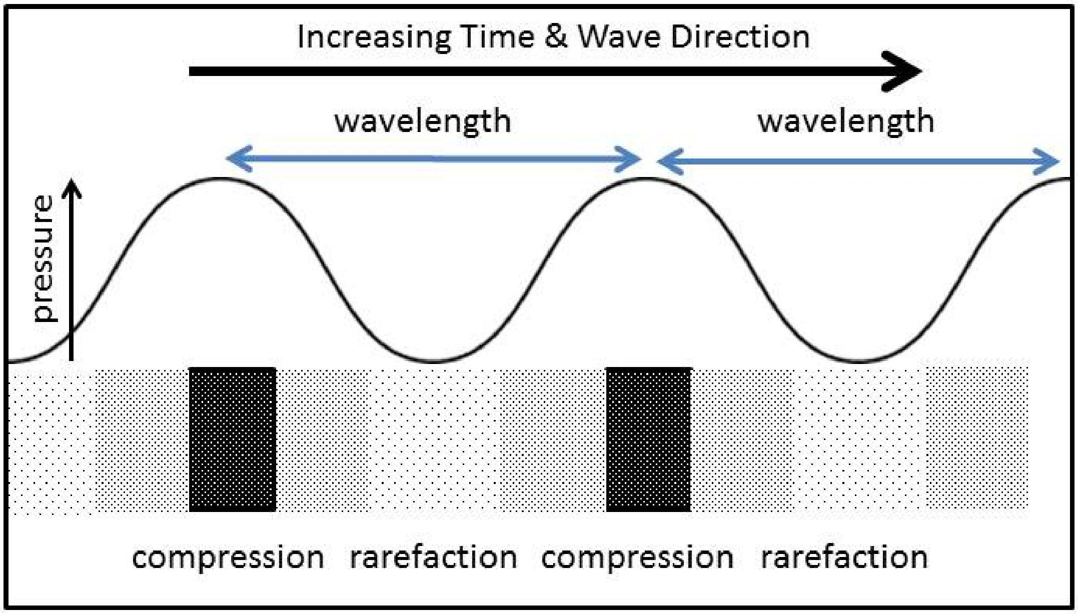


Figure 1. Example of the creation of a sound wave that results from the rarefaction and compression of air or water molecules as they bump into one another in a chain reaction. Note that rarefaction is associated with low pressure and compression with high pressure.

- Now take a moment to think about how sounds are produced, and answer the following questions:

Q1. Do you think that sounds travel faster through air, liquids, or solids? Why?

Q2. What sort of effect do you think that temperature might have on sound transmission?

Though all sounds travel in waves, sound differences are due to shape or frequency differences in the waves. As you learned above, one way that sounds may differ is in terms of wavelength, called **pitch**. If the wavelength is shorter, then the wave frequency (number of waves of the same shape per unit time), is higher. Trumpets have a higher pitch than tubas because trumpets have a higher frequency of short waves and tubas a much lower frequency of long waves. You will learn more detail about how sound waves differ in exercise 6b, but for now, let's focus on the basics of how animals communicate with sounds.

Exercise 6a1. Simulating Animal Communication Methods

There are four general mechanisms that animals use in producing sounds with different wave patterns (Figure 2).

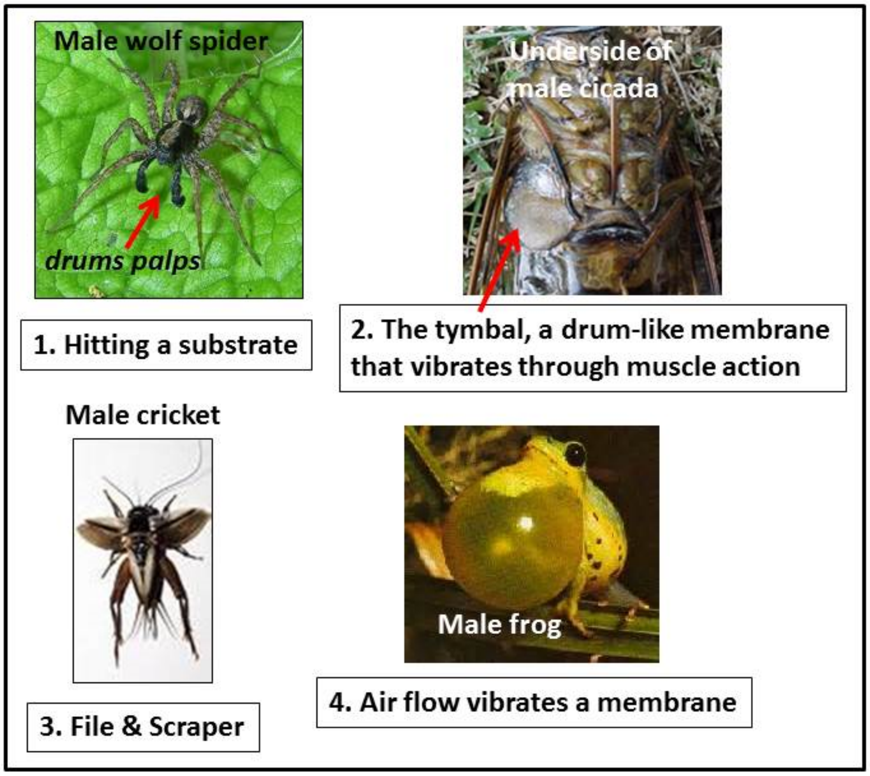


Figure 2. Examples of four sound production mechanisms exhibited in animals

1. Probably the simplest way some animals produce sound is by **striking a substrate** (surface) with part of their body. Wolf spiders of the family *Lycosidae*, for example, have bulbs on the front accessory legs that look like boxing gloves. The spiders use these bulbs to drum on leaves or other substrates. Perhaps you have heard male woodpeckers drum their beaks on trees and even metal electric boxes in the spring. They do this to announce their presence to females they want to impress.

2. A second, similar way of producing sound is to use muscles to **vibrate a membrane.** A membrane is a thin, flexible structure that resembles the top skin of a drum.

3. A third way animals produce sound is by scraping a stiff structure against a rough surface, essentially a file and scraper mechanism. This process is

known as **stridulation**. Male crickets use stridulation when courting females. The male chirps to females by rubbing one wing over the bottom vein of another wing which has a row of teeth on it.

4. The most complex way that animals produce sound is by **passing air over a vibrating membrane**. This method allows for a rather large variety of sounds to be produced, as both the rate and intensity of the membrane's vibration, as well as the flow of air over the membrane, can be regulated. The courting frog in Figure 2 is using this song production method.

In this exercise you will explore these various sound production mechanisms by making these sounds yourself with various instruments. You will also evaluate sound clips of animals producing sounds. Before you do this, it is important to understand the most important function of sound communication in the animals shown in Figure 2,**courtship signaling**.

Exercise 6a2. Courtship Signaling

- Students should take a moment to drum on the surface of their desks using the palm of their hands or fingers, listening to the sound that is produced.

Q3. Which of the four ways of producing sound is this most like? Let's assume that you are a male looking for a potential mate. How would you use your hand or finger tapping to make a courtship signal that is unique to your species so that it reaches the correct audience?

Before checking your answer under this exercise at the end of the unit book, discuss this problem as a class and come up with a solution that you all agree on.

- Divide the class into teams of five or six students, depending on class size. Each team should come up with a unique name and give a list of their names under the team name to the teacher.
- Each team should develop a unique tapping signal that members of the group share only amongst themselves.
- After the signal has been decided on and team members have had the opportunity to practice it a few times, the teacher will go out into the hall with one member of each team, closing the door behind them.

- Each student in the hall will draw a number which reflects the order that they will present their team's signal to the class by rapping it on hall side of the closed door when his or her number is called through the door.
- The teacher will return to the room and prepare the class for the exercise as follows:
  - When the students hear a rap pattern, they will remain seated if it is not the unique signal decided upon by their team.
  - They will stand up if they recognize the pattern as their team's unique signal.

- The teacher will record the following information **without telling the class the results until the experiment is complete:**
  1. The number of students who correctly identified the pattern as belonging to their team by standing up.
  2. The number of students who failed to identify the pattern as their team's signal by remaining sitting when they should have stood up.
  3. The number of students from other teams that incorrectly identified the pattern as their team's pattern and stood up when they should have remained seated.

- Repeat the trial process until all team representatives have had the opportunity to rap their team's unique signal on the hall side of the door.
- The teacher will summarize the results and the class should discuss the role of sound in courtship. The class should consider the following questions:

Q4. What are the advantages, problems, etc. of using sound in courtship?

Q5. If discrimination errors are made by females, what is the immediate consequence?

Q6. What will discrimination errors ultimately lead to?

Exercise 6a3. Exploring Sound Producing Mechanisms

(NOTE TO TEACHERS: ***To avoid spreading germs, a rubber bulb syringe is included for playing the whistle in this unit. To use it, simply insert the tapered end of the syringe tightly into the mouthpiece of the whistle, and squeeze the bulb to force air through the mouthpiece.*****)**

- Divide the class into four teams.
- Find the container labeled Exercise 6b. There are four instruments in the container mimicking the four kinds of sound communication exhibited by animals.
- The teams should rotate with each team examining one of the instruments provided in the box at a time.
    - Try playing the instrument, listening to the sound produced.
    - Answer the following questions about the instrument you have examined. Commit your answers to paper under your team name.

Q7. To which animal sound production method is this instrument most similar?

Q8. Are there different ways of playing this instrument that might be more related to one of the other animal communication methods?

Q9. Can you think of other instruments that produce sound in similar ways?

- Repeat this process for each of the other instruments provided.

- Discuss as a class the answers the teams have offered for questions 7–9 about each instrument.

Exercise 6a4. Animal Sound Production Quiz

Now that you have examined these various methods of sound production yourself, let's think a little more about how animals use them!

- Examine the pictures of animals on the following page in Figure 3.Think about what types of structures or behavior that these animals might use to make sounds in ways similar to the instruments that you have examined.
- Take out a sheet of paper and make three columns, leaving the last two columns blank for the moment. In the first column, number the rows 1–9, label the

second column with “Animal Name” and the third column “Sound Production Mechanism(s).”

- Now listen to the audio recordings of sounds produced by the pictured organisms presented in no particular order as unknowns 1–9 on Track 1 (labeled ‘Production Mechanisms’) of the accompanying CD. Save the recording 10 on Track 1 for later.
- Decide what organism produced each sound and what sound production mechanism generated that sound. Record your guesses in your table. Remember that the potential sound production mechanisms are: **1) Striking a Substrate**, **2) Muscles Vibrating a Membrane, 3) Stridulation**, and **4) Air Flow Vibrating a Membrane**.
- As a class make a table on the board and fill in the number of students that assigned a number to a particular animal.
- Do the same for the assignment of the audio clip of a particular number to the production of the respective four classes of sound production mechanisms.
- If students disagree about a particular sound and present arguments as to why they favor one taxon or production mechanism over another, the sound clip should be replayed additional times with an attempt at reaching a class consensus as to the animal and the sound production mechanism.
- At the end of this process, check your answers under Exercise 6a4: Sound Production Quiz at the end of this unit.
- Play the sound clips again after each student has made corrections to their answer sheet.

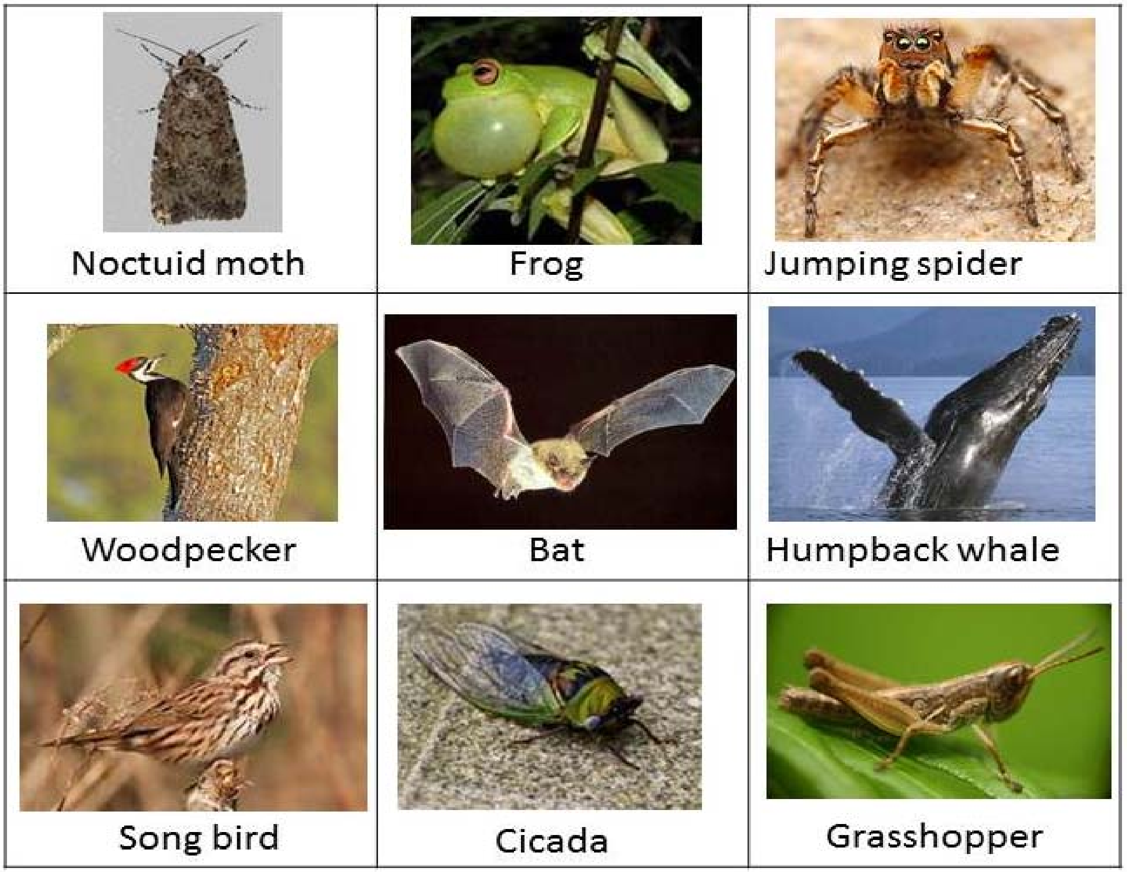


Figure 3. Examples of animals that use various forms of sound communication.

Complex Sound Production in Nature

- Biological systems are very complex. It is difficult to pigeonhole organisms into categories such as we have done when identifying communication mechanisms. For example, male woodpeckers both drum and vocalize (air flow vibrating a membrane) during courtship communication. While most bats use their larynx (air Flow vibrating a membrane), some bats communicate by flapping their wings, others through flapping of the tongue. And then there are fish that lack lungs and a larynx. Listen to the communicatory sounds produced by the piranha (sound clip 10) under Production Mechanism of Track 1 on the CD. *Pygocentrus natterei* produces three sounds. Drumming and barking sounds result from rapid contractions of sonic muscles that insert on a tendon on the underside of the swim bladder, an air-filled chamber that gives fish buoyancy. The piranha also produces a short pulse barking sound through snapping of the jaws.

Open-ended Exploration:

1) Using materials that you can find around the classroom or at home, see how many different instruments you can make that produce sound using each of the four mechanisms. Compare your instruments with those produced by your classmates.
2) Search the web for sound clips produced by additional animals. Bring a copy of a clip to class to attempt to stump your classmates as to animal taxonomic affiliation and sound production mechanism.
3) Find *YouTube* videos that show various sound producing apparati in action to share with fellow classmates.

Exercise 6a5. Identifying Frogs by Sound

Like birds, male frogs and toads sing to attract females. It is important to both sexes that they locate only individuals of the same type or species, so each species has a unique song or call. However, the calls of closely related species are more similar to one another than to other frog or toad calls. In Tennessee, we have three major groups of frogs: true frogs, toads, and tree frogs (Figure 4). In this exercise, you will learn the differences in calls among these three major frog groups and then assign the calls that you hear to the correct group.

- Take out a sheet paper and make a list of numbers from 1–11.
- Find the CD for this unit. This exercise uses Tracks 2–4.
- Listen to Track 2 ‘Introduction to Frog and Toad Calls’.
- Follow your guide through the exercise.
- Track 3 presents the unknown calls.
- On Track 4, the guide will play the calls again, telling you what animal produced it.

You may also check your answers in the answer section at the end of this unit.

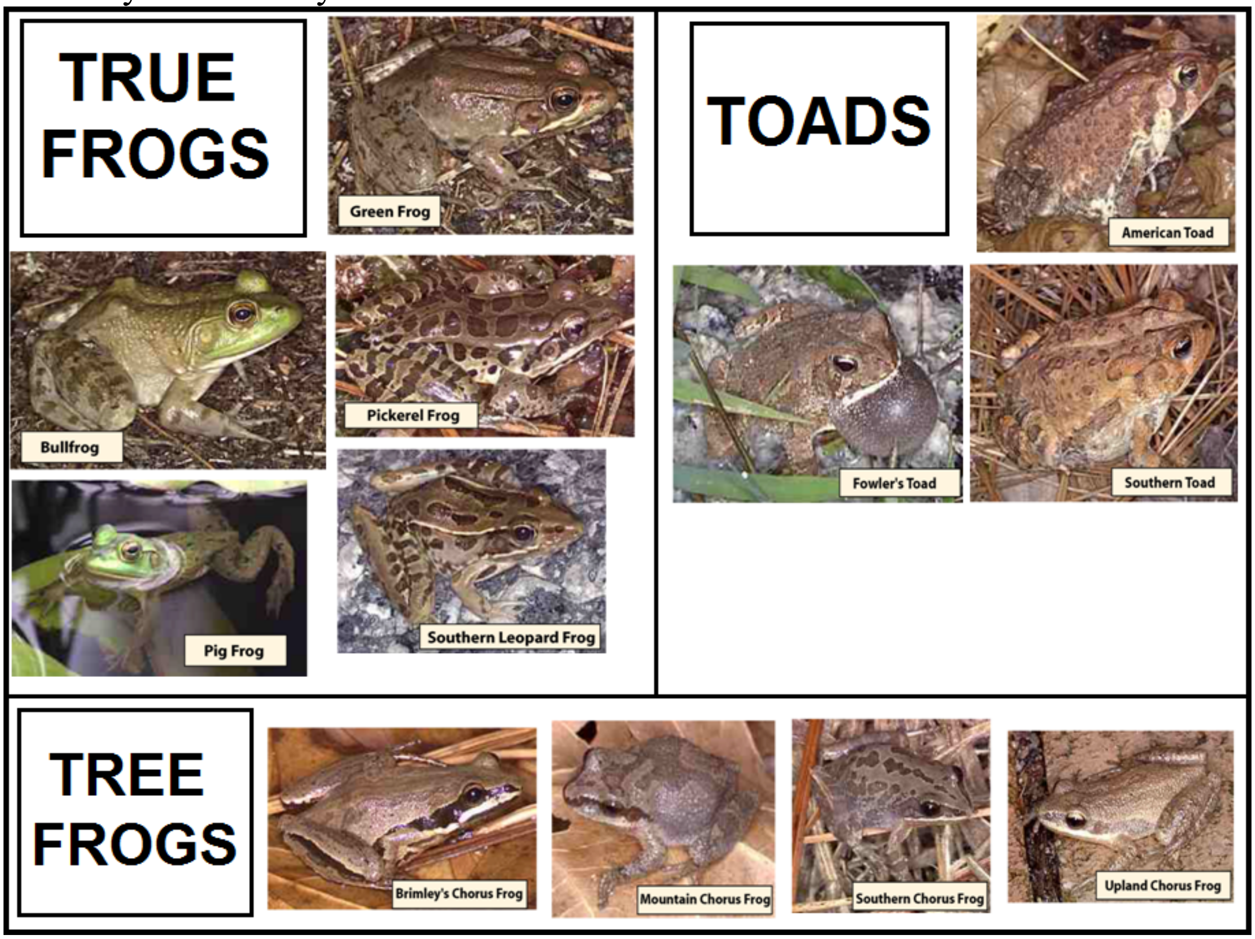


Figure 4. Images of the amphibians that produce the mating calls you will hear.

Exercise 6b. Sounds are Waves

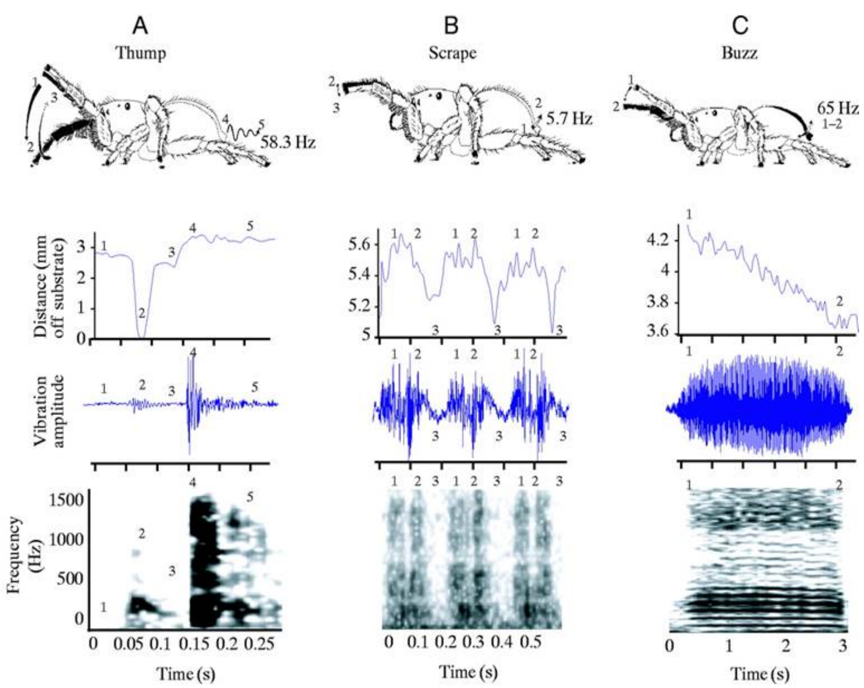
Jumping spiders, such as the male shown in Figure 3, have long been known for the highly visual courtship displays they make towards females. You may find links to these under the Tree of Life website (genus *Habronattus*) **http://tolweb.org/Habronattus/3069.**

Dr. Damian Elias was the first scientist to examine the sound that accompanies the visual displays that these spiders exhibit. Let's examine what he learned about the role of sound communication in the first species he examined, *Habronattus dossenus.*

- Your teacher will play the video clip of the courtship of this species, found on track 5 of the CD accompanying this unit or at https://www.youtube.com/watch?v=4gOiujoR-5o.What you are looking at is a male courting a female on a sheet of graph paper. The cone-shaped object sticking up from the head of the female spider is a phonograph needle (piezoelectric device) glued to her head with bees wax. This device receives and transmits the vibrations as an electrical signal to be converted into the sound wave patterns shown in Figure 5.

- Each student will be given a copy of Figure 5, or it will be displayed for all to see.
- Your goal is to identify the 'thumps' that occur first in the sequence, the 'scrapes' appearing second and finally the third new sound, 'buzz'.
- You will probably need to play the sequence more than once to understand how leg and abdomen movement is associated with the sounds the spider is producing.
- While you listen to and view the video to the sound recording examine the images of male spider position and the position of that sound on the sound wave patterns shown for amplitude (iii) and frequency (iv).

Fig. 5. Types of seismic signals in the courtship sequence of the Jumping Spider *Habronattus dossenus* https://www.youtube.com/watch?v=4gOiujoR-5o



Damian O. Elias et al. J Exp Biol 2003;206:4029-4039

The Journal of Experimental Biology

Remember, in Exercise 6a, you learned that sounds are transmitted through a medium such as air through waves consisting of regions of low pressure, or **rarefaction**, and regions of high pressure, or **compression**. Your ears and the hearing organs of other animals (*e.g*. trichobothria of spider legs), interpret sound waves (Figure 6).

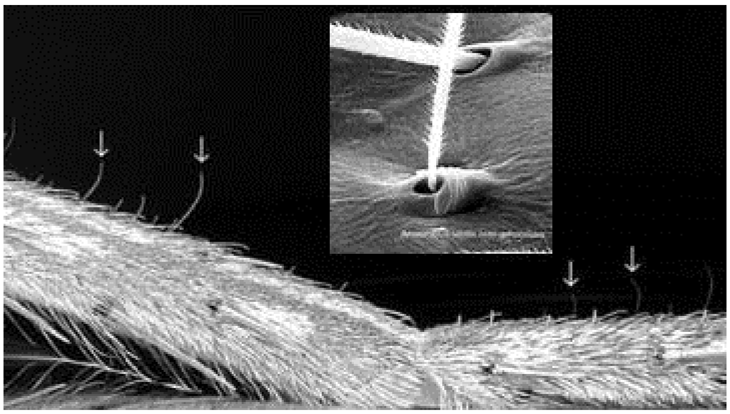


Figure 6. Two images of the hearing sense organs of spiders, trichobothria: distal section of a leg showing the position of trichobothria and an electron microscrope image showing the anatomy of the organ. (leg image:openi.nlm.nih.gov)

A sound wave is a type of disturbance that travels through air or some other medium (*e.g*., water, substrate) by mechanically exciting the particles in its path. As the air particles, for instance, move back and forth, they transmit the disturbance further down the line in the direction the wave is moving.

- Find the slinky available in the materials for Exercise 6b. In initiating movement in the slinky coil you are holding, you can see the wave of motion travel down the slinky.
- Pass the slinky through the class giving every student the opportunity to see how this mechanical disturbance moves from coil to coil transferring the energy first applied to the coil the student is holding.

A sound wave is described by its amplitude, period, and frequency.

- Examine the plot of a pressure wave in Figure 7 below. Pressure is measured along the vertical y-axis and time is measured along the horizontal x-axis.

The **amplitude** of a sound wave reflects the degree to which the particles the wave travels through are mechanically disturbed. People refer to the loudness of a particular sound on a scale from barely audible (quiet) to painfully loud. This is a qualitative assessment of loudness. The quantitative measure of the loudness of a 'sound' is its **amplitude**. By definition, amplitude is the unit difference between the peak (loud extreme) and the trough (quiet extreme)of a sound wave. Looking at the plot of a sound wave in Figure 7, you can see that the amplitude of this wave is 6 units of pressure. The *unit* here is unspecified. The typical unit used is decibels (dB), a logarithmic unit expressing relative power. OSHA guidelines set 0 dB as the threshold of hearing by humans and 150 dB as the threshold for eardrum rupture.

Exercise 6b1. Rank that Sound

- Divide the class into teams of three to four students.
- Each team should copy the following table on a sheet of paper

SOUND PRESSURE(dB) RANK*	SOUND SOURCE
10 highest loudness	
9	
8	
7	
6	
5	
4	
3	
2	
1 lowest loudness	

- The team should then fill in the table they have made using the following list of 10 common sounds **presented in alphabetical order.** Balloon Popping, Breathing, Cannon Firing, Lawn Mower, Library Reading Room, Normal Conversation, Refrigerator, Rock Concert, Vacuum Cleaner, Whisper. *Assume typical distance away from the respective sources! That is you are in bed with an alarm clock positioned within reach, running the vacuum cleaner, are a safe distance from a firing cannon, the person popping the balloon, etc.*

- Your teacher will record the rankings of the different sounds on the board.
- The class should have a discussion as to those sounds the teams did not agree on.

- A final ranking should be made following the discussion and voting where required.
- Check your ranking against that present under **Exercise 6b1. Rank that Sound** which includes the actual estimate of decibels of sound pressure produced.

The period, frequency and pitch of a sound wave are interrelated, frequency building on period and pitch on frequency as follows:

1. The **period** of a traveling wave is the *time between two successive peaks of the wave*. The period of the wave depicted in Figure 7 is 2 units of time (the peaks are at 2.5 and 0.5, so the difference between them is 2.5 – 0.5 = 2.)

2. The **frequency** of a traveling wave is the number of periods per unit time. As a result, the frequency is the reciprocal of the period. The frequency of this wave is ½ (or one wave period per 2 units of time).*Note that sounds with higher frequencies represent more rapid cycles of compression and rarefaction (quicker vibration of molecules).*

3. The **pitch** of the sound is determined by the frequency of the wave**:** the greater the repetition of the wave pattern/unit time (frequency), the higher the pitch.

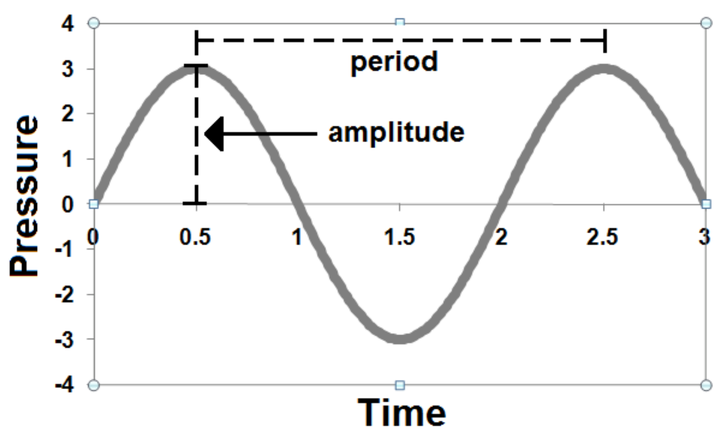


Figure 7. Plot of a pressure wave

Both the amplitude and frequency together determine how the wave sounds. Each of these characteristics of a wave determines its auditory properties – how this occurs is discussed next.

Effects of frequency and amplitude of a sound wave

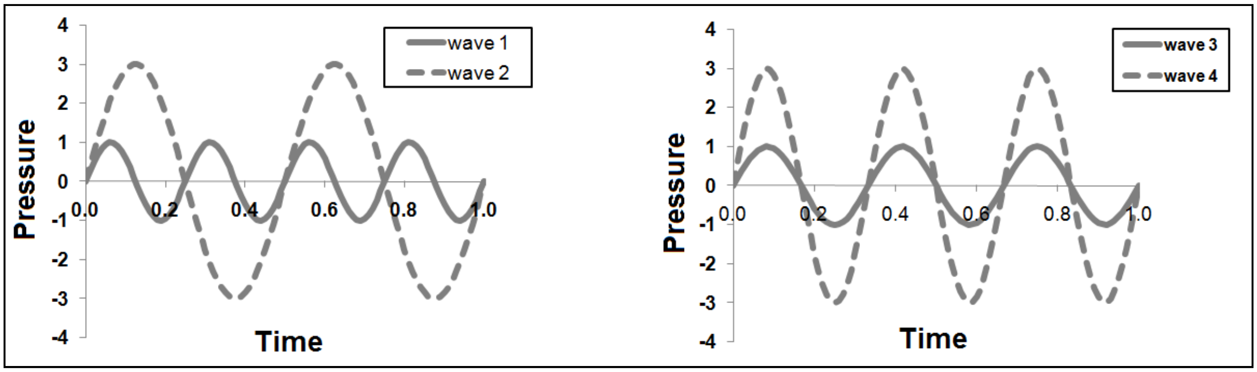
Scientists usually measure the frequency of sounds in units known as **hertz** (**Hz**).*A hertz is defined as one vibration or wave cycle per second.* Different species have differing capabilities of detecting sounds of particular frequencies. For example, people can hear sounds in the frequency range of 20 to 20,000Hz. This appears to be a rather large range. However, many animals including bats, dogs, dolphins, whales and insects can hear sounds at frequencies in excess of 100,000 Hz. In fact, quite a few species communicate with one another using sounds that lots of other animals can't even hear! This includes sounds at the low end of the scale as well. Elephants, for instance, use very low frequency sound (14 Hz) to communicate with each other at distances of as much as 10 miles (16.1 kilometers). This is called infrasonic sound and is something that whales also use for communication at long distances.

Note that while an organism's hearing organ may be more sensitive to certain frequencies than others, all organisms should be able to distinguish amplitude differences between two sounds of the same frequency as long as the frequency falls within its range.

- Answer the following questions. You may check your answers under Exercise 6 Acoustics at the end of this unit.

Q10. Why might it be advantageous for animals to communicate with each other at a frequency that other animals can't hear?

Look at the plots of the waveforms below, and answer the following questions.



Q11. What are the frequencies of sound waves 1 and 2? Which one has the highest pitch?

Q12. What are the amplitudes of sound waves 3 and 4? Which one is the loudest?

Q13. Draw a wave over the time period of 1 unit with a period of 0.2 and amplitude of 4.

Exercise 6b2. Infrasound and Ultrasound

As mentioned above, humans can typically hear sounds in the approximate range of 20–20,000 Hz. However, other animals may have a broader range with some animals communicating at much lower sound frequencies and others at very high sound frequencies. A rule of thumb is that organisms cannot produce a loud sound that has a wavelength that is larger than their body length. Thus, small insects, frogs, etc. exhibit high frequency sound production and hearing while very large animals, particularly those that live in water such as whales, have exceptionally low frequency sound communication systems.

Sounds with frequencies below and above “normal” human hearing ranges have been given special names. Sounds that fall below the lower limit of “normal” human hearing (20 Hz) are referred to as **infrasound**. Under ideal conditions, humans may hear some sounds at the upper range of infrasound (around 12 Hz). This is usually not the case because there is so much background noise present in our environment. While we are generally unable to hear infrasound vibrations, we may feel them when they are in the range of 4–16 Hz. Because they can be sensed, exposure to infrasound frequencies has been shown to cause feelings of fear, nervousness, anxiety, or even sadness in some people. Sounds of this wavelength have even been linked to ghost sightings as infrasound wavelength might match the resonant frequency of the human eye (18hz). This phenomenon was discovered by lab worker Vic Tandy from personal experiences suffered in a research laboratory. A fan that removes exhaust in the laboratory was vibrating at a frequency close to 18hz.

Infrasound technology is used quite often by geologists to help monitor earthquakes, and to detect different types of rock layers and petroleum deposits below the earth's surface. It is also used in the medical field to study the function of the human heart.

Sounds that are above the typical upper range of human hearing (20,000 Hz) are known as **ultrasound**. Ultrasound is used by dolphins, toothed whales and bats in murky waters on the one hand or darkness on the other. It helps them to navigate through their environment, avoid obstacles, and to find prey when visibility might be limited. By sending out high frequency sound waves and processing the echo patterns returned, these animals make acoustic mental images of their environment. They in essence "see" with sound. Humans use ultrasound applications for a similar function, including detecting underwater objects like sunken ships, geological features, and even animals.

You may have heard the term ultrasound in your doctor's office. The most well-known medical use of ultrasound is to view babies before they are born. A transducer emits the high frequency sound pulses. When the sound waves hit a boundary between tissue types, some of them are reflected back to the probe while others travel on to additional boundaries. Using the speed of sound in tissue and the time of each echo's return, the sound wave data are converted into a digital image.

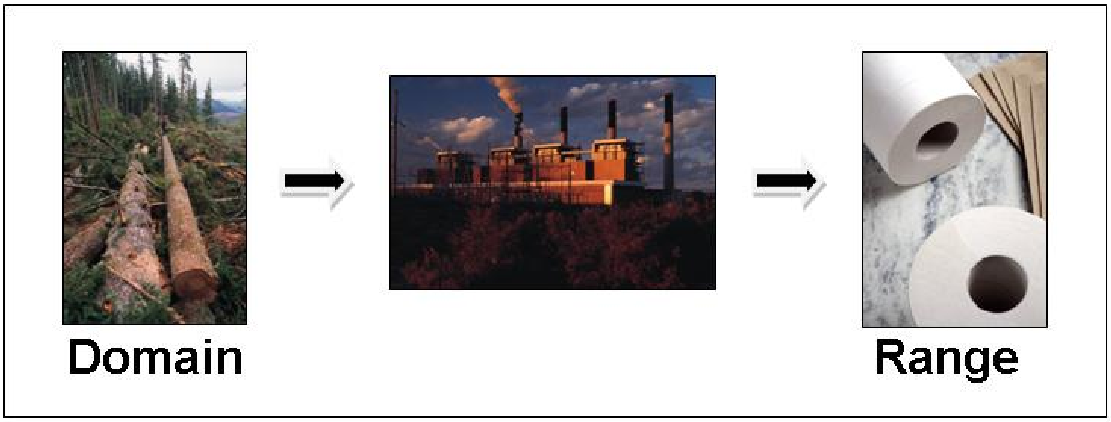
Because high frequency sound waves can carry a lot of vibrational energy, ultrasound is also used in applications such as cleaning teeth or other surfaces, and even to disintegrate bacteria and kidney stones.

Use the chart of approximate hearing ranges of various animals on the following page to answer the questions that follow.

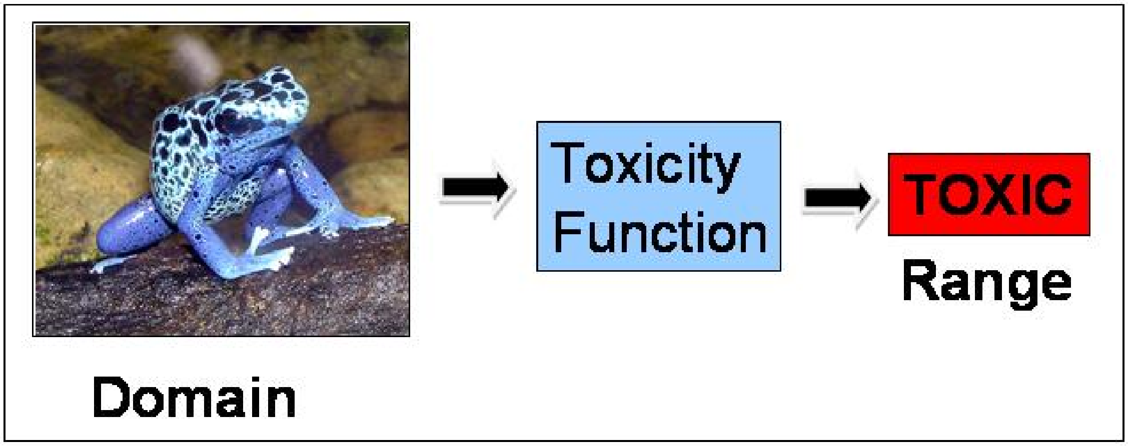
NOTE: The chart uses a logarithmic scale. If you don't understand the concept of logarithms, complete the exercise below titled 'Functions' before proceeding.

FUNCTIONS: A QUICK INTRODUCTION

Functions are useful mathematical tools. You can think of a function as a factory that takes elements from one set called the domain and produces elements belonging to another set called the range. The picture on the next page illustrates this metaphor. Logs go into a paper factory and paper comes out.

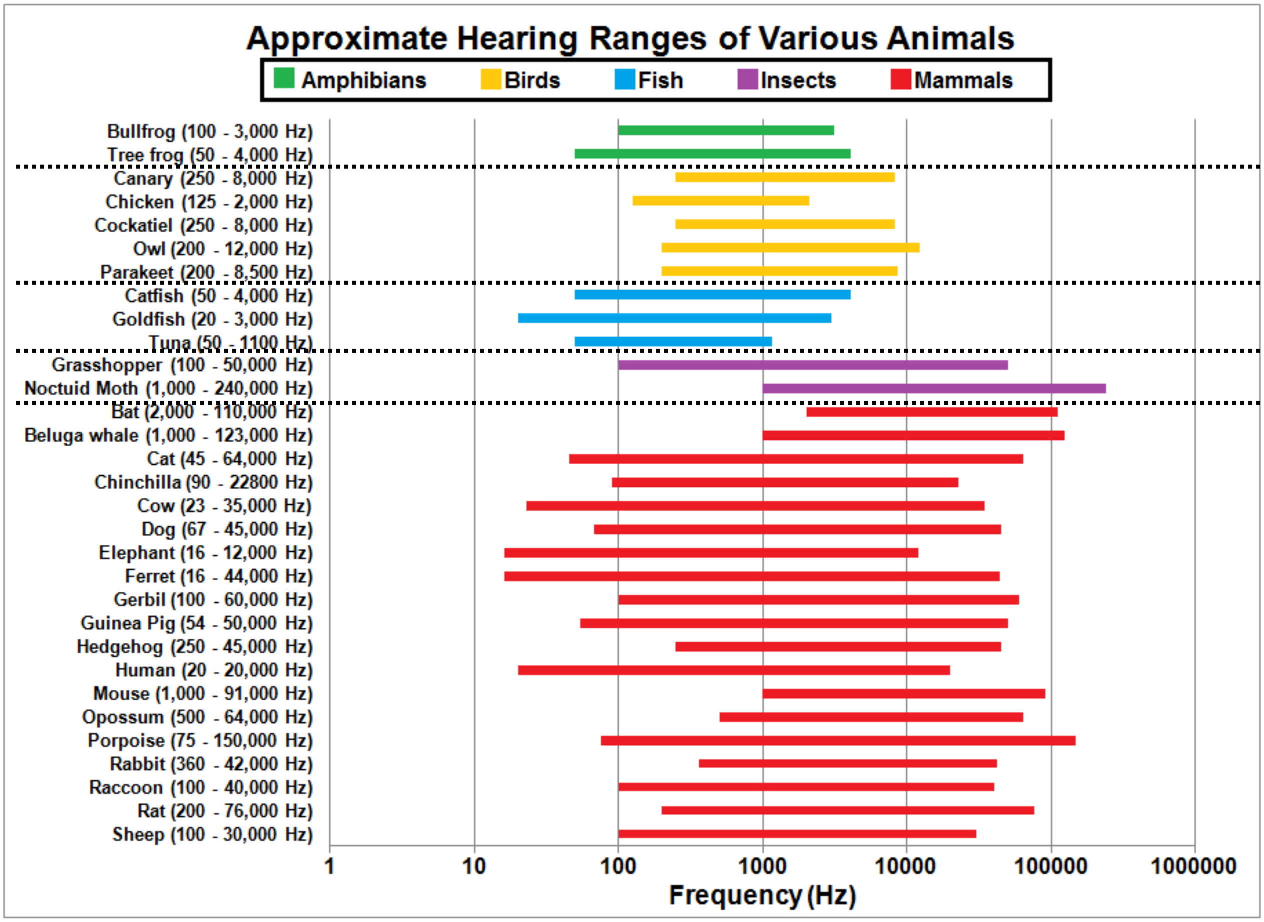


Let's look at a biological example: a poison dart frog. You can think of a function also as a rule that takes elements from a set of inputs, the domain, and returns elements belonging to a set of outputs, the range. The picture below illustrates the idea with a function (rule) we call the toxicity function. This function takes organisms as its input and returns the toxicity of the organism as an output.



It is important to know that a function takes *one* element from the domain to *exactly one* element in the range. Graphically this means that every vertical line intersects the graph of a function just one time. Thus, in the example above, every organism is either defined as toxic or nontoxic. It is impossible to be both.

A LOGARITHMIC SCALE is a function that expresses large values of a physical quantity in terms of 10-fold increases or decreases so that the differences are within a range that people find easier to manipulate ordo calculations on. For example, when a variable spans several orders of magnitude as sound does, it is easier to visualize and compare 2 or 3 digit numbers than to compare, say 10 digit numbers. The logarithmic scale represents a one-to-one function because it takes distinct values in the domain to distinct values in the range.



Q14. Which animals in the chart can hear infrasound frequencies?

Q15. Which animals in the chart can hear ultrasound frequencies?

Q16. Are there any animals in the chart that can hear both infrasound and ultrasound frequencies?

Q17. Which three mammals in the chart can hear the broadest range of frequencies? Why do you think this might be adaptive for those animals?

Q18. Which bird in the chart can hear the highest range of frequencies? Why might this be important to that particular type of bird?

Q19. Which insect in the chart can hear the highest range of frequencies? Why might this be important to that particular type of insect?

Q20. Why do you think it might be important for an organism to hear frequencies outside the range of the sounds that they are able to produce?

Exercise 6b3. Understanding Decibels (For grades 9-12)

What is the loudest animal on earth? And just how loud is that animal? To answer these questions, you need to understand how sound intensity is measured.

In this exercise, you will complete qualitative and quantitative comparisons of sound level differences (ratios) between pairs of sounds animals make**. Qualitative** involves subjective estimation, while **quantitative** involves a measurement process.

We will complete a **qualitative comparison** first.

- Your class should go to *YouTube* for the following recordings or others made by the animals listed below.
- Each student should listen to the examples of sound files for the pair of animals under consideration as in example 1, two vocalization patterns offered for the African elephant.
- Qualitatively compare the two vocalizations. That is '*Which sound track of a given pair is louder and how much louder by your estimation (15%, 5X etc.)?'*
- Once all students have committed their estimates to paper, summarize the results on the board at the front of the room.
- Examine these results with respect to how much variability there was in the answer as to which member of the pair of vocalizations was the louder one and how much louder it was.
- Repeat the process for all five of the comparisons offered.
- Attempt to rank the comparison by the greatest difference in loudness compared to the least difference.

1. **Elephant trumpeting:** https://www.youtube.com/watch?v=8dMtEVjgsHs:
   Elephant rumbling: https://www.youtube.com/watch?v=T3Xx4rCO0Uk

2. **Bluewhale:** https://www.youtube.com/watch?v=0M89w2DsKOQ
   Sperm Whale: https://www.youtube.com/watch?v=1ZKnrHSbkjg

3. **Howler Monkey:** https://www.youtube.com/watch?v=HsCfqLEJKNQ
   Siamang Monkey: https://www.youtube.com/watch?v=zrud6S_L5mc

4. **Domestic Cat purring**:
   https://www.youtube.com/watch?v=CY7t8ow2gOM
   Big Cat purring (e.g., cougar):
   https://www.youtube.com/watch?v=W461djpQl2s

5. **Cow Mooing:** https://www.youtube.com/watch?v=YDYDK7oFjzQ
   Horse neighing:
   https://www.youtube.com/watch?v=L1Q1IkUpFp0

6. **Hippopotamus:**
   https://www.youtube.com/watch?v=EBTDIertZ28
   Spotted hyena:
   https://www.youtube.com/watch?v=Vd8cnaS6fcU

- Now you are ready to examine the same pairs of sounds quantitatively. You were introduced to the term **decibel** in the introduction to section 6b. **Decibels (dB)** ***are base 10 logarithmic units used to indicate the ratio of one physical quantity relative to a standard reference level.*** Different forms of decibels are used in various fields, such as optics, electronics, and digital imaging, but most people are familiar with decibels as they relate to sound. The intensity level ***I****(in dB)*, of any sound with an intensity of I_x, would be:

$$I(in\ dB) = 10 \log_{10} \frac{I_x}{I_0}$$

whereI_0 is the intensity of some reference level, and the logarithm uses base 10.

When we express something as an exponent, such as 10^2 (ten to the power of two) or 10^3 (ten to the power of three), we really are indicating the base (10, in this case) multiplied by itself a number of times equal to the exponent (twice or three times, in these cases).

Base 10 Exponents	**Base 10 Logarithms**
$10^0 = 0$	$\log_{10}(0) = 0$
$10^1 = 10 = 10$	$\log_{10}(10) = 1$
$10^2 = 10 \times 10 = 100$	$\log_{10}(100) = 2$
$10^3 = 10 \times 10 \times 10 = 1000$	$\log_{10}(1000) = 3$
$10^{½} = \sqrt{10} \approx 3.16$	$\log_{10}(10^{½}) = ½$

A **base 10 logarithm** of a particular number ***x*** tells us to what exponent we have to raise 10 to get that number. So, back to our previous examples of 100 and 1000, $\log_{10}$ (100) = 2, since 10 has to be raised to the second power (10^2) to equal 100, and $\log_{10}$ (1000) = 3, since 10 has to be raised to the third power (10^3) to equal 1000.

Exponents (and thus logarithms) may also be negative. For example, for a > 0, $a^{-k} = \frac{1}{a^k}$.

Logarithms of decimal numbers between 0 and 1 are negative. For example:

$$\mathbf{0.01 = 1/100 = 1/10^2 = 10^{-2}}$$

Thus, $\log_{10}$ (0.01) = -2.

Base 10 with Negative Exponents	**Base 10 Logarithms**
$10^{-1} = 1/10 = 0.1$	$\log_{10}(0.1) = -1$
$10^{-2} = 1/(10 \times 10) = 0.01$	$\log_{10}(0.01) = -2$
$10^{-3} = 1/(10 \times 10 \times 10) = .001$	$\log_{10}(0.001) = -3$
$10^{-½} = \frac{1}{\sqrt{10}} \approx 0.316$	$\log_{10}(10^{-½}) = -½$

NOTE: Base 10 logarithms are not always easy to calculate in your head, unless the number of which you are trying to find the logarithm is equal to a power of 10.This is where calculators come in handy!

Now that we've reviewed logarithms, let's return to our equation of intensity and decibels to understand what it means. The intensity level ***I*** *(in dB)*, of any sound with an intensity of I_x, would be:

$$\boldsymbol{I = 10\ log_{10}\left(\frac{I_x}{I_0}\right)}$$

where I_0 is the intensity of some reference level, and the logarithm is to the base 10. Decibels themselves are logarithmic units relating one quantity or intensity to a standard level. Therefore, if you know how many decibels of difference there are between two sounds, you also know how many times louder one is than the other. Conversely, if you know how many times louder a sound is than the reference level, you know the measurement in decibels of the sound.

With sound, the standard reference level (I_0) is usually 20 micropascals, where a pascal is a unit of pressure equal to 1,000,000 micropascals (10^{-6}pascals). Twenty micropascals is approximately equal to the sound of a mosquito buzzing from about 3 meters (≈ 9 feet) away. This represents the lowest limit of human hearing. Notice that at the threshold of hearing, β = 10log (20/20) = 10 log 1 =0. Therefore, the intensity level at the lower threshold of human hearing is 0 dB.

If the pressure produced by a sound is 10,000 times greater than that of the reference level, you would calculate the intensity of the sound in decibels as follows:

$$\boldsymbol{I\ = 10\ log_{10}\left(\frac{I_x}{I_0}\right)}$$

$$\boldsymbol{I = 10\ log_{10}(10,000)}$$

$$\boldsymbol{I = 10(4)}$$

$$\boldsymbol{I = 40}$$

However, what if you know the intensity (in dB) of a sound, and you wanted to calculate how much greater the pressure produced by that sound is relative to the reference of zero decibels? Well, if you stop to think about it, in this case, we would be solving for the quantity I_x/I_0.This can easily be done from the previous equation, just by solving for that quantity.

$$\boldsymbol{I\ = 10\ log_{10}\left(\frac{I_x}{I_0}\right)} \qquad \textbf{(1)}$$

If we divide both sides by 10, then we have:

$$\frac{I}{10} = log_{10}\left(\frac{I_x}{I_0}\right)$$

However, how do we now get rid of that pesky logarithm on the right side of the equation? If you remember that x = 10^y means the same thing as y = $\log_{10}(x)$, you should see that we can get rid of the log10 in the equation by raising 10 to the power equal to each side of the equation:

$$10^{\frac{I}{10}} = 10^{log_{10}\left(\frac{I_x}{I_0}\right)}$$

$$10^{\frac{I}{10}} = \left(\frac{I_x}{I_0}\right)$$

In other words, if the base 10 logarithm of a number is equal to x, 10 raised to the x power gives you back the original number. The logarithmic and exponential functions are thus **inverse functions** of one another.

So, if you know a sound's intensity in decibels, you can now calculate how many times louder it is than the reference. If you want to know how many times louder or softer a sound (let's call it sound A) is than another sound (sound B), which is not equal to the reference, you can use the same equation (1).In this case, however, the left-hand side of the equation becomes the **difference** in decibels between the two sounds. Using equation 1, we obtain

$$I_A = 10\ log_{10}\left(\frac{I_{xA}}{I_0}\right)$$

and

$$I_B = 10\ log_{10}\left(\frac{I_{xB}}{I_0}\right)$$

Subtracting these equations gives:

$$I_A - I_B = 10\ log_{10}\left(\frac{I_{xA}}{I_0}\right) - 10\ log_{10}\left(\frac{I_{xB}}{I_0}\right)$$

Using the log property

$$log_{10}(C) - \ log_{10}(D) = log\left(\frac{C}{D}\right)$$

We can then reduce the equation to

$$I_A - I_B = 10\ log_{10}\left(\frac{I_{xA}}{I_{xB}}\right)$$

You now have acquired the information necessary to make quantitative comparisons of the sound level differences (ratios) between the five pairs of sound you have already qualitatively evaluated.

- Let's compare your results obtained from application of a qualitative approach to a quantitative examination based on measured decibel levels.
- Make the appropriate comparisons, using a calculator where necessary.

Source of Sound		Intensity Level (dB)
1.	Elephant trumpeting	117
	Elephant rumbling	85
2.	Blue Whale	188
	Sperm Whale	236
3.	Howler Monkey	140
	Siamang Monkey	95
4.	Average domestic cat purring	25
	Big cat purring (e.g., cougar)	100
5.	Cow moo	85
	Horse neighing	38
6.	Hippopotamus	114
	Spotted hyena	112

- Answer the following questions:

Q21. Which animals in the above chart make sounds that would cause a human ear pain?

Q22. Water is much denser than air, so it takes more work to propagate sounds under water. Generally, bioacoustics experts accept that sounds in water lose about 62 decibels when propagated through water. In order to see how loud the organisms really would be to you, recreate the table above, but subtract 62 decibels from all of the water-dwelling animals. Who is louder, the Howler monkey or the Blue whale?

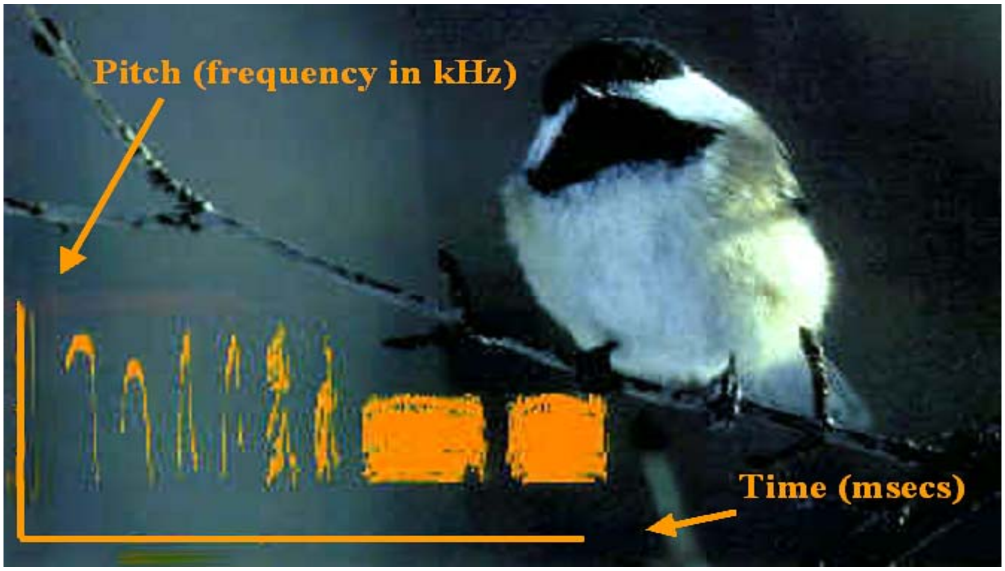
Q23. The sound of a jet engine from 100 meters away is approximately 100 times louder than a power saw (110 dB).What then is the intensity, in dB, of a jet engine's sound from 100 meters away?

Q24. Bob went to a rock concert with his friends. The concert reached sound levels of an ear-blasting 120 dB. How many times louder was the concert than a normal conversation (approximately 60 dB) between Bob and one of his friends?

Exercise 6c. Seeing Sound

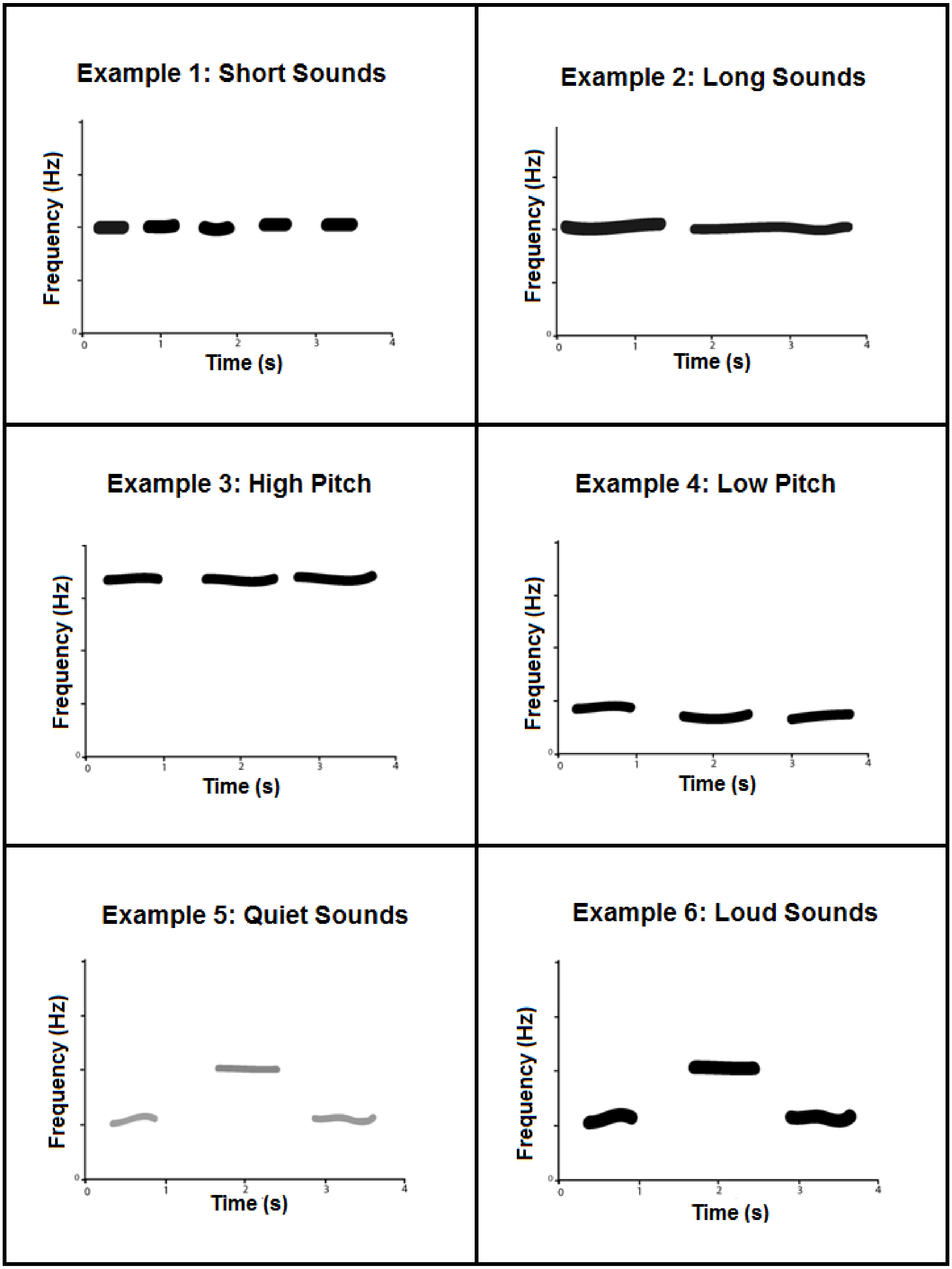
It is easy enough to listen to various animal sounds and qualitatively describe the differences among them with words. Biologists, however, need to be able to physically measure (***quantify***) the differences and determine the extent to which these calls vary. Why is this important? Objective measurements are needed so that we can apply statistics in assessing the differences and relationships between organisms and among groups of organisms. Acoustic signals are useful in examining phylogenetic relationships (the evolutionary history of animals) because the courtship calls animals make are used by females in recognizing their own species from other species, thereby avoiding wasted matings that would fail to produce viable offspring. It is also a useful tool in distinguishing among the variety of behavioral contexts individuals convey acoustic messages in. Researchers must be able to quantify the information an individual's message conveys to others in social interactions (hierarchies), between parents and offspring, in coordinating group foraging as in conveying the location of food, and in warning others of threats from predators and competing groups. Quantitative examination of acoustic signals is also used to understand the relationship between signal pattern and the habitat species occupy.

We cannot simply take out a ruler and measure the differences in calls, something we do in measuring the length of a leg or the height of an individual. The basic technique biologists use to analyze non-visual traits is to ***present the information graphically***, a form that can be measured visually. Sounds can be converted to sound **spectrograms** or **sonograms,** in which they are laid out in two dimensions, as shown on the following graph of the black-capped chickadee's call notes.

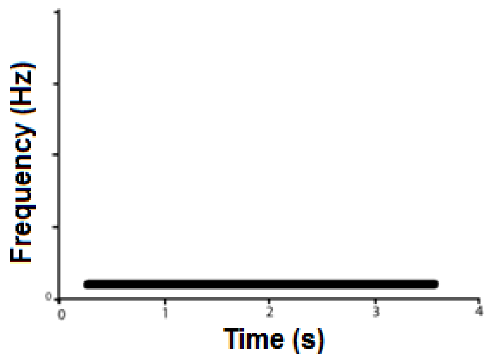


As you can see in the picture, spectrograms of sounds are graphs displaying the frequency (pitch) of a sound on the vertical y-axis, and time along the horizontal x-axis. As you work through this exercise, you will learn how to read sonograms, starting with some simple examples. Ultimately, you will be challenged to try to identify the sonogram that belongs to each of the mystery calls made by various true frog, tree frog and toad species.

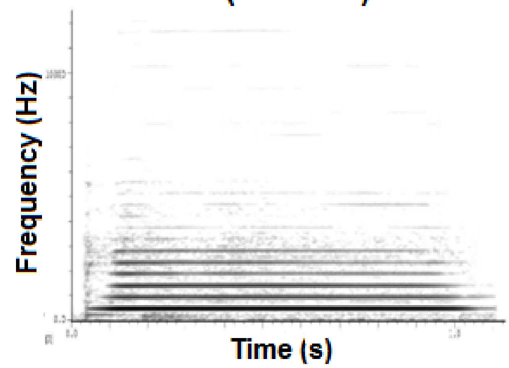
- On the CD for this unit, open the folder titled "Audio Exercises for Biology & Engineering," and listen to track 6.
- Next, follow along with the sonograms on the following pages as instructions are given to you on track 7 of the CD. Your teacher will either display these images on a whiteboard at the front of the room or provide each individual with a copy of the sonogram images.


Example 1: Short Sounds
Frequency (Hz)
Time (s)
Example 2: Long Sounds
Frequency (Hz)
Time (s)
Example 3: High Pitch
Frequency (Hz)
Time (s)
Example 4: Low Pitch
Frequency (Hz)
Time (s)
Example 5: Quiet Sounds
Frequency (Hz)
Time (s)
Example 6: Loud Sounds
Frequency (Hz)
Time (s)

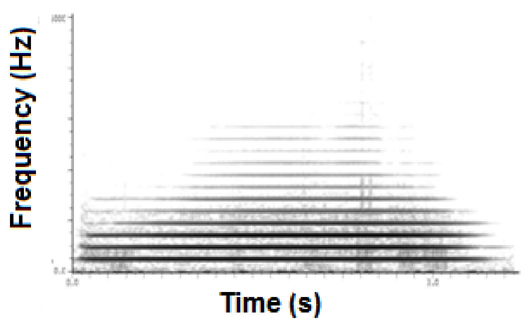
Example 7: Simple Sound (Sine Wave)



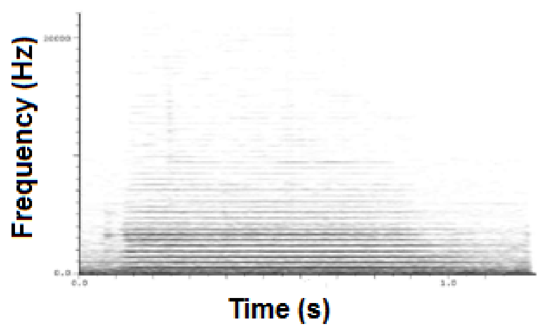
Example 8: Complex Sound (Clarinet)



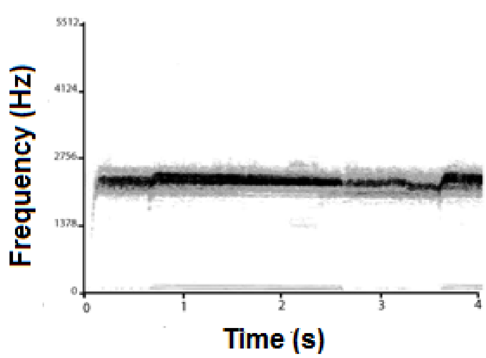
Example 9: Complex Sound (French Horn)



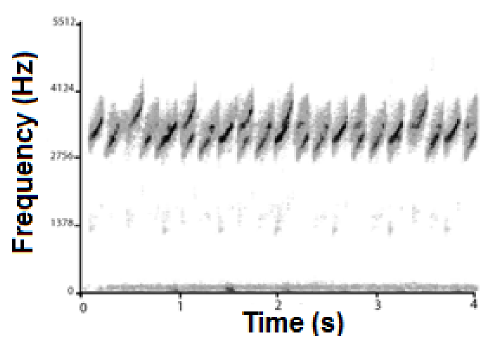
Example 10: Complex Sound (Violin)



Example 11: Animal Sound (Toad)



Example 12: Animal Sound (Tree Frog)



Fill Out the Following Comparison Chart:

Comparison	Describe the Difference in the Sonograms
Short vs. Long Sounds (Ex 1&2)	
High vs. Low Pitch (Ex 3&4)	
Quiet vs. Loud Sounds (Ex 5&6)	
Simple vs. Clarinet (Complex) Sounds (Ex 7&8)	
French Horn vs. Violin (Ex 9&10)	
Toad vs. Tree Frog (Ex 11&12)	

Q25. What would you expect a sonogram to look like that was of a pencil being tapped on a desk?

Exercise 6c1. Matching Frog Calls to Sonograms

Now that you have been introduced to the translation of sounds to their graphical representation, you will be challenged in this exercise to match each of several frog species with the graphical representation of its call.

- Listen to instructions for this exercise on track 8 of the CD.

- Listen to the calls of the frogs pictured below on track 9 of the CD.
- Try to match each call to the correct sonogram on the following page.
- Explain why you chose to match that sonogram to each frog call. You may use your chart and the example sonograms to help you.

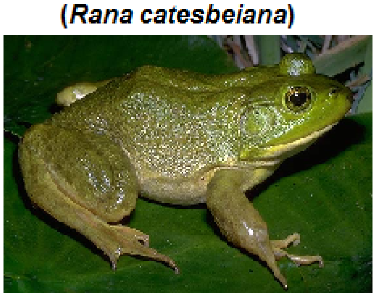
Pictures and identities of frogs whose calls are used in Exercise 6c1

Call 1: Mountain Chorus Frog
(*Pseudacris brachyphona*)

Call 2: Southern Chorus Frog
(*Pseudacris nigrita*)

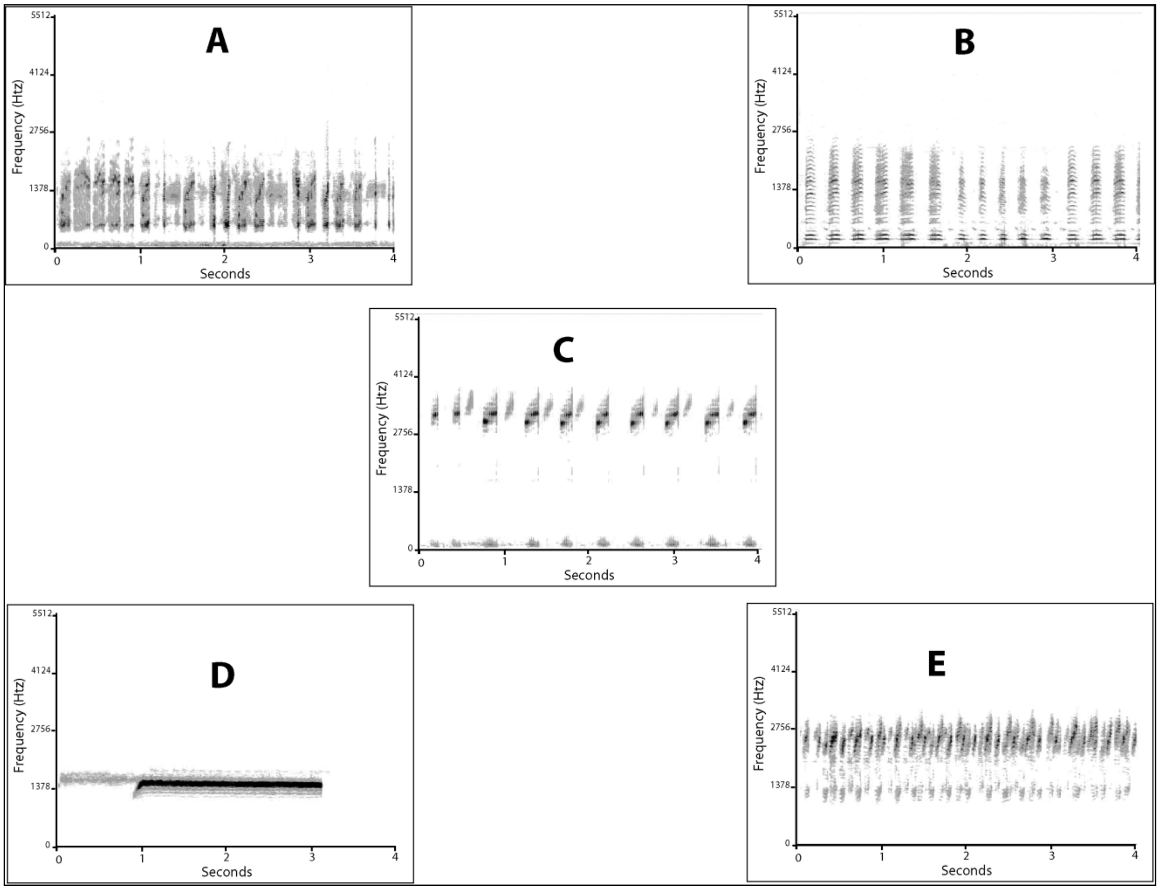
Call 3: American Toad
(*Bufo americanus*)

Call 4: American Bullfrog
(*Rana catesbeiana*)



Call 5: Southern Leopard Frog
(*Rana sphenocephala*)

Sonograms to be matched to frog calls in Exercise 6c1



<u>**Open-ended Exploration:**</u>

- Collect sonograms from the web and describe characteristics of the wave patterns, periods, frequencies and amplitudes.
- Find additional animal calls for which sonograms are available and follow the repeated copies of the call on the graph, marking where the call starts anew in each case.

Exercise 6d. Communicating at a Distance

Sound can travel very quickly. In fact, sounds travel at about 343.2 meters per second (about 768 mph) at 20 ºC in dry air. However, you have probably noticed that sounds appear quieter when they are farther away. Why is this so? The reason that sounds decrease in apparent loudness the farther one gets away from the source of the sound is due to a phenomenon known as **attenuation**. Attenuation is the gradual loss in intensity of the rate of flow of the sound pressure wave as it travels through a medium such as air, water or another substrate. The attenuation of sound with distance from its source is related to **scattering** and **absorption**.

- *Scattering occurs when sound does not move in a straight trajectory through the medium in which it is transmitted but bounces off in other directions. This occurs when particles are encountered in the medium or when different regions of the medium offer different densities, for example air with different concentrations of water vapor.*
- *Absorption occurs when sound vibrations strike a surface that transforms the sound energy into another form of energy, usually heat.*

Both scattering and absorption pose difficulties for animals that need to communicate with one another. Being able to be heard at a distance is important in a number of social contexts. Many animals call to attract mates, to bring others to a food source, to drive other animals away from their territories and to alert others to the presence of predators. Note, however, that there are cases in which an animal needs to be heard by others that are close and being heard by competitors or predators that are further away would be disadvantageous. For example, an insect might want to attract a nearby mate, but it would be in trouble if its sounds were detected by birds that might be some distance away. Thus many animals can vary the frequency of a call depending on whether the intent is for short versus long distance communication.

In this exercise, you will examine the phenomenon of attenuation by using a simple sound meter to measure the intensity of sounds of different frequencies with increasing distance and under different conditions. You will also again examine the musical instruments that simulate the major methods of sound production in animals as you consider the various adaptations of sound producing structures that help animals deal with attenuation.

NOTES TO TEACHER:

1. You will need to insert a 9-volt battery into the sound meter device. Besure to remove the battery when your class is finished with the exercise. *Batteries left in the sound meter will corrode the unit!* You may need to supply a new battery if the original one is drained.

2. To activate students' higher order analysis thinking skills, you may wish to lead your students through a class discussion of all the variables they might need to control for this experiment to work after you have given them a brief introduction to how it will proceed.

To Students:

1. ***The included sound meter is sensitive, so when using it to measure sounds in this exercise, keep conversation and other background noise in the classroom to a minimum, so as not to affect your results.***
2. ***Take several readings at each specified point in the exercise and use the averages of these readings to reduce the influence of incidental noise on your results!***
3. ***Compare your sound meter readings to the following qualitative test:* How many teams can still hear the sound at increasing distances from the source? Use a 0/1 technique for recording this data: record a zero for team members that can hear the tone, and record a 1 for team members that can hear it.**

Exercise 6d1. Attenuation of Pure Tones of Different Frequencies

In this exercise, you will examine the attenuation of simple sounds (pure sine wave tones of varying frequencies) created by a tone generator. This exercise involves the use of a computer with attached speakers.

- Find the tape measure, sound meter and CD associated with Unit 11.

- In preparation for the experiment, place pieces of tape on the floor in a straight line at .25 m distances from the computer up to a distance of 3 m. If you can move farther away from the speakers than 3 meters, you may then increase the distance increments to 1 m, and if you can then move farther away than 20 m, you may then increase the distance increments to 5 m. With a marker note the distance from the computer in meters on each piece of tape. Try to take as many distance readings as space allows.

- Divide the class into teams of 3–4 individuals. During these trials, one team member should be the designated **"scribe"**, the individual responsible for recording all data. The remaining team members will take turns in the role of "***meter reader***."

- Each scribe should have a lined notepad and pencil or pen.

- The team scribe should make a chart similar to the one below. Reading number 1 through 4 might be replaced by the name of the team member doing that reading. The column labeled "#0s/#1s" is where the scribe should record the number of team member that failed to hear the sound (0) versus the members that could hear it (1) for that particular frequency and distance from the source. For example, for a team where 1 team member could hear it and three could not, the scribe would record 1/3.

Hz	Dist. (m)	Reading 1	Reading 2	Reading 3	Reading 4	#0s / #1s

- **Your teacher will work the Tone Generator program. The teacher may show the class how the program works before beginning the experiment:**
- On the CD for this unit, find the executable file for the "Tone Generator" program, and double click it to open the program.
- In the program, in the top left of the program window there is a section labeled "Audio Frequency Hz". This area, which includes a numeric keypad and an "Enter" key, allows one to select tone frequency. The program will use the computer's sound card to generate tones of any chosen whole number frequency between 100 and 15000 Hz.
- Take note of the "Output Level" slider, which allows one to set the volume of the tones produced, and the "Tone On/Off" button, which turns the generated tones on and off.
- Click on the "Output Level" slider of the program, and drag it all the way to the top.
- Now, use your mouse to enter a frequency of 100 on the program's keypad, and then click the "Enter" button.
- Now click on the "Tone On/Off" button.
- Everyone should now hear a very low, constant tone coming from your computer's speakers. If you do not, check to make sure that your computer's speakers are turned on.
- For now, turn the tone off and go over the rest of the instructions for the exercise together.

* Student teams will take turns reading the sound meter for a given tone through all distances. The team will produce 3–4 readings for the frequency at each distance they are testing.
* Teams that are not having a turn with the sound meter at the moment will be responsible for recording the qualitative 0/1 data for the frequency being tested at each distance marked by tape on the floor.

- **Remember, silence is essential, so team members will need to use thumbs-up/thumbs-down to communicate their ability to hear a particular tone at each distance tested.**
- The "meter reader" will read the ***minimum*** measurement obtained from the "Max/Min" button. WHY? By using the minimum decibel level reading for these tones, you are in effect filtering out any background noises that might be louder than the tones at various distances.
- Turn on the sound meter by pressing the power button.
- Your teacher makes sure the tone generator program on the computer is set to a frequency of 100 Hz, and then turns the tone on.
- Place the tip of the microphone on the meter as close as possible to one of the computer's speakers without actually touching it.
- Press the "Max/Min" button on the sound meter. You should see that the display screen has "Max" on it. This means that it is displaying the maximum sound intensity as long as this mode is activated.
- Press the "Max/Min" button again. Now you should see that the display now says "Min" along with the intensity. The sound meter now will display the lowest sound intensity detected as long as this mode is activated.
- Once the sound meter has been set at the "Min" reading, each team's Meter Readers should each take a reading of the first sound level (100 Hz) at 0 m from the computer's speakers and call out the minimum sound intensity to the team's scribe.
- After all meter readers of a team have taken a measurement in the given trial, they will move on to the next distance marked by tape on the floor and repeat the process.
- When a distance is reached at which the sound can no longer be heard or registered on the sound meter, the teacher will play the next frequency level on the tone generation program and the sound meter should be passed on to a new team.

- Depending on the number of teams, you have in the class, repeat this procedure with the following frequencies: 200 Hz, 500 Hz, 1000 Hz, 2000 Hz, 5000 Hz, and 10,000 Hz.

- When you are finished with data collection, the teacher will turn the last sound played off and exit the Tone Generator program.

  *Note to teacher: In order to exit the Tone Generator program, the sound of a tone must not be actively playing. If you cannot exit the program, click the "Tone On/Off" button and try again.

- The scribes for each team will enter the data on a table that the teacher has set up on the board at the front of the room.

- Make two plots of your data, one using the sound meter readings (quantitative measure) and the other your qualitative 0/1 test. Both graphs should have distance on the x-axis and loudness on the y-axis (as shown below). For the quantitative y-axis, loudness will be in decibels while for the qualitative 0/1 test, use proportion of team members hearing the sound (i.e., part/whole). Use a particular symbol for each frequency level so that one can tell which points belong to which frequency. Present a 'Key' to these symbols alongside your graph (*example of such a key is below*).

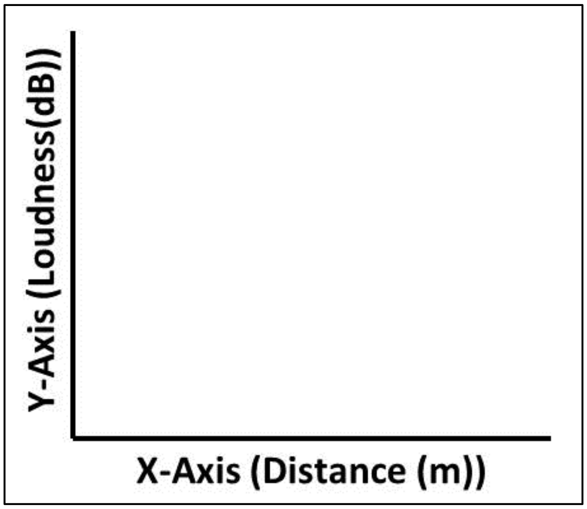
- Because there may be a lot of 'noise' associated with your sound measurements, you might want to remove outliers (extreme values) or plot your averages for each frequency and distance from the source rather than all measurements. Remember that the average or arithmetic mean is equal to the sum of the numbers you obtained divided by N or the total number of values:

$$A = \frac{1}{n} * \sum_{i=1}^{n} x_i$$

A = average (or arithmetic mean)

n = the number of terms (e.g., the number of items or numbers being averaged)

x_1 = the value of each individual item in the list of numbers being averaged



KEY HZ

*100
- 200
^500
.1000
+2000
05000
X 10000

- Have a class discussion about your results.

NOTE TO TEACHER:
As a follow up to your initial discussion with your class on confounding factors, you might include in this wrap-up discussion additional confounding effects that cropped up during the course of the experiment. This gives students a chance to understand and challenge the validity of the data they collected, a core process in science and engineering.

Exercise 6d2. Production Mechanism - Sound Attenuation

As this exercise uses one sound meter, this may be completed with each team demonstrating the testing of a particular instrument to the class one at a time.

- Find the tape measure associated with Unit 11.
- In preparation for the experiment, place pieces of tape on the floor in a straight line at 0.25 m distances from the computer up to a distance of 3 m. If you can move farther away from the speakers than 3 meters, you may then increase the distance increments to 1 m, and if you can then move farther away than 20 m, you may then increase the distance increments to 5 m. With a marker note the distance from the computer in meters on each piece of tape. Try to take as many distance readings as space allows.

- Find the sound meter and gather the four provided musical instruments from the Unit 11 Box. Recall what animal communication sound production mechanism each represents: drum (vibrating a membrane), thumb piano (muscle vibrating a membrane), wooden file and rod (stridulation), and whistle and bulb (air moving across a membrane)..
- Choose one of the musical instruments to work with first. Note that one of the instruments can be played in two ways: by striking it with the included mallet and by scraping the handle of the mallet (or a pencil or another stiff object) along the ridges on its side. You will use this instrument as a file and scraper (ridges method).
- The teacher should insert a 9-volt battery into the sound meter, test the functioning of the meter and explain its use to the class.

Instructions for Sound Meter use:

Press the power button. Notice that right away, the sound meter will begin reading decibel levels of the sounds present in the room. The readings will probably change rapidly because of fluctuations in the background sound intensity. To deal with this, you will be measuring the maximum volume, also called intensity, produced by a particular instrument. This is recorded in decibels or *dB*. **This is the point at which all in the classroom should be as quiet as possible, to minimize errors in readings due to sounds other than the musical instrument in question. One team member should hold up a sign that reads SILENCE.**

- Divide into teams of 3–4 individuals. Each team should choose a unique instrument. During these trials, team members will take the roles of "***musician***," "***meter reader***," and "***scribe***." Note that while students within the team may alternate between meter reader and scribe, best results will be obtained if the same person is the musician throughout all trials with that instrument. She/he should further try to play the instrument the same way each time.

- The scribe should make a chart similar to the one below. Reading numbers might be replaced by the name of the team member doing that reading. The column labeled “#0s/#1s” refers to the number of team members that failed to hear the sound (0) versus heard it (1) for that particular instrument and distance from the source. For example, for a team where 1 team member could hear it and three could not, the scribe would record 1/3.

Hz	Dist. (m)	Reading 1	Reading 2	Reading 3	Reading 4	#0s / #1s

- The meter reader should hold the tip of the sound meter as close as possible to the musical instrument in question, without actually touching the instrument. We will denote this as a distance of 0 m.
- The meter reader should then cue the musician by saying “ready.”
- Another team member should hold up the SILENCE sign.
- The meter reader should then press the min/max button on the side of the sound meter. The sound meter will display the intensity, in dB, of the loudest sound it detects as long as this button is pressed.

- The musician should then play the instrument several times (at least 5–10 quick notes/strikes).
- The meter reader should note the maximum intensity of the sound displayed on the sound meter. ***It is important, if there are any other noises produced after the min/max button is depressed, that you turn the sound meter off, and back on to reset it to repeat the measurement, as the maximum decibel level displayed by the meter may actually be the intensity of the other noise, and not the maximum intensity produced by the instrument itself. This is why it is crucial to keep all other noise as quiet as possible during these tests!***
- The scribe should record this intensity (loudness) in dB, along with the instrument being used, as well as the distance at which the reading was taken.
- To achieve more accurate results which minimize the effects of fluctuations in background noise, repeat the above steps at least twice (or three times, as the example table shows), so that you will have multiple measurements of sound intensity from the instrument at this distance. A little later, you will then take the average of the intensity measurements for analyzing and comparing your overall data.
- In addition to taking the meter reading at each distance, the team should qualitatively score the loudness as thumbs up (1) = can hear vs. thumbs down (0) = cannot hear.
- The scribe will record the number of team members scoring 1 vs. 0.
- The scribe will then read each value to the class as it is obtained so that individuals can add these points on two graphs that they are preparing at their desks, one showing the quantitative meter readings and the other, the qualitative hear/no hear score that they will express as proportion of team members that heard the sound of that instrument at each distance:
    - Quantitative Estimate Graph: Make a graph of the attenuation of each of the instruments by plotting distance (in meters) on the horizontal x-axis, and maximum volume (in dB) on the vertical y-axis, using D for drum, T

for tymbal, S for scraper and W for whistle. Label the x-axis “Distance (m)”, and the y-axis “Maximum Volume (dB)”.

- Qualitative Estimate Graph: Draw a second graph where you plot the qualitative estimate of loudness as indicated by the drop-off in ability to hear the sound produced by the instrument being tested. Your y-axis in this second graph will be proportion of team members that hear the sound produced by the given instrument at a particular distance. For example, if 3 of 4 team members could hear the sound, then the y value at that distance for that instrument would be ¾.

- Following the above protocol, the first team will measure the quantitative and qualitative loudness estimates at increasing distances. How the sound is attenuated will depend on the sound itself as well as the acoustic qualities of your classroom. However, since you will be holding the environment of the classroom relatively constant across all trials, you will gain a better sense of the attenuation characteristics of each of the different sounds.
- **Remember to turn the sound meter off and then back on to reset the meter before taking readings at each distance. Otherwise, the maximum sound intensity from previous trials (or any other loud sounds) will show up as the maximum reading, which will affect your results!**
- Keep repeating this procedure, increasing the distance between the sound meter and the source, at each of the points you had measured and marked on the floor.
- Repeat the entire procedure above for each of the provided instruments, with different teams running the experiment in front of the rest of the class.
- In the end each team will meet with their scribe to fill in the missing data on their graphs (i.e., those that they had collected).
- Draw smooth curves passing through the points, ignoring outlier values, to connect the data points on your graphs, generating one curve for each instrument. However, if the relationship between distance and maximum intensity appears to be linear, draw straight lines that pass as closely to each point for an instrument as possible.

- Add a legend to your graph, so that an observer will be able to know which points and curves/lines correspond to each instrument.
- Add descriptive titles to your graphs.

For a more accurate line fitting to your data, you may use a spreadsheet program, such as Microsoft Excel, to produce this graph for you. We have provided a template that you may use to enter your data, and which will construct this graph for you as your data are entered. Use the following instructions if you will be using this template:

- On the CD for this unit, open the Microsoft file titled “Sound Attenuation”.
- Click the “Musical Instruments” worksheet tab near the bottom of the screen to select the correct data sheet, if it is not already the active worksheet.
- Enter your data in the appropriate cells in the spreadsheet.
- To the right of your data, you should see your graph, which will be updated each time you add a new data point.

NOTE: You will notice that there are actually three graphs produced, which are identical, except with regards to scale. There is one graph with a maximum x-axis value of 3m, one with a maximum x-axis value of 20 m, and one with a maximum x-axis value of 100 m. This is just simply to allow you to more clearly view the trends in your data based on the maximum number of distance measurements you were able to take. You may wish to change the maximum x-axis value of one of these as appropriate to your data if necessary. To do so, simply right-click the x-axis, then click the “Format Axis” option. Click the bubble marked “Fixed” beside the “Maximum” selections, and enter an appropriate value based on your data, then click the “Close” button. Don’t change any of the other options, as they are configured to display your data as clearly as possible.

Now that you have graphed your data, answer the following questions:

Q26. What is the general shape of each of your plots of the sound attenuation of each instrument? Are they all similar? Why do you think this may or may not be the case?

Q27. Do some of the instruments seem to show stronger attenuation than others? In other words, are there differences in how quickly the intensity of their sounds decreases with increasing distance from the instrument?

If you noticed differences in the attenuation of these sounds, why do you think this is the case? Each of the simulated animal sounds that you just used are fairly complex, and real animal sounds can be even more complex than that! You thus will need to draw on your experience from the examination of attenuation for pure tones (Exercise 6d1) in answering this question.

- If you wish, you can recreate your graphs from Exercise 6d1with Microsoft Excel. To do so, you may use the same file you used for the musical instrument portion of this exercise.
- Click the "Pure Tones" worksheet tab near the bottom of the screen to select the correct data sheet, if it is not already the active worksheet.
- Enter your data from Exercise 6d1 in the appropriate cells in the spreadsheet.
- Graphs should be produced for you to the right of your data, updating as each new data point is entered.
- Examine the graphs that you produced, and answer the following question:

Q28. What trends do you notice? Is there a general relationship between the frequency of a sound, and how quickly it is attenuated?

Compare the trends in the graphs from the experiments in attenuation for both the pure tones and the musical instruments.
Using what you learned in these exercises, answer the following question:

Q29. Based only on comparisons of the pure tone attenuation graphs and the musical instrument attenuation graphs, can you make inferences about the relative *frequencies* of the sounds produced by the various musical instruments?

Now try playing each of these instruments again, trying to rank the relative frequency (lower or higher) of each instrument to the others. Now answer the following questions:

Q30. Did your rankings based on the instruments' sounds match up to the relationships of their frequencies that you predicted in the previous question?

Q31. What are some other possible characteristics of each of the sounds, other than pitch (frequency) that may have affected how they were attenuated?

Q32. Knowing what you know now, what is a general statement you can make about the possible distance ranges of communication of animals that communicate at different frequencies?

Q33. Can you think of any possible factors that might change the relationship between the frequency of a sound and how it is attenuated?

<u>Open-ended Exploration:</u>

- Take sound clips of various animals they have researched in the web and investigate the distance calls are propagated within different habitats etc.
- Search the web and your experiences in these sound attenuation exercises in thinking about the following questions:

  What are some adaptations (whether physical or behavioral) that animals might have for modifying the ranges at which their communication might be heard by others?
  - What habitat characteristics might play a role in differences in attenuation?
  - Is directional orientation towards or away from sounds easier at particular frequencies? How might this be related to hearing ranges of the organism(s) in question?

There may be many other questions that you can think of regarding the phenomenon of sound as it relates to animals, whether involving sound production or sound perception. Share these with your classmates so that they too can search for answers. THIS IS WHAT SCIENTIFIC INQUIRY IS ALL ABOUT.

- Working in teams, try to design an experiment, using the equipment provided in this unit (and/or possibly inexpensive, easy-to-obtain materials) that might be useful, to help you approach your question using the scientific method.

- If time and resources permit, try to actually conduct this experiment, and prepare a brief report on your findings to present to your classmates.
- Even if you are not able to actually conduct the experiment, try to write out a detailed plan on how you would approach this question.
- Take notes during other individual's or team's reports, and after all presentations have been given, discuss each project as a class.
- Think about the following questions to help guide your discussion:
    - How effectively and efficiently was the experiment able to address the question?
    - Are there any other methods that could be used to address the same question?
    - What are some improvements that could be made regarding the proposed (or completed) experimental design?
    - How might the experimental design work in conjunction with others to improve overall understanding regarding sound and communication in animals?
    - What are some possible additional applications that could be gained from the study?

Exercise 6e. Crank it Up!

As you have learned in the previous exercises, sound is a pressure wave that results from vibration of particles. To produce sound, there must first be a source of vibration and secondly there must be a medium that it can spread through. The medium may be air, water or even the ground. Animals use one or more of the four mechanisms of producing vibrations (i.e., striking a substrate, stridulation, using muscles to vibrate a membrane or forcing air over a vibrating membrane). Thunder and lightning propagate sound waves as do engineered machines.

In the acoustics and music industries a major goal is to improve the distance at which sounds can be detected while maintaining sound quality in the variety of contexts where sound transmission is desired such as in radios, televisions, computers, intercoms and in auditoriums. Sounds are transmitted through a speaker, a simple electronic device that uses electromagnetism to produce vibrations that create sound pressure waves. Speakers are essentially very simple devices, consisting of only a few components. All speakers basically consist of a coil of wire (the voice coil), a magnet, a source of signal input, and a diaphragm or membrane that can vibrate, attached to a frame. See Figure 1 below for a schematic of a generalized speaker.

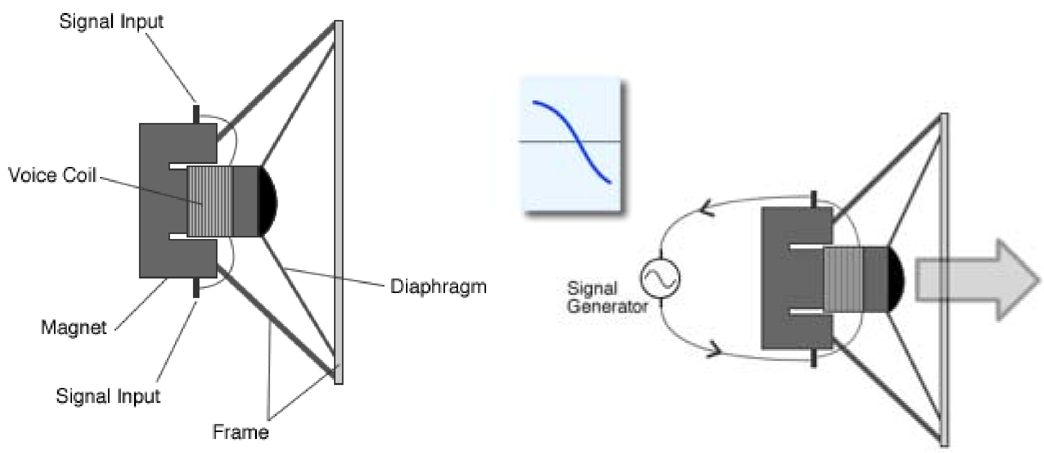


Figure 1. Elements of a speaker that lead to sound augmentation and, thus, transmission at a distance.

- For comparison to Figure 1, find and examine the speaker provided with this unit in the container labeled *Exercise 6: Bioacoustics*.
- Pass the speaker around the class so that all can find the electric coil of wire, the magnet, location of signal input and the diaphragm that the electromagnet vibrates to propagate the sound wave.

The way that a speaker works is that when an electrical current is passed through the voice coil around the magnet, it becomes an electromagnet, generating a magnetic field. Changing direction of the current changes the polarity of the electromagnet (the voice coil), causing it to alternately be attracted to and repelled by the permanent magnet inside it. This motion of the magnet and/or voice coil causes the flexible diaphragm, which is in contact with the voice coil and/or magnet, to vibrate and generate sound waves.

On the web, one can find protocols for students to build and test their own speakers using magnets, electric wire and playing cards. These materials are expendable and, thus, not something we can offer in our unit.

In the exercise presented below, students will explore the effect of the medium (speaker diaphragm) on projection distance and the perceived transmission of specific frequencies and overall sound quality. Students will use a bone conduction oscillator that combines the magnet and coil parts of a speaker in the experiments you will conduct. The goal is to play the role of an engineer in determining those diaphragm design elements that make the best speaker in terms of sound amplification (loudness for distance carried) and quality.

- Find the items shown in Figure 2 in the container labeled Exercise 6 in the Unit 11 Box.

Figure 2. Items required for use in Exercise 6e Crank it up! Top row offers a variety of diaphragms. Bottom row from left to right: Speaker (protected in clear 8oz deli cup with audio cable soldered on), Bone Conduction Transducer (embedded in wood block with audio cable soldered on), and Mini Signal Amplifier (Boostaroo) with batteries.

- Spread the potential diaphragms on the front table with a descriptive label or number tag placed in front of each one. Options may include paper cups, wax paper, etc. supplied by the teacher.

- Divide the class into teams of 3–4 students.

- Each team should visit the table and produce two hypothesized rankings of the diaphragms present which they commit to paper.
  1) amplitude: (1 (greatest)…..n (least))
  2) sound quality: (1 (best).….n (worst))

- Meanwhile, the teacher will set up the computer, plugging in the Boostaroo signal amplifier into the headphone output connector of the computer and the Bone Conduction Transducer into the Boostaroo amplifier. Single tones of different frequency may be tested, available through the tone generation program provided on the CD accompanying the unit (see instructions following). Or, the teacher or class might select music, animal calls, or another interesting sound from *YouTube* or some other source to use for the test.
- Play the sound file through each diaphragm which a volunteer will hold flush to the top of the Bone Conduction Transducer.

***For teacher:* Guide to using the Tone Generation Program**

On the CD for this unit, find the icon representing the "Tone Generator" program, and double click it to open the program.

The program is fairly simple to use. Notice in the top left of the program window, there is a section labeled "Audio Frequency Hz". This area, which includes a numeric keypad and an "Enter" key, allows you to select the frequency of a tone, which the program will use your computer's sound card to produce. The program allows you to generate tones of any whole number frequency between 100 and 15000 Hz.

Also take note of the "Output Level" slider, which allows you to set the volume of the tones produced, and the "Tone On/Off" button, which turns the generated tones on and off.

Click on the "Output Level" slider of the program, and drag it all the way to the top.

Now, use your mouse to enter a frequency of 100 on the program's keypad, and then click the "Enter" button.

Now click on the "Tone On/Off" button. You should now hear a very low, constant tone coming from your computer's speakers. If you do not, check to make sure that your computer's speakers are turned on.

- To experimentally determine which diaphragms produce the best sound amplitude and quality, students will compare diaphragms to each other two at a time. For each pair, the class will vote as to which of two options is louder on the one hand and which offers greater sound clarity on the other. Note that the two qualities for a particular diaphragm may well be independent.
- Diaphragms should be assigned unique identifying numbers to help with recording comparisons.

- Results will be recorded in two comparison matrices, one for loudness and one for sound clarity. The louder of the sound pair will be assigned a **1** in the loudness matrix and the member of the pair having the higher quality sound assigned a **1** in the clarity matrix.
- An example template for a matrix comparing 6 different diaphragms is offered below. The first column of a pair of columns of the same identifying number (say 1) is the comparison pair (1× 2) and the second column under the identifying number gives space to record the result for that diaphragm. Record a 0 if the diaphragm for that column has lesser loudness or quality, a 1 for higher loudness or quality and a 0.5 if the class cannot discern a difference between the two sounds with respect to the test.

    Example: Let's take the comparison of loudness for the pair 1× 3. If more students voted for diaphragm 3 having a louder sound than diaphragm 1 in a loudness comparison, the score under 1 for 1× 3 would be 0, while the score for the comparison 3 × 1 under 3 would be assigned 1 point for diaphragm 3.

  The sum row at the bottom of the graph represents the total score for the diaphragm indicated at the top of the column. If there is a tie in the sums at the end, the comparison score between the two diaphragms can be used as the deciding factor.

Sample Diaphragm Comparison Matrix Comparison: 0 is <, 1 is >

Diaphragm 1		Diaphragm 2		Diaphragm 3		Diaphragm 4		Diaphragm 5		Diaphragm 6	
1X2		2X1		3X1		4X1		5X1		6X1	
1X3		2X3		3X2		4X2		5X2		6X2	
1X4		2X4		3X4		4X3		5X3		6X3	
1X5		2X5		3X5		4X5		5X4		6X4	
1X6		2X6		3X6		4X6		5X6		6X5	
sum											

- A second volunteer should serve as a scribe filling in two matrices at the front of the room. Students in the class may be asked to fill in the same matrices at their desks. In this case, your teacher will provide you with blank copies or have your make your own.
- Complete all of the qualitative comparisons for loudness and quality by filling out both matrices.
- Next, complete a quantitative test for loudness using the sound meter.

- The teacher should insert a 9-volt battery into the sound meter, test the functioning of the meter and explain its use to the class.

Instructions for Sound Meter use:

Press the power button. Notice that right away, the sound meter will begin reading decibel levels of the sounds present in the room. The readings will probably change rapidly because of fluctuations in the background sound

intensity. To deal with this, you will be measuring the maximum volume produced by a particular speaker diaphragm. **This is the point at which all in the classroom should be as quiet as possible, to minimize errors in readings due to sounds other than the speaker diaphragm in question. One team member should hold up a sign that reads SILENCE.**
Remember to turn the sound meter off and then back on to reset the meter before taking readings for each diaphragm. Otherwise, the maximum sound intensity from previous diaphragm (or any other loud sounds) will show up as the maximum reading, which will affect your results!

- Compare your qualitative evaluation to the quantitative results for speaker loudness
- Have a class discussion as to which diaphragm performed best in the respective loudness and clarity trials and develop hypotheses that student teams or the class might test by rounding up additional materials. Do not restrict your discussion to the best scoring diaphragm, but include trends in the test results, perhaps lining up the diaphragms tested in groups from least successful to most.
- Answer the following question:

Q34. How does a microphone work?

Open-ended Exploration:

Compare speaker structure to the morphological adaptations possessed by animals to project sound as well as behavioral use of features of the environment.

Exercise 4f. Stop that Noise! (*Open-ended exploration*)

Animal communication and signal exchange is constrained by noise. Noise refers to the sound pressure particular sources produce that are intrusive or unwanted by those receiving them. These may be loud, unpleasant, unexpected or just undesired sound pressure waves. Nature, itself, produces a cacophony of sounds in the environment collectively referred to as the soundscape. The soundscape consists of biological sounds produced by males courting females, vocal displays and emissions during fights and playing which occurs when animals are learning how to fight, etc. Animals also emit sound pressure waves as they go about their daily activities of procuring food and moving from place to place. There is no question that the dawn chorus of insects and the courtship chorus of breeding frogs can be deafening and thus viewed as noise.

Non-biological sounds contributing to the soundscape include relatively constant environment noise such as that produced by water flowing over rocks in a stream, waves crashing on a shoreline, and wind moving through trees or grasses. There are also the irregular noise events generated by thunderstorms, falling trees, glaciers, avalanches and earthquakes.

- Before reading further, discuss as a class what kinds of responses animals might have to the natural soundscape with respect to constant background noise on the one hand and the occasional noise events.
- Read on to learn what researchers have found in studies completed to date.

Noise as defined is unwanted. There is evidence from reef studies, however, that the background noise produced both by water hitting a reef and the multitude of organisms living and feeding there is used by crustacean larvae of reef species to orient them towards suitable habitat. On the other hand, reef noise acts as a deterrent to the larvae of pelagic (deep sea) crustaceans which permit them to avoid the predators that are abundant on the reefs. This study demonstrates that to some extent at least, the definition of noise depends on the 'ear of the beholder'.

Noise of any origin is definitely a problem for animals attempting to use auditory signals to communicate at long distances. Various studies indicate that animals actually assess the level of noise in their environment and make changes in their auditory communication to enhance signal detection under adverse signaling conditions. One such adaptation to noise involves initiating communication with a conspicuous 'alert' signal. Coyotes, for example, will produce a sharp bark before a howl sequence, and calling frogs an initial low frequency sound that may carry longer distances. In birds, the alert signal entails a few simple introductory notes prior to beginning a more complicated sequence of notes.

Bird species may also change the frequency of their calls to compensate for a noisy environment. For example, song sparrows will raise the frequency of their low notes to avoid interference from background noise. Whales, too, have been found to change their call in response to noise pollution in their environment. Instead of changing the frequency of their calls, however, they increase call amplitude. If this does not work, they will cease calling altogether.

What about escaping a noisy environment?

Clearly animals retreat from loud noises into their nest holes or to quieter locations. Further, it is well documented that animals will insulate their nests with fur, feathers, grass litter, etc. to provide protection against unfavorable temperatures. The insulation helps a nest to stay warmer in the colder climates and cooler in the warmer climates. The extent to which such nest insulation dampens noise and or is an adaptation against noise has not been the subject of research in the scientific literature.

If animal species are found to line their nests with materials to dampen sound, they would be engaging in soundproofing, a very important application of the field of acoustic engineering. Noise, also called clamor and hubbub, is commonplace in our technological world with vacuum cleaners and sound systems in the home and lawnmowers and leaf and snow blowers in use outdoors. There is a general problem with noise. Many workplaces, such as construction sites and factories, subject workers to potentially dangerous noise levels. Noise also is a distraction to workers in offices, students in classrooms, and for people trying to have a discussion in a restaurant or sleep in their homes.

With all the sources of noise pollution, soundproofing is a major industry. Sound reduction ear muffs are required head gear for some factory workers.

In the music industry, soundproofing is not only used to prevent outside noise from filtering in, but also to improve sound quality within the recording booth by reducing echo, for example.

- Do some research on soundproofing applications, and working in groups, design a soundproofing booth made from inexpensive materials to surround the mini amplifier-speaker provided in this unit.
- Different teams might choose to sound proof their booth to meet Maximum Acceptable decibels (dBA) for a particular context: Bedroom (30 dBA); School Classroom (35 dBA); Industrial Workplace (90 dBA); Restaurant (50 dBA). Alternatively, teams might use natural materials (e.g., loose versus packed dirt,

fur, feathers, woven weeds and grasses) to test the soundproofing qualities of animal homes

- Design an experiment to evaluate the noise level of various sounds from the speaker both with and without your soundproofing booth installed. In your testing protocol, you are welcome to use the included sound meter, tone generator included on the Teacher CD, as well as music or white noise.
- Each group should share your targeted application and procedure with the rest of the class and gather suggestions from them that you might use in your design.
- As a class, decide on one or more testing procedures that will then be applied in testing all of the soundproofing booths produced.
- Collect your data.
- Each team will present their data to the class
- Discuss, as a class, the following questions for each team's results:
  1. Was the soundproofing booth effective for the environment it was designed for?
  2. Did the effectiveness of the soundproofing booth vary for different frequencies and types of sounds? If so, under which conditions did the booth perform the best?
  3. What unique feature(s) of the sound proofing booth blocked the most noise?
- Think about cost effectiveness, and the amount of material used. Try to calculate an estimated cost of your group's soundproofing booth.
- Devise a way of simultaneously evaluating soundproofing effectiveness and cost effectiveness.
- Which group's design performed the best, while also incurring a low cost?
- Research currently used soundproofing technologies. Is your design similar to any soundproofing materials or designs currently in use?
- If not, would your design be feasible for larger scale production? Why or why not?

Open-ended Exploration:

1. Take a field trip seeking out animal homes (e.g., hollow logs, burrows in the ground or in rock piles, squirrel and bird nests (ground, shrubs, trees), bird houses, etc. Be a good naturalist and don't disturb or destroy anyone's occupied home!

Place the sound source (e.g., pocket radio played at same volume level; noise maker) within the 'home' and record the sound pressure at 'x' distance away or the qualitative distance at which the sound can no longer be heard. Record these data for examination back in the classroom.

2. As teams, search the web for examples of noise pollution of human origin that interferes with animal life. Pay close attention to the source of the noise, the effects on the animals. Following a discussion and additional research on the life history of the animals and the noise pollution source, come up with a solution that might alleviate the disturbance. Report your problem and solution to the class.

ANSWERS FOR EXERCISE 1: INTRODUCTION TO BIOMIMETICS

Biomimetics Challenge:

Technological Application	Biological Source
5 Swimsuit materials	**B** Dermal denticles of shark skin
6 Inexpensive solar cells	**D** Light capture and transfer processes in leaf chloroplasts
1 Velcro fasteners	**C** Hitchhiking seed (bur) design
2 Bioactive coronary stents	**E** Internal artery wall function
3 Walking robots	**F** Kinematic configurations of a stick insect
4 Shopping center design for air flow	**A** Termite Mound Structure

ANSWERS FOR EXERCISE 2: FROM BONES TO BRIDGES

Q1. Which types of stress(es) did the pencil most effectively withstand? Which type of stress(es) would have made it easiest to break the pencil?
The pencil should have clearly most effectively withstood the stresses of tension and compression, with it being nearly impossible to break the pencil under either type of stress. However, applying bending stress is a very easy way to break a pencil!

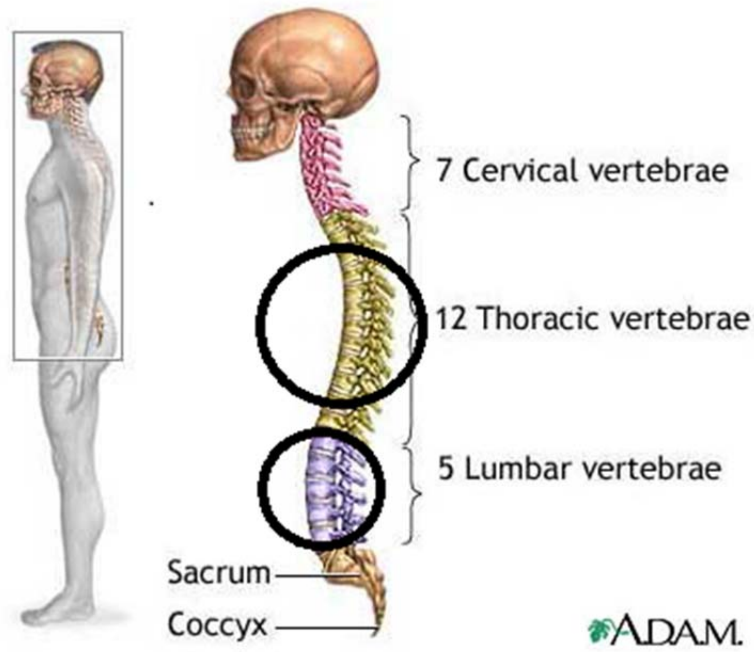
Q2. Think about the different types of materials used in building bridges. Do you think that each of these materials responds to the different main types of stresses in the same way?
Different materials vary in their strength relative to the various types of stresses. Typically, materials withstand different types of stresses in different ways. For example, concrete is strong when subjected to compression, cables are strong when subjected to tension, and steel beams are strong when subjected to both compression and tension. Overall, structural members (i.e. beams and posts) can support much larger forces of tension and compression than of bending.

Q3. Consider the forces of tension, compression, and bending in the case of bipedal animals (animals that walk on two hind legs), like the human shown in Figure 13.

a) **Which force is most limiting/important in the case of the bipedal mammal?** Compression

b) **Does the curvature of the spine help to minimize the effects of that force?** No. Ideally, for pure vertical loads, like those experienced due to gravity when walking upright, a spine with no curvature would offer significant stress reduction under pure compression, approximately 2 orders of magnitude lower than the stress generated on a curved spine.

c) **If not, why does curvature exist?** Without the lumbar curve, the vertebral column would always lean forward, a position that requires much more muscular effort for bipedal animals. Also, combining the lumbar and thoracic curves bring the body's center of gravity directly over the feet, increasing balance. Therefore, the shape of the human spine represents a compromise between strength and the need for balance.



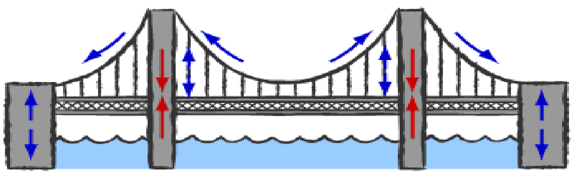
Q4. In one of the most spectacular bridge collapses in history, the Tacoma Narrows Bridge fell into the Puget Sound in 1940, shortly after it opened. At the time it was the third longest suspension bridge, 5,939ft. The deck of the bridge fell 195ft into the water and the splash it created was 100ft high.

a) **Convert all measurements to metric equivalents: show your work.**
Answers below are rounded to the appropriate number of significant figures.
1 meter = 3.2808 feet
Bridge length: 5,939ft/3.2808 = 1.810×10^{3} m
Bridge height: 195ft/3.2808 = 59.4 m
Splash height: 100ft/3.2808 = 30 m

b) **Determine the ratio of the spray height to the drop distance?**
Ratio: 30 m :59.4 m which reduces to 1:2

c) **How much larger was the drop distance to the spray height?**
For feet: 195/100 = 2 times larger
For meters: 59.4/30 = 2 times larger

Q5. Compression and tension are the major forces that apply to suspension bridges like the one shown here. Bridge span is the distance between bridge supports which might be land edges or piers anchored in the water body below the bridge. **Where do compression and tension forces apply to this bridge and why would having a tower with support wires strengthen a bridge, permitting a longer span?**



The force of compression pushes down on the suspension bridge's deck. However the cables transfer the compression to the towers, which dissipate the compression directly into the earth where they're firmly entrenched. The supporting cables, running between 2 anchorages, receive tension forces. They are stretched from the weight of the bridge and its traffic as they run from anchorage to anchorage. The anchorages are also under tension, but since they, like the towers, are held firmly to the earth, the tension they experience is dissipated or scattered.

ANSWERS FOR EXERCISE 3: JAWS ARE LEVERS

Answers for Exercise 3a1. Structure and Function of the Class 1 Lever

- **Summarize, in words, the relationship you observe between the position of the fulcrum on your beam and the effort required to lift your load.** The longer the effort arm and the shorter the load arm the less effort needed to counteract the load.

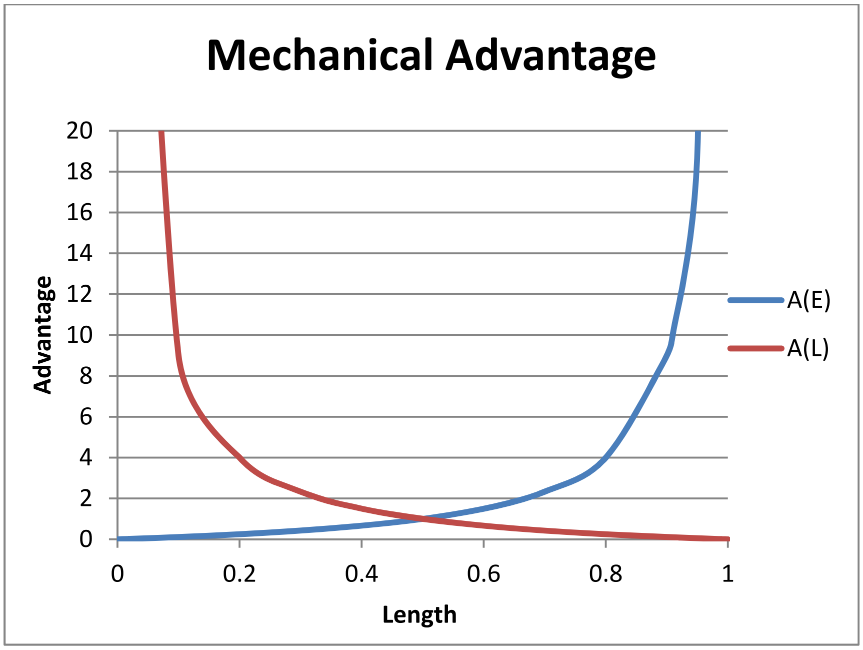
- **In your own words – what is meant by "Mechanical Advantage"?** Mechanical Advantage is the increase in force gained by using a tool.

Supersolver Question

Given a lever of fixed total length T, let L =length of the load arm. Note that this implies that the length of the effort arm E = T – L. Express the Mechanical Advantage as a function of L when T = 1 meter, and draw a line graph for this function choosing a few L values between 0 and 1.Then express Mechanical Advantage as a function of E and draw the corresponding line on the same graph. Compare your two lines and record your conclusions about the relationship between the two functions (L and E).

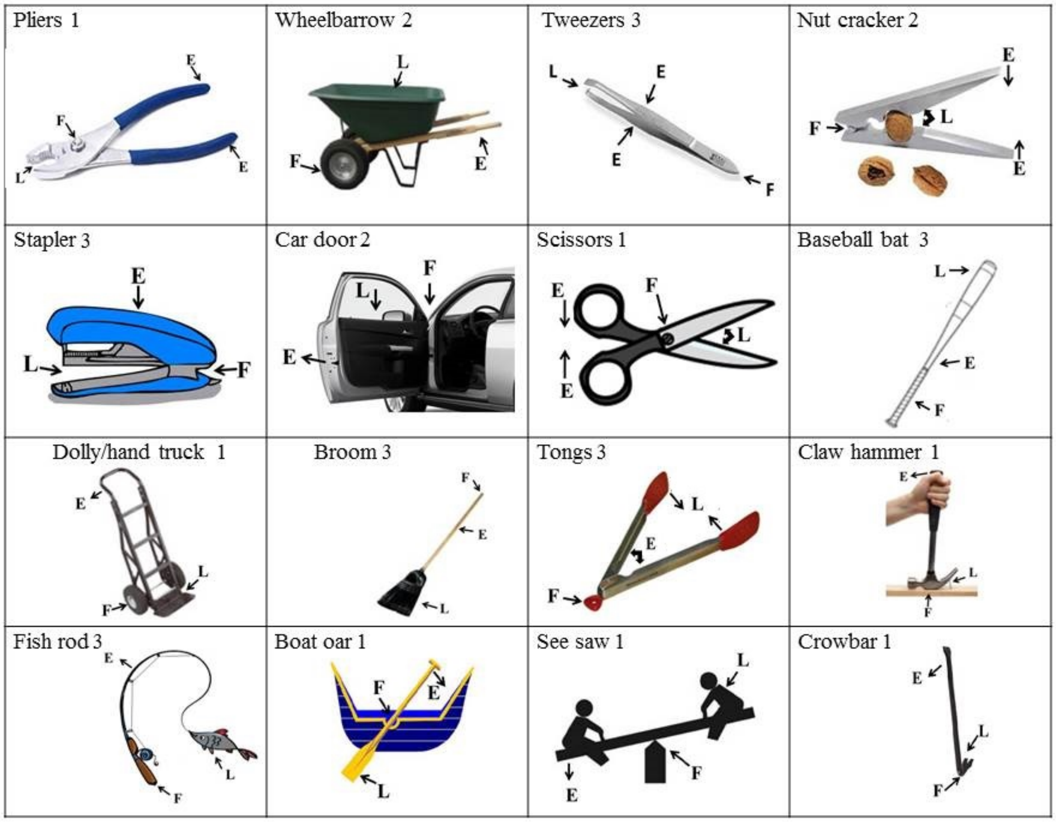
$$E = length\ of\ effort\ arm$$
$$0 \leq E \leq T$$
$$L = length\ of\ load\ arm$$
$$0 \leq L \leq T$$
$$T = total\ lever\ length$$
$$E + L = T$$
$$A(E)\ is\ the\ Mechanical\ Advantage\ as\ a\ function\ of\ the\ effort\ arm:$$
$$A(E) = \frac{E}{T - E}$$
$$A(L)\ is\ the\ Mechanical\ Advantage\ as\ a\ function\ of\ the\ load\ arm:$$
$$A(L) = \frac{T - L}{L}$$

The graph below is a representation of the mechanical advantage of a lever when: $T = 1$



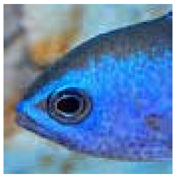
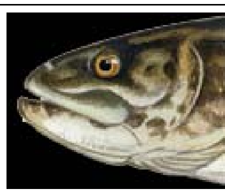
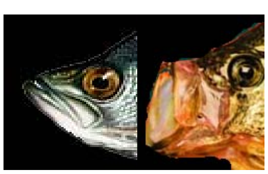
- **As the length of the effort arm increases and the load arm decreases, the Mechanical Advantage increases. But the relationship is not linear – as you approach the maximum possible effort arm, you are getting a much greater increase in Mechanical Advantage! Of course, there comes a point where it is physically impossible to make the effort arm any longer. In the real world, it is impossible to have an effort arm of 1 and a load arm of 0 and still have a lever, because where would you put the fulcrum or the load? The graph of these functions predicts this issue. Notice how the lines approach asymptotes at the extreme ends. The Mechanical Advantage is getting better and better as L gets smaller and E gets bigger, but there are limits. This is because the functions you are graphing where T=1, when L = 0 and E = 1 the functions will both yield a zero as the denominator, which is termed "undefined" in mathematics.**

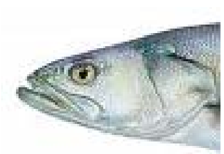
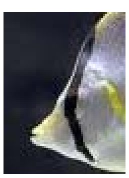
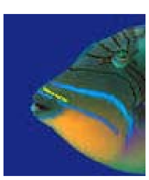
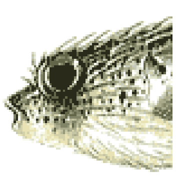
Answers for Exercise 3a2. Levers We Use Every Day



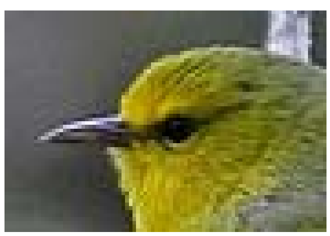
The Pliers and Scissors are examples of double Class 1 levers.
The Nutcracker is a double Class 2 lever.
Tweezers and Tongs are double Class 3 levers.

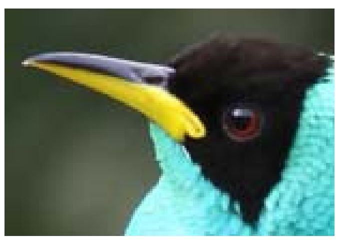
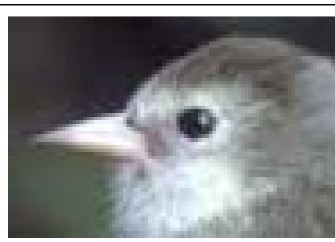
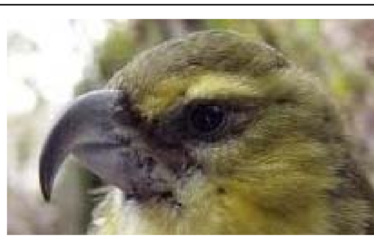
Answers for Exercise 3b1. Mouth Shape and Size Predicts Feeding Habits in Fish.

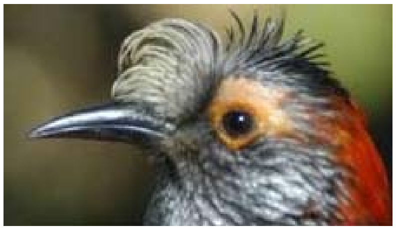
	***Chromiscyanea* (Blue chromis)** **Attack Strategy:** Ram-Suction **Pliers Type:** **Diet:** jellyfish, zooplankton
	***Archosargusprobatocephalus*(Sheepshead)** **Attack Strategy:** Grasper-Manipulator **Pliers Type:** **Diet:** polychaete worms, crustaceans and algae
	***Cephalopholisfulva* (Coney)** **Attack Strategy:** **Pliers Type:** **Diet:** fish and crustaceans
	***Hypoplectrus indigo* (Indigo hamlet)** **Attack Strategy:** Ram-Suction **Pliers Type:** **Diet:** fish
	***Ocyuruschrysurus* (Yellowtail snapper)** **Attack Strategy:** **Pliers Type:** **Diet:** crabs, shrimp, fish
	***Labidesthessicculus* (Brook Silverside)** **Attack Strategy:** Grasper-Manipulator **Pliers Type:** **Diet:** crustaceans, molluscs, insect larvae, algae
	***Amia calva* (Bowfin)** **Attack Strategy:** Grasper-Manipulator **Pliers Type:** **Diet:** crayfish, molluscs, aquatic insects, fish
	***Pomoxis annularis*(Crappie)** **Attack Strategy:** Ram-Suction **Pliers Type:** **Diet:** fish

	***Esoxamericanus* (Redfin pickerel)** **Attack Strategy:** Ram-Suction **Pliers Type:** **Diet:** fish
	***Lepisosteusoculatus*(Spotted Gar)** **Attack Strategy:** Grasper-Manipulator **Pliers Type:** **Diet:**
	***Percinasquamata*(Olive darter)** **Attack Strategy:** **Pliers Type:** **Diet:** fish and crustaceans
	***Melichthysniger*(Black triggerfish)** **Attack Strategy:** Grasper-Manipulator **Pliers Type:** **Diet:** shrimp, algae
	***Cynoscion nebulosus* (Spotted seatrout)** **Attack Strategy:** Ram-Suction **Pliers Type:** **Diet:** fish
	***Sparisomarubripinne*(Redfin parrotfish)** **Attack Strategy:** Grasper-Manipulator **Pliers Type:** **Diet:** coral
	***Chaetodonocellatus* (Spotfin butterflyfish)** **Attack Strategy:** Grasper-Manipulator **Pliers Type:** **Diet:** polychaete worms, tunicates
	***Balistesvetula*(Queen triggerfish)** **Attack Strategy:** Grasper-Manipulator **Pliers Type:** **Diet:** clams, crabs
	***Diodonhystrix*(Spotfin porcupine fish)** **Attack Strategy:** Grasper-Manipulator **Pliers Type:** **Diet:** clams

Answers for Exercise 3b3. Bird Beaks (Bills) as Simple Machines.

A		*Hemignathusmunroi* (Akiapolaau) Specialist Feeder Woodpecker niche- feeds on insects hidden in branches. Long bill pries open bark: upper bill probes out meal, lower crushes it.
B		*Telespizacantans* (Laysan Finch) Generalist feeder Soft parts of grass stems, bush shoots, seeds and bird eggs
C		*Paroreomyzamontana* (Maui Creeper) Generalist feeder Insects and grubs
D		*Hemignathusvirens* (Amakihi) Generalist Feeder Nectar, insects and spiders
E		*Himatione sanguines* (Laysan Honeycreeper) Specialist feeder Nectar feeder

F		*Vestiariacoccinea* (Liwi) Generalist feeder Nectar feeder
G		*Cyanerpescyaneus* (Redlegged honeycreeper) Generalist feeder Primarily insects, but also nectar and fruits
H		*Hemignathusobsurus* (Akialoa) Specialist feeder Nectar feeder, hummingbird-like
I		*Chlorophanesspiza* (Green Honeycreeper) Specialist feeder Fruit
J		*Loxioidesbailleui*(Palilia)Specialist feeder Seed Specialist
K		*Oreomystisbairdi* (Kuau'i Creeper, Akikiki) Specialist feeder Insects(Like a nuthatch)
L		*Pseudonestorxanthophrys* (Maui parrotbill/kiwikiu) Specialist feeder Insects (beak removes bark to eat moth pupae & beetle larvae, etc.)

M		*Palmeriadolei* (Crested honeycreeper, Akohekohe) Generalist feeder Nectar
N		*Loxopscoccineus* (Akepa) Specialist feeder Assymetric cross bill for opening terminal leaf buds in search of insects

3b4. Supersolver Question Answers

Q1. Where in the beak should a bird grip a seed to break it open most easily?
The closer the seed is to the fulcrum of the pliers' axis of rotation, the shorter the load arm. Since Mechanical Advantage is the ratio of the effort arm length to the load arm length, you want to make the load arm as short as possible to maximize Mechanical Advantage. Note that the effort arm length is fixed (distance between masseter muscle and jaw hinge). Thus, the answer should be ‘as close to the jaw hinge as possible’.

Q2. If an input of 0.6 N is required to lift a rock of 36 N, what is the actual Mechanical Advantage? Show your calculations.
Mechanical Advantage = Original Force/Reduced Force
Mechanical Advantage = (36 N)/(0.6 N) = 60)

Q3. What is the correlation between lifestyles of animals and their jaw Mechanical Advantage and velocity ratios?
Students should comment on the interrelationships between mechanics and animal feeding strategies. In general, higher Mechanical Advantages are found in animals that chew and crush food while lower Mechanical Advantages are associated with adaptations for speed of attack or gathering food where animals swallow food without needing to crush or chew it as much or at all.

Q4. Would you expect to find a high Mechanical Advantage and a high velocity ratio in the same animal jaw? Explain.

Necessarily, a high mechanical advantage and a high velocity ratio cannot occur simultaneously because the velocity ratio is the inverse of mechanical advantage. They would require the opposite lever arm ratios.

This is a difficult problem, one addressed in large mammals such as deer that use speed to escape predators. Such mammals have pairs of muscles that act like a gearshift in a car. One muscle inserted far from the joint provides Mechanical Advantage in getting the limb moving. Another muscle then takes over. This second muscle is inserted closer in and moves the limb rapidly.

Q5. Does a generalist feeder seem to have any advantages over a specialist? Justify your answer.
Specialists thrive when conditions are just right---when the food type they are adapted to feeding on is in abundant supply. They can out compete generalists for these foods and consume the food source at a higher rate. However, generalists can adapt to changing environments and thus respond better to uncertainty in food supply. Specialists are more likely to suffer extinction than generalists.

ANSWERS FOR EXERCISE 4: DROP, SQUIRT, THROW: PROJECTILE MOTION

Answers for 4a. Free Fallin'

Q1. What influence does height from which an object is dropped have on the amount of time it takes for an object to hit the ground?
If the drop height is increased, the free fall time is increased as well. However, based on the graphical relationship of the three trials, the relationship is not linear. Thus if we were to double the drop height, the free fall time would not be doubled as well.

Q2. Does the material/mass of an object influence its free fall?
Under the assumption that air resistance is negligible under projectile motion, which is generally a good assumption for the materials provided and the heights used in this exercise, neither the mass, shape, or material composition of an object would have any effect on the time it takes for the object to reach the ground.

Q3. Which object do you think hits the ground with the highest speed/velocity?
All hit the ground with the same velocity.

Q4. If you were to throw the object downward would it take more or less time for it to reach the ground than if you dropped it?

Less time, because the initial velocity would be higher.

Q5. Besides mass and distance, **what other factors affect how much time it takes for a falling object to reach the ground?**
From the aforementioned relationships the critical factors are release height, acceleration due to gravity, and initial velocity, assuming that air resistance is not a factor (negligible).

Q6. We have learned from this exercise on free fall that all objects regardless of their mass accelerate downwards at the same rate due to gravity. Why then, may a leaf swirl downwards in a glide-like manner.
Air resistance is not negligible in this case given the shape and small mass of a leaf.

Answers for Exercise 4a1. The Numbers Behind Free Falling

Q1. If h_0 is doubled, how does t change?
The value of *t* would increase by a factor of 1.414 (the square root of 2).

Q2. Do the trial data your team collected under Exercise 4a support this? Explain.
Yes to the extent that higher heights led to longer drop times. One would need much higher heights and more accurate time measurements to determine a more precise relationship.

Q3. Think about your trials where you dropped objects with different mass and from different heights. Did the objects sometimes hit the ground at a greater velocity during certain trials? Justify your answer using the equation above.
The longer an object is falling, the greater the velocity it achieves. So the answer is yes. In the trials involving greater heights, the objects achieved greater velocity.

Q4. **Revise your answers to Q4 and Q5 under Exercise 4a to incorporate what you've learned about the mathematics of falling. Do the mathematics support or change your initial answers?**
If you throw an object downwards, it will have greater initial velocity. Release height, acceleration due to gravity and initial velocity are the important factors. The mathematics support these answers, though some students might need to change their answers depending on what they came up with in exercise 4a.

Answers for Exercise 4b. Launching

Q6. What is the relationship between the pressure to which the assembly is inflated and the distance the projectile travels?
The greater the pressure, the larger the force applied to the straw rocket, which results in a greater acceleration. This results, in a greater launch velocity, and thus a greater travel distance.

More information about this relationship is provided here. The relationship between pressure and launch velocity can be modeled with simple mathematics. **Pressure** is defined as **force acting over an area** ($P = F/A$, where P = pressure, F = force, and A = area).The force exerted on the straw rocket then becomes $F=PA$. Since we also know that an object's acceleration is equal to $a=F/m$ where m = mass, this becomes $a=PA/m$. The area that the pressure affects (the inner surface of the straw's cap), as well as the mass of the straw rocket, remains constant among trials. Assuming that all of the pressurized air in the assembly is released when the launch button is pressed, the rocket's acceleration is only dependent on the pressure, to which the assembly is inflated, with greater pressure leading to greater acceleration, and thus a greater distance traveled.

As identified in Exercise 4a, the velocity with which something is launched directly affects the distance traveled. However, the analysis presented in Exercise 4a was simple compared to that of launching, as it only needed to include motion in the vertical direction under the influence of gravity. As you probably noted in your trials, projectile motion can include motion both in the vertical and horizontal directions. While they occur simultaneously, they can be analyzed independently as illustrated in the following figure:

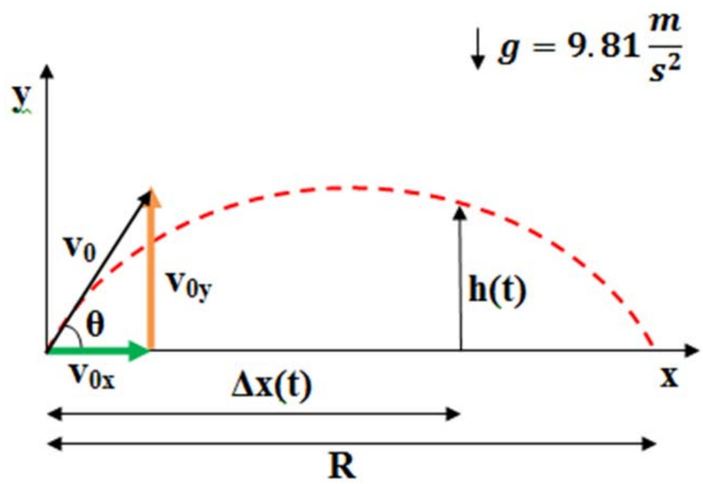


Figure 7. Projectile motion involving both horizontal and vertical movement.

In Figure 7, the following equations can be used to analyze the motion of the projectile in both horizontal and vertical directions in time.

Vertical Direction

$\boldsymbol{v_{fy}(t) = v_{oy} - gt}$ (Equation 6)

$\boldsymbol{h(t) = v_{oy}t - \frac{1}{2}gt^2}$ (Equation 7)

Horizontal Direction

$\boldsymbol{v_{fx}(t) = v_{ox}}$ (Equation 8)

$\boldsymbol{\Delta x(t) = v_{ox}t}$ (Equation 9)

If start and end points are at the same elevation

$$\boldsymbol{R = \frac{v_o^2}{g} sin(2\theta)} \qquad \text{(Equation 10)}$$

In each of the equations above, the variables represent the following quantities:

$v_{fy}(t)$ = vertical component of velocity at time t;
v_{oy} = vertical component of initial velocity;
g = acceleration due to gravity ($9.81\ m/s^2$);
t = time;
$h(t)$ = height at time t;
$v_{fx}(t)$ = horizontal component of velocity at time t;
v_{ox} = horizontal component of initial velocity;
$\Delta x(t)$ = horizontal distance traveled at time t;
R = range; v_o = initial velocity;
θ = angle of launch

Since the motion in the first set of trials involving pressure occurs only in the horizontal direction (since fired at an angle of 0°), we are concerned only with the initial horizontal velocity v_{ox}. It can be observed from Equation 8 above that the velocity in the horizontal direction is unaffected by gravity, and thus the distance traveled is simply the velocity multiplied by the time of flight (as an example, an airplane traveling at 60 mph for 1 hour will travel 60 mph × 1h = 60 miles). In this manner, the distance the projectile travels is directly related to the initial velocity, in that the faster it is fired, the further it will fly.

The relationship between the initial velocity and the pressure to which the apparatus is inflated can be determined from an energy formulation. The compression of the air in the apparatus essentially stores potential energy. At the moment of release, all of this potential energy is converted into kinetic energy by the law of conservation of energy. A greater pressure in the system means that there is more air compressed in the apparatus, which thus provides more potential energy (which can be converted into kinetic energy).Therefore, the greater the pressure to which the air in the apparatus is compressed, the farther a projectile of the same mass will fly when launched at that pressure.

Q7. For the same pressure reading, which of your launch angles results in the greatest distance?
The launch angle of 45 degrees, or the angle that students chose that was closest to 45 degrees, likely results in the greatest distance.

The 45 degree angle as optimal could have been predicted using mathematical modeling. For this question we refer to Equation 10 from the explanation for **Q6**, which is commonly referred to as the range equation. It is derived from the simultaneous solution of motion equations in both the horizontal and vertical directions. Note the following assumption is being made when using the formulation in Equation 10 repeated below: both the start and end elevations are at the same level.

$$\boldsymbol{R = \frac{v^2}{g} sin(2\theta)}$$

This equation is dependent on the angle θ by the trigonometric function sine (which is defined as the ratio of the side, opposite the angle itself, to the hypotenuse of a right triangle with the given angle).Therefore, angles with a larger value of *sin(2θ)* would result in a greater range. For the angles you used, the values of *sin(2θ)* are as follows:

ϑ	*sin(2ϑ)*
0°	*0*
30°	*0.87*
60°	*0.87*
90°	*0*

Note that in the chart above, the value of *sin(2θ)* is equal to zero, and substituting zero into Equation 10 should result in a range of zero for the projectile. Remember, however, the range equation applies when the start and end points of the projectile are at the same elevation. Due to the construction of the rocket launcher, the initial elevation of the projectile is slightly above the final elevation of the ground, so the projectile does travel some horizontal distance.

Theoretically, you should have obtained the same distances for launches at both 30° and 60°.However, if you examine a graph of *sin(θ),* you will see that the function has a maximum at 90 degrees. Thus for maximum distance we want to exploit this relationship and make the quantity *2θ* equal to 90 degrees:

$$\boldsymbol{2\theta = 90^\circ}$$

Which gives:

$$\boldsymbol{\theta = \frac{90^\circ}{2} = 45^\circ}$$

Therefore, to achieve maximum distance we would ideally like to choose a launch angle of 45 degrees. In practice, however the launch platform is sometimes above or below the landing elevation, just as they were with your rocket launcher. If the projectile is launched from above the final elevation, a slightly shallower angle is preferable. Conversely, if the launching platform is below the final elevation, a steeper angle will result in a greater distance.

Q8. If a flea wishes to reach a larger height to jump on an animal what would be the best launch angle to take? Would it use the same launch angle to range further horizontally as it tries to catch up with an animal it wishes to feed on? Explain your answer.

The closer the launch angle is to 90 degrees, the higher the jump. For maximum horizontal distance the angle of launch shoulbe less than 45 degrees.

Q9. We mentioned that many seeds are launched by plants and trees to disperse them away from the parent tree. Seeds vary a great deal in size. Would you expect seeds of any size to fit the predictions of projectile motion? Might there be size constraints on the predictions of dispersal distance, for example, as a function of launch angle and velocity?
One might predict that in small seeds, air resistance becomes more important and this would change the seed trajectories, making it hard to predict using what we know about projectile motion.
Steven Vogel is a biophysicist who examines the effects of physical principles on organisms. He reports that the predictions for projectile motion in small seeds and pollen fail, because air resistance is neglected in the equations for projectile motion. His rule of thumb is ‘the smaller the organism, the greater the deviation from predictions. (Steven Vogel, 2005)

Answers for Exercise 4c. Stop the Monkey's Escape

Q1.**What equations (from the answers to Exercise 4b) apply to the motion of the monkey and the dart**? Consider both the horizontal and vertical directions.

<u>Vertical Direction:</u>
For the Monkey: $\Delta \boldsymbol{h} = -\frac{1}{2}\boldsymbol{g}\boldsymbol{t}^2$
For the Dart: $\Delta \boldsymbol{h} = \boldsymbol{v}_{0y}\boldsymbol{t} - \frac{1}{2}\boldsymbol{g}\boldsymbol{t}^2$

<u>Horizontal Direction:</u>
For the Monkey: $\Delta \boldsymbol{x} = \mathbf{0}$
For the Dart: $\Delta \boldsymbol{h} = \boldsymbol{v}_{0x}\boldsymbol{t}$

Where:
$g = 9.81 m/s^2 = 32.2 ft/s^2 = acceleration\ \ due\ \ to\ \ gravity$
$\Delta h = change\ \ in\ \ height$
$\Delta x = horizontal\ \ displacement$
$t = elapsed\ \ time$
$v_{oy} = initial\ velocity\ in\ the\ vertical\ direction$
$v_{ox} = initial\ velocity\ in\ the\ horizontal\ direction$

Q2. Is there a useful trick for determining where one should aim the straw rocket to hit the monkey before it escapes?

The zookeeper should aim straight at the monkey, because both the dart and the monkey are accelerated by gravity at the same rate and in the same direction, and both follow the equations of projectile motion.

Explanation using mathematical modeling:
The aim line represents the path of the dart if gravity was not present and therefore the equation that represents motion along this line would be:

$$\Delta \boldsymbol{h}_{\boldsymbol{aim}} = \boldsymbol{v}_{\boldsymbol{0y}}\boldsymbol{t} + \boldsymbol{v}_{\boldsymbol{0x}}\boldsymbol{t}$$

or in only the vertical direction:

$$\Delta \boldsymbol{h}_{\boldsymbol{aim}} = \boldsymbol{v}_{\boldsymbol{0y}}\boldsymbol{t}$$

In the real world, of course, gravity affects every object that travels through the air, causing the dart to follow a parabolic path described by

$$\Delta \boldsymbol{h}_{\boldsymbol{real}} = \boldsymbol{v}_{\boldsymbol{0y}}\boldsymbol{t} - \frac{\boldsymbol{1}}{\boldsymbol{2}}\boldsymbol{g}\boldsymbol{t}^{\boldsymbol{2}}$$

Therefore, the difference between the aim line and the trajectory of the dart is

$$\Delta \boldsymbol{h}_{\boldsymbol{real}} - \Delta \boldsymbol{h}_{\boldsymbol{aim}} = \boldsymbol{v}_{\boldsymbol{0y}}\boldsymbol{t} - \frac{\boldsymbol{1}}{\boldsymbol{2}}\boldsymbol{g}\boldsymbol{t}^{\boldsymbol{2}} - \boldsymbol{v}_{\boldsymbol{0y}}\boldsymbol{t} = -\frac{\boldsymbol{1}}{\boldsymbol{2}}\boldsymbol{g}\boldsymbol{t}^{\boldsymbol{2}}$$

Upon careful inspection, you should see that this is the same as the equation that governs the monkey's fall. Thus when the dart reaches the horizontal location of the monkey, the dart has fallen from the aim line the same distance the monkey has fallen from the tree. Therefore, if the zookeeper aims directly at the monkey, the shot will be a success. Notice that this result is only dependent on the aim location and not the velocity of the shot or the masses of the monkey or the dart. Likewise, assuming negligible air resistance, a bullet fired from a gun perfectly horizontally will hit the ground at the same instant as one dropped from the same height.

ANSWERS FOR EXERCISE 5: SIMILAR THINGS TO WINGS: DRAG

Q1. What force(s) do you think were acting on the paper as it fell?
Gravitational and drag.

Q2. Were the gravitational forces acting on the pieces of paper different? Why or why not? And if not, what was happening?
The gravitational force acting on each piece of paper was the same, since they are the same mass. The papers experienced different drag forces, as explained in the text.

Q3. Consider this scenario: You are completing a comparison study of lizard energetics in the desert. You use a stop watch to record the speed with which two equal-sized fence lizards run distance X after you present them with a predatory cue, a shadow of a bird passing overhead. You find that subject A ran the distance twice as fast as subject B. As a result, subject A experienced how many times as much drag as subject B and how much more energetic cost?
The faster lizard A experienced 4 times more drag than the loser lizard B but also incurred 4 times greater energetic cost.
Both lizards were of the same size and shape, so the variable C_d was not relevant to the cost in this case. C_d is the drag coefficient, which depends on an object's shape. An illustration of various drag coefficients is shown in Figure 6 of Exercise 5.

Q4. **What explanation can you give for the observed results?**
In this experiment involving a sheet of paper versus a piece of card stock, you should have observed that the cardstock hit the floor first, simply due to a greater mass. If you have completed the Free Fall experiment under Exercise 4a Free Fallin', you will recall that when gravity is the only significant force acting on an object, the acceleration is simply the same as the acceleration due to gravity, and not related to mass. But as this experiment demonstrates, when you factor in some significant drag, suddenly this changes. Both sheets are the same size and shape, so therefore have the same surface areas and drag coefficients (see Figure 6 of exercise 5). However, since the cardstock has more mass, it

experiences less drag and therefore, a greater acceleration overall. This relationship is illustrated by:

$$a = \frac{\vec{F}_{net}}{m} = \frac{\vec{F}_g - \vec{F}_d}{m} = \frac{mg - \frac{1}{2}\rho v^2 A C_d}{m} = g - \frac{\rho v^2 A C_d}{2m}$$

As you increase *m*, the term that is subtracted from *g* becomes smaller, so *a* will increase.

Q5. What explanation can you give for the observed results? Hint: What was different about the way in which one set of coffee filters fell?

You probably noticed that the array of coffee filters fell much more slowly than the stack of coffee filters, almost like a parachute. Again, one reason for this is the greater surface area of the array, which results in a greater drag force acting on the array, which slows the acceleration.

Q6. **Check to see if the following points are on the line** $y = 3x + 4$

$(1, 8) 3(1) + 4 = 7 \neq 8$ NO

$(2, 10) 3(2) + 4 = 6 + 4 = 10$ YES

Q7. Find the slope of the line in the figure.

$$\mathrm{m} = 2$$

Q8. What is the y-intercept of the line $y = 3x + 4$?

$$\mathrm{b} = 4$$

Q9. Suppose that a line has slope $m = 2$ **and that the point** $(2, 7)$ **is on the line. Write down the point-slope formula for the line.**

$$2 = \frac{7 - \mathrm{y}}{2 - \mathrm{x}}$$

Q10. Find the slope-intercept formula for the line in Q4.

$$2 = \frac{7 - \mathrm{y}}{2 - \mathrm{x}} \rightarrow$$

$$2(2 - \mathrm{x}) = 7 - \mathrm{y} \rightarrow$$

$$\mathbf{4 - 2x = 7 - y \rightarrow}$$

$$\mathbf{y = 2x + 3}$$

Q11. Record the slope of the best fit line for both the American and Chinese infant growth data. Which best fit line has the largest slope? How would you interpret this fact?

Chinese female infants: $\mathbf{m = 1.2\ \frac{cm}{month}}$

American female infants: $\mathbf{m = 1.8\ \frac{cm}{month}}$

This means that American female infants grow faster than Chinese female infants.

Q12. Record the y-intercept of the best fit line for the Chinese and American infant growth data. Which data set has the smallest y-intercept? How would you interpret this fact?

Chinese female infants: $\mathbf{b = 57}$ cm
American female infants: $\mathbf{b = 58}$ cm

This means that Chinese females are shorter at birth than American females.

Q13. What does the slope of the line in Figure 11 indicate about the relationship between seed mass and the velocity of that seed type's descent?
It indicates that the two parameters are positively correlated: as seed mass increases, so does the velocity of the seeds descent.

Q14. According to Figure 11, when seed mass is at or/approximates zero, what is the speed of descent of a seed of that mass according to the linear analysis?
It is the Y intercept of the line which is 0.929088 (b).

Q15. What can you say about the samara type designated by the point at the top right corner of Figure 11?
This is samara that is of exceptionally high mass, which has a lower descent velocity than would be predicted by its mass.

Q16. Interpret the relationship between mass and descent velocity for samaras below the best fit line in the lower left corner.

These are samara types that are close to 0 mass and fall below velocity of descent predictions based on a linear relationship between mass and descent velocity.

Q17. You may find the horizontal range of your samara types were unexpectedly low and not showing species differences. Why then would the species expend energy to produce a winged fruit? Discuss as a class why you obtained the results you did.

The samara wing is designed to keep the seed aloft so that it can be caught by a gust of wind and transported away from the parent tree. In fact, wind is likely responsible for disengaging the seed from the branch to which it was attached in the first place. If you carried out your experiment in a building, these air currents would be absent, leading to little lateral movement of the samara from the drop position of the drop.

Q18. From your vertical drop results what prediction can you make about the relationship between wing loading ratios and dispersal ability of maple samaras?

Samara wing loading ratios are inversely proportional to dispersal ability. Seeds with low wing loading thus fall more slowly than those with larger wing loading values, allowing them to disperse farther as they are caught by wind currents.

Q19. Rank the three maple species from the potential to have high dispersal distances to the species that would exhibit the lowest dispersal distances. What would be the relationship between the species dispersal capabilities and the niche each of the tree species occupies (i.e., its status as a climax forest or sub climax forest species versus a pioneer species that invades habitats that have been disturbed (e.g., cleared by a hurricane or landslide or human activity))?

Silver maple is the climax forest species and disperses capability only a meter or two; Sugar Maple is the sub climax forest species and exhibits moderate dispersal distances averaging 10 m and up to 40 m distant; and Red Maple is the pioneer forest species occupying disturbed habitats and has long range dispersal capability in the wind currents.

Q20. The traits organisms exhibit represent the trade-offs in selection pressures on them. Think about the characteristics a samara needs to have to disperse the long distances required to settle in habitats where there is less competition for resources, as opposed to the samara that needs to be a good competitor and grow fast in the place it lands in the shade of overhead trees. Discuss the wing-loading characteristic of each of the three maple species with respect to such trade-offs.

Samaras with a low wing loading will travel very far in the wind, but this great dispersal ability comes at a cost. Low wing loading is only feasible when the seeds themselves are quite light (have little endosperm, the tissue produced inside the seed that surrounds the embryo and provides nutrition to it.) There is a built-in tradeoff, then, between seed provisioning, which can help in the critical life stage of establishment and dispersal distance of the samara. The seeds of species that are characteristic of mature climax forests are already in preferred habitat. They emphasize having resources to establish in the shade where energy from photosynthesis will be low. They tend to have larger seeds with higher wing-loading because they have more endosperm in the seed.

Q21. In what types of habitats would you then expect to find each of the species whose samaras you examined?

Red maples will be pioneer species sending out lots of samaras to occupy disturbed habitat while sugar maples and even more so silver maples will be climax species occupying prime habitat. Heavier fruits have more nutrients than lighter ones, giving these seeds a better chance for competition in the place the moist forest occupied by the parent tree.

Answers for Exercise 5b. Exploring Dispersal in Nature

Q22. How does the monkey move from tree to tree and what limitations are placed on its movement through the forest?

It must find overlapping branches or alternatively make its way to the ground and run along it to the closest tree. On the ground it is exposed to both additional predation risk and being crushed by falling fruits. Why fruits? In the tropical rainforest frequented by this monkey some of these fruits are larger in diameter than grapefruits and will have achieved high velocities as they may have fallen from branches that are as high up as 100–275 feet above the forest floor.

Q23. What advantage does the gliding mammals pictured in Fig. 10 have over the marmoset?

Gliders have the advantage of traveling from tree to tree without the disadvantage of having to descend to the ground. Gliding offers an efficient means of locating food and avoiding predators.

Q24. How is gliding achieved? A third force is involved besides gravitational and drag forces. What is it and what is the nature of their interaction in enabling gliding behavior.

The speed of the drop is slower in a gliding mammal than a monkey lacking the expanded surface area of the same mass. This is due to drag forces. The measure of performance of a patagia is a function of the glide ratio, expressed as the horizontal acceleration divided by the vertical drop acceleration. For the sugar glider, the horizontal acceleration is on average twice the vertical drop acceleration producing more horizontal movement than free fall. Drag force reduces the vertical drop/unit time and horizontal distance traveled is enhanced by 'lift' force. As air moves over the top of the animal it slows, creating an upward force called lift. Limb movements are utilized to control body rotations that might occur during a glide.

Q25. What difficulty does a glider have to deal with and how might it counter such problems.

Although it may be important to travel as far as possible, landing safely at the desired location is a problem the glider has to deal with. Limb movement helps to control rotation and produce safe landings.

ANSWERS FOR EXERCISE 6: ACOUSTICS

Answers for 6a. Methods of Animal Communication

Q1. Do you think that sounds travel faster through air, liquids, or solids? Why?

As a general rule, sounds travel faster through solids than liquids, and more quickly through liquids than in gases. The rate at which sound travels through a medium is related to both the medium's density, as well as its elasticity, according to the following equation:

$$V = \sqrt{\frac{C_{ij}}{\rho}}$$

In this equation, V is the speed of sound, C_{ij} is the elasticity of the medium, and ρ is its density. Thus, the greater a medium's elasticity, the greater the speed at which sound can travel through it. However, on the other hand, the more dense a medium, the more slowly sound travels through it. The elasticity of a particular medium depends on the strength of the bonds between its molecules. Stronger bonds such as those seen in solids generally result in higher elastic constants, while the bonds between gas molecules are typically lower, leading to a lower elastic constant. There are some occasional exceptions, however!

Substance	Temp (°C)	Speed (m/s)
Gases		
Carbon Dioxide	0	259
Oxygen	0	316
Air	0	331
Air	20	343
Helium	0	965
Liquids		
Chloroform	20	1004
Ethanol	20	1162
Mercury	20	1450
Water	20	1482
Solids		
Lead	–	1960
Copper	–	5010
Glass	–	5640
Steel	–	5960

Q2. What sort of effect do you think that temperature might have on sound transmission?

In air, the speed at which sound travels depends on temperature, and follows the equation below:

$$v = 331 m/s + 0.6 m/s/C * T$$

In this equation, v is the speed of the sound, and T is the temperature in degrees Celsius. This relationship holds in dry air (0% humidity) at 1 atmosphere of pressure. In the equation, you should see that sound moves more quickly through air at higher temperatures. This is because at higher temperatures, gas molecules move more quickly, allowing sound waves to be propagated more quickly. However, changes in air pressure and humidity can affect the speed of sound in air, as well.

Answers for 6a2. Courtship Signaling

Q3. Which of the four ways of producing sound is this most like? Let's assume that you are a male looking for a potential mate. How would you use your hand or finger tapping to make a courtship signal that is unique to your species so that it reaches the correct audience?

Drumming on the edge of your desk is most similar to striking a substrate. To use drumming in courtship, one could come up with a repeated pattern of rapping that is consistent and species specific.

Q4. What are the advantages, problems etc. of using sound in courtship?
There are numerous advantages of sound communication over other forms of communication. Sound can travel long distances and around corners or objects (e.g., trees in a forest, rock outcrops), be transmitted both in the day and night and can be transmitted through air, water and even solid substrates. Signals too can be complex/highly variable compared to other forms of signaling. There are potential disadvantages, however. A potential predator can follow the sound to the signaler and in noisy environments; the message may be garbled (unclear or confusing).

Q5. If discrimination errors are made by females, what is the immediate consequence? The immediate consequence is that the female may misidentify males and end up mating with a male of a different species, leading to the wastage of gametes (sperm and eggs).

Q6. What will discrimination errors ultimately lead to? Ultimately, gamete wastage will lead to refinement of the species signal to better ensure that species differentiation is maintained.

Answers for Exercise 6a3: Exploring Sound Producing Mechanisms

Q7. To which animal sound production method is this instrument most similar?
Below are examples of animal sound production methods most similar to each of the instruments:

Drum: Vibrating a membrane
Scraper: Stridulation
Thumb piano (kalimba): Vibrating a membrane
Whistle: Passing air over a vibrating membrane

Q8. Are there different ways of playing this instrument that might be more related to one of the other animal communication methods?
The scraper can also be struck with the mallet, making it more similar to striking a substrate.

Q9. Can you think of other instruments that produce sound in similar ways?
Striking a substrate: Tone blocks, solid drums
Vibrating a membrane: drums, stringed instruments (guitars, pianos, etc.)
Stridulation: A washboard, guiro
Passing air over a membrane: kazoos, woodwinds

Answers for Exercise 6a4. Animal Sound Production Quiz

1. Song Bird: Air Flow Vibrating a Membrane
2. Cicada: Muscles Vibrating a Membrane
3. Frog: Air Flow Vibrating a Membrane
4. Grasshopper: Stridulation
   It is physically difficult for a small animal to produce a loud sound with a wavelength much larger than the length of its body. For this reason small animals such as insects produce high frequency sounds of extremely small wavelength (i.e., thousands of waves/sec). Do you think that a muscle can twitch that fast? Nope! The file and scraper strategy takes care of the problem. For example, only a single muscle contraction is required to drag a leg over a comb, thereby hitting numerous teeth and producing a whole sequence of sound waves. This is referred to as frequency multiplication. You may confirm this analogy with applying a swipe of your thumb along the prong edge of your comb.

5. Humpback Whale: Air Flow Vibrating a Membrane
6. Jumping Spider: Striking a substrate
7. Noctuid Moth: Muscles Vibrating a Membrane
8. Woodpecker Male: Striking a substrate
9. Bat: Air Flow Vibrating a Membrane

Answers to Exercise 6a5. Identifying Frogs by Sound

1. True Frog - Pig Frog (*Rana grylio*)
2. Toad - Southern Toad (*Bufo terrestris*)
3. Tree Frog - Upland Chorus Frog (*Pseudacris feriarum*)
4. Tree Frog - Southern Chorus Frog (*Pseudacris nigrita*)
5. True Frog - Southern Leopard Frog (*Rana sphenocephala*)
6. Toad - Fowler's Toad (*Bufo fowleri*)
7. True Frog - American Bullfrog (*Rana catesbiana*)

8, Tree Frog - Brimley's Chorus Frog (*Pseudacris brimleyi*)
9. Toad - American Toad (*Bufo americanus*)
10. True Frog - Pickerel Frog (*Rana palustris*)
11. Tree Frog - Mountain Chorus Frog (*Pseudacris brachyphona*)

Answers for Exercise 6b1. Rank that Sound

SOUND PRESSURE(dB) RANK*	SOUND SOURCE	DECIBELS (dB)
10	CANNON FIRING	225
9	BALLOON POPPING	125
8	ROCK CONCERT	110
7	LAWN MOWER	90
6	VACUUM CLEANER.	75
5	NORMAL CONVERSATION	60
4	REFRIGERATOR	50
3	LIBRARY	40
2	WHISPER	20
1	BREATHING	10

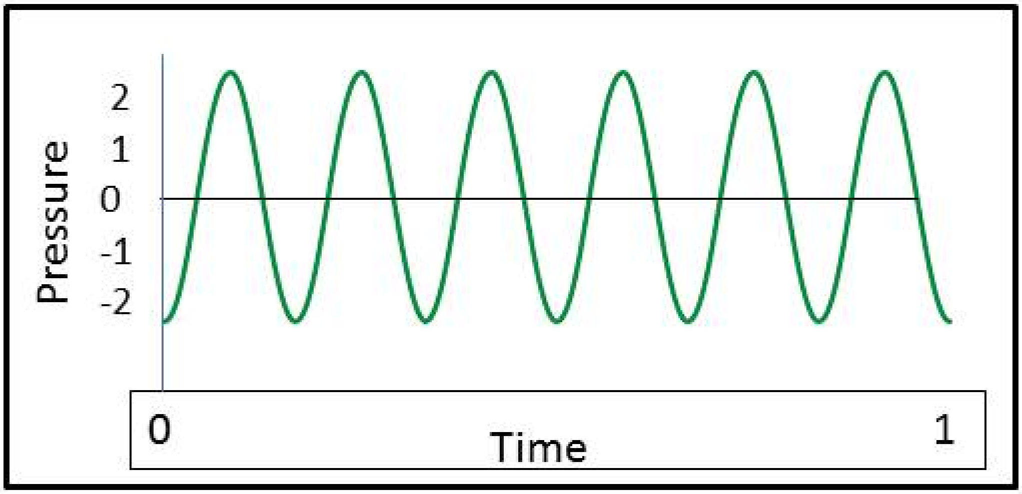
*****Assuming typical distance away from the respective sources.*

Q10. Why might it be advantageous for animals to communicate with each other at a frequency that other animals can't hear? Eavesdroppers might be predators seeking the location of potential prey. If they can't hear you, they are less likely to locate you. Secondly, if species communicate at different frequencies, cross-species mating errors will be avoided.

Q11. What are the frequencies of sound waves 1 and 2? Which one has the highest pitch?
Wave 1 has a frequency of 4, while wave 2 has a frequency of 2. Therefore, wave 1 has a higher pitch.

Q12. What are the amplitudes of sound waves 3 and 4? Which one is the loudest?
Wave 3 has an amplitude of 1, while wave 4 has an amplitude of 3.Therefore, wave 4 is louder.

Q13.Draw a wave of 1 unit in time with a period of .2 and an amplitude of 4.



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Answers for Exercise 6b2. Infrasound and Ultrasound

Q14. Which animals in the chart can hear infrasound frequencies?
Elephants and ferrets can hear infrasound frequencies.

Q15. Which animals in the chart can hear ultrasound frequencies?
Grasshoppers, noctuid moths, bats, beluga whales, cats, chinchillas, cows, dogs, ferrets, gerbils, guinea pigs, hedgehogs, mice, opossums, porpoises, rabbits, raccoons, rats, and sheep can hear ultrasound frequencies.

Q16. Are there any animals in the chart that can hear both infrasound and ultrasound frequencies?
Ferrets can hear both infrasound and ultrasound frequencies.

Q17. Which three mammals in the chart can hear the broadest range of frequencies? Why do you think this might be adaptive for those animals?
Porpoises, beluga whales, and bats are the three mammals in the chart with the greatest hearing range. Porpoises and beluga whales use ultrasound frequencies to communicate underwater in their marine habitats, as well as to navigate their surroundings, as well as to find prey. Bats, which are primarily nocturnal, also rely on echolocation via ultrasound in the same way. The broad range of hearing in these animals also helps them detect prey or predators that produce very high or very low frequency sounds before they are even able to pinpoint the predator or prey visually.

Q18. Which bird in the chart can hear the highest range of frequencies? Why might this be important to that particular type of bird?
Owls, which are nocturnal, have the greatest hearing range of the listed birds. This provides an advantage at finding prey in the dark, just as mentioned above with bats and whales.

Q19. Which insect in the chart can hear the highest range of frequencies? Why might this be important to that particular type of insect?
Noctuid moths are also nocturnal. Their greater hearing range is a possible adaptation to better help them avoid bat predators.

Q20. Why do you think it might be important for an organism to hear frequencies outside the range of the sounds that they are able to produce?
Hearing sounds outside the range of that produced by one's own species could still help locate prey and/or predators that may make sounds outside of that range.

Answers for Exercise 6b3. Understanding Decibels

Source of Sound		Intensity Level (dB)
1.	Elephant trumpeting	117 (9.18 times louder)
	Elephant rumbling	85
2.	Blue Whale	188
	Sperm Whale	236 (27.9 times louder)
3.	Howler Monkey	140 (22.6 times louder)
	Siamang Monkey	95
4.	Average domestic cat purring	25
	Big cat purring (e.g., cougar)	100 (181 times louder)
5.	Cow moo	85 (32 times louder)
	Horse neighing	38
6.	Hippopotamus	114 (1.26 times louder)
	Spotted hyena	112

Rank greatest difference in loudness to least difference in loudness:

1. Big cat purr versus domestic cat purr
2. Cow moo versus horse neighing
3. Sperm whale versus blue whale

4. Howler monkey versus Siamang Monkey
5. Elephant trumpeting versus rumbling
6. Hippopotamus versus Spotted Hyena

Q21. Which animals in the above chart make sounds that would cause a human ear pain? Blue and sperm whale and howler monkey

Q22. Water is much more dense than air, so it takes more work to propagate sounds under water. Generally, bioacoustics experts accept that sounds in water lose about 62 decibels when propagated through water. In order to see how loud the organisms really would be to you, recreate the table above, but subtract 62 decibels from all of the water-dwelling animals. Who is louder, the Howler monkey or the Blue whale? Howler monkey

Q23. The sound of a jet engine from 100 meters away is approximately 100 times louder than a power saw (110 dB).What then, is the intensity, in dB, of a jet engine's sound from 100 meters away?

$$I_A(dB) - 100(dB) = 10\ log_{10}(100)$$

$$I_A(dB) - 100(dB) = 10(2)$$

$$I_A(dB) - 100(dB) = 20$$

$$I_A(dB) = 20 + 100(dB)$$

$$I_A(dB) = 120\ (dB)$$

Q24.Bob went to a rock concert with his friends. The concert reached sound levels of an ear-blasting 120 dB. How many times louder was the concert than a normal conversation (approximately 60 dB) between Bob and one of his friends?

$$120(\mathrm{dB}) - 60(\mathrm{dB}) = 10\ \log_{10}\left(\frac{\mathrm{I_A}}{\mathrm{I_B}}\right)$$

$$60(\mathrm{dB}) = 10\ \log_{10}\left(\frac{\mathrm{I_A}}{\mathrm{I_B}}\right)$$

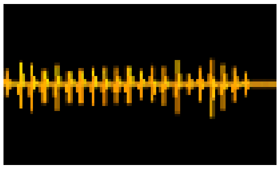
$$6(\mathbf{dB}) = \mathbf{log_{10}}\left(\frac{\mathbf{I_A}}{\mathbf{I_B}}\right)$$
$$\mathbf{10^6} = \left(\frac{\mathbf{I_A}}{\mathbf{I_B}}\right)$$

The concert was a million times louder than a normal conversation with his friends!

Answers for Exercise 6c. Seeing Sound

Comparison	Describe the Difference in the Sonograms
Short vs. Long Sounds (Ex 1&2)	
High vs. Low Pitch (Ex 3&4)	
Quiet vs. Loud Sounds (Ex 5&6)	
Simple vs. Clarinet (Complex) Sounds (Ex 7&8)	
French Horn vs. Violin (Ex 9&10)	
Toad vs. Tree Frog (Ex 11&12)	

Q25. What does a sonogram of a pencil tapping on a wood desk top look like.



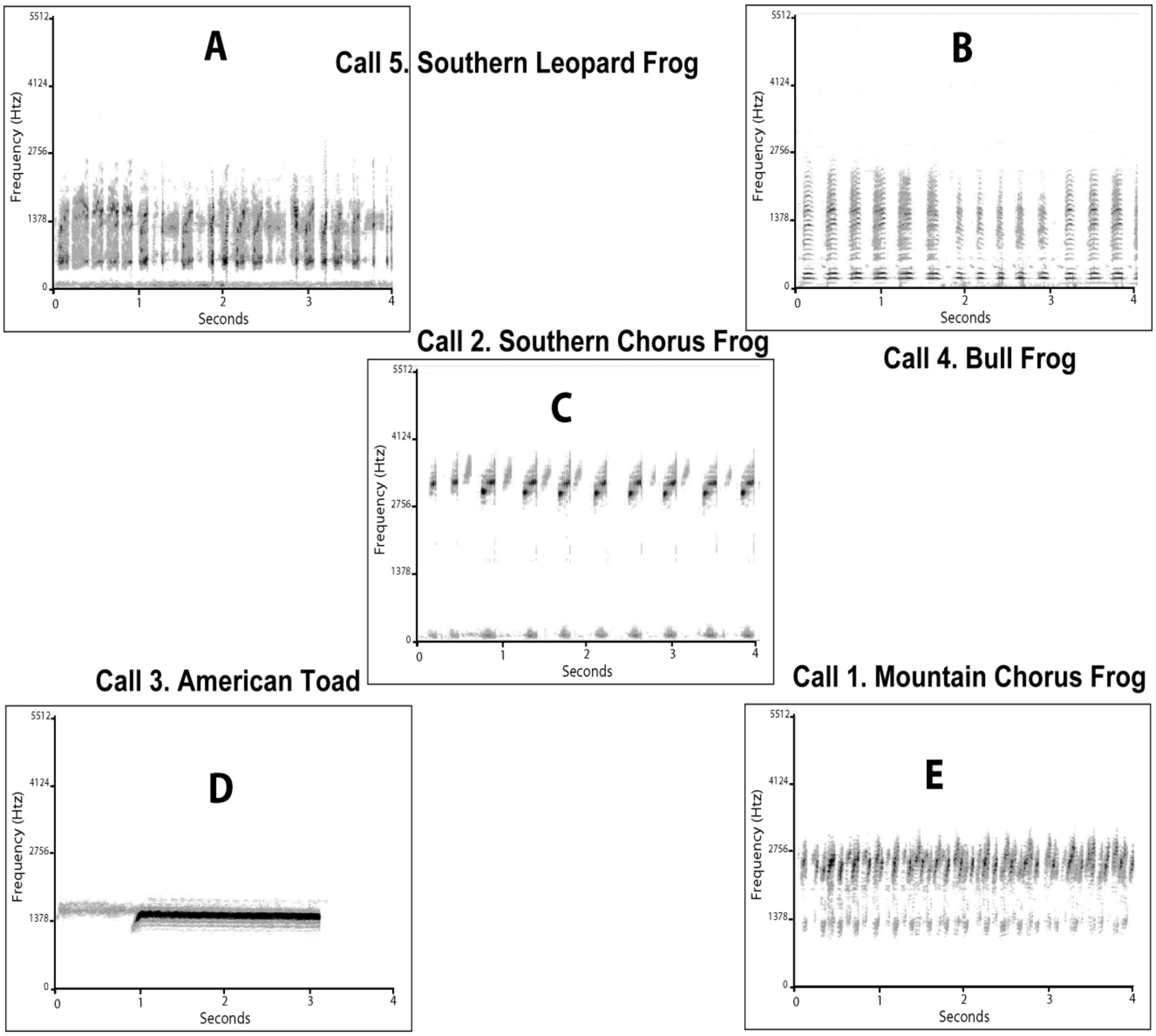
SOUND IDEAS:

Does man-made noise (air planes, traffic) have an effect on sound attenuation?

What modifications could be made to overcomes various types of interference?

http://www.philtulga.com/MSSActivities.html

Answers to Exercise 6c1. Matching Frog Calls to Sonograms



Answers for Exercise 6d. Communicating at a Distance

Q26. What is the general shape of each of your plots of the sound attenuation of each instrument? Are they all similar? Why do you think this may or may not be the case?

You should have noticed that each curve appears to show exponential decay. This is because even though the sounds are different, they are all similar in that they are waves moving through a medium (air), and thus behave similarly.

Q27. Do some of the instruments seem to show stronger attenuation than others? In other words, are there differences in how quickly the intensity of their sounds decreases with increasing distance from the instrument?
Answers will vary based on student results.

Q28. What sort of trends do you notice? Is there a general relationship between the frequency of a sound, and how quickly it is attenuated?
Higher pitched sounds attenuate more quickly (carry a shorter distance).

Q29. Based only on comparisons of the pure tone attenuation graph and the musical instrument attenuation graph, can you make a statement about the relative frequencies of the sounds produced by the various musical instruments?
Answers will vary based on student results.

Q30. Did your rankings based on the instruments' sounds match up to the relationships of their frequencies that you predicted in the previous question?
Answers will vary based on student results.

Q31. What are some other possible characteristics of each of the sounds, other than pitch (frequency) that may have affected how they were attenuated?
Using the instruments may not always happen in a uniform way. For example, an instrument may have been played louder or softer in one trial versus another. Though not a characteristic of the sounds themselves, the location at which each reading was taken could have affected the results, because of possible differences in absorption/reflection of sound waves by surrounding objects.

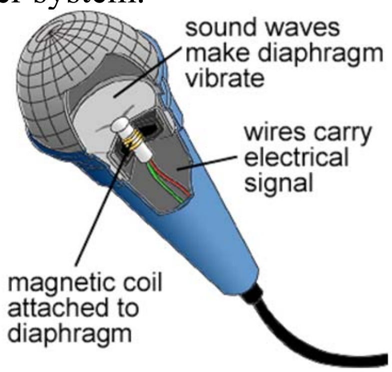
Q32. Knowing what you know now, what is a general statement you can make about the possible distance ranges of communication of animals that communicate at different frequencies?
Animals that communicate primarily with high frequencies typically communicate at shorter distances than those that communicate at lower frequencies. However, localization of sound is also important. Localization of higher frequency sounds is easier than with lower frequency sounds. Therefore, animals that communicate at higher frequencies may face a greater risk of being discovered by predators. Therefore, in addition to communication distance, predator density (as well as habitat characteristics) is also a likely factor in which frequency range an organism communicates, with there being a tradeoff between maximum communication distance and detection by predators (or prey), as well as decreased locatabilty of

organisms using primarily low frequency sounds (which may make it to find be found by potential mates).

Q33. Can you think of any possible factors that might change the relationship between the frequency of a sound and how it is attenuated?
Environmental conditions, surroundings, etc. can also play major roles in how sound is attenuated within a particular habitat.

Answers for Exercise 6e. Crank it Up!

Q34. How does a microphone work?
A pressure wave is produced by the vocal chords of the person using the microphone. That pressure wave travels through the air. The variations in pressure produce a varying force on a diaphragm of the microphone, making it vibrate, A magnetic coil is attached to the diaphragm and wires carry the electric signal to a speaker system.



SUGGESTED READING:

Exercise 1. Introduction to Biomimetics

Azad, M.A.K., D. Ellerbrok, W. Barthlott, and K. Koch. 2015. Fog collecting biomimetic surfaces: Influence of microstructure and wettability. *Bioinspiration and Biomimetics* 10(1).

Benyus, J.N. 1997. Biomimicry: Innovation Inspired by Nature. William Morrow.

Tong, J., W. Ji, H. Jia, D. Chen, and X. Yang. 2015. Design and Tests of Biomimetic Blades for Soil-rototilling and Stubble-breaking. *Journal of Bionic Engineering* 12(3): 495–503.

Sitti, M. and R.S. Fearing. 2003. Synthetic gecko foot-hair micro/nano-structures as dry adhesives. *Journal of Adhesion Science and Technology* 17: 1055–1073.

Wang, Q., J. Hon, and Y. Yan. 2014. Biomimetic Capillary Inspired Heat Pipe Wicks. *Journal of Bionic Engineering* 11(3): 469–480.

Winter, V.A.G., R.L.H. Deits, D.S. Dorsch, A.H. Slocum, and A.E. Hosoi. 2014. Razor clam to RoboClam: burrowing drag reduction mechanisms and their robotic adaptation. *Bioinspiration and Biomimetics* 9(3): 1–11.

Exercise 2. From Skeletons to Bridges

Kirtley, D.W., and W.F. Tanner. 1968. Sabellariid worms: builders of a major reef type. *Journal of Sedimentary Research*, 38(1): 73–78.

Meier, U. 1992. Carbon fiber-reinforced polymers: modern materials in bridge engineering. *Structural Engineering International*, 2(1): 7–12.

Phillips, A.T.M. 2012. Structural optimisation: biomechanics of the femur. In: Proceedings of the ICE. Engineering and Computational Mechanics, vol. 165.

Tonias, D. E. (1994). BRIDGE ENGINEERING. DESIGN, REHABILITATION, AND MAINTENANCE OF MODERN HIGHWAY BRIDGES.

Zioupos, P. and J. D. Currey (1998). "Changes in the Stiffness, Strength, and Toughness of Human Cortical Bone With Age." Bone 22(1): 57-66.

<u>Exercise 5: Similar Things to Wings: Drag</u>

Augspurger, C. K., and Franson, S. E. (1987). Wind dispersal of artificial fruits varying in mass, area, and morphology. *Ecology*, 27-42.

Benkman, Craig W. "Wind dispersal capacity of pine seeds and the evolution of different seed dispersal modes in pines." *Oikos* (1995): 221-224.

Ford, R. H., Sharik, T. L., and Feret, P. P. (1983). Seed dispersal of the endangered Virginia round-leaf birch (*Betulauber*). *Forest Ecology and Management*, *6*(2), 115-128.

Green, D. S. (1980).The terminal velocity and dispersal of spinning samaras. *American Journal of Botany*, 1218-1224.

Greene, D.F., and Johnson, E.A. (1992). Can the variation in samara mass and terminal velocity on an individual plant affect the distribution of dispersal distances?.*American Naturalist*, 825-838.

Greene, D.F., and Johnson, E.A. (1992).Fruit abscission in *Acer saccharinum* with reference to seed dispersal.*Canadian Journal of Botany*, *70*(11), 2277-2283.

Guries, R.P., and Nordheim, E.V. (1984). Notes: Flight Characteristics and Dispersal Potential of Maple Samaras. *Forest Science*, *30*(2), 434-440.

Jackson, S.M. (2000). Glide angle in the genus *Petaurus* and a review of gliding in mammals. *Mammal Review*, *30*(1),: 9-30.

Minorsky, P.V., and Willing, R.P. (1999). Samara Dispersal in Boxelder: An Exercise in Hypothesis Testing. *The American Biology Teacher*. 56-59.

LINKS:

Exercise 1: Borrowing Designs from Nature

Biomimetic Robotics Lab at MIT. Various robotic projects borrowing design ideas from nature are showcased.
http://biomimetics.mit.edu/

Biomimetic Millisystems Lab at Berkeley. The lab's current research is centered on all-terrain crawling using nanostructured adhesives and bioinspired flight.
https://robotics.eecs.berkeley.edu/~ronf/Biomimetics.html

Design by Nature on National Geographic. Examples of biomimetics are shown.
http://ngm.nationalgeographic.com/2008/04/biomimetics/clark-photography

Exercise 2: From Skeletons to Bridges

Famous Bridges lesson plan on Discovery Education website: Objectives are to understand the benefits and drawbacks of different types of bridges, and to think about the challenges involved in building bridges.
http://www.discoveryeducation.com/teachers/free-lesson-plans/famous-bridges.cfm

Five Animals that are Awesome Architects on National Geographic: Weird and Wild. Structures built by animals are described.
http://voices.nationalgeographic.com/2014/01/27/5-animals-that-are-awesome-architects/

Bone Structure and Function Curriculum from ASBMR. This page discusses various functions, properties and structures of bone.
https://depts.washington.edu/bonebio/ASBMRed/structure.html

Exercise 3: Jaws are Levers

Basic Biomechanical Factors and Concepts summarized by R.T. Floyd from the Manual of Structural Kinesiology.
http://www.kean.edu/~jeadams/docs/Kinesiology/Kines_Power_Points/Kines_PPT_PDF_Chap3.pdf

Basic Biomechanics descriptions of levers and related concepts by Aaron Swanson.
http://www.aaronswansonpt.com/basic-biomechanics-levers/

Interactive presentation on Biomechanics: Torques, Levers and More, by Mary Owen.
https://prezi.com/swpxzoyjm5eb/biomechanics-torque-levers-and-more/

Exercise 4: Drop, Squirt, Throw: Projectile Motion

Projectile Motion -- Real-life Applications, on Science Clarified.
http://www.scienceclarified.com/everyday/Real-Life-Chemistry-Vol-3-Physics-Vol-1/Projectile-Motion-Real-life-applications.html

Interactive Projectile Motion game, on PhET/University of Colorado at Boulder.
https://phet.colorado.edu/en/simulation/projectile-motion

http://physicsbuzz.physicscentral.com/2012/09/applying-physics-education-to-biology.html

Exercise 5: Similar Things to Wings: Drag

FoilSim software download at NASA. FoilSim is interactive simulation software that determines the airflow around various shapes of airfoils.
https://www.grc.nasa.gov/www/k-12/FoilSim/index.html

Exercise 6: Bioacoustics

Raven Lite is a free software program that lets users record, save, and visualize sounds as spectrograms and waveforms. Raven Lite is intended for students, educators, and hobbyists, and can be used for learning about sounds, as an aid in birdsong recognition, and in musical instruction.
http://www.birds.cornell.edu/brp/raven/RavenOverview.html