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| **Nature’s Flying Machines** |  |

*The original version of this laboratory module was developed by Blake Cahill as part of the BIO 620: Curriculum Design for the 21st Century Biology Classroom and the Biodiversity Literacy in Undergraduate Education: BLUE Network (National Science Foundation DBI 1730526). References and websites used in part or whole for the laboratory development are cited within the module.*

## Objectives

Students completing this module will be able to:

* Explain the forces acting on flight.
* Describe how lift is created by wings.
* Compare how antagonistic muscles (flexors, extensors) power flight in animals with endoskeletons and exoskeletons.
* Discuss how wing morphology (form) relates to flight ability (function).
* Evaluate the impact of body mass and wing morphology on bird migration distance.

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| “The construction of an airplane is simple compared with the evolutionary achievement of a bird. If I had to choose, I would rather have birds than airplanes.”  - Charles Lindbergh, American aviator  “I’m obsessed with insects, particularly with insect flight. I think the evolution of insect flight is perhaps one of the most important events in the history of life. Without insects, there’d be no flowering plants. Without flowering plants, there would be no clever, fruit-eating primates giving TED talks.”  - Michael Dickinson, American neuroscientist |

## Introduction

Movement is a key function required for the survival and reproduction of organisms. Microorganisms, such as bacteria and unicellular protists, achieve movement via cellular structures such as cilia and flagellae. Plants and fungi are incapable of individual locomotion but can disperse their offspring via seeds and spores and can grow towards or away from environmental stimuli. Animals have evolved a multitude of methods for movement in terrestrial, aquatic, and aerial environments. One of the most successful types of animal locomotion is **flight**. Flight has evolved at least four separate times, in the insects, pterosaurs, birds, and bats. In today’s lab, you will investigate the forces involved in the form and function of flight in birds and insects.

All actively flying objects, from commercial airliners to Canada geese (*Branta canadensis*), are acted on by forces that impact their flight. These forces are vector quantities, meaning they have both **magnitude** and **direction**. The four forces that impact an object in flight are:

* + - * 1. **Drag** is a resistance force, friction, generated by an object moving through liquid or gas. For flight, we are talking about air. Drag always acts in a direction opposite to the motion of the object. Shape, size, and speed of a moving object and the mass and velocity of the air all impact the magnitude of drag. Drag increases with an increase in air density, surface area of the animal exposed to the air, or animal or air speed. To reduce drag many flying animals have streamlined bodies.
        2. **Thrust** is a force that propels an object in the direction of motion. Thrust is only produced by animals capable of powered flight; primarily by the downstroke of the wingbeat. To produce enough thrust to counteract the opposing forces of **drag,** flying animals typically have powerful flight muscles.
        3. **Weight** is the force exerted on an object due to gravity. On earth, weight’s force is always directed downward towards earth’s center. Its magnitude depends on the mass of the flying object; greater mass equals greater weight.
        4. **Lift** is the force that pushes up on a flying object, opposing the object’s **weight**. The force of lift acts at a 90-degree angle to the direction of motion through the air. Wings produce lift by altering the flow of air over their surfaces. Air is deflected downward from the lower surface of the wing. This downward deflection of air creates an upward force of lift. Several factors influence the amount of lift a wing creates, including the object’s weight, shape, velocity, angle at which it meets the airstream (angle of attack), and the density of the air. To maintain steady flight, the amount of lift must be equal to the object’s weight.



Flight abilities can be grouped into two broad categories, **powered** and **unpowered**. In powered flight, thrust is generated by flapping of wings. In unpowered flight, air currents and thermals are used to glide and soar through the air without any additional power sources. Many flying animals, from birds to bats to butterflies, alternate between bouts of powered and unpowered flight. This flying style, where bouts of flapping are interspersed with gliding, is called **intermittent flight**. Intermittent flight strategies reduce energy consumption and can be beneficial for animals that migrate long distances.

Flying animals have a diversity of body forms and aerial abilities. They can teach us a lot about form and function. In fact, scientists study animal flight to develop flying robots, airplanes, and rocket ships. In this lab, you will explore the physics of flight, the adaptations that make powered flight possible, and the evolution of powered flight in vertebrates and invertebrates.

**Activity 1: Angle of Attack**

The angle of the wing, or **angle of attack,** is the angle between the chord line of a wing and the direction of flight (Figure 1) and can have an effect on the amount of lift created by a wing. As the angle of attack increases, more air is deflected downward by the lower surface of the wing, creating more lift. However, if the angle of attack is too great then the airstream above the wing begins to flow less smoothly and separates from the upper surface of the wing creating drag and reducing the amount of lift created. Have you ever held your hand out the window of a moving car, or in front of a strong fan? How does changing the angle of your hand affect the lift force thatyou feel (imagine your hand is a wing)?



Figure 1. Wing angle of attack.

In this activity, you will work with your team to determine how angle of attack impacts the lift generated by artificial butterfly wings. Below are four species that have been studied by Harvard scientists studying the mechanics of butterfly flight.

**[Citation:** <https://www.sciencebuddies.org/science-fair-projects/project-ideas/Aero_p049/aerodynamics-hydrodynamics/butterfly-wings-using-nature-to-learn-about-flight>**]**

You and a partner will select one of the four butterfly species below. Circle the species you select.

1. Monarch (*Danaus plexippus*)
2. Glasswing (*Acraea andromacha*)
3. Four-barred swordtail(*Protographium leosthenes*)
4. Orange aeroplane (*Pantoporia consimilis*)

*Procedure:*

*Building your paper butterfly*

1. Cut out the outline of your butterfly.
2. Fold the butterfly in half along the middle dashed line.
3. Fold the wings down along the other two dashed lines, in the opposite direction of your first fold.
4. Unfold the wings. The middle part of the butterfly should now form a "V" shape, which you will use to clip on to the test stands later.
5. Tape a craft stick onto the back of your butterfly. This will prevent the wings from folding back when you test it in your wind tunnel.

*Conducting the experiment*

1. Clip your butterfly onto your 0° support structure using two binder clips.
2. Place your scale and your fan approximately 1 m away from each other on a hard, flat surface.
3. Place your support structure, with a butterfly clipped on, on top of the scale with the butterfly facing toward the fan.
4. Use washers to weigh down the bottom of the support structure.
5. Press the "tare" button on the scale. This makes the scale re-zero so it does not include the weight of the support structure in its measurement.
   * *Important*: Starting with this step, be as careful as you can not to move the scale. Moving the scale to an area where air is flowing at a different speed will affect your results.
6. Turn on the fan. Set it at the lowest speed.
7. Observe the value on the digital scale's display for 15 seconds. Record the maximum lift coefficient (most negative value) observed during the 15 seconds on the data table below.
8. Turn off the fan and wait for it to come to a complete stop. If the scale's value has drifted away from zero, press the "tare" button again.
9. Repeat steps 6–8 two more times, for a total of three trials.
10. Repeat steps 3–9 four more times for 20°, 40°, 60°, 80°, and 100° angles of attack.
11. Answer the associated questions on the assessment pages.

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| Angle of Attack | Trial 1 | Trial 2 | Trial 3 | Average |
| 0° |  |  |  |  |
| 20° |  |  |  |  |
| 40° |  |  |  |  |
| 60° |  |  |  |  |
| 80° |  |  |  |  |

**Activity 2A: Powering Avian Flight**

Muscles can only exert force by contracting. They do not forcibly extend. Therefore, antagonistic muscle pairs are necessary to move body parts in opposite directions. Antagonistic muscle pairs are composed of two opposing muscles: **flexors** (bends a joint…think flex) and **extensors** (extends or straightens a joint). As one muscle contracts, the other relaxes and is re-extended via the skeleton.

Most animals that have an **endoskeleton** move using contraction of antagonistic muscles attached to the outside of their skeleton. In vertebrates with endoskeletons, flexors pull bones closer together, decreasing the joint angle between them. Extensors have the opposite function; their contraction increases the joint angle between two bones. Antagonistic muscles in animals with **exoskeletons** work in a similar fashion; however, their muscles are attached to the inside of their jointed skeleton.

The antagonistic pair of muscles primarily responsible for powering bird flight are the **pectoralis** and **supracoracoideus**. These are large powerful muscles that can make up as much as 1/3 of a bird’s total body mass. Both muscles originate from an extension of the sternum, called a keel, and attach to the humerus of the wing (Figure 2).

The pectoralis is the largest of the flight muscles and makes up the “breast” of a bird (Figure 2). Contraction of the pectoralis muscles pulls the humerus in each wing down, depressing the wings. This movement is the downstroke of the wing beat and generates lift and thrust. In addition to powering flight, the pectoralis muscles are also used during takeoff, level flight, and landing.

The upstroke of the wing beat is powered by the contraction of the supracoracoideus. It lies beneath and is typically smaller than the pectoralis. You’re likely familiar with the supracoracoideus muscles of domestic fowl, as they are popularly sold as “tenders” in grocery stores. The tendon of the supracoracoidues passes through the triosseal canal and inserts dorsally on the humerus of the wing (Figure 2). As the supracoracoideus contracts, it pulls its tendon and raises the wing, despite its position below the wing. This unique muscle and tendon attached is referred to as a “rope and pulley” system and it is crucial to bird flight. Without the supracoracoideus and its tendon, a muscle above the shoulder would be required to raise the wing.

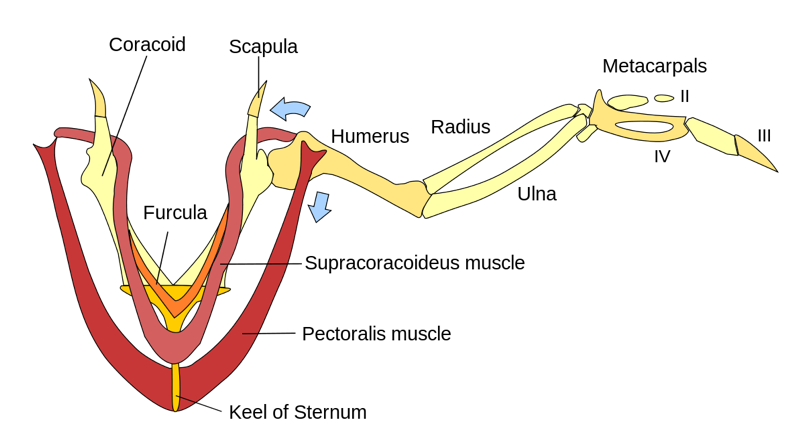
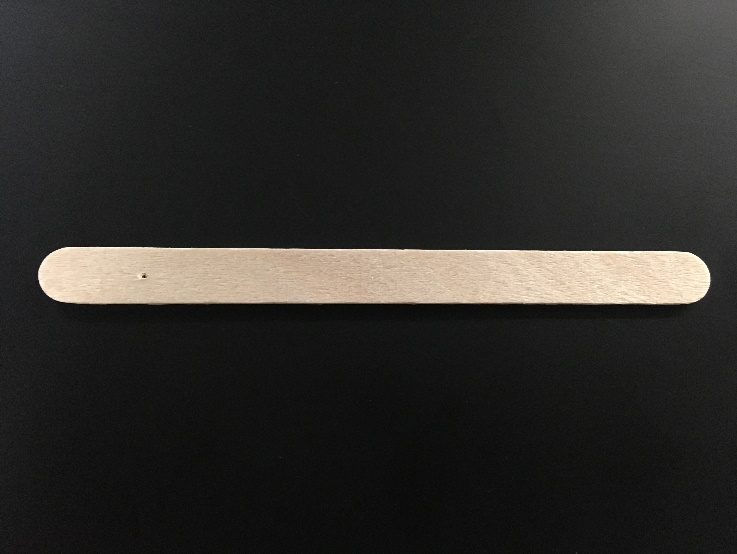


Figure 2. Avian wing muscle and skeletal anatomy

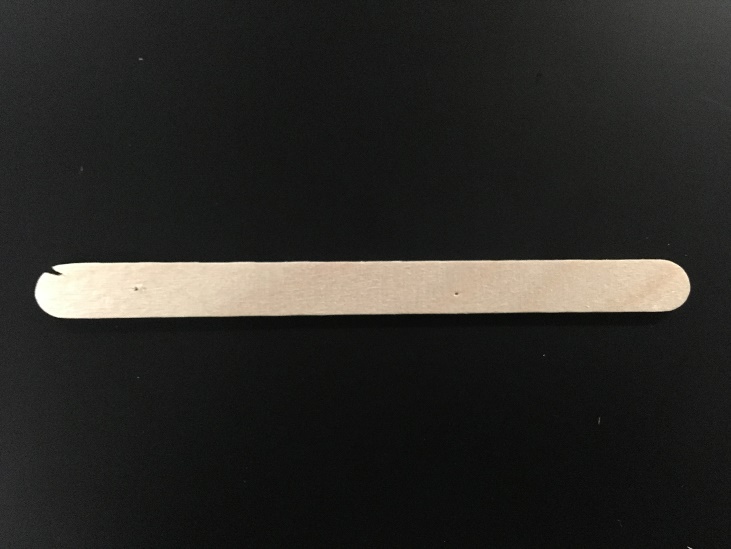
In this activity, you will model the antagonistic muscle pair responsible for powering the upstrokes and downstrokes of powered (flapping) flight. Follow the instructions below to build a model that demonstrates the form and function of the pectoralis and supracoracoideus.

*Procedure:*

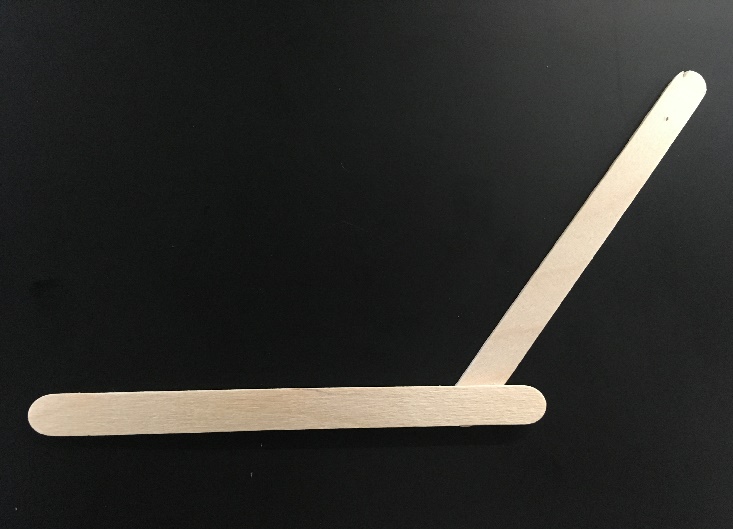
Using a thumbtack, puncture a hole through a craft stick (hereafter craft stick 1) 2 cm from the tip.



Using a razor blade, carefully carve a notch into the rounded edge of craft stick 1 on the same end that you made the hole.



Glue the unaltered tip of craft stick 1 to another craft stick. See the image below for the correct positioning of the craft sticks. Make sure the orientation of the notch on craft stick 1 matches the image below. This is important for proper functioning of the model.

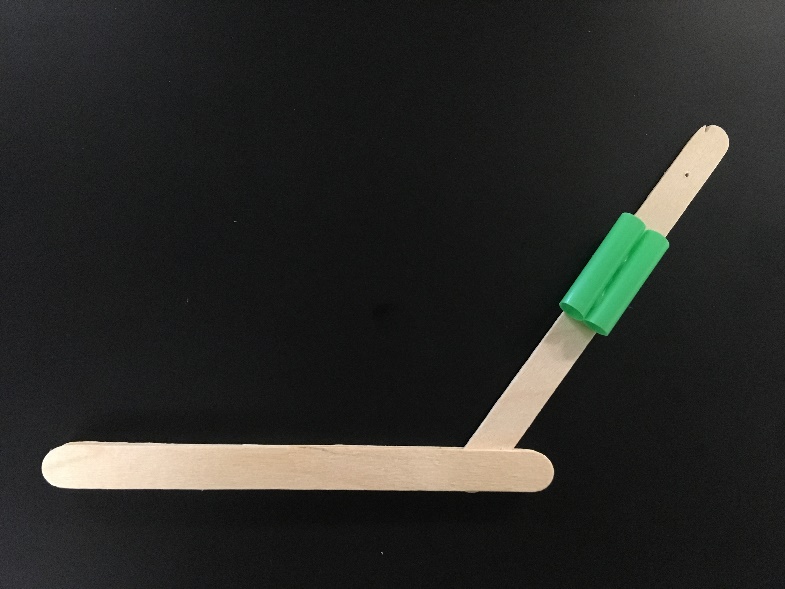


notch

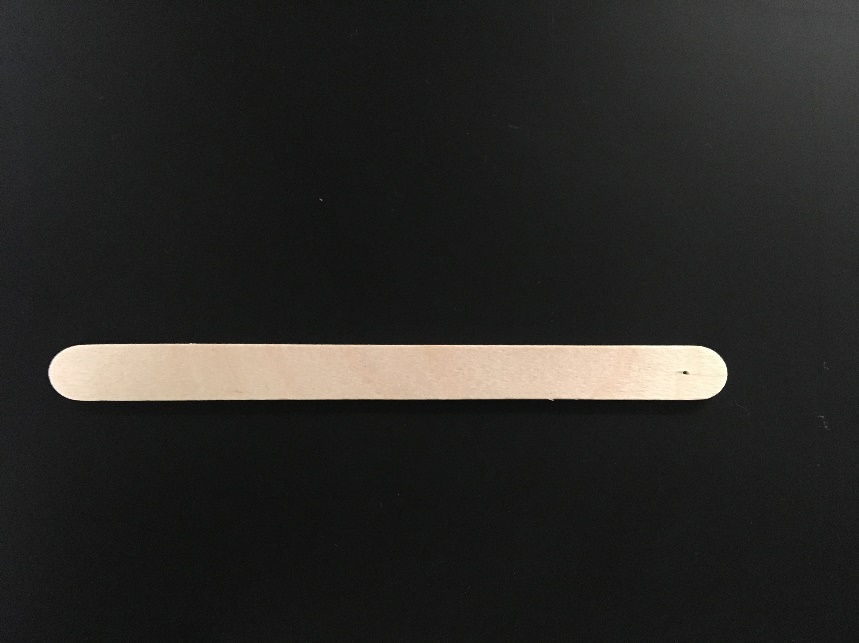
Once the glue has dried, flip the piece made in step 3 over. Glue a craft stick onto the tip of craft stick 1, matching the placement of the craft stick glued in step 3. Then break a craft stick in half and glue it between the two craft sticks that are glued to craft stick 1. From above, this will look like the picture below.



Cut a straw into two 2.5 cm pieces. Glue these pieces together. Then glue the two pieces onto craft stick 1, 2 cm from the hole you made in step 1. Set this part of the model aside for now.



Using a thumbtack, puncture a hole in a craft stick (hereafter craft stick 2) 0.5 cm from the tip.



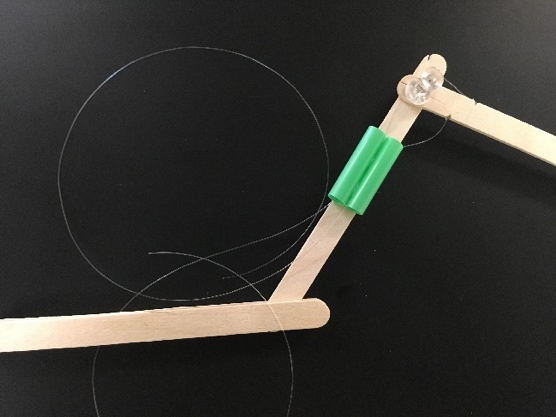
On the same end that you punctured the hole, take a razorblade and carefully carve two notches into the edges of craft stick (2). Make the first notch 2 cm from the tip. Make the second notch 2.5 cm from the tip, on the opposite side that you made the first notch.



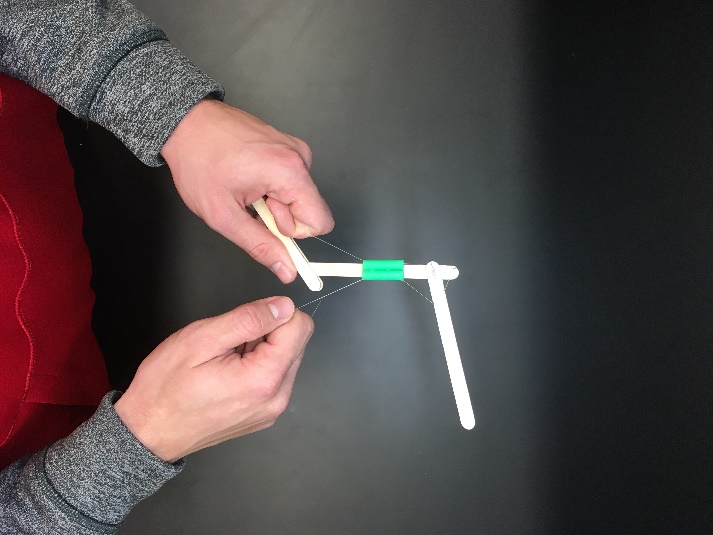
Cut two strings of fishing line that are at least 30 cm long. Tie one string of fishing line around each of the notches, making sure the knots rest within the notches.



Attach craft stick 1 to craft stick 2 by inserting a thumbtack into the holes punctured in step 1 and 6. Feed the fishing line tied to the notch on the bottom of craft stick 2 into the 2nd straw. Feed the fishing line that is tied to the notch on the top of the craft side 2 into the notch on the tip of craft stick 1 and then downward into the 1st straw. To prevent the fishing line from falling out, a tiny dab of glue can be used to enclose the notch on the tip of craft stick 1.



To operate the model, hold its base and alternate between pulling each string of fishing line. See the image below for the correct hand placement.

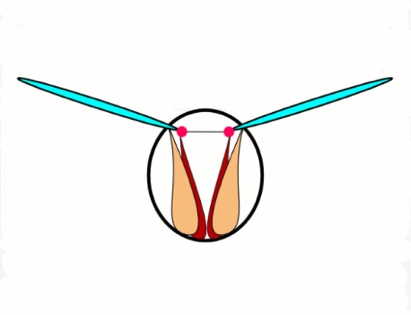
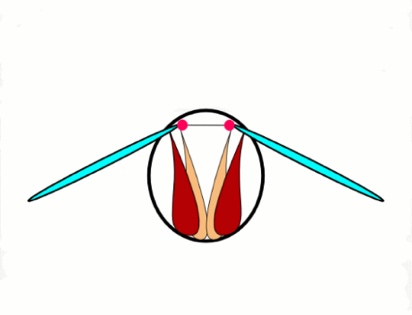


Using your model as a reference, answer the associated questions on the assessment pages.

**Activity 2B: Powering Insect Flight**

The antagonistic muscles that power insect flight are located in the thorax and can constitute as much as 30% of an insect’s total body mass. There are two types of flight mechanisms that insects can use to fly, **direct** and **indirect**. These two mechanisms differ based on how their muscles transmit force to the wings.

Insects that fly via the **direct flight mechanism** have at least one flight muscle that inserts directly to the base of the wing. This mechanism is found in the more ancestral insect groups, such as the Ephemeroptera (mayflies) and the Odonata (dragonflies and damselflies). In the direct flight mechanism, the downstroke of the wing beat is powered by the contraction of basilar muscles (Figure 3). These muscles originate from the thoracic wall and connect, through ligaments, to the base of the wing.

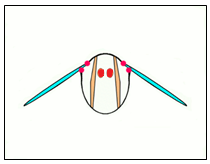
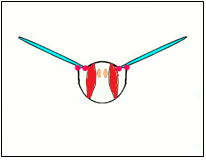


Contracting muscle

Relaxed muscle

Figure 3. Insect direct flight mechanism.

The majority of flying insect species, such as the house fly (*Musca domestica*), use the **indirect flight mechanism**; where force from antagonistic muscle contraction is transmitted indirectly to the wings. In this mechanism the contraction of antagonistic muscles cause the thorax to deform, which, in turn causes the wings to move (Figure 4).



Contracting muscle

Relaxed muscle

Figure 4. Insect indirect flight mechanism.

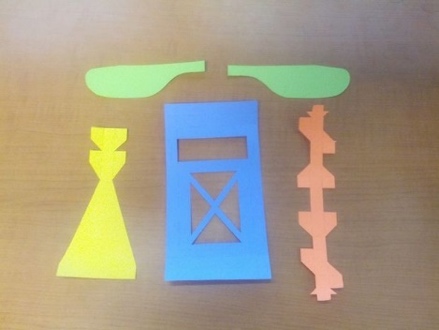
In this activity you and your partner will construct a paper model of a bee’s anatomy to demonstrate its flight mechanics.

***Citation:*** *The instructions and images for the paper RoboBee model were created by Ben Fino ([CC BY-NC-SA 2.5]) and adapted for this lab activity.* <https://www.instructables.com/id/Build-a-Paper-Robobee-Model/>

*Procedure:*

*Cut out the parts*

1. Cut out each part along the solid lines.



*Assemble the airframe*

1. Fold each long edge up 90° along the perforated line.
2. Fold in the square tabs at all four corners, then fold up the front and back walls.
3. Apply glue inside the tabs and then pinch in place until the glue dries. Paper clips can also be used to hold the tabs in place while the glue dries.

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*Fold the transmission*

1. Start out with the transmission lying flat. It has multiple perforated fold lines. Crease each of these lines in both directions, then lay the transmission flat again. This will ensure that the moving joints can move freely in both directions later.
2. Fold the first joint up 90°, as shown in the second picture below.
3. There are two tabs sticking out next to the joint you just folded up. Fold those in and apply glue, as shown in the third picture below.
4. Fold two joints down 90° as shown in the fourth picture below.
5. There should be two tabs sticking out to the sides next to the joints you just folded down. Fold these tabs in and apply glue as shown in the fifth picture below.
6. Repeat steps 1-5 for the other half the transmission.

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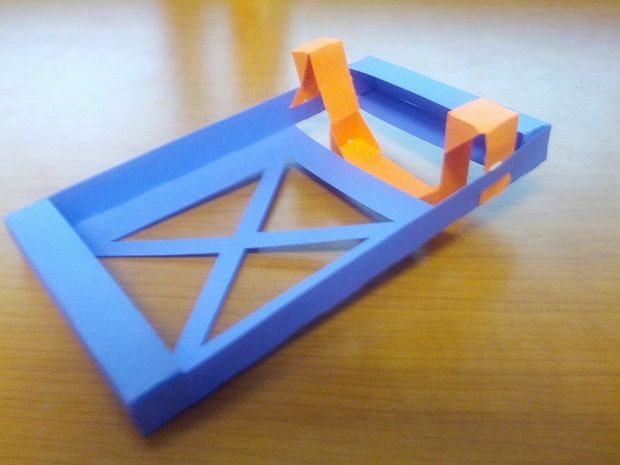
*Fold the actuator*

1. Start with the actuator flat, crease all the joints in both directions, then lay the actuator flat again.
2. Fold two joints up 90° as shown in the second picture below.
3. Fold in the tabs and apply glue to fix the 90° joints in place. The tabs work the same way as the ones in the transmission, so refer back to those pictures if you need help.

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*Mount the transmission to the airframe*

1. The airframe has slots in it for mounting the transmission. Slide the tabs at the end of the transmission into these slots, then apply glue as pictured below.



*Mount the actuator*

1. Lower the actuator into place from above the airframe. The base of the actuator (the wide part) fits onto the flat surface on top of the airframe. The tip of the actuator (the skinny part) should line up with the middle link of the transmission. Apply glue to both surfaces and let dry.

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*Attach the Wings*

1. The tabs at the base of the wings should fit onto the two flat surfaces facing up on the left and right sides of the transmission. Use glue to attach these two tabs, and make sure your wings are facing in the right direction (as pictured below).

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1. To flap the wings, push and pull back and forth on the tip of the actuator.
2. Using your model for reference, answer the associated questions on the assessment pages.

**Activity 3A: Form and Function Constraints on Avian Flight [Paper Modelling]**

Wing morphology, particularly shape and size, impact flight speed, maneuverability, and energy consumption. The shape and size of wings are adapted to suit the various modes of flight (e.g., flapping, soaring, hovering) and are often associated with certain habitats. Two morphological parameters of wing shape and size that have a substantial effect on flight ability are:

* + - * 1. **Wing loading** - the ratio of body mass to wing area. It represents the amount of mass that must be supported by each unit area of wing during flight. An animal that has a large body size and small wings relative to its body size has high wing loading and will need more power to sustain flight. For example, Common Loons (*Gavia immer*) have high wing loading and must run across the water while flapping their wings to generate enough lift for takeoff. Likewise, birds with smaller body mass relative to large wings, such as tree swallows (*Tachycineta bicolor*), have low wing loading and are often considered to be among the best avian flyers.

**Wing loading** = body mass/wing area

* + - * 1. **Aspect ratio** - the square of the length of a wing relative to its area. As aspect ratio increases so does wings’ lift-to-drag ratio. Longer, more narrow wings have higher aspect ratio. Birds that spend extended periods of time soaring typically have high aspect ratio wings, like the Wandering Albatross (*Diomedea exulans*) that can fly 500-600 miles in a day without flapping its wings. Birds that require more maneuverability in flight typically have lower aspect ratio wings.

**Aspect ratio** = wing span2/wing area

*Procedure*

1. On your web browser, search [www.foldnfly.com](http://www.foldnfly.com). Here you will see a variety of paper airplane designs.
2. Given what you have learned about wing morphology, choose a paper airplane design to compete in a contest of longest time aloft.
3. Build your airplane.
4. When you have completed your paper airplane folding, test its flight time.
5. Submit your time to your laboratory instructor for the class competition.
6. Answer the associated questions on the assessment pages.

**Activity 3B: Form and Function Constraints on Avian Flight [Data Modelling]**

**Migration**

Every year billions of birds fly thousands of miles to migrate to areas with more favorable conditions. The migration is typically along a north and south gradient, from breeding grounds to overwintering grounds. Bird migration is often in response to the seasonal availability of resources (e.g., food, nesting locations). Although many bird species migrate (over half of the species in North America), there is great variation in migration distance between species. For example, the Osprey (*Pandion haliaetus*) breeds in northern North America and migrates up to 8500 km to its over-wintering grounds in Central and South America while the Bald Eagle (*Haliaeetus leucocephalus*) can migrate up to 2300 km from its breeding and overwintering grounds within North America. The constraints related to the form and function of flight have an influence on variation in migration distance between bird species.

Wing loading and aspect ratio influence the energetic costs of flight. These costs act as a selection pressure on body mass and wing morphology relative to the flight style and migration distance of different species. Watanabe (2016) compiled data from published literature on migration distance, body mass, and wing morphology for flapping and soaring bird species. We will be using these data to investigate the relationship between these variables.

**Citation:** Watanabe YY. 2016. Flight mode affects allometry of migration range in birds. *Ecology Letters* 19, 907-914.

*Procedure*

* + 1. Obtain the data file Watanabe Data.xls
    2. Using the data provided, calculate the aspect ratio and wing loading for each species.
    3. Create a scatterplot with trendline of the relationship between aspect ratio and migration distance for flapping birds. Repeat for soaring birds. Answer the associated questions on assessment pages.
    4. Create a scatterplot with trendline of the relationship between wing loading and migration distance for flapping birds. Repeat for soaring birds. Answer the associated questions on assessment pages.

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| **Nature’s Flying Machines**  **Assessment** |

**Activity 1: Angle of Attack**

1. Graph the results of your angle of attack experiment below. Put angle of attack on the x-axis and lift on the y-axis**.**

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1. The angle of attack that generates the most lift is called the **critical angle of attack**. What happened once the critical angle of attack was surpassed for the butterfly wings?
2. Which of the other three forces changes as angle of attack changes? What effect does this force have on flight?

**Activity 2A: Powering Avian Flight**

1. With reference to your model, explain how two antagonistic muscles that are both primarily beneath the wing are responsible for powered movement of the wing both up and down.

**Activity 2B: Powering Insect Flight**

1. Explain the difference between direct and indirect flight mechanisms. Describe how your model represents an indirect flight mechanism.

**Activity 3A: Form and Function of Flight [Paper Modeling]**

1. Which airplane design won for the class? Why do you suppose this is? Explain you answer in terms of aspect ratio and wing loading.
2. Which plane would require less energy to fly the same distance? Explain your answer.

50,000 kg

2 m

6m

41,000 kg

2 m

6m

1. Which of these planes would be better designed for extended periods of gliding? Explain your answer.

2 m

6m

2 m

10 m

**Activity 3B: Form and Function of Flight [Data Modeling]**

1. Print out your completed graphs and turn them in with your assessment pages.
2. Compare the relationship between wing loading and migration range for flapping vs soaring birds. [Be sure when making visual comparisons that your axes for both graphs are the same.] For which flight mode is wing loading more of a constraint? Explain why this is the case.
3. Compare the relationship between aspect ratio and migration range for flapping vs soaring birds. [Be sure when making visual comparisons that your axes for both graphs are the same.] For which flight mode is aspect ratio more important? Explain why this is the case.
4. Now visit the following Website: <https://www.allaboutbirds.org/mesmerizing-migration-watch-118-bird-species-migrate-across-a-map-of-the-western-hemisphere/>.
   1. What does this interactive map show?
   2. What was the data source for this map?
5. Can you follow the migration of *Euphagus carolinus* (Rusty Blackbird)on this map: [*https://www.allaboutbirds.org/mesmerizing-migration-map-which-species-is-which*](https://www.allaboutbirds.org/mesmerizing-migration-map-which-species-is-which)*.* Tell me what you learn about the migration of this bird from the map.
   1. Where has it been observed and when?
   2. Is it ever in Michigan?