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| **Nature’s Flying Machines**  (online version) |  |

*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).*

## Objectives

Upon completion of this module, each student should be able to:

1. Explain the four forces of flight.
2. Describe how lift is created by wings.
3. Compare how antagonistic muscles (flexors, extensors) power flight in animals with endoskeletons and exoskeletons.
4. Discuss how wing morphology (form) relates to flight ability (function).
5. 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 a 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. **Thrust** is the 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** (see below) flying animals typically have large powerful flight muscles.
        2. **Drag** is a resistance force, friction, generated by an object moving through liquid or gas. In the case of flight, we are talking about air. Drag always acts in a direction that is opposite to the motion of the object. The shape, size, and speed of the moving object and the mass and velocity of the air all impact the magnitude of drag. Drag increases with an increase in air density, in the surface area of the animal exposed to the air, or in the animal or air speed. To reduce drag many flying animals have streamlined bodies.
        3. **Lift** is the force that pushes up on a flying object, opposing the object’s **weight** (see below). 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 objects weight.
        4. **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.

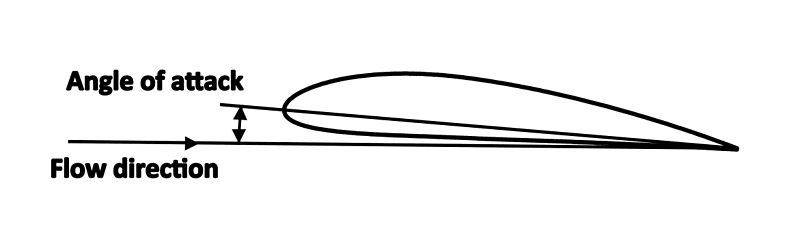
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Flight abilities can be grouped into two broad categories, **powered** and **unpowered**. In powered flight, thrust is generated by flapping of wings. In unpowered flight, air currents and thermals are used to glide and soar through the air without 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 relationship between form and function related to flight.

**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 (pretend your hand is a wing)? In this activity, you will review the results of research on the relationship between angle of attack and lift.



**Chord line**

**Angle of attack**

**Flow direction**

Figure 1. Wing angle of attack.

**Citation**: Ortega Ancel A, Eastwood R, Vogt D, Ithier C, Smith M, Wood R, Kovaç M. 2017. Aerodynamic evaluation of wing shape and wing orientation in four butterfly species using numerical simulations and a low-speed wind tunnel, and its implications for the design of flying micro-robots. Interface Focus 7: 20160087. <http://dx.doi.org/10.1098/rsfs.2016.0087>

**Methods**:

Researchers tested models of wings from four butterfly species at nine different positions. We will be focusing on the results for onlu the “fully open” position, as shown below.

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| Monarch  *Danaus plexippus*  *A close up of a logo  Description automatically generated* | Glasswing  *Acraea andromacha* | Four-barred Swordtail  *Protographium leosthenes* | Orange Plane  *Pantoporia consimilis* |

Lift was measure at three different wind speeds, 2 m s-1, 3.5 m s-1, and 5 m s-1 across a range of angle of attack from 0° to 40°. The results are shown in the figure below.

A close up of a map

Description automatically generated

Figure 13. Coefficient of lift as a function of angle of attack for the four butterfly species studied, comparing the performance of the wings open and closed. (a) glasswing, (b) orange plane, (c) monarch and (d) four-barred swordtail.

*Procedure*

Using the graph, fill in the table with the lift coefficient for each angle of attack. Highlight the maximum value for each species. **[1 pt]**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Angle of Attack | Glasswing | Plane | Monarch | Swordtail | Average |
| 0° |  |  |  |  |  |
| 5° |  |  |  |  |  |
| 10° |  |  |  |  |  |
| 15° |  |  |  |  |  |
| 20° |  |  |  |  |  |
| 25° |  |  |  |  |  |
| 30° |  |  |  |  |  |
| 35° |  |  |  |  |  |
| 40° |  |  |  |  |  |

The angle of attack that generates the most lift is called the **critical angle of attack**. Why does lift decrease as angle increases above the critical angle? Identify which of the other three forces (drag, gravity, thrust) also change(s) as angle of attack changes.

What causes different species have different critical angles?

**Activity 2A: 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.

**Calculation: 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.

**Calculation: 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. Use the checkboxes on the left to choose a design optimized for distance.
3. Use the checkboxes on the left to choose a design optimized for time aloft.
4. Build your airplanes.
5. Fly your airplanes three times each, measuring distance and time aloft.
6. Enter your paper airplane data in the tables below.

Distance (m)

|  |  |  |
| --- | --- | --- |
|  | Distance Model | Time Aloft Model |
| Replicate 1 |  |  |
| Replicate 1 |  |  |
| Replicate 1 |  |  |
| Average |  |  |

Time Aloft (s)

|  |  |  |
| --- | --- | --- |
|  | Distance Model | Time Aloft Model |
| Replicate 1 |  |  |
| Replicate 1 |  |  |
| Replicate 1 |  |  |
| Average |  |  |

Did the models perform as predicted (i.e., did the “distance” model you chose fly farther than the “time aloft model”)?

How do the two models compare in terms of aspect ratio and wing loading? How does this relate to their performance?

**Activity 2B: 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 Watanabe data file from your instructor.
    2. Using the data provided, calculate the aspect ratio and wing loading for each species using the formulas provided in Activity 2A.
    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 the lab assessment.
    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 the lab assessment.

Paste your Wattanabe graph for aspect ratio here.

Paste your Wattanabe graph for wing loading here.

Describe the relationship between wing loading and migration range shown in the graph.

Compare the relationship between wing loading and migration range for flapping vs soaring birds. For which flight mode is wing loading more of a constraint? Explain why this is the case.

Describe the relationship between aspect and migration range shown in the graph.

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.

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?

1. 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 your home state?

**Assessment**

1. Which plane would require less energy to fly the same distance? Explain your answer using the relevant vocabulary.

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 using the relevant vocabulary. **[1 pt]**

2 m

6m

2 m

10 m