National Aeronautics and Space Administration

GRADES K-4

Four Forces

principles of flight

Aeronautics
Research
Mission
Directorate

Museum in a BOX Series

Four Forces

Lesson Overview

Through physical experimentation, students will learn about the position and motion of objects and the properties of objects and materials as they explore the basics behind the four forces of flight. Students will be divided into four groups and witness the effects of gravity on a tennis ball, the thrust provided by an inflated balloon, the drag created by friction and the lift produced by their own hands in a stream of air.

Objectives

Students will:

1. Gain, through experimentation, a basic understanding of the four forces of flight.

Materials:

In the Box

Balloons

Provided by User

Balloon pump (optional)
Tennis ball (or similar)
Box fan
High friction material (sandpaper, carpeted floor, or similar)
Large book (telephone directory or similar)
Tables (2-4)

GRADES **K-4** **Time Requirements:** 1 hour 30 minutes

Background

The Forces of Flight

Every vehicle, whether it's a car, truck, boat, airplane, helicopter or rocket, is affected by four opposing forces: Thrust, Lift, Drag and Weight (Fig. 1). It is the job of the vehicle's designer to harness these forces and use them in the most advantageous way possible, providing the pilot with an efficient way to control the aircraft.

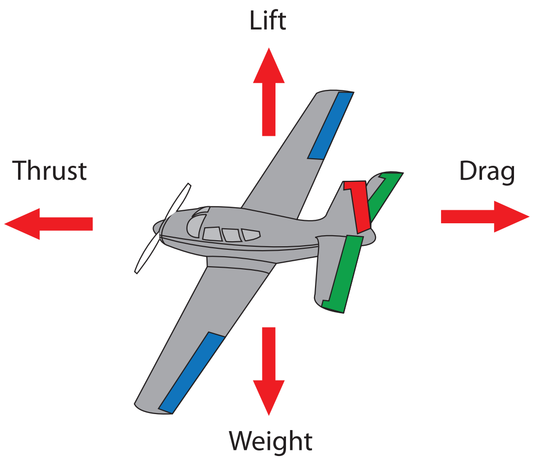
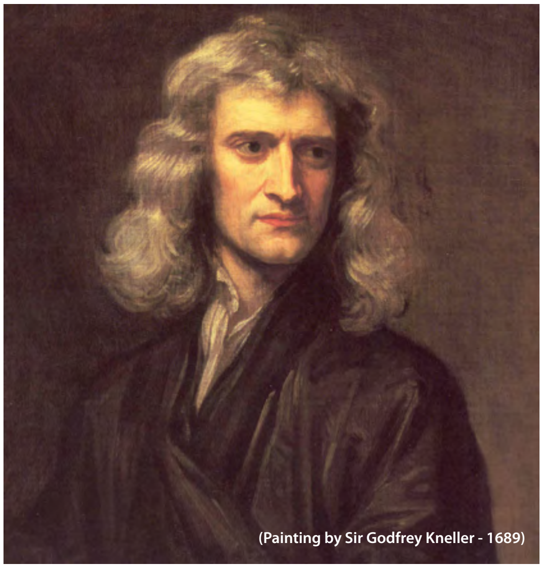


Fig. 1 Four forces of flight

A force can be thought of as a pushing or pulling motion in a specific direction. It is referred to as a vector quantity, which means it has both a magnitude (quantity or amount) and a direction. In some cases, the goal is to remove as much of a specific force as possible. Race cars, for example, have very little weight in comparison to its thrust, while aircraft use all four forces working in harmony, although not always in equilibrium, in order to achieve successful flight.

Within this lesson we specifically refer to these principles in relation to fixed-wing airplanes. While other aircraft, such as helicopters and airships, use the same basic principles, the methods they use to harness these forces are quite different. With a helicopter for example, the rotor blades on the top of the aircraft produce both lift and thrust forces, controlling them using gyroscopic principles far outside of the scope of this lesson.


(Painting by Sir Godfrey Kneller - 1689)

Img. 1 Sir Isaac Newton (age 46)

Thrust

Thrust should be thought of as the driving force and is produced by an aircraft's propulsion system, or engine. The direction of the thrust dictates the direction in which the aircraft will move. It works using Sir Isaac Newton's (Img. 1) Third Law of Motion which states that "To every action, there is always an equal and opposite reaction." He demonstrated quite simply that if Object A exerts a force on Object B, then Object B must exert an equal force on Object A but in the opposite direction (Fig. 2). So for example, the engines on an airplane propel the aircraft forwards by moving a large quantity of air backwards. In technical terms, it is said that the airplane's thrust vector points forwards. (Reverse thrust simply uses metal components known as clamshells to reverse the direction of the airflow, thereby reversing the thrust vector.)

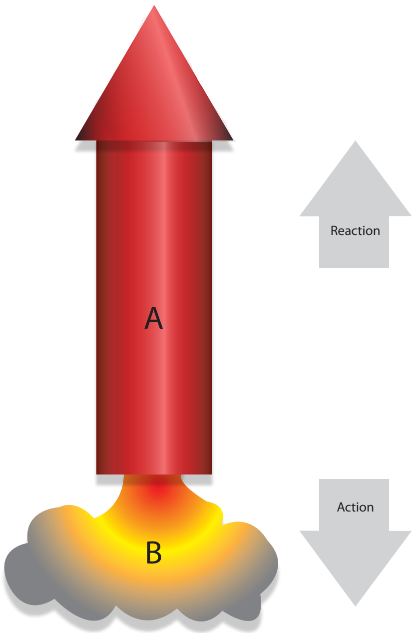


Fig. 2 Action & Reaction

The magnitude of the thrust depends on many factors such as the number and type of engines installed, environmental conditions such as temperature and air density, and the throttle or thrust setting. As a general rule of thumb, propeller-driven aircraft (Img. 2) produce less thrust and are therefore slower than those aircraft powered by jet engines (Img. 3).

One important item of note is that the job of the engine is to propel the aircraft, not to provide lift. It is primarily the wings that perform the task of lifting, not the engines.

Img. 2 A NASA modified Cessna 190

Img. 3 A NASA modified Boeing 747

Lift

Lift occurs when a moving flow of gas is turned by a solid object. The flow is turned in one direction, and the lift is generated in the opposite direction, according to Newton's Third Law of action and reaction. Because air is a gas and the molecules are free to move about, any solid surface can deflect a flow. For an aircraft wing, both the upper and lower surfaces contribute to the flow turning. Because the air moving over the top of a curved wing tends to go faster than the air under the wing, there is also less pressure at the top of curved wings, and more pressure below the wings. This principle of fast moving air having less pressure is known as Bernoulli's Principle, and also helps generate lift (Fig. 3).

To learn more about what causes lift, and three examples of incorrect theories of lift that people often believe, visit: *http://www.grc.nasa.gov/WWW/k-12/airplane/lift1.html*

Fig. 3 Air approaching and passing over the surface.

Drag

Drag is produced any time a solid object tries to pass through a liquid or gas. In the case of an aircraft, drag is simply the resistance of the air against the aircraft. There are two types of drag, of which the first, Parasitic Drag, has three categories.

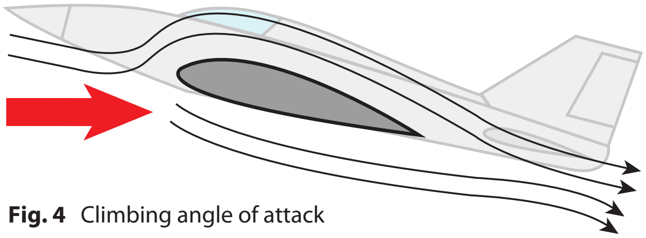


Fig. 4 Climbing angle of attack

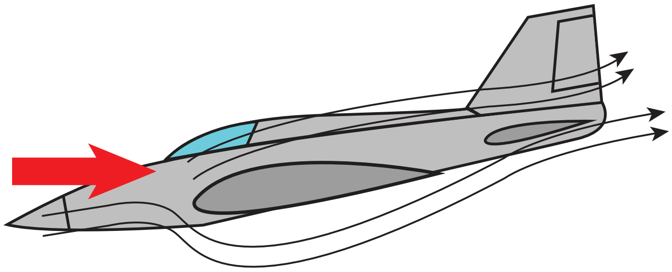


Fig. 5 Descending angle of attack

Skin-Friction Drag: The resistance to movement created just by trying to pass an object through the air. It can be thought of as the same feeling a runner might experience when running into a strong wind. Just the act of physically pushing through the air creates resistance which must be overcome to move forwards. This can be reduced by polishing or smoothing the surface exposed to the air. The runner in a tightly fitted running suit would experience much less skin-friction drag than if running in a fitted fluffy coat.

Interference Drag: The drag caused by two different airflows meeting and resisting each other. This is commonly seen where the wing is attached to the fuselage of an aircraft, otherwise known as the root.

Form Drag: The drag caused by the design of an aircraft. While the body of an aircraft may be extremely smooth and aerodynamic, the many objects attached to it, such as radio antennas or windshield wipers, are not. These objects create drag in a similar way to sticking a hand out of a car window. The car is aerodynamic, but the hand is not.

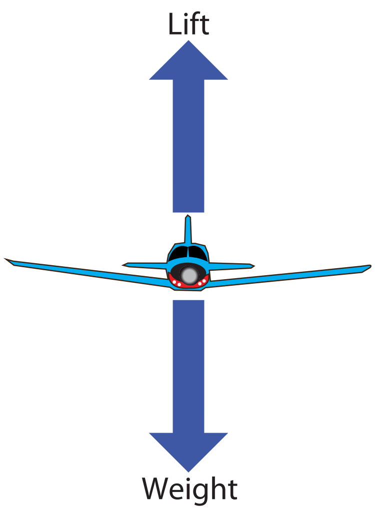


Fig. 6 Forces of straight and level flight

The second type of drag is Induced Drag. It is a by-product of lift, created by the higher pressure air below the wing traveling around the side of the wing to the lower pressure area, rather than pushing upwards (Fig. 7). This causes a swirling motion of the air, creating what are known as wingtip vortices, which can occasionally be seen when flying through clouds. These vortices disturb the smooth airflow over the wing, creating additional drag. The magnitude of this drag is usually inversely proportional to the magnitude of the lift being produced.

To reduce the amount of induced drag, some aircraft have an additional part to their wings, called winglets (Img 4). Winglets prevent the air from rotating around to the lower pressure area, thereby reducing the induced drag produced (Fig. 8).

NASA has performed many wingtip vortex studies in an attempt to reduce or eliminate the effects of induced drag on an aircraft. Typically these tests are performed by attaching smoke generators to the wing tips of aircraft and watching the resultant formations (Imgs. 5 & 6).

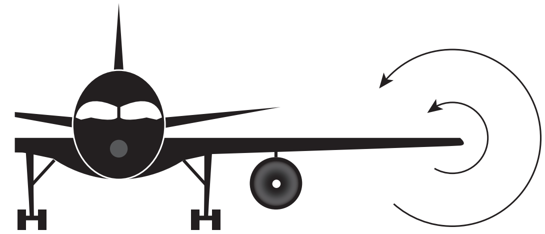


Fig. 7 Induced drag

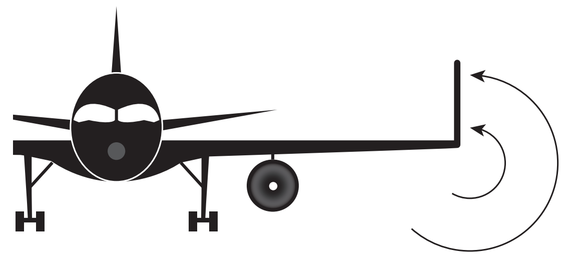


Fig. 8 Winglets' affect on drag

Img. 4 A NASA-modified KC-135

Img. 5 A Boeing 727 vortex study

Img. 6 A wake vortex study at Wallops Island, VA

Weight

Weight is a force that is always directed toward the center of the earth due to gravity. The magnitude of the weight is the sum of all the airplane's parts, plus its payload, which is the sum of all the fuel, people and cargo. While the weight is distributed throughout the entire airplane, its effect is centered on a single point called the center of gravity. When an aircraft is loaded, it is vital that its center of gravity remain within certain limits. An aircraft that is too nose- or tail-heavy will either not fly, or be so difficult to control that it becomes too dangerous to try.

The goal of any aircraft design is to keep the weight to a minimum. The lighter an aircraft is, the less fuel it requires for flight, and the more payload it can carry.

The Forces in Flight

While each of the forces is completely independent of the others, in flight they work opposite each other to guide the aircraft as directed by the pilot. In straight and level, un-accelerated flight the total amount of thrust is equal to the total drag, while the total amount of lift is equal to the total weight (Fig. 9). For the aircraft to accelerate, the pilot must add additional thrust to overpower the drag and cause the aircraft to gain speed. If the need is to slow down however, the pilot will reduce the thrust to a value less than that of the drag, allowing the drag to slowly decelerate the aircraft.

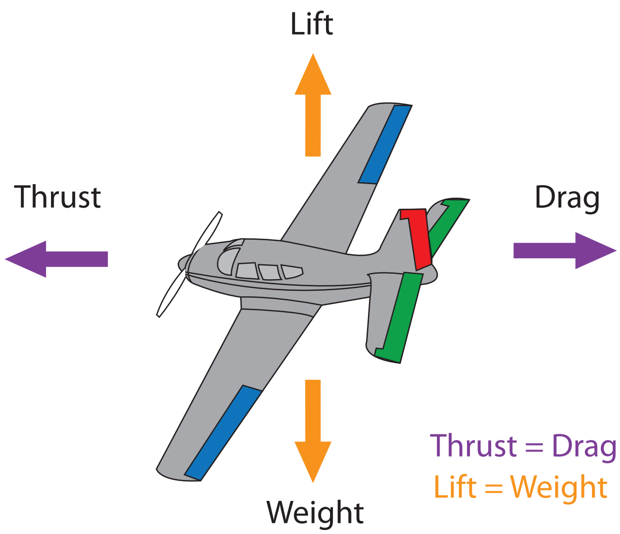


Fig. 9 The four forces of flight in balance

The same is true for the weight and lift vectors, although once in flight, the weight of the aircraft remains mostly constant, becoming only slightly lighter as fuel is consumed. Once again, with the aircraft at cruise altitude, it has no need to climb or descend and therefore the total lift produced equals the total weight and is sufficient to do no more than support the weight of the aircraft. If the aircraft must climb, the pilot pitches the nose of the aircraft slightly upwards, increasing the difference in air pressure between the top and bottom surfaces of the wings and therefore producing more lift.

It is important to remember that changing one vector typically results in a change to the other three as well. For example, typically increasing thrust also increases the speed of the air over the wings, which in turn increases lift. If there was no need to climb, the pilot would have to also lower the nose, reducing the angle of attack of the wing and therefore the lift produced, restoring the balance between lift and weight. The opposite is true for a climb where an increase in lift would also increase the induced drag, requiring the pilot to add additional thrust not to accelerate, but to simply compensate for the increased drag component.

Activity 1 Understanding the Forces

GRADES

Time Requirements: 1 hour 30 minutes

Materials:

In the Box

Balloons

Provided by User

Balloon pump (optional)
Tennis ball (or similar)
Box fan
High friction material (sandpaper, carpeted floor or similar)
Large book (telephone directory or similar)
Tables (2-4)

Worksheets

Table Toppers (Worksheet 1)

Reference Materials

None

Key Terms:

None

Objective:

Through experimentation, students will learn about position and motion of objects as they gain a basic understanding of the four forces of flight.

Activity Overview:

The work area will be divided into four stations, with one station specific to each force. Students will be divided into four teams and each team assigned to a station. After performing the listed tasks at that station, the groups will rotate to the next.

Note: This activity works best when four adults are available and can each be assigned to monitor a specific station. Depending on the size of the group and the number of adults available, you may find it more convenient to keep all of the students in a single group and rotate between stations together.

Activity:

1. **Prior to performing this activity, print Worksheet 1 onto thick card stock, then fold as indicated to make the table toppers required for each station.**

   Prepare the area by dividing the room into 4 stations. Each station should be comprised of a table, its table topper from Worksheet 1 and the following items:

   a. Station One: Thrust
      - Balloons (one per student, plus a few extra in case any break)
      - Balloon pump (optional)

   b. Station Two: Drag
      - Large book
      - A high friction material such as sandpaper, carpet, a thick sweater, etc.

   c. Station Three: Weight
      - Tennis ball (or similar)

   d. Station Four: Lift
      - A box fan

3. **As a single group, discuss the Background information with the students.**
The topics discussed are quite detailed in nature. As such, it should be simplified as required to suit the abilities of the students. It is more important to convey the basic concepts of thrust, weight/gravity, lift and drag than it is to understand how they interact together in flight.

4. **If appropriate, divide the class into four approximately equal-sized groups and assign each group a station.** Have each group perform the activities described at each station.
As noted previously, this can also be performed as a single group if class size or number of adults available to assist dictates as such.

Station One: Thrust

- Have each student, or designated students, blow up a balloon using either their mouths or a balloon pump. Let them discover how thrust is produced when they let go of the balloon.

Station Two: Drag

- Each student should slide the book across a smooth surface such as the table. Next, ask them to slide the book again, but this time over a sandpaper or carpeted surface. Ensure they discover how much harder it is to push the book on the rougher surface.

Station Three: Weight

- Ask each student, or designated students, to roll the ball along the table and watch what happens as it reaches the end of the table.

Station Four: Lift

- Have each student hold one hand flat against the blowing stream of air. Now have them tilt the front of their hands slightly. They should feel their hands start to rise. This is due to lift being produced as the air travelling over the top of the hand is moving quicker than the air underneath.
If a box fan is not available, students can also see the same effect by blowing a stream of air across a strip of paper.

Note: Encourage the students to relax their arms. Holding them stiff will not allow the students to feel the lift.

5. **After all students have had an opportunity to complete the four activities, gather them back into a single group to review the discussion points that follow.**

Discussion Points:

1. **What are the four forces that allow an airplane to fly?**
   Thrust, lift, drag and weight.

2. **What is thrust?**
   Thrust is a force that moves the airplane forwards through the air.

3. **Why did the balloon fly around the room?**
   When the balloon was let go, the air escaped out of the rear of the balloon, creating thrust.

4. **What is lift?**
   Lift is a force that allows an aircraft to climb or stay in the air, rather than fall to the ground.

5. **Why did your hand rise when you turned it upwards slightly?**
   When we turned our hands, it caused the air passing over the top of our hands to move faster than the air on the bottom. This produced a lower air pressure on top, which meant the higher air pressure underneath could push our hands upwards.

6. **What is drag?**
   Drag is a force that opposes thrust. It is a type of friction and makes objects harder to move.

7. **Why was the book harder to push the second time?**
   It was harder to push the second time because it had to move across a rough surface. When pushed along the table it had very little resistance and slid easily, but the rough texture created drag, which had to be overcome by pushing the book harder.

8. **What is gravity?**
   Gravity is a force that pulls objects towards the center of the Earth.

9. **What is weight?**
   Weight is the effect of gravity on an object (mass). A 200lb man on Earth weighs almost nothing in space due to the much lower levels of gravity.

10. **Why did the ball fall to the floor rather than just keep moving sideways?**
    If there were no gravity, the ball would have just kept moving sideways. Instead, once the table was no longer there to support the ball, the effects of gravity took over, pulling the ball to the floor. Had the floor not been there, it would have continued falling until reaching the center of the Earth!

NATIONAL SCIENCE STANDARDS K-4

SCIENCE AS INQUIRY

- Abilities necessary to do scientific inquiry
- Understanding about scientific inquiry

PHYSICAL SCIENCE

- Property of objects and materials

SCIENCE AND TECHNOLOGY

- Abilities of technological design
- Understanding about science and technology

Reference Materials

Fig. 1 Four forces of flight

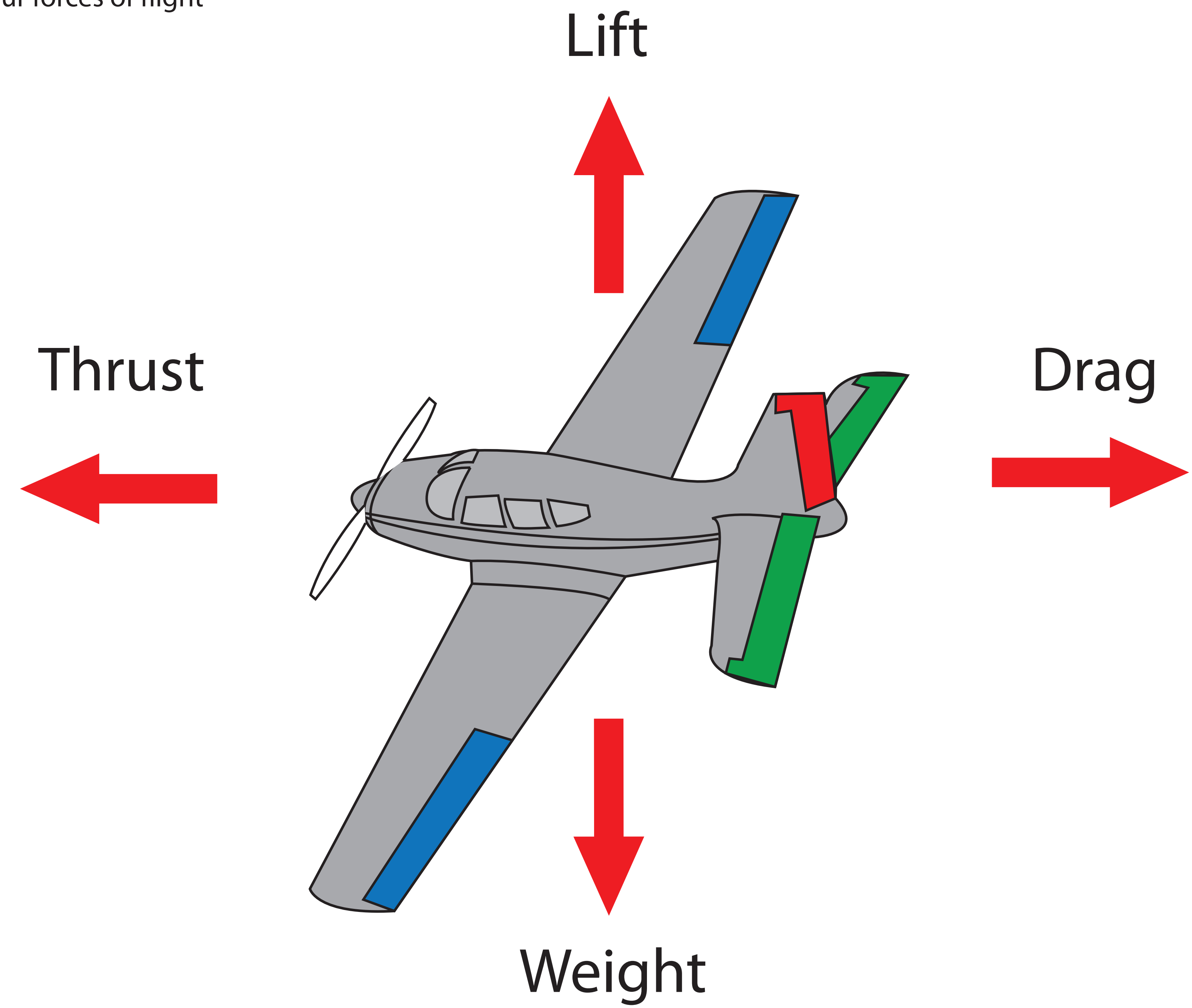


Fig. 2 Action & Reaction

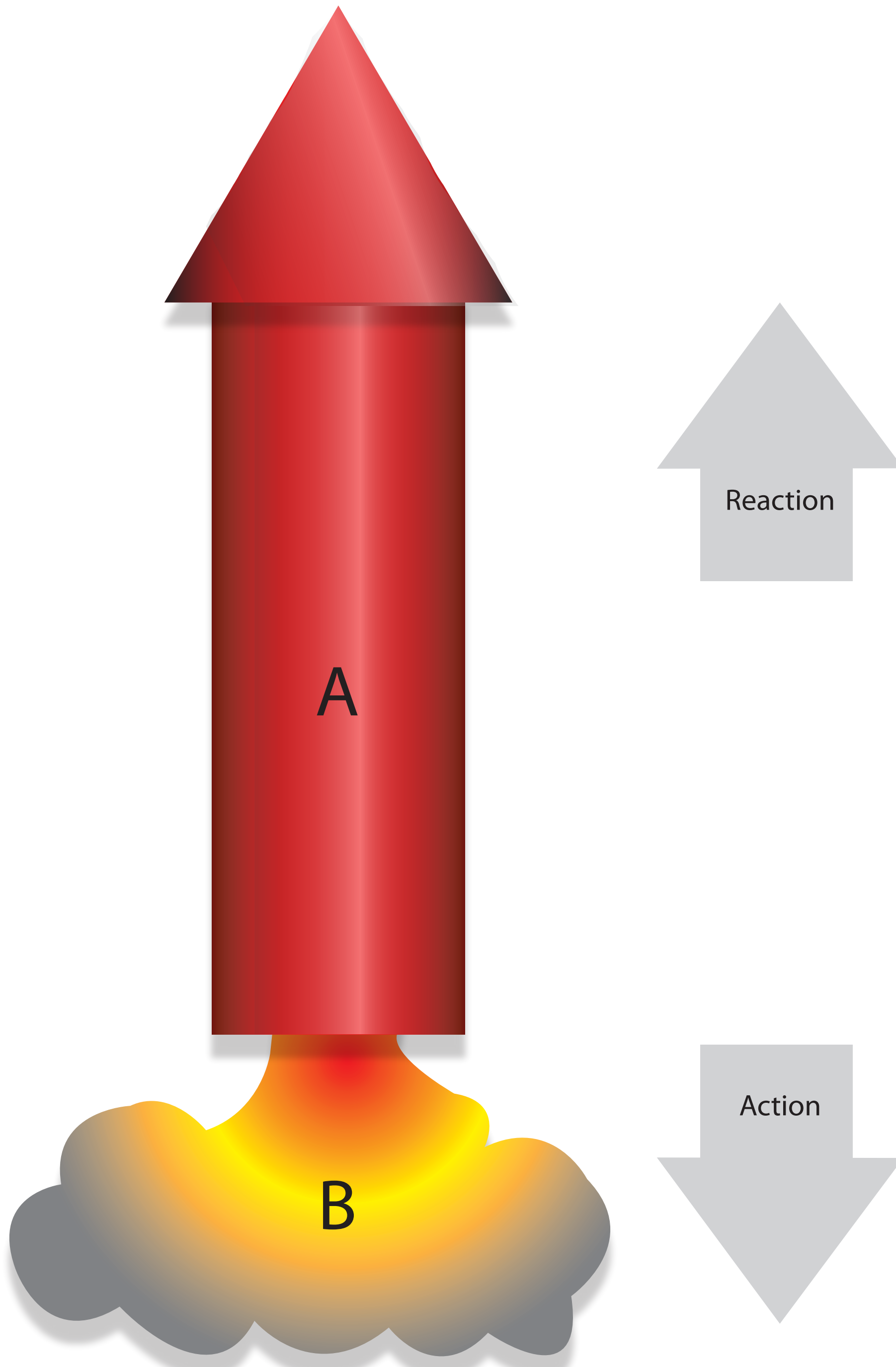


Fig. 3 Air approaching and passing over the surface.

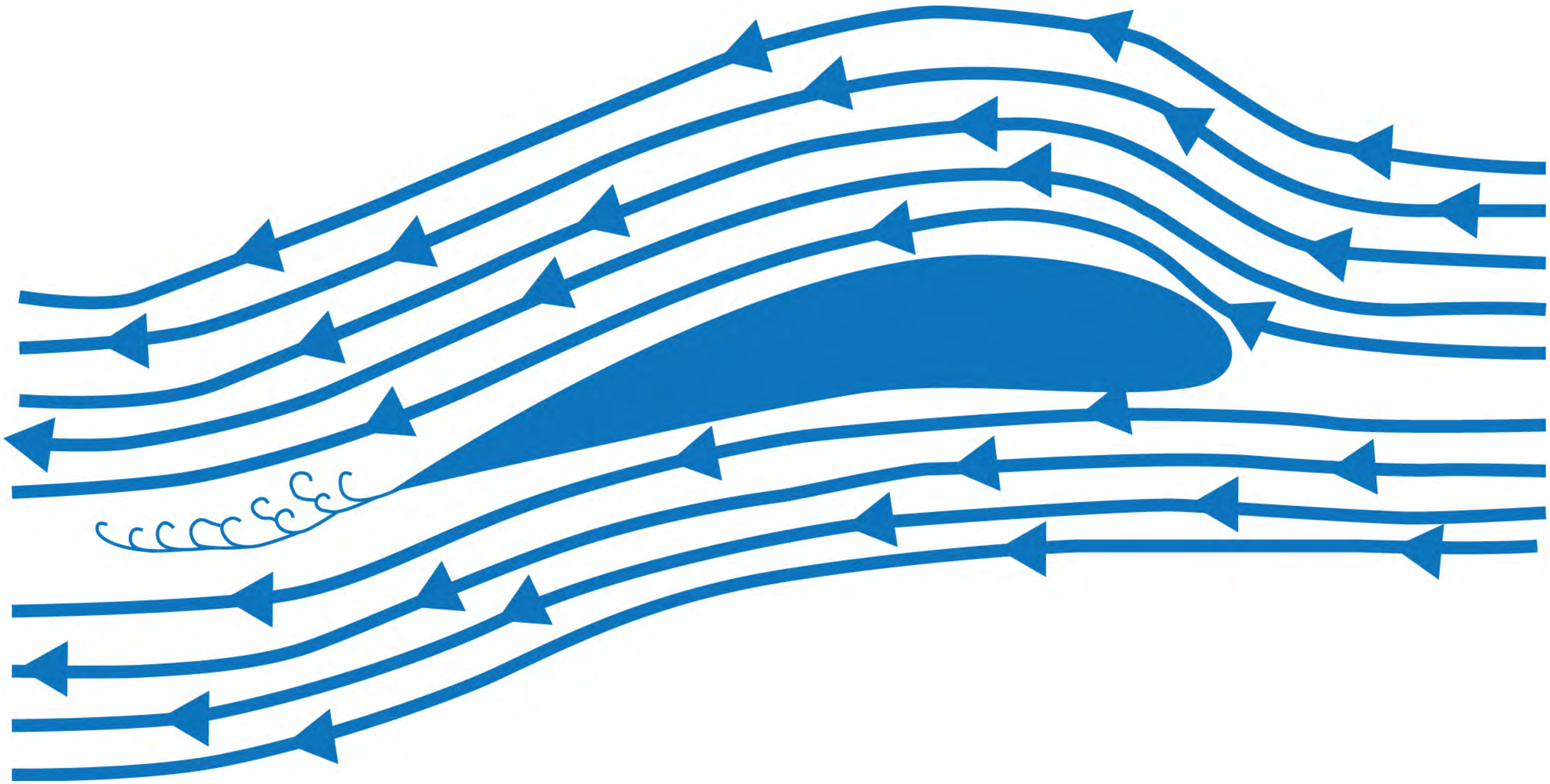


Fig. 4 Climbing angle of attack

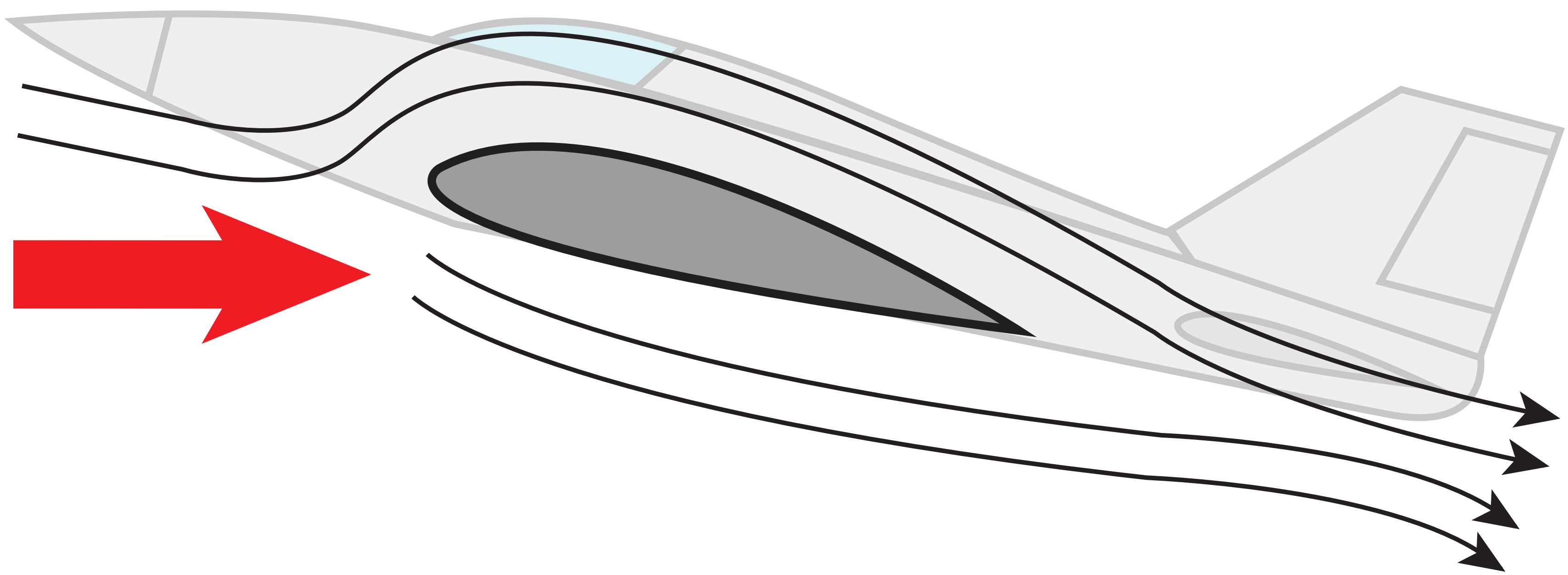


Fig. 5 Descending angle of attack

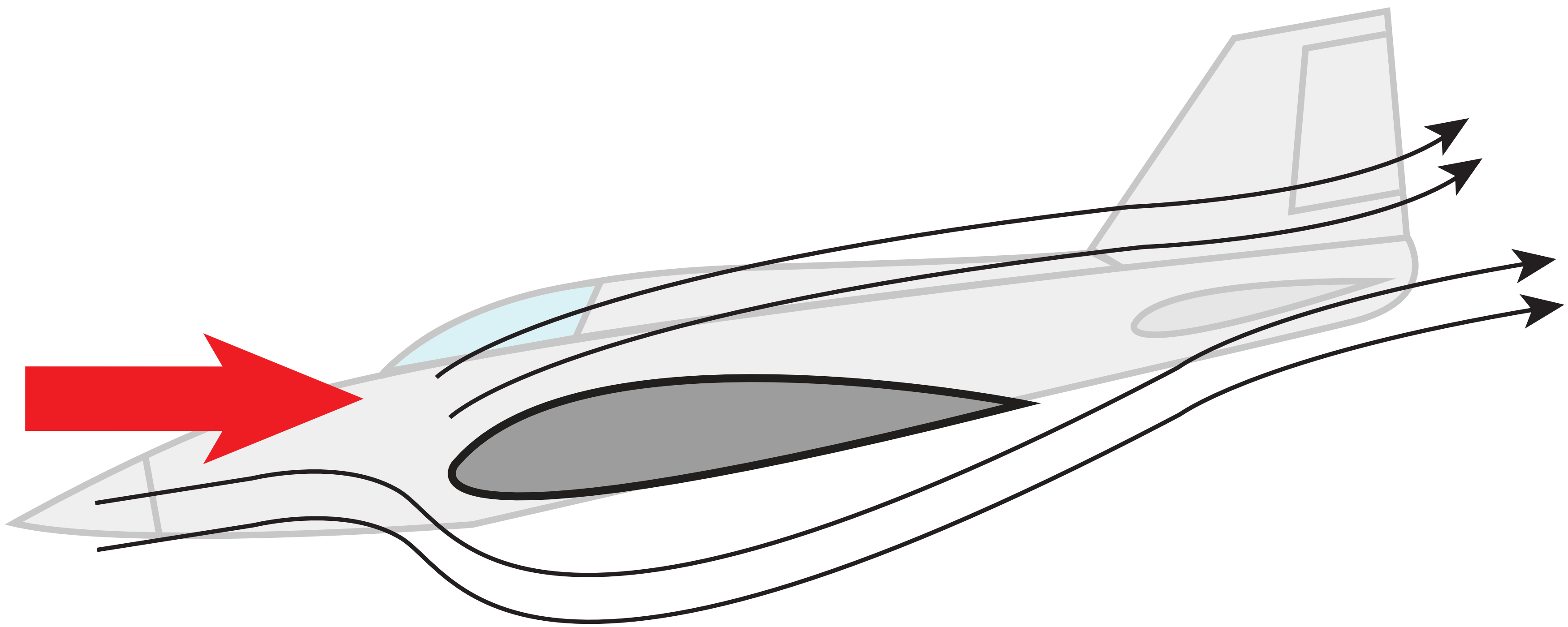


Fig. 6 Forces of straight and level flight

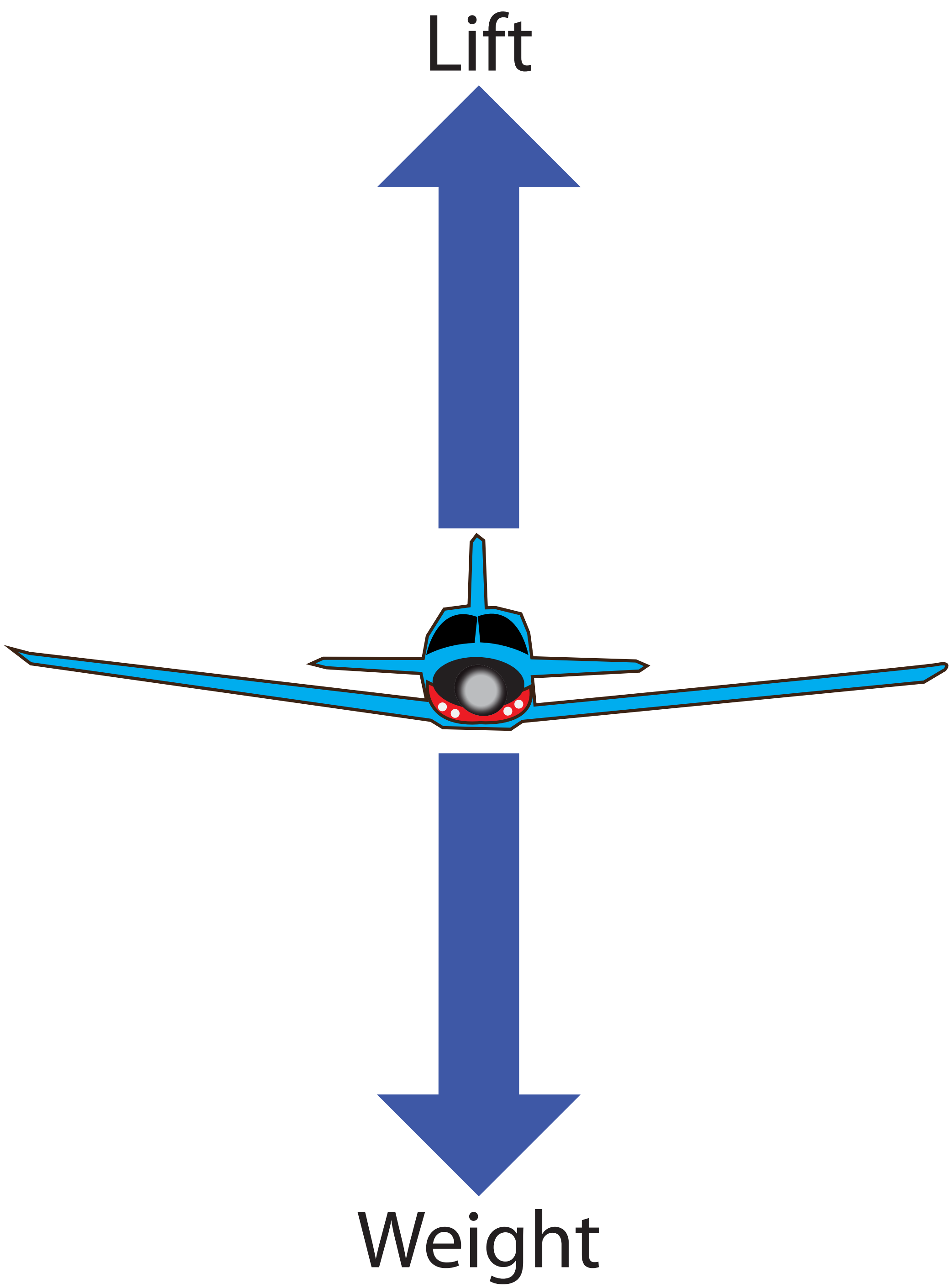


Fig. 7 Induced drag

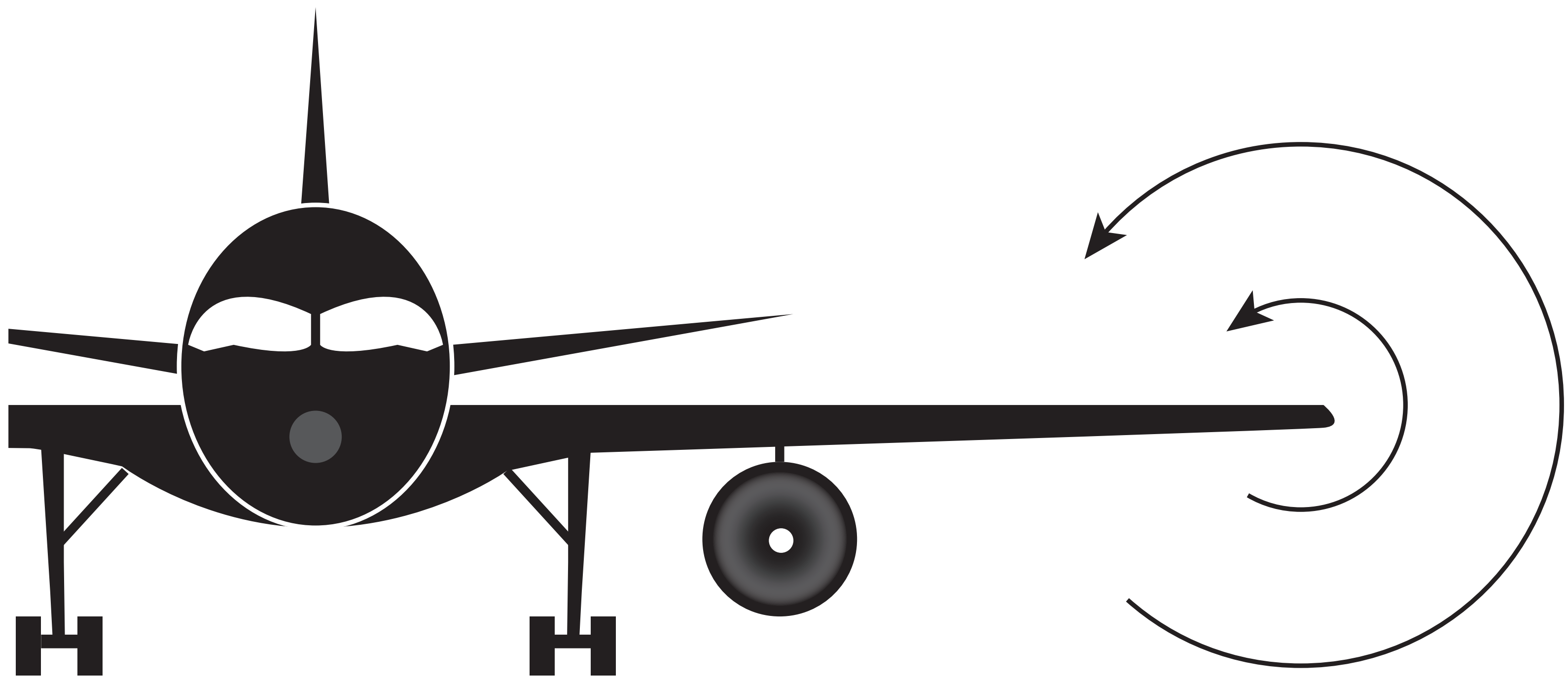


Fig. 8 Winglets' affect on drag

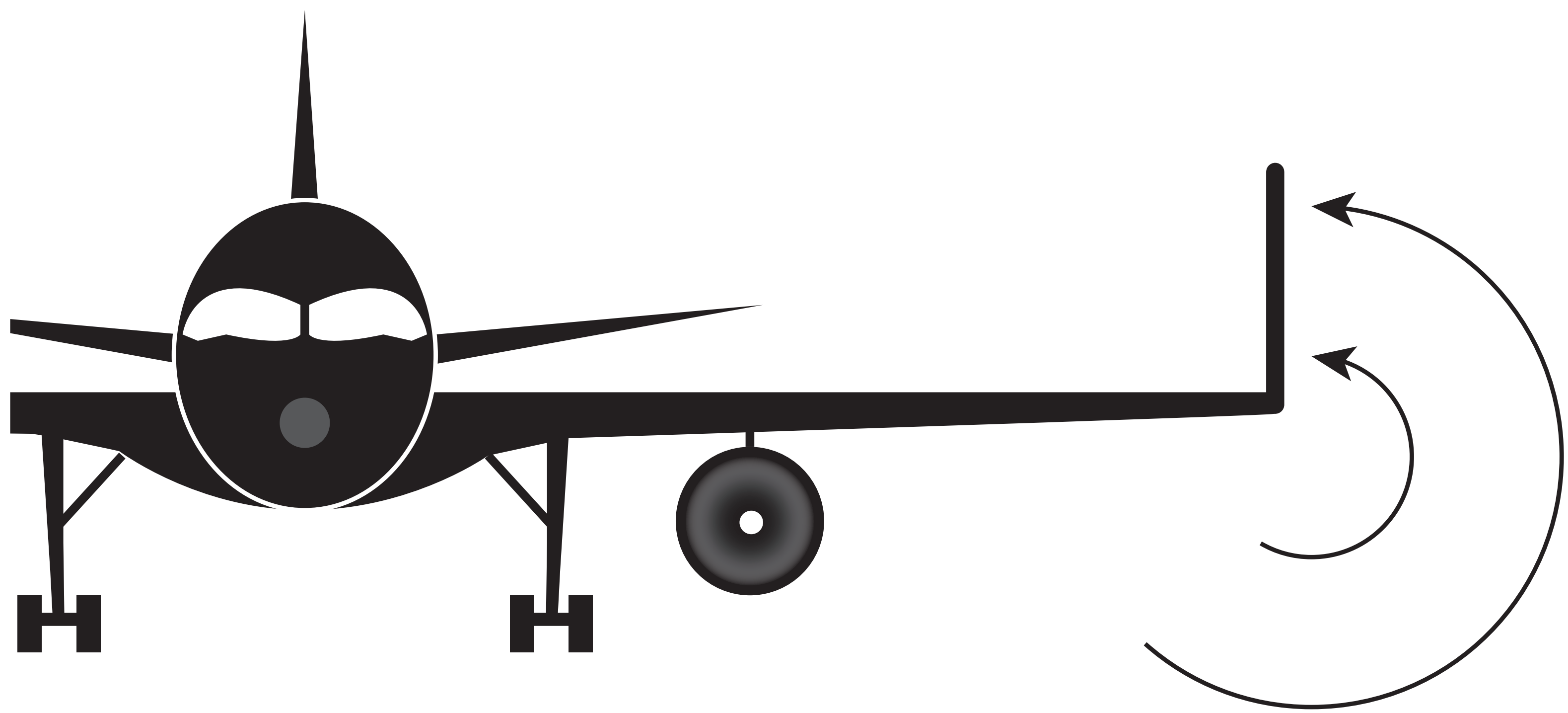
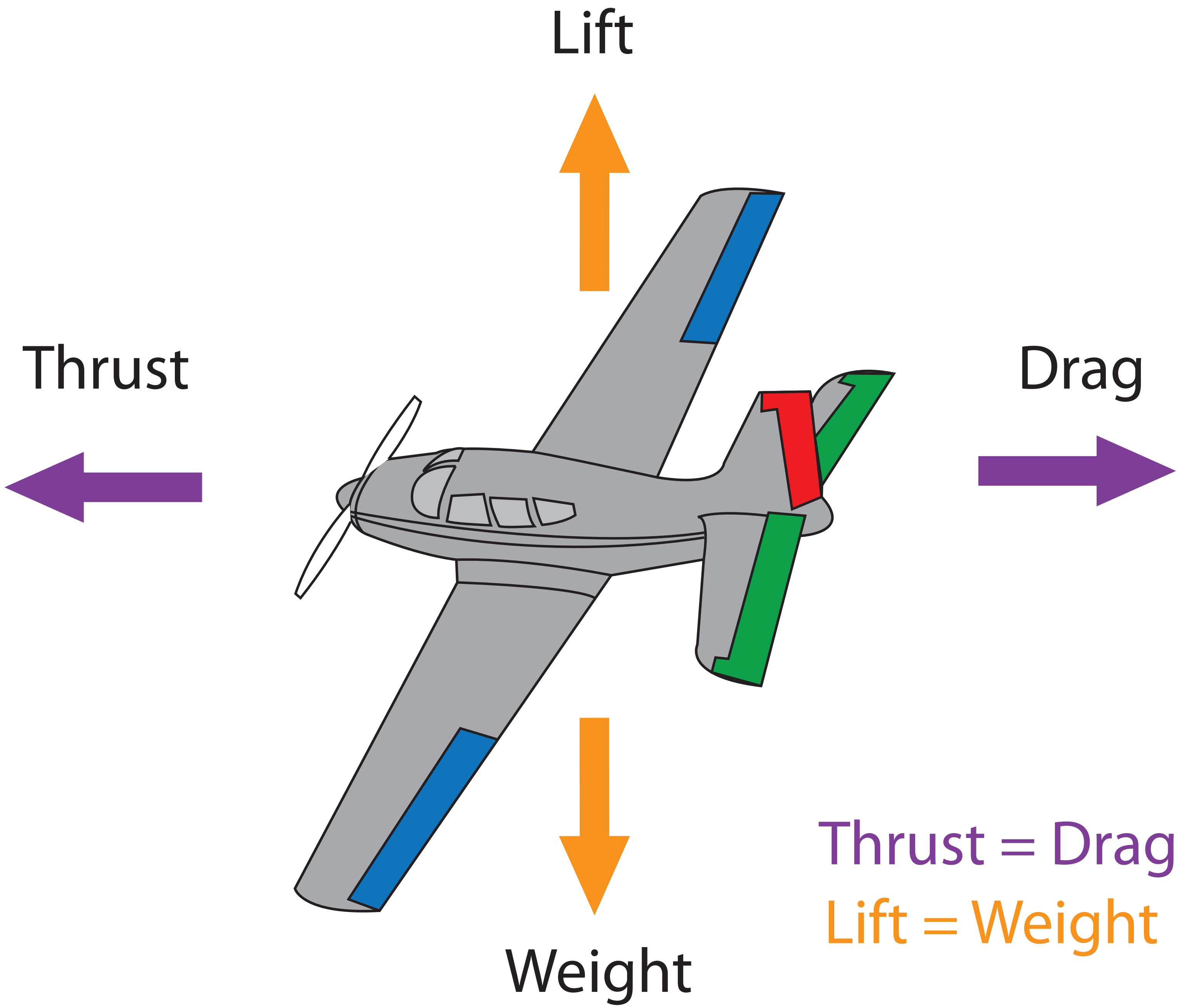


Fig. 9 The four forces of flight in balance

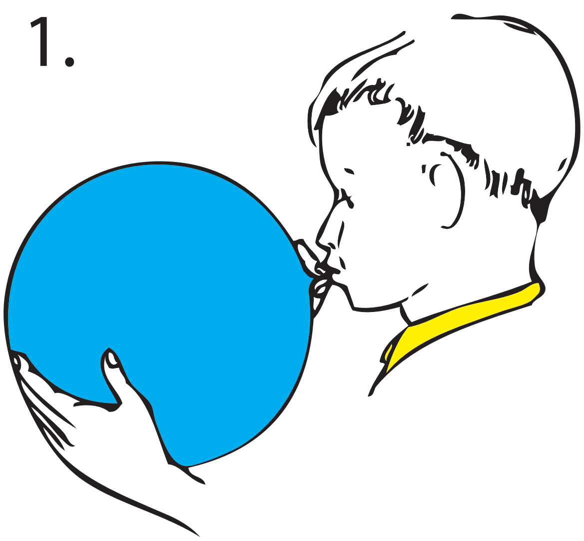


Worksheets

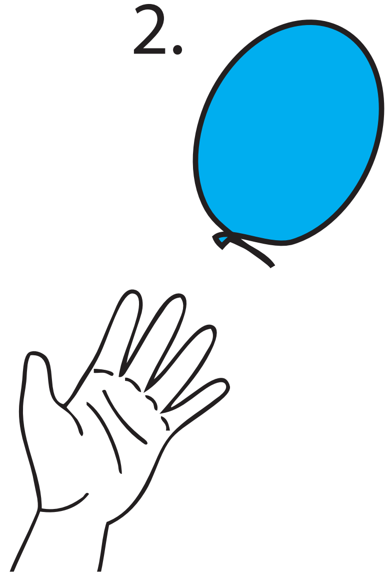
fold fold

Station One: Thrust

1.



2.



fold fold

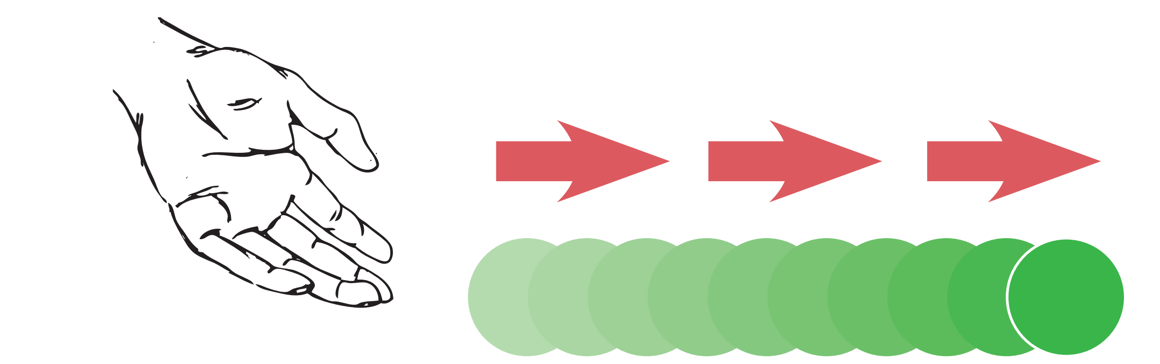
Station Two: Drag

1.

2.

fold fold

Station Three: Weight



fold

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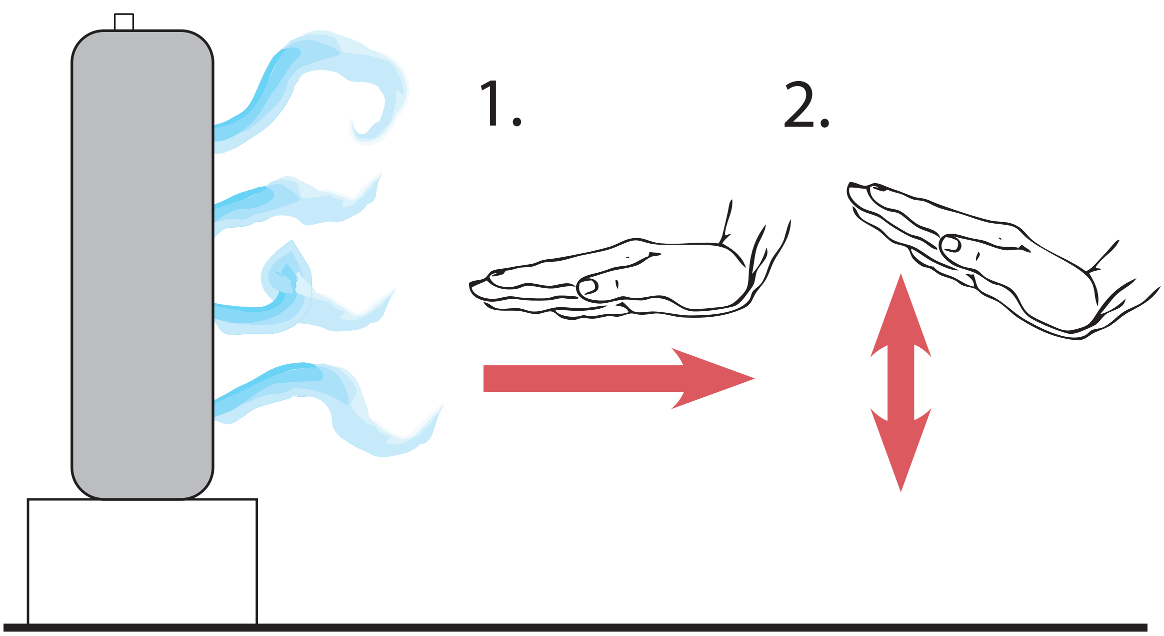
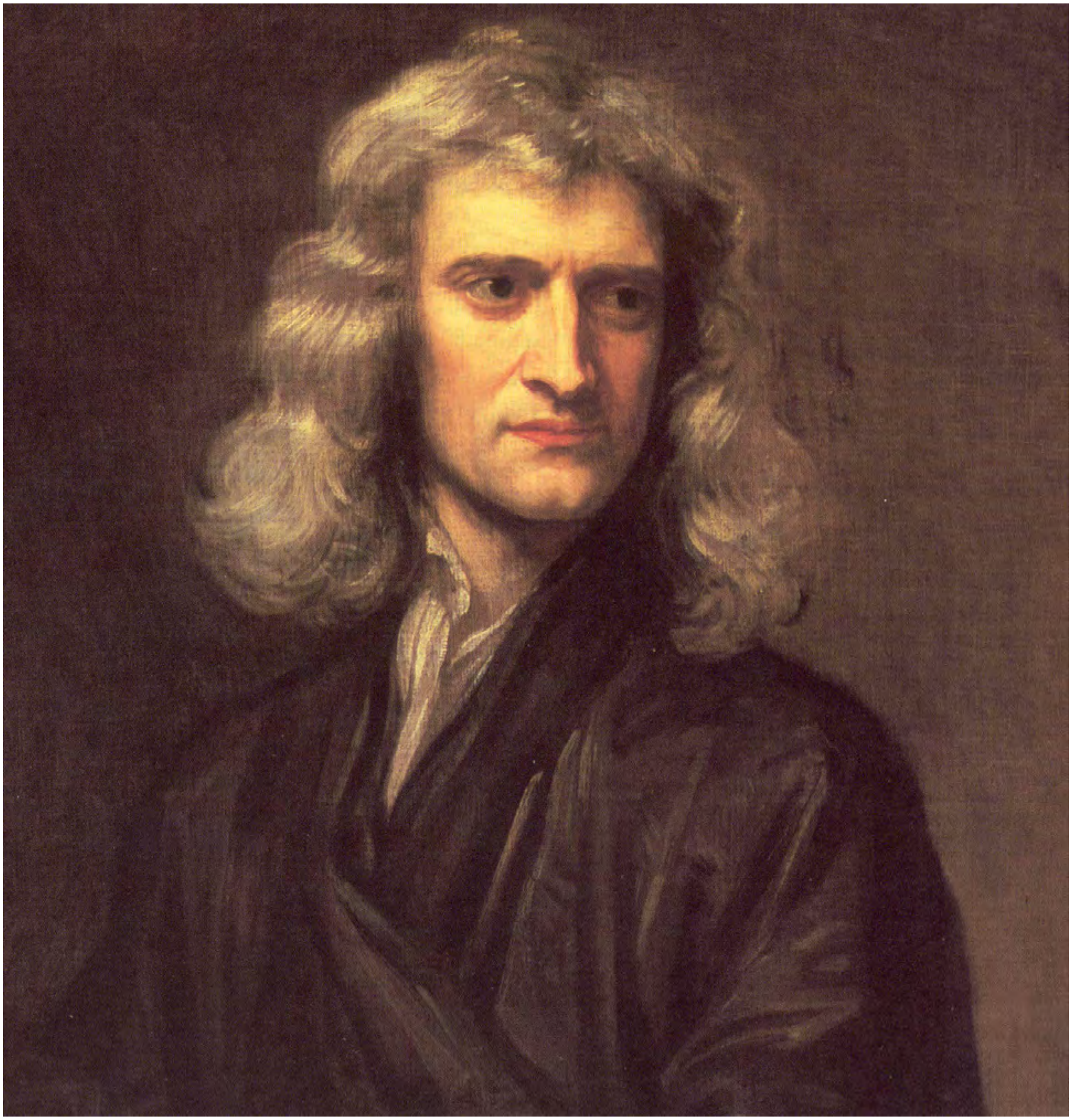
Station Four: Lift



Images

Img. 1 Sir Isaac Newton (age 46)



(Painting by Sir Godfrey Kneller - 1689)

Img. 2 A NASA modified Cessna 190

(Photo courtesy of NASA)

Img. 3 A NASA modified Boeing 747

(Photo courtesy of NASA)

Img. 4 A NASA-modified KC-135

(Photo courtesy of NASA)

Img. 5 A Boeing 727 vortex study

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Img. 6 A wake vortex study at Wallops Island, VA

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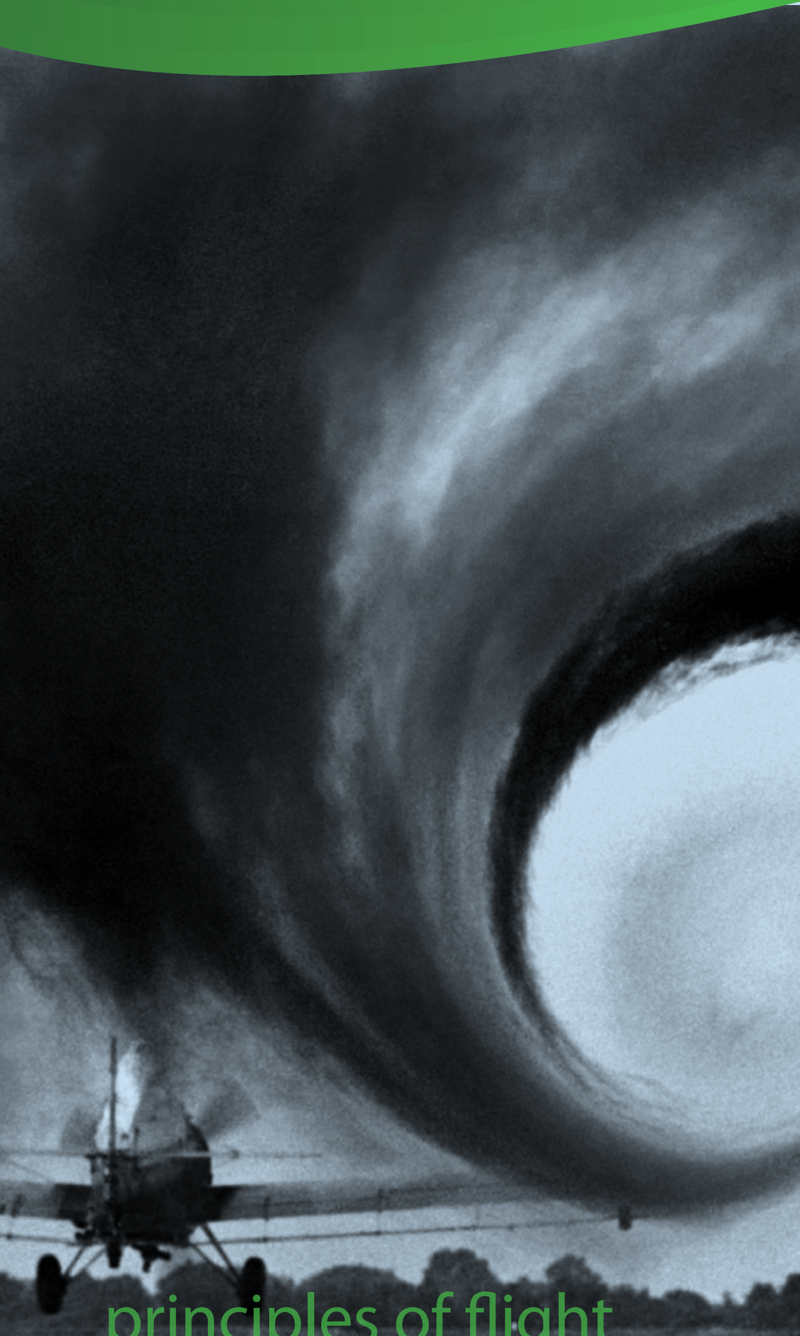

principles of flight

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