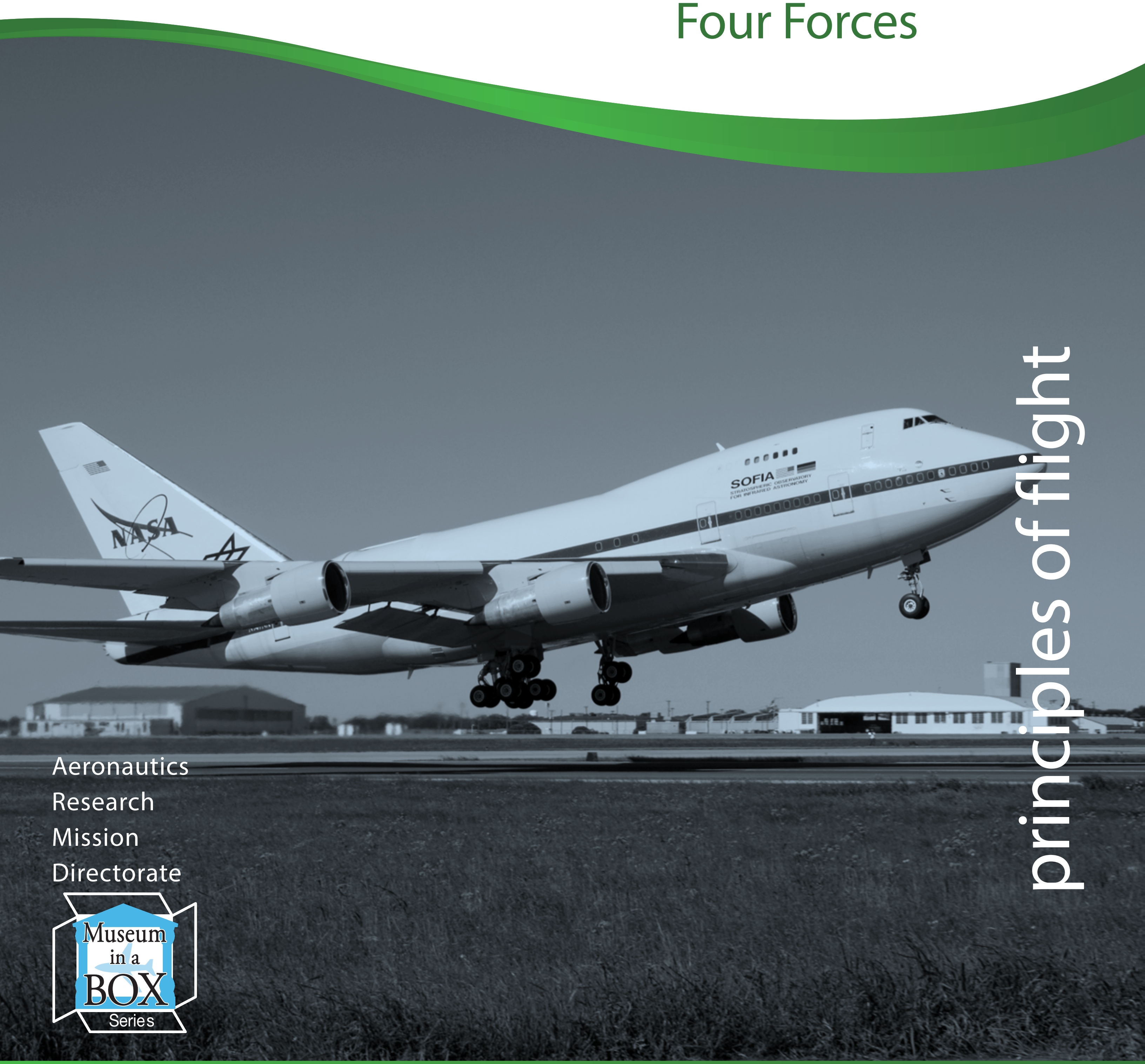
National Aeronautics and Space Administration

GRADES **5-8**

Four Forces



principles of flight

Aeronautics
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Four Forces

Lesson Overview

Through physical experimentation, students will learn about motions and forces, and transfer of energy 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 air resistance 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

Stopwatch (2)

Scale

2 balls of similar size but different weights

Fan

Umbrella

Provided by User

Balloon pump (optional)

Copy paper (8 sheets)

GRADES **5-8**

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.

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.

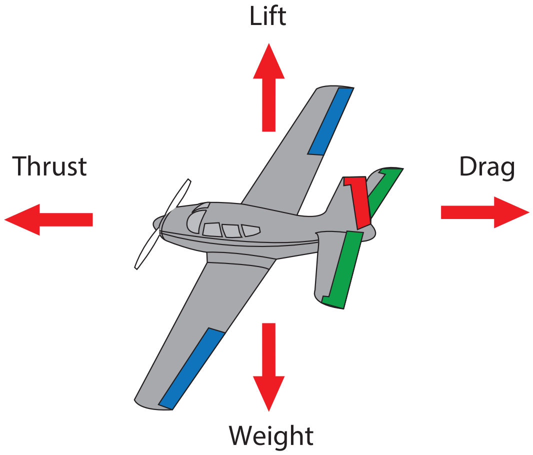
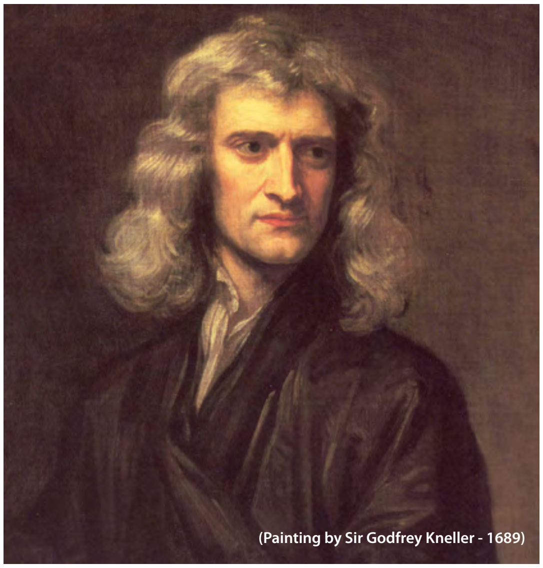


Fig. 1 Four forces of flight



(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.)

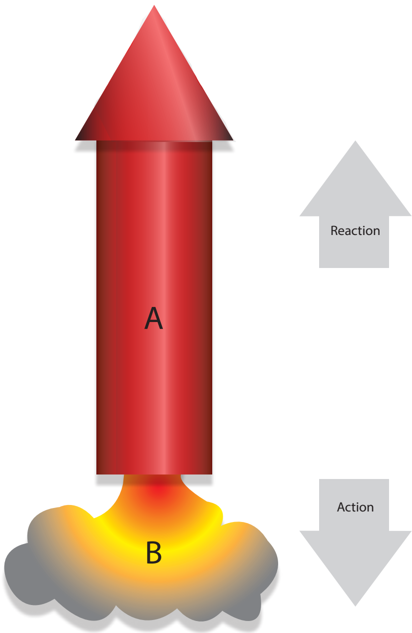


Fig. 2 Action & Reaction

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.

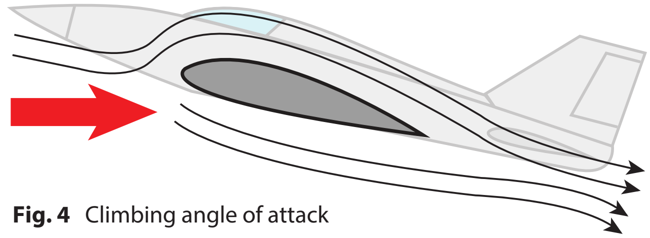


Fig. 4 Climbing angle of attack

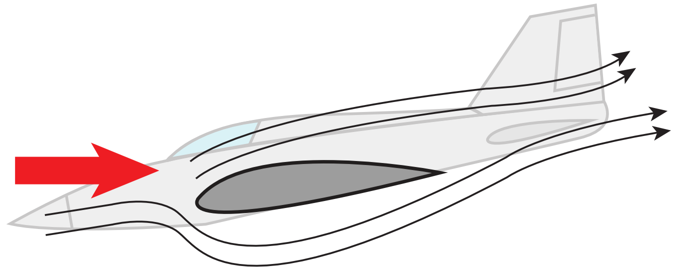


Fig. 5 Descending angle of attack

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.

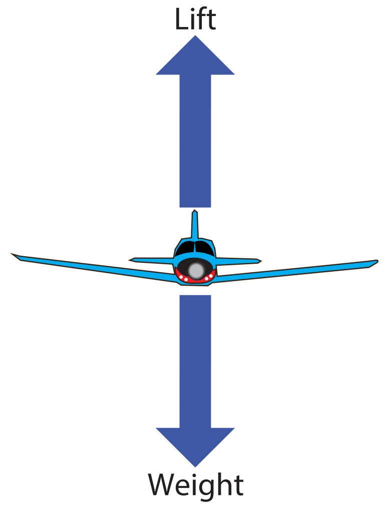


Fig. 6 Forces of straight and level flight

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).

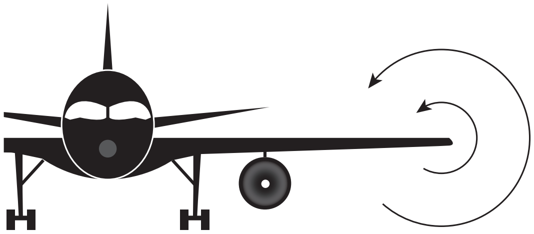


Fig. 7 Induced drag

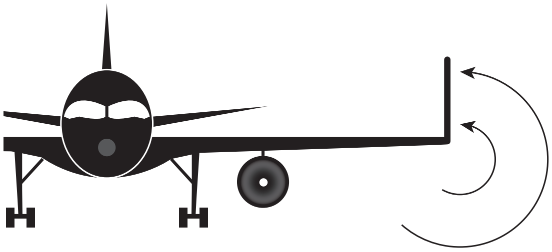


Fig. 8 Winglets' affect on drag

Img. 4 A NASA-modified C-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.

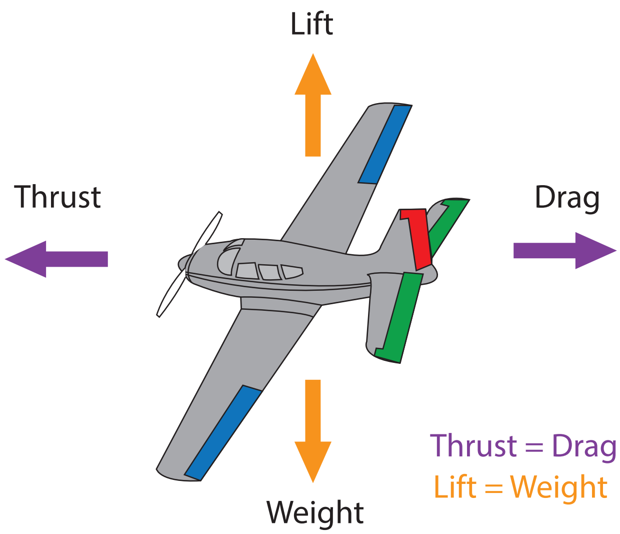


Fig. 9 The four forces of flight in balance

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, 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 5-8

Time Requirements: 1 hour 30 minutes

Materials:

In the Box

Balloons
Stopwatch (2)
2 balls of similar size but different weights
Fan
Umbrella
Scale

Provided by User

Balloon pump (optional)
Copy paper (8 sheets)

Worksheets

Table Toppers (Worksheet 1)
Thrust & Time (Worksheet 2)

Reference Materials

None

Key Terms:

None

Objective:

Through experimentation, students will learn about energy transfer, as well as motions and forces, 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.**

2. **Prepare the area by dividing the classroom 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)
   - Balloon pump (optional)
   - Stopwatch
   - Worksheet 2 (one per student)

   b. Station Two: Drag
   - Umbrella
   - Stopwatch

c. Station Three: Weight

- 2 balls of similar size but different weights
  Type of ball is irrelevant. The important part is the difference in weight. Examples might include a tennis ball and an orange, or a marble and a grape.
- Sheets of blank copy paper
  Scale

d. Station Four: Lift

- A fan

3. **As a single group, discuss the Background information with the students.**

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 above, 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 inflate the balloon using either four breaths or four pumps of a balloon pump.
- Next, have the student let go of the balloon while another student times the length of the flight.
- Record the time the balloon spent airborne on the worksheet.
- Repeat the experiment multiple times with various levels of inflation, recording the number of breaths and the flight time for each trial.

Station Two: Drag

- Assign two points on opposite sides of the room between which the students can safely run.
- Have one student in the group run at a steady pace from one point to the other, while another student times the journey.
- Now have the same student run again at the same pace as before, but this time holding the open umbrella behind them. Again, time the journey.
- Have each student perform this activity noting the difference between the two times.

Station Three: Weight

- Pass the two balls around the group. Ensure the students note that the two balls are of different weights by weighing them on the scale.
- Have one student stand on the table or a chair for additional height. Next, have the same student hold the two balls at arm's length and at equal height.
- Ask the students which ball will hit the ground firs , the lighter or the heavier.
- Have the student holding the balls drop them simultaneously while the other students watch.
- Repeat this with the other students taking turns dropping the balls until it is accepted that both balls hit the ground at approximately the same time.
- Next, take two sheets of copy paper and pass them around the group to confi m they are identical.
- Take one sheet of paper and scrunch it into a tight ball, leaving the other untouched.
- Remind the students that both sheets of paper weigh the same. Based on the previous demonstration, ask them to hypothesize as to which sheet of paper will hit the ground first.
- As before, have the students take turns dropping the two pieces of paper, noting which one landed first.

Station Four: Lift

- Using the fan, have each student hold one hand flat against the blowing stream of air. Now have them tilt the front of their hand slightly. They should feel it start to rise.

Discussion Points:

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

2. **What is thrust and how is it produced?**
   Thrust is a force that moves an airplane forwards through the air. It is produced by the aircraft's engines, which accelerate the air around the aircraft.

3. **What correlation was there between the amount of air in the balloon and its flight time?**
   It should have been discovered that as the amount of air in the balloon increased, the longer it stayed in flight.

4. **In what direction did the balloon move?**
   The open end of the balloon always pointed away from the direction of travel. This proves Newton's Second Law of Motion because as the air escaped from the rear of the balloon, it pushed the balloon forwards, in an equal and opposite direction. The direction and speed the balloon moved is the balloon's thrust vector.

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

6. **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 the hand to move faster than the air below. As Bernoulli's principle states, this produced a lower air pressure on top, which meant the higher air pressure underneath could push the hand upwards.

7. **What is drag?**
   Drag is a force that both opposes thrust and is a byproduct of lift. It is a type of friction, making objects harder to move.

8. **Why was it significantly harder to run with the open umbrella? Why were the sprinting times longer with the umbrella than without?**
   Without the umbrella, the main drag component was the air resistance against your body as you ran. With the umbrella open, it provided a much larger surface area which also had to be pulled through the air. This created additional drag, which meant that you had to work harder, or provide more thrust, in order to complete the journey. As you had already given 100% of your available thrust on the first run, the additional drag slowed you down, creating a slower time.

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

10. **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.

11. **Why did both balls fall to the floor at approximately the same time even though one was heavier?**
When it comes to gravity, the weight of an object is irrelevant. The speed at which an object falls due to gravity will always be the same. A stationary object accelerates by 9.8m/s for each second it falls (9.8m/s^2 or meters per second, per second). To put it another way, after one second a falling object will be moving at 9.8 meters per second. After 2 seconds it will be at 19.6 (9.8 + 9.8) meters per second, after 3 seconds its speed will be 29.4 (9.8 + 9.8 + 9.8) m/s, and so on. It doesn't matter whether that object is a grape or an elephant, they will both fall at the exact same speed. In actuality however, the elephant will hit the ground after the grape. This is due to the elephant being larger and therefore having more resistance against the air through which it is falling (drag).

12. **If the speed of gravity is the same for all objects, why did the ball of paper drop much quicker than the sheet?**
The ball of paper had very little resistance as it fell through the air, meaning it had very little drag. The sheet of paper on the other hand had a large, exposed surface area, which slowed down the rate of acceleration. This is precisely how a parachute works in slowing down a falling skydiver. It provides additional drag, allowing the skydiver to touch the ground at a much slower, safer speed.

NATIONAL SCIENCE STANDARDS 5-8

SCIENCE AS INQUIRY

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

PHYSICAL SCIENCE

- Properties and changes of properties in matter
- Transfer of energy

SCIENCE AND TECHNOLOGY

- Abilities of technological design
- Understanding about science and technology

Reference Materials

Fig. 1 Four forces of flight

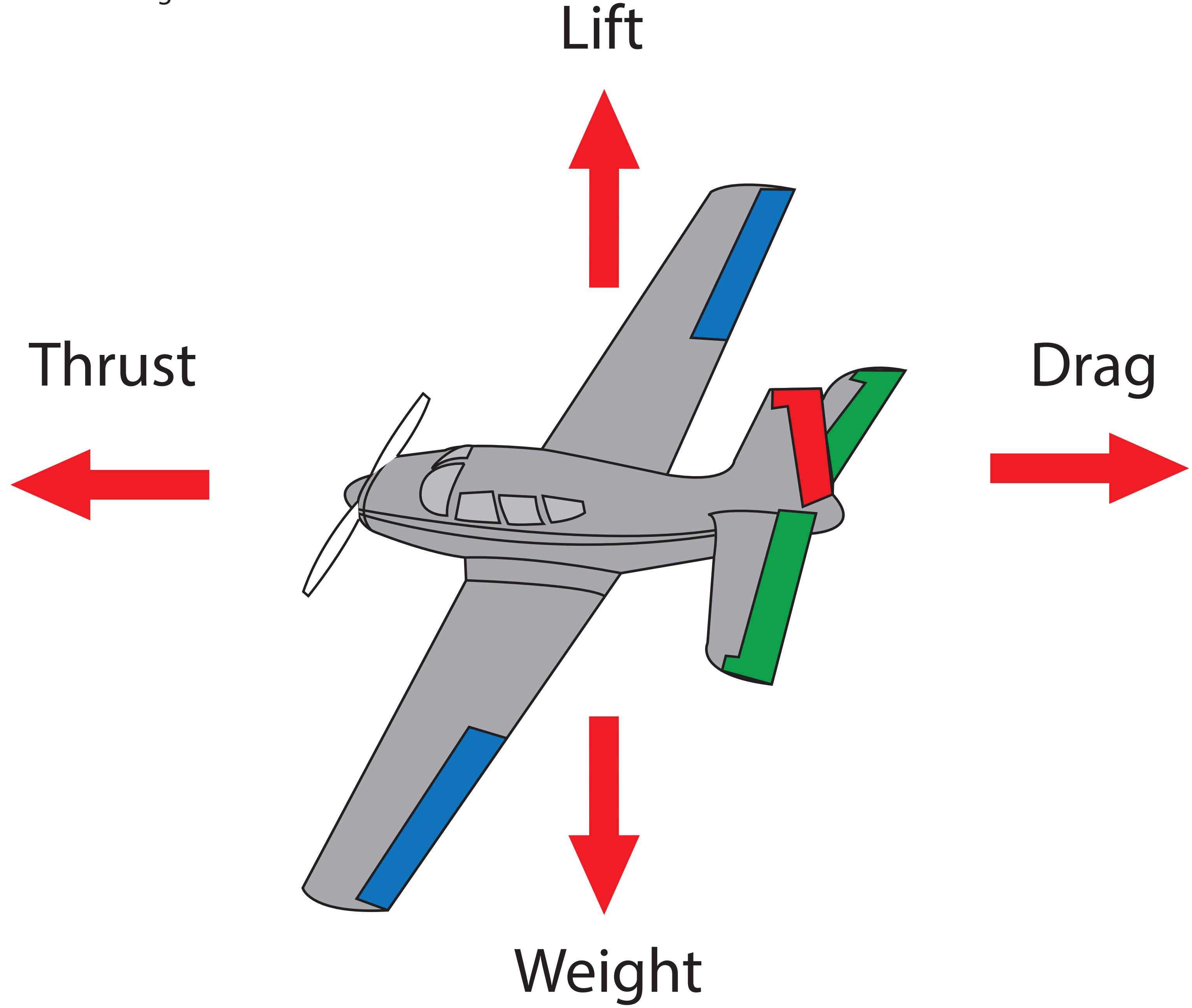


Fig. 2 Action & Reaction

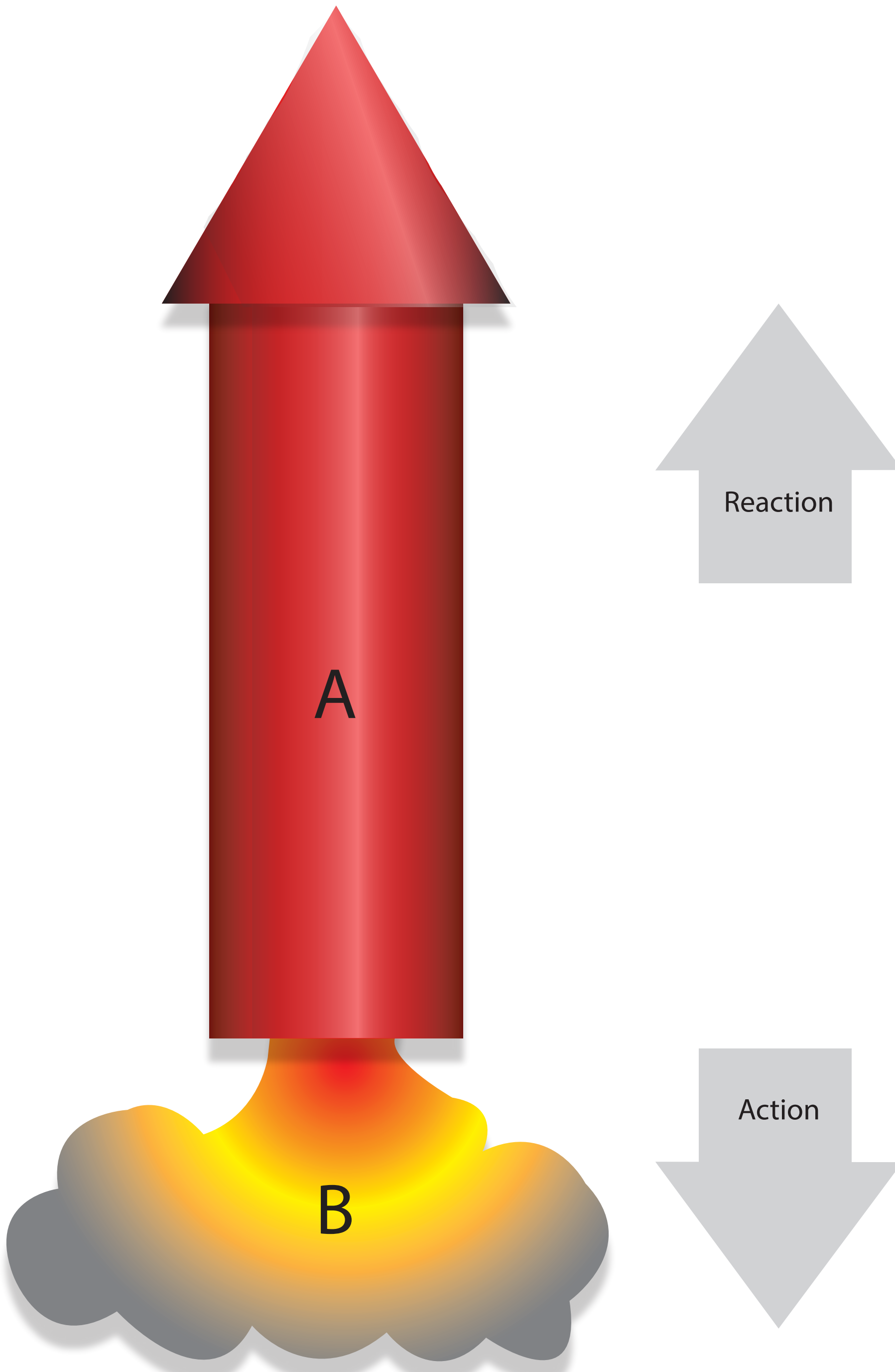


Fig. 3 Air approaching and passing over the surface.

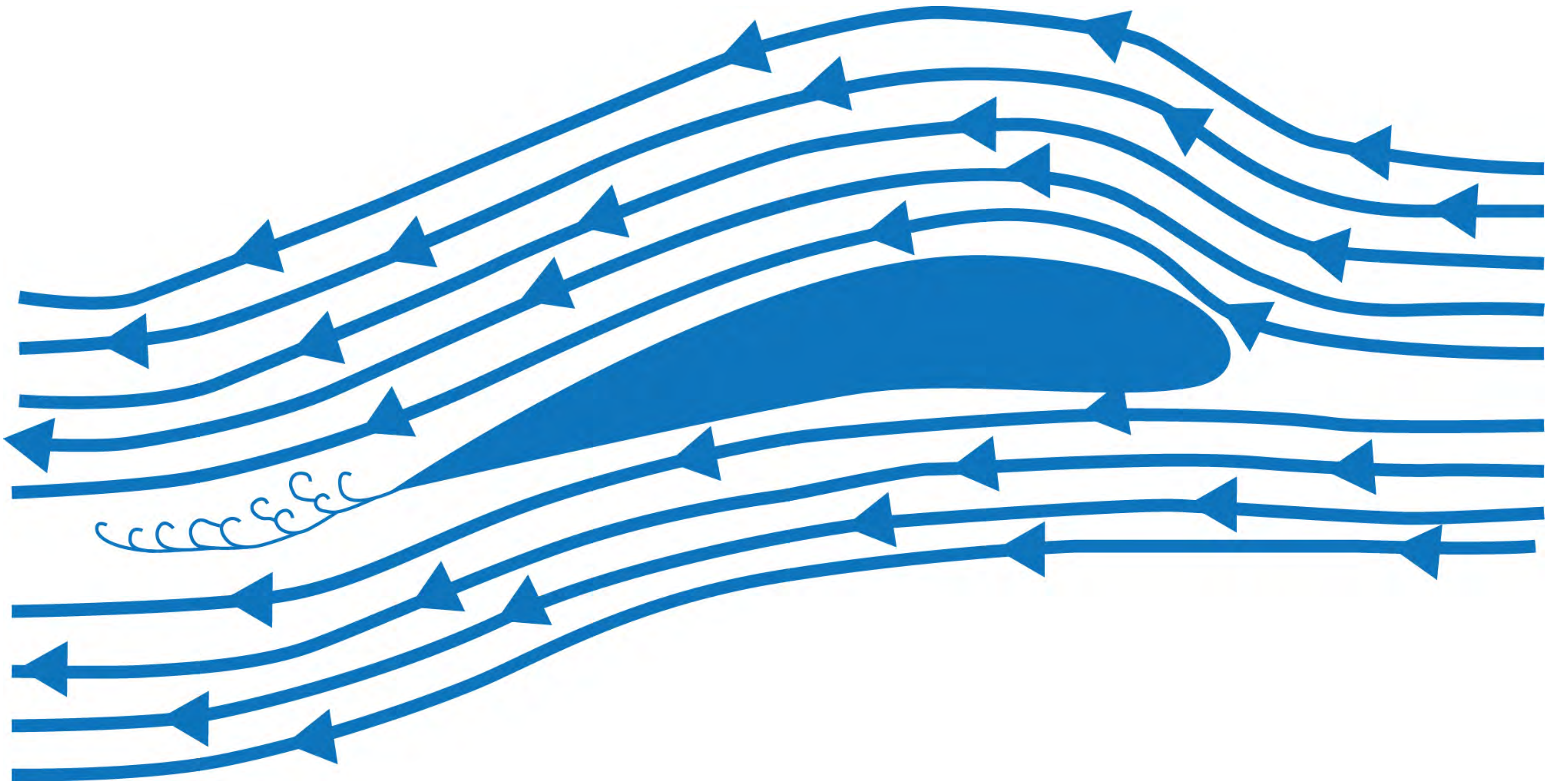


Fig. 4 Climbing angle of attack

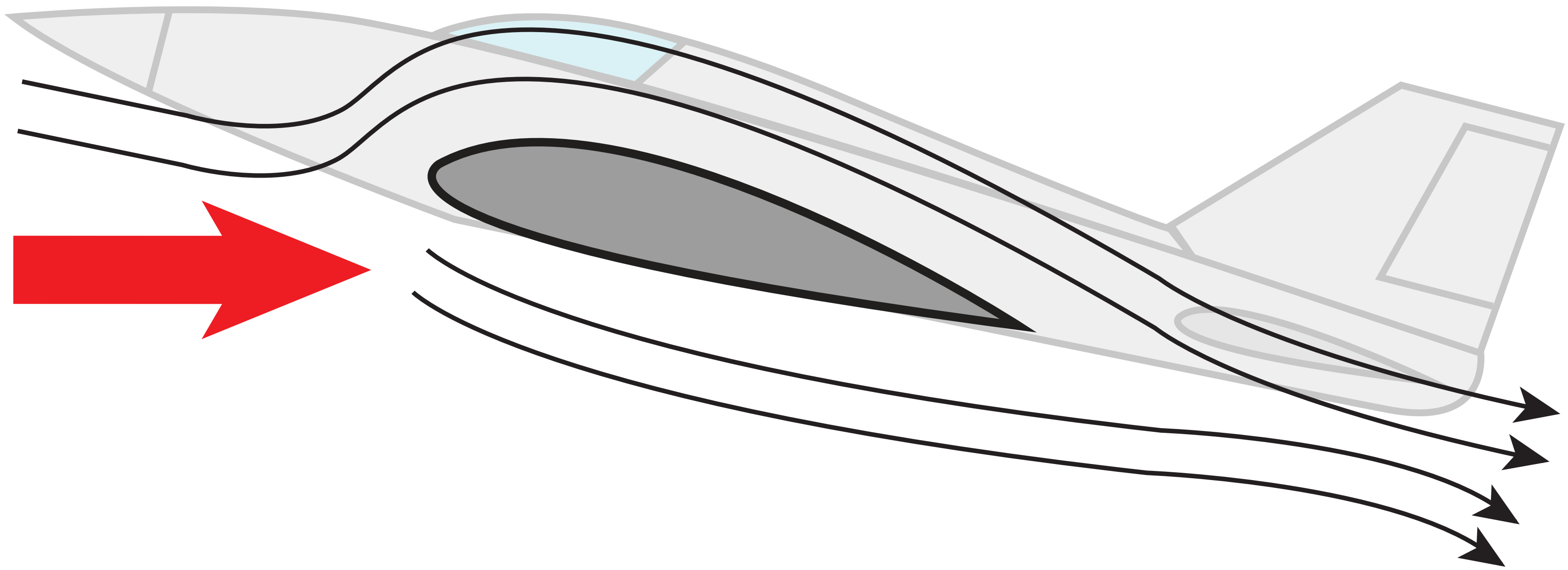


Fig. 5 Descending angle of attack

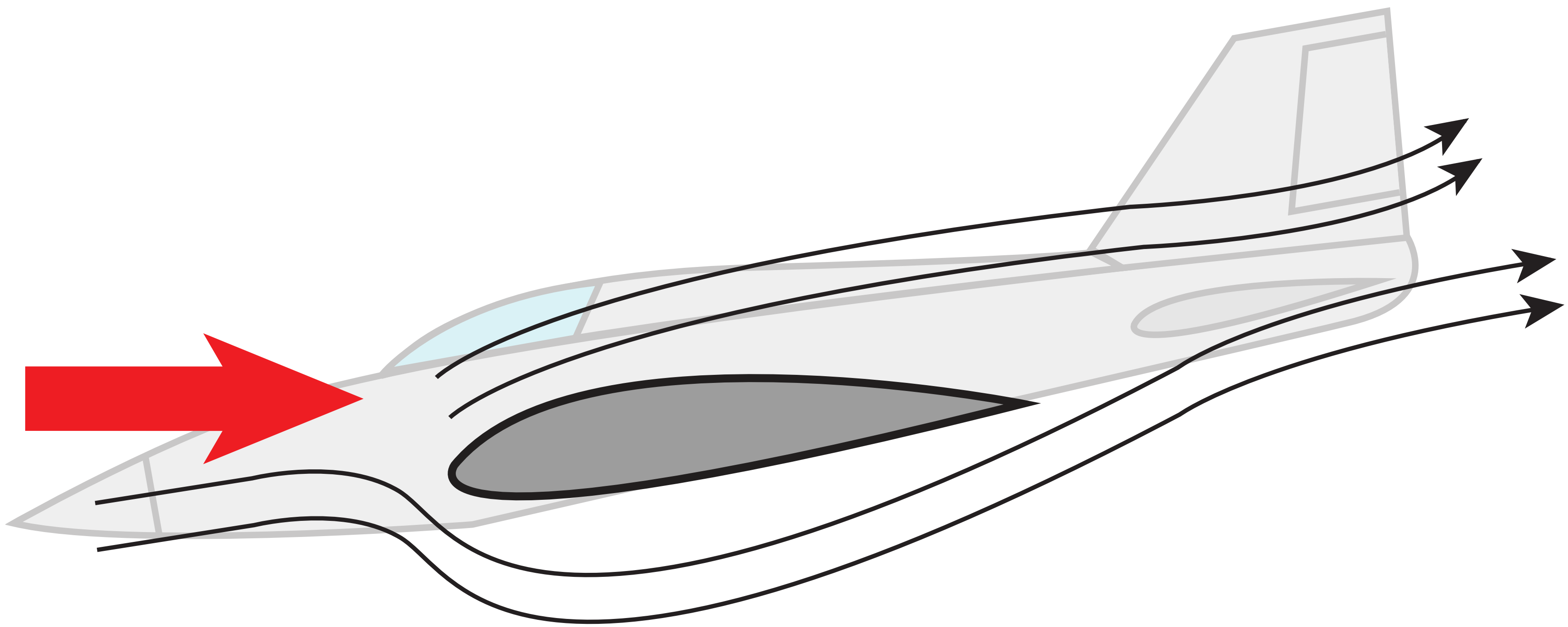


Fig. 6 Forces of straight and level flight

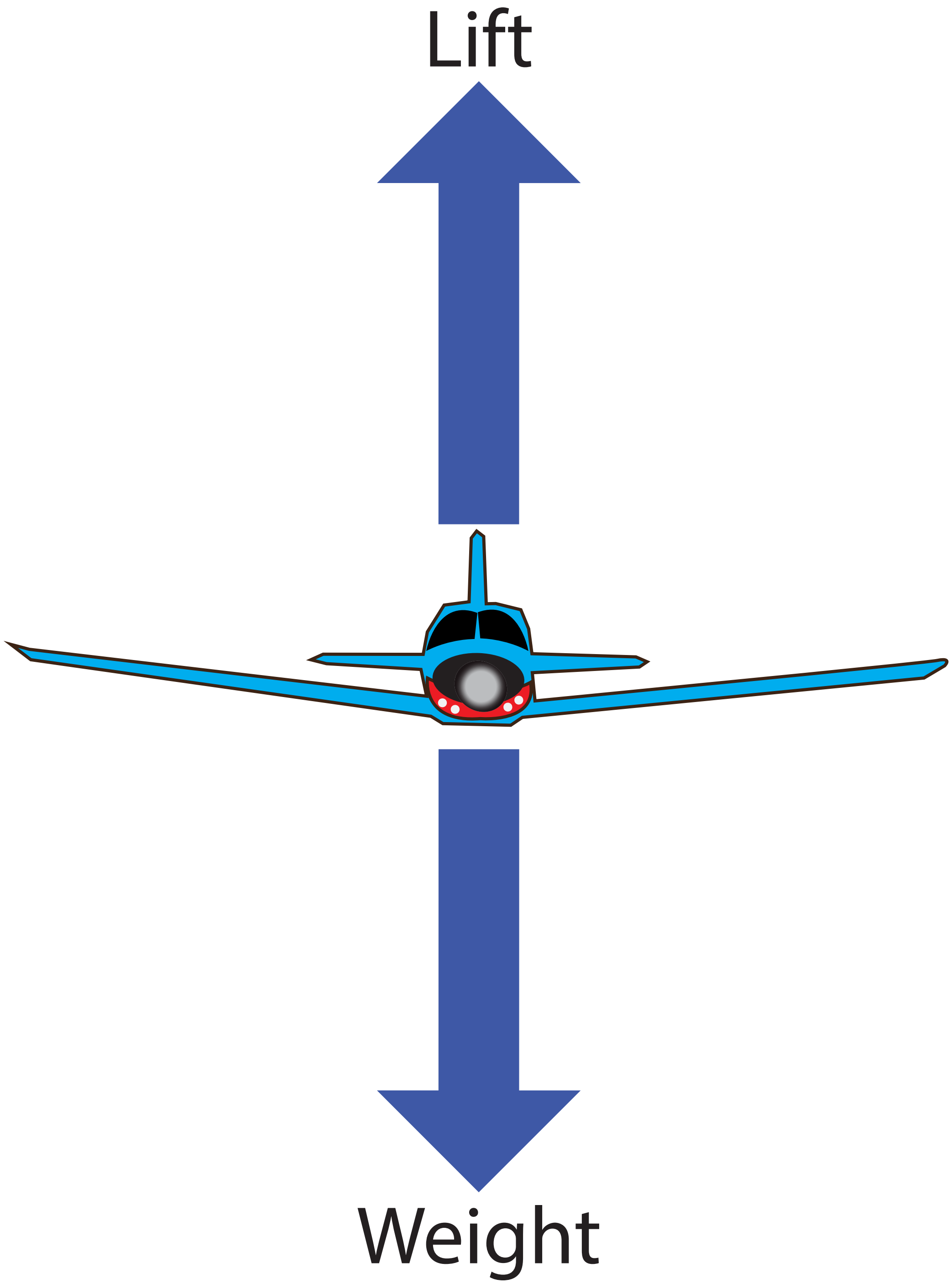


Fig. 7 Induced drag

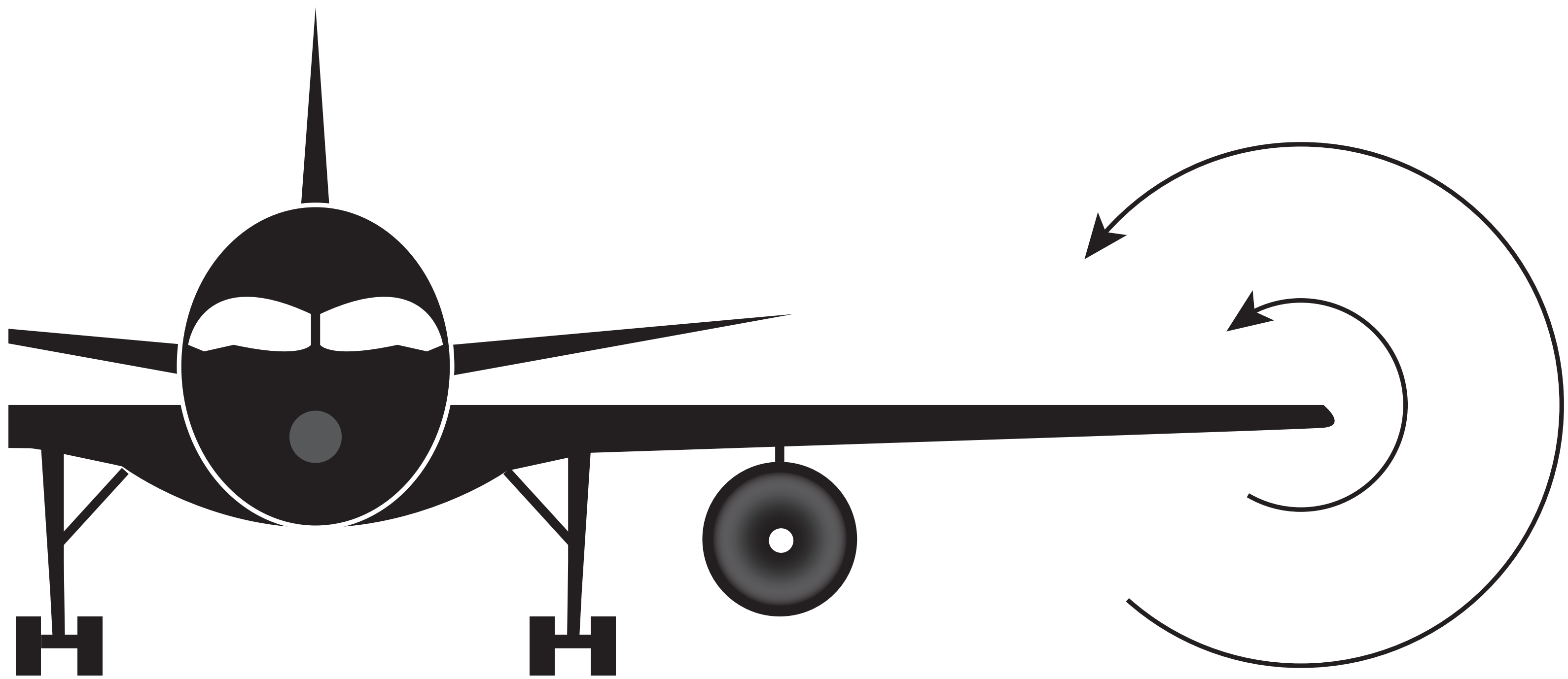


Fig. 8 Winglets effect on drag

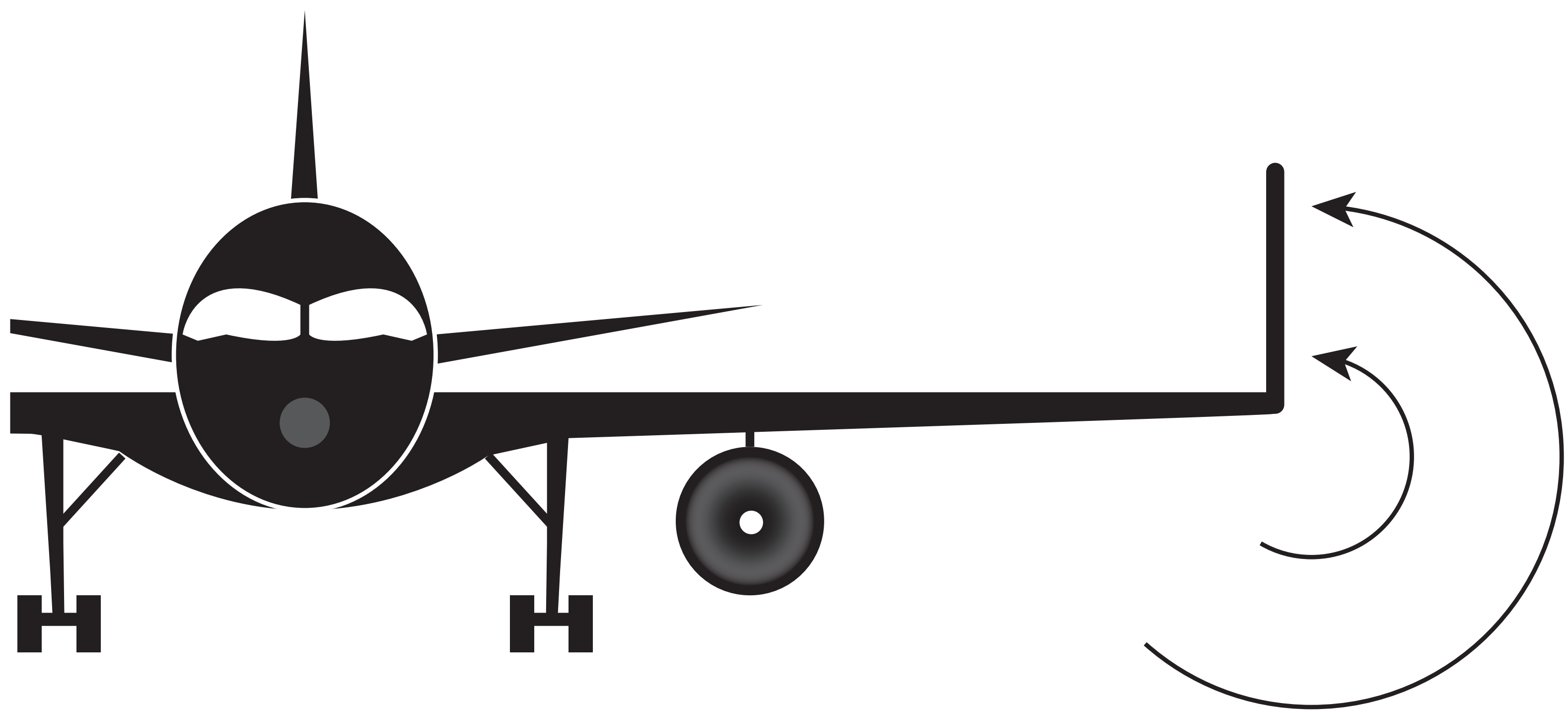
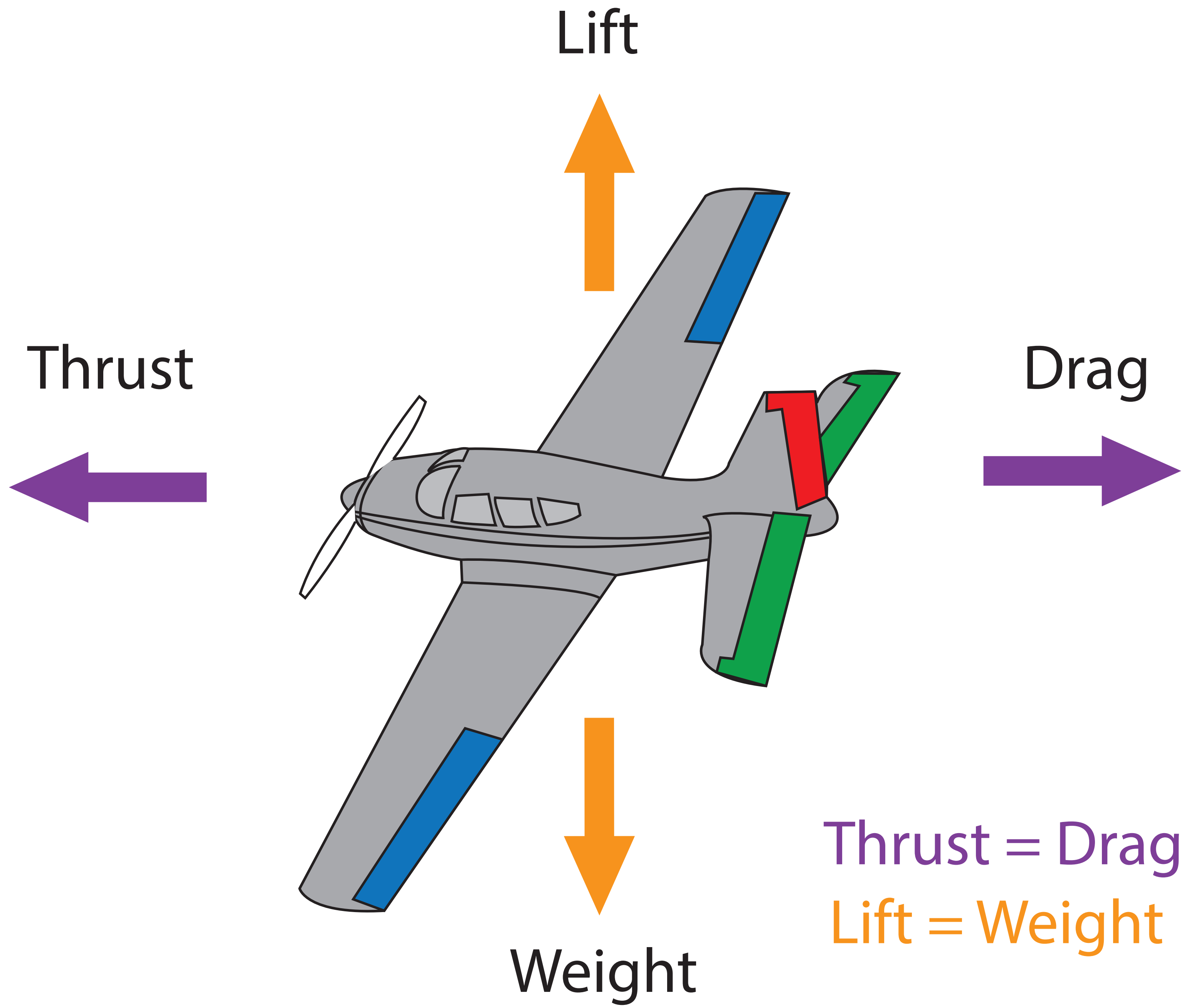


Fig. 9 The four forces of flight in balance



Worksheets

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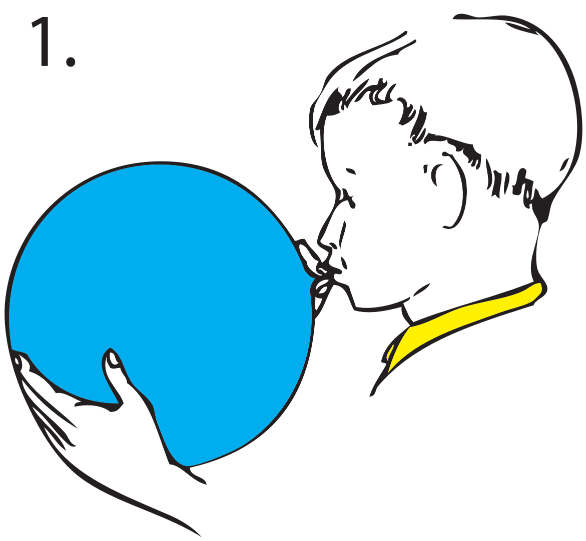
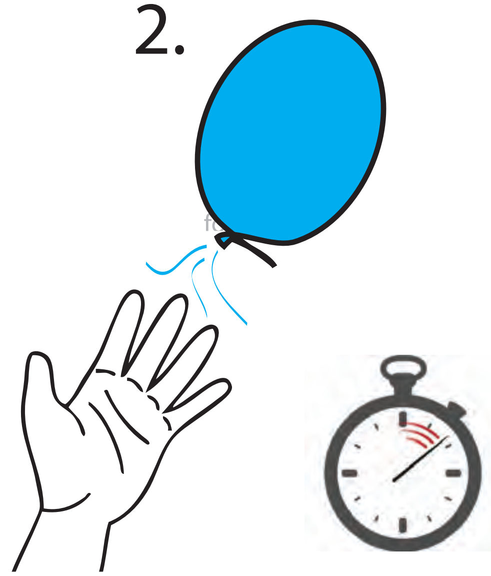
Station One: Thrust

1.



2.



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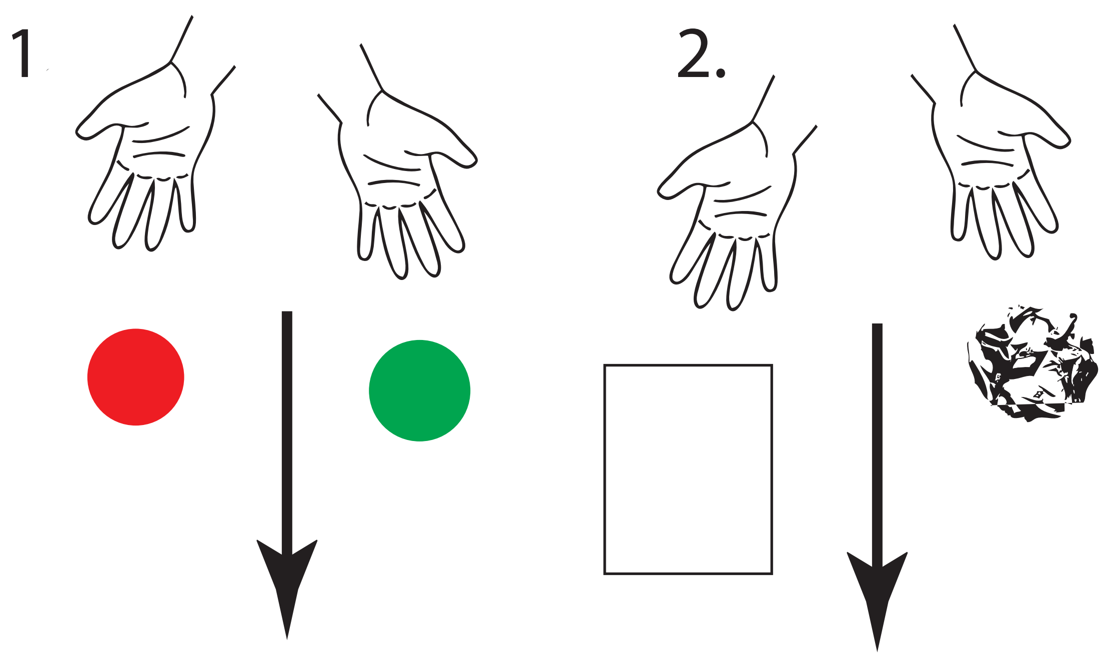
Station Two: Drag

1.  

2.  

fold fold

Station Three: Weight



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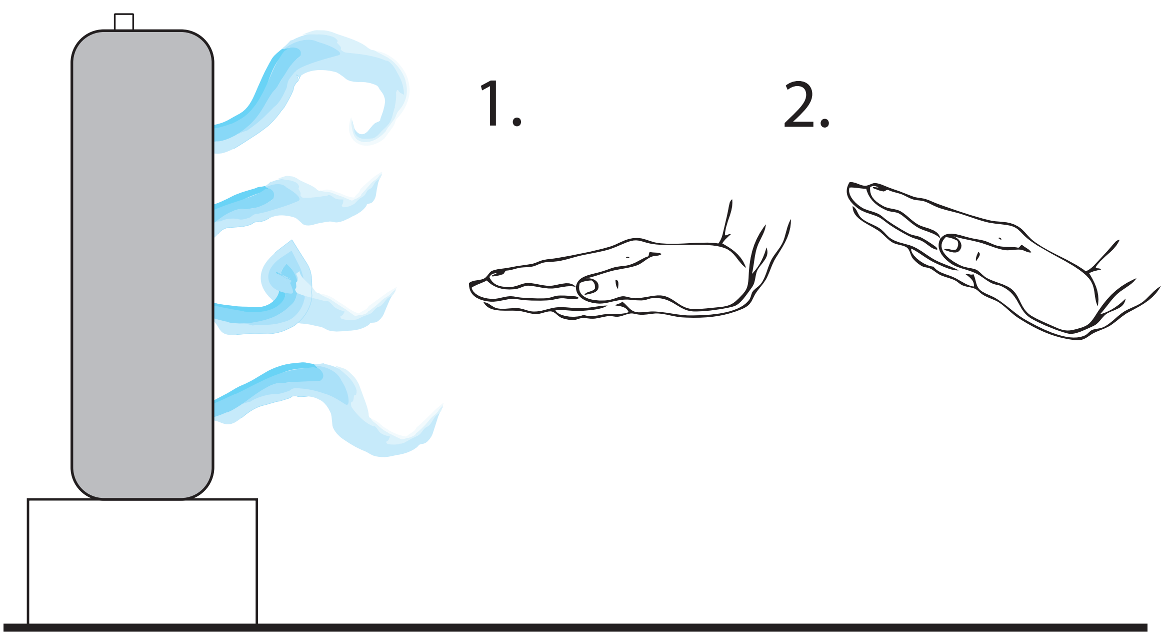
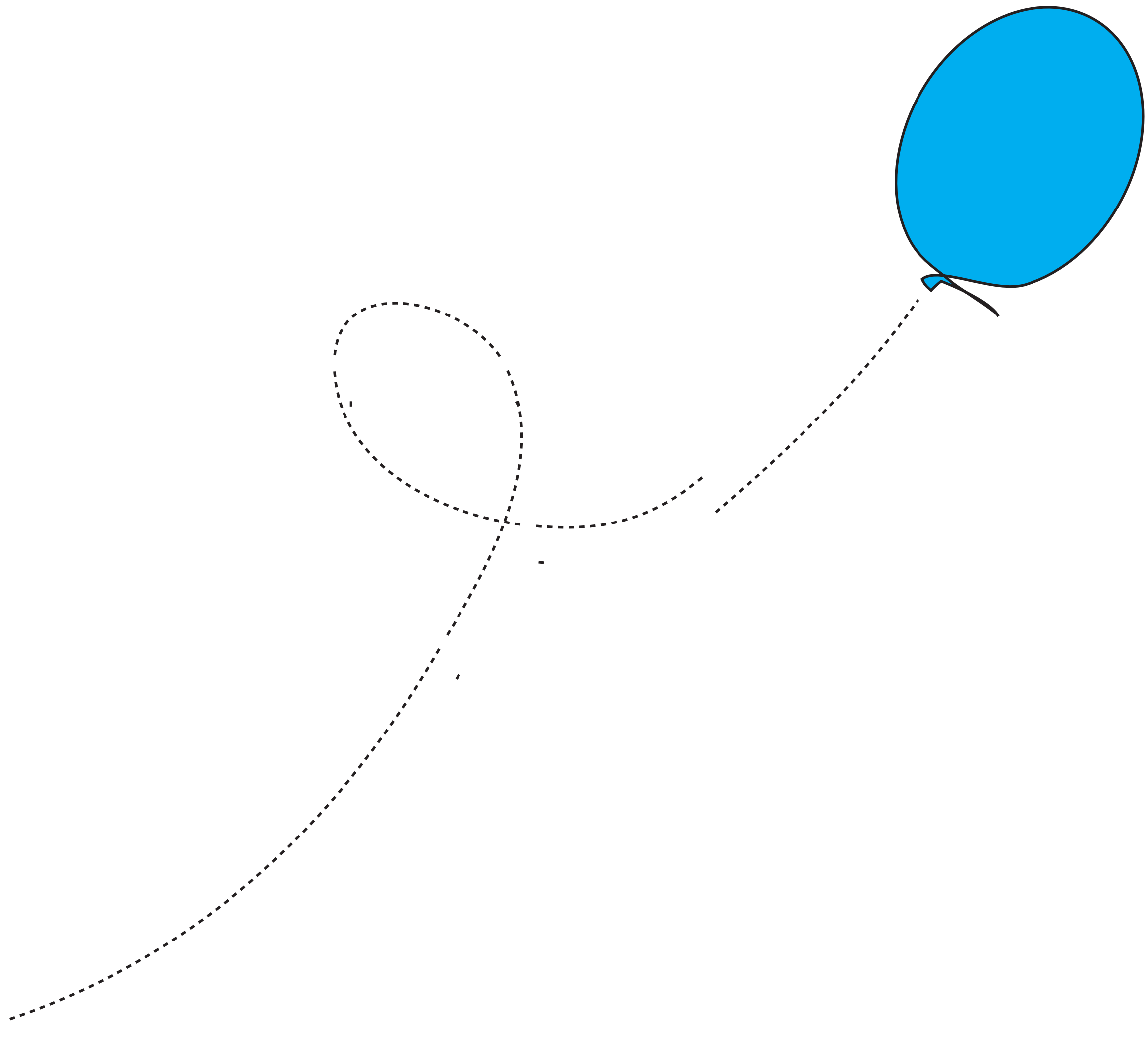
Station Four: Lift



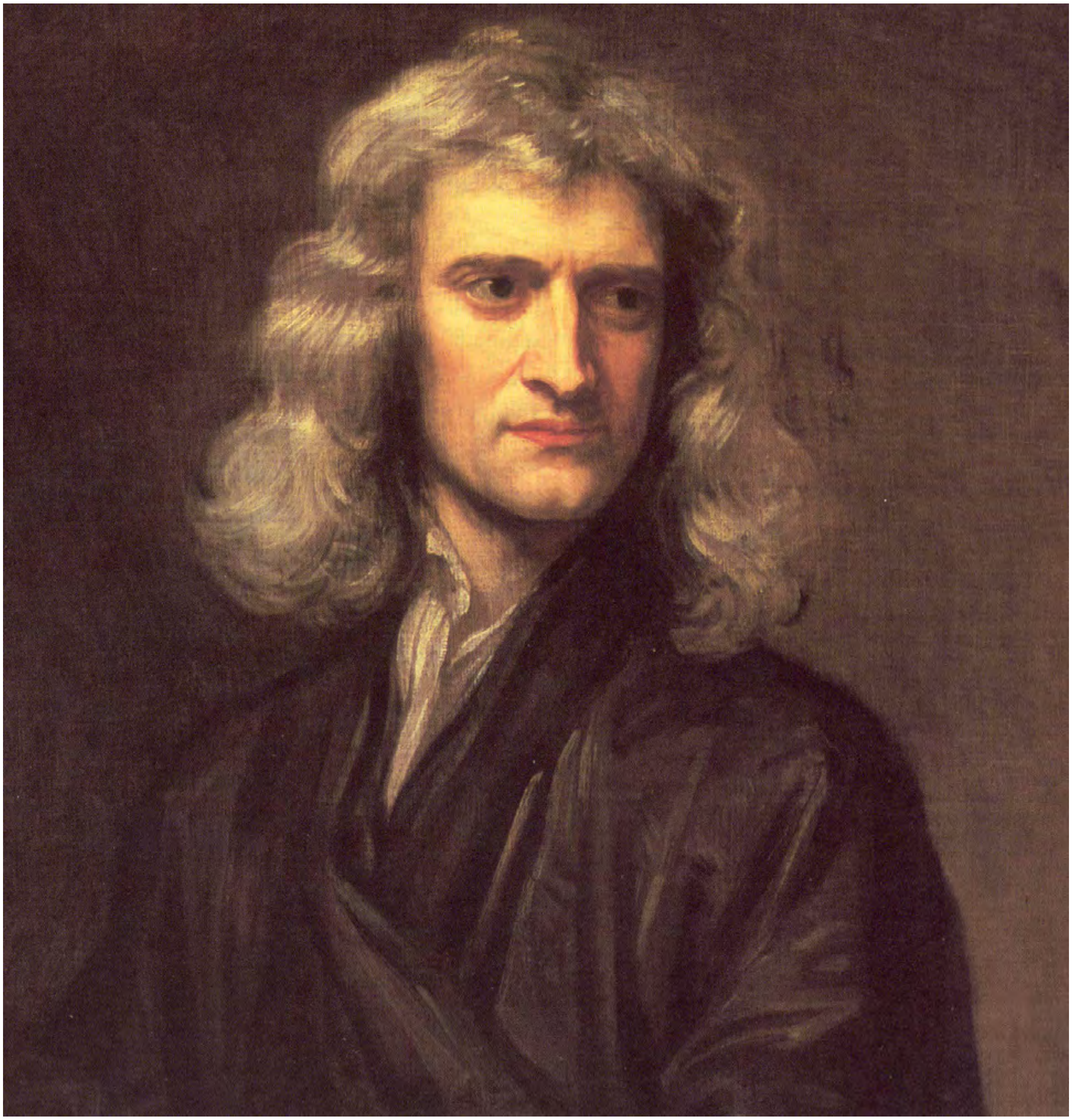
Worksheet 2 Thrust & Time



Number of Breaths	Flight Time

Images

Img. 1 Sir Isaac Newton (age 46)



(Painting by Sir Godfrey Kneller - 1689)

Img. 2 A NASA modified essna 190

(Photo courtesy of NASA)

Img. 3 A NASA modified Boeing 747

(Photo courtesy of NASA)

Img. 4 A NASA-modified C-135

(Photo courtesy of NASA)

Img. 5 A Boeing 727 vortex study

(Photo courtesy of NASA)

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

(Photo courtesy of NASA)

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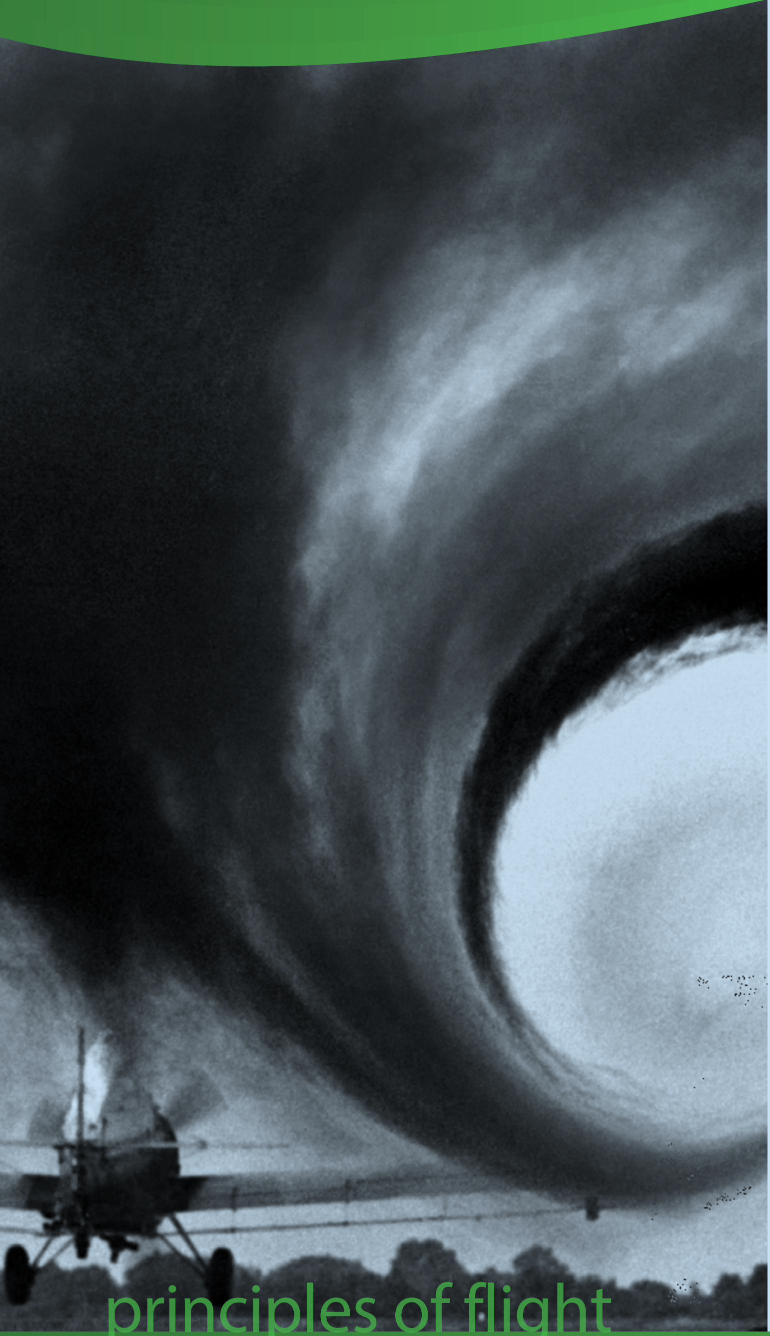

principles of flight

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