Octave Chanute’s expertise in designing bridges gave him the know-how to tackle some big questions in aviation, such as the structure of biplane wings. What skills have you acquired from school that you could apply to a hobby?

Chanute’s great interest in flight led him to lecture on the subject, write books on its history, tinker with and design aircraft, and correspond with aviators. He served as a one-man clearinghouse for information on aviation discoveries.

The French-born American spent his career as a civil engineer working on railroads and bridges. Aviation was a hobby. He devoted himself to it wholeheartedly after retiring from the railroad business at age 57. Among his career achievements was designing the country’s first railroad bridge over the Missouri River. He also invented a way to preserve wood for rail ties, specialized in iron bridges, and had a great knowledge of how to build a truss—a support structure—which he applied to bridges and later to his gliders.

Chanute’s first book on aviation—Progress in Flying Machines (1894)—was invaluable to the Wrights and other aviators in their experiments. It was like an instruction manual; it examined the technical findings already made. The book also analyzed the errors of would-be aviators and helped others correct them.

Chanute never patented any of his work. In fact he didn’t approve of the Wright brothers’ efforts to sell their powered aircraft. He argued that knowledge should be freely shared.
Even so the three men kept in close contact over the years, and Chanute saw their test flights numerous times in 1902, 1904, and 1905. He had conducted his own glider experiments in the 1890s from the Indiana dunes on Lake Michigan. He applied much of what he had learned building bridges to his glider construction, especially to wing structure. The biplane—an aircraft with two main supporting surfaces, usually placed one over the other—still uses his strut-wire-braced wing framework. He also laid the groundwork for aircraft control and stability.

The former Chanute Air Force Base in eastern Illinois (closed in 1993) was named after him. The Chanute Air Museum is still located there.
How Lift Is Generated

Aircraft are subject to four forces: lift, weight, thrust, and drag. Newton referred to such forces in his first law (Figure 2.1): “Objects at rest remain at rest and objects in motion remain in motion in a straight line unless acted upon by an unbalanced force.” These forces push and pull airplanes in numerous directions—up and down, back and forth, and side to side.

You can measure all four of these forces. They all have a magnitude—a measurable amount, such as a size, speed, or degree. For example, you can measure how fast (the magnitude) an aircraft is traveling.

In order to safely fly, you must understand these four forces and their effect on your aircraft. This lesson will explain these forces in greater detail and how they interact with one another during flight.

What Lift Is

In the previous lesson you read that to fly, you need a lifting force. Lift is the upward force on an aircraft against weight. At less than the speed of sound, you create lift by increasing the aircraft’s forward motion and the airfoil’s angle of attack—up to the stall speed.

Remember that an aircraft’s motion through the air generates lift as the air passes over an airfoil, or wing. Therefore, lift is an aerodynamic force—one that deals with an object moving through air or air moving around an object.

Airfoils generate most of an airplane’s lift, although the amount of lift an aircraft achieves also depends on the plane’s shape, size, and velocity—speed and direction. The major role played in lift by airfoils explains why the Wright brothers spent so much time researching wing shape and size. As you can see from Table 2.1, the Ohio inventors continued to increase the wingspan’s length and the wings’ surface area to produce greater lift and control.

How to Control Lift

When you pilot an airplane, you adjust lift with the controls that allow you to direct the angle of attack. If you need more lift, you can increase the angle of attack (only up to the critical angle of attack, though, because you don’t want to stall). If you need less, you can decrease the angle of attack.
The Wright brothers focused a lot of attention on developing the wings for their gliders. Over time they increased the wingspan (the distance from wingtip to wingtip) and the chord, increasing the wing area on their gliders. This gave their aircraft, including the powered 1903 Wright Flyer, more lift, stability, and control, as well as the ability to fly with more weight. Table 2.1 shows their steady progress.

<table>
<thead>
<tr>
<th>Gliders</th>
<th>Wingspan</th>
<th>Wing Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900 glider</td>
<td>17 feet</td>
<td>165 square feet</td>
</tr>
<tr>
<td>1901 glider</td>
<td>22 feet</td>
<td>290 square feet</td>
</tr>
<tr>
<td>1902 glider</td>
<td>32 feet</td>
<td>305 square feet</td>
</tr>
<tr>
<td>1903 Wright Flyer</td>
<td>40 feet 4 inches</td>
<td>510 square feet</td>
</tr>
</tbody>
</table>

Table 2.1 The Wrights’ increasing wingspan

Orville Wright with the 1901 glider at Kitty Hawk
Courtesy of Library of Congress, Prints & Photographs Division [LC-DIG-ppprs-00574]
As mentioned earlier, you also need velocity for lift. Stated mathematically, lift is proportional to velocity squared. At low speeds, every time you double your velocity, you get four times as much lift. For example, an aircraft traveling at 200 knots has four times as much lift as an aircraft traveling at 100 knots, all other factors remaining constant.

Besides adjusting your angle of attack, you can also increase or decrease lift by changing your velocity. Your aircraft will climb if you keep a steady angle of attack and increase your velocity. It will also climb if you hold your velocity steady and increase your angle of attack. Therefore, to keep to a level, straight flight path, you must balance angle of attack and velocity.

Air density also affects lift. This density is determined by the air's pressure, temperature, and humidity. The higher you go, the less dense the air is. So at higher altitudes you must fly at a different airspeed for any given angle of attack to maintain lift.

Further, warm air is less dense than cool air, and moist air is less dense than dry air. So on a humid day in the middle of summer, you'll need to fly at a greater velocity to maintain lift than you will on a dry day in the middle of winter.

**How Weight Affects Flight**

The downward force that directly opposes lift is weight. Weight is always directed toward the center of Earth because of the force of gravity. Weight acts through a single point called the center of gravity (Figure 2.2). The center of gravity is the average location of an object's weight.
Unlike lift, and drag, weight is not an aerodynamic force. Weight is the gravitational force on an object due to its mass. The nature of these forces differs: aerodynamic forces are mechanical forces, meaning an aircraft must be in physical contact with air to generate them. On the other hand, an aircraft doesn’t have to be in physical contact with Earth (the source of the gravitational force) for gravity to pull down on it.

The magnitude, or size, of an aircraft’s weight depends on the aircraft’s mass, made up of its parts, fuel, passengers, and freight. Remember that weight and mass are not the same thing: weight relates to gravity, but mass is a measure of inertia. This means the more mass an object has, the more difficult it is to overcome its inertia or resistance to moving.

Think of a cannonball versus a child’s beach ball—they may be approximately the same size, but the cannonball is much more difficult to roll forward than the beach ball. This is because the cannonball has more mass than the beach ball. An object’s weight varies depending on where it is in the universe. Its mass is always the same.

**Weight’s Major Challenges**

Weight poses two major challenges in flying: overcoming an aircraft’s weight and controlling the aircraft in flight. You overcome weight with lift. As you increase the angle of attack and speed, you get more lift than weight and the aircraft climbs. Just the opposite would also be true: a lower angle of attack and speed decreases the lift. When the weight is greater than the lift, the aircraft descends.
Newton’s second law, also explained in the last lesson, addresses the question of overcoming weight. A heavy aircraft requires more acceleration to take off (net force = mass × acceleration, or \( F = ma \)), while a lighter plane requires less acceleration.

Controlling the object’s flight also requires handling the aircraft’s weight and the location of its center of gravity. An aircraft’s weight changes during flight because it consumes fuel. (You’ll read more about the fuel cells in the next lesson.) The distribution of weight and its center of gravity also shift during flight, so pilots have to constantly trim—or balance—the aircraft. (Pilots have to trim the aircraft because of changes in speed, as well.)

### How Thrust Affects an Aircraft’s Movement

Another force that affects flight is thrust. Thrust is a forward force that moves an aircraft through the air. Its opposite force is drag, the pull or slowing effect of air on an aircraft.
Where Thrust Comes From

Engines provide a powered aircraft’s thrust. It is important to note that the engine’s only job is to provide thrust; it does not lift an aircraft. The wings (airfoils) provide the aircraft’s lift; thrust provides forward motion to overcome drag and allows the airfoils to produce lift.

The placement of engines, their number, and their type affect thrust. Some aircraft have the ability to change the direction of the thrust rather than changing the angle of attack. For instance, a Harrier jet can rotate its nozzles to direct thrust downward.

Thrust demonstrates Newton’s third law, as illustrated particularly by jet engines. The hot gas pouring out the engine nozzle thrusts the jet forward. The engine pushes on the gas, and the gas pushes on the engine. This is the action and equal and opposite reaction Newton laid out in this law.

Adjusting Thrust

Just as you can increase or decrease the amount of lift on your plane, you can also adjust the amount of thrust your engine produces. If you reduce your engine power while in level flight, your thrust drops and the aircraft slows down. As long as thrust is less than drag, your aircraft decelerates until its airspeed will no longer provide enough lift to support the plane in the air.

On the other hand, if you increase your engine power while in level flight, your thrust grows greater than drag and your airspeed increases. As long as this particular imbalance continues, you will accelerate. When the two forces are equal, you will fly at a constant airspeed.

You can maintain straight and level flight at a wide range of airspeeds. To maintain the balance between lift and weight and so maintain straight and level flight, you must properly coordinate thrust and angle of attack at any speed. Experts group flight into three main categories: low-speed flight, cruising flight, and high-speed flight (Figure 2.3).
• **Low-speed flight**—When airspeed is low, you must keep the angle of attack fairly high. This greater angle of attack generates a lift force equal to the aircraft’s weight. You’ll be flying slowly but you can maintain level flight this way.

• **Cruising flight**—In this situation, straight and level flight occurs at a higher speed than during low-speed flight. During this steady flight, you must decrease your angle of attack as you increase thrust and airspeed.

• **High-speed flight**—When airspeed is high (high thrust), you decrease your angle of attack even more. Otherwise, you will continue climbing. You can even fly at a slightly negative angle of attack if your thrust is great enough. By decreasing the angle of attack, you bring lift and weight back in balance and your aircraft remains in level flight.

**How Drag Slows an Aircraft**

Drag results from the air resisting an aircraft’s forward motion. Drag pulls in the opposite direction of the flight path. An aircraft’s shape, its speed, and the air’s viscosity—stickiness, or the extent to which air molecules resist flowing past a solid or other object—determine the magnitude of the drag.

As an aircraft moves through the air, molecules stick to its surface. This layer of air near a plane's surface is the boundary layer. It actually changes the shape of the airflow over the aircraft. So now as the plane flies, the air flows not only around the aircraft body, but it flows around this new shape created by the boundary layer. This flow creates vortices—a vortex is a kind of whirlpool of wind or water with a vacuum at its center.

Sometimes when the angle of attack nears the stalling point, the boundary layer separates from the aircraft to create an even more unusual shape. In this way the boundary layer can produce unsteady flying conditions. The boundary layer also plays a large role in determining an object’s drag (Figure 2.4).
The angle of attack has become too large. The boundary layer vortices have separated from the top surface of the wing, and the incoming flow no longer bends completely around the leading edge. The wing is stalled, causing a significant drag. However, much of the lift remains because the separated vortices are still above the wing.

Figure 2.4 This series of simulations shows how the boundary layer (the black-and-white dots) can separate from the wing and cause a stall. Courtesy of Leon van Dommelen, FAMU-FSU College of Engineering
Figure 2.5 Form drag
Reproduced from US Department of Transportation/Federal Aviation Administration
Types of Drag

Drag comes in two main forms: parasite drag and induced drag. Parasite drag does nothing to help an aircraft fly. It does just what it sounds like—drains flight of needed energy. Induced drag, on the other hand, results from an airfoil developing lift.

Parasite Drag

There are three types of parasite drag: form drag, interference drag, and skin friction drag. Antennas, engine covers (cowlings), and other items that determine an aircraft’s shape create form drag. When air passes over an aircraft, it parts when it hits one of these objects, then rejoins when it gets to the other side. Think of a rock in the middle of a stream and how the water flows around the rock. How smoothly the air flows around objects on an aircraft determines how much form drag impedes flight. Engineers try to make aircraft and their parts as streamlined as possible to reduce form drag (Figure 2.5).

Interference drag is a bit more complex. When airplane surfaces meet at perpendicular angles (such as the body and wings) or other sharp angles, the air flows over each in different currents. When these currents collide, they create interference drag. Designers try to overcome this drag with such things as fairings (a fairing is a cover or structure used to reduce drag) and by putting some distance between airfoils and not-so-streamlined parts such as radar antennas.

Skin friction drag concerns air stickiness and the boundary layer. No matter how smooth an aircraft’s “skin,” when you get down to the molecular level there is always something for air molecules to stick to and create a boundary layer. Designers reduce skin drag by using flush mount rivets and removing anything that sticks up above the plane’s surface. Polishing the surface of the plane also reduces drag. Pilots of smaller aircraft can fight skin drag by keeping their aircraft cleaned and waxed.
Induced Drag
Because no work is 100 percent efficient, balanced flight always includes *induced drag*. The presence of induced drag means more energy must be expended to counteract it.

As you’ve read, airfoils produce lift by taking advantage of the energy of the airflow. Whenever you have lift, the area above the wing has less pressure than the area below the wing. The high-pressure area then flows up toward the low-pressure area on the wing’s upper surface. When these two pressures meet at the wingtips, they equalize and shoot air in a lateral (sideways) stream toward the wings’ upper surface. The resulting vortices are sometimes visible as you can see in the accompanying photo. If you ever spot wingtip vortices and you are viewing these swirling currents from the aircraft’s tail, you will see that they spin clockwise at the left wingtip and counterclockwise at the right wingtip.
These vortices produce induced drag (Figure 2.6). The greater the vortices, the greater the induced drag. In a vortex the air flows above the tip and then comes back in a downwash behind the wing. This downwash pulls down and back on the aircraft. This rearward pull is induced drag.

Wingtip vortices can be very dangerous. They have caused or contributed to several aviation accidents.

**How the Four Forces of Flight Interact With Each Other**

The motion of the airplane through the air depends on the relative strength and direction of the four forces. If the forces are balanced, the aircraft cruises at a constant velocity. If the forces are unbalanced, the aircraft accelerates in the direction of the largest force.

During steady, level flight the opposing forces are in balance. Simply put, the sum of the opposing forces of lift and weight are zero, and the sum of the opposing forces of thrust and drag are zero. Put yet another way, lift has an equal value to weight and thrust has an equal value to drag so they cancel each other out.

To maintain a constant airspeed, your thrust and drag must remain equal; for a constant altitude, your lift and weight must be equal.

In this lesson you’ve read about the relationship between the four forces of flight and flight stability. You must control these forces to get an aircraft aloft, remain there, and land safely. The next lesson will study the parts of an airplane and how they help you do that.
Lesson 2 Review

Using complete sentences, answer the following questions on a sheet of paper.

1. What generates most of an airplane’s lift?
2. What do you do if you need more lift?
3. Where is weight always directed?
4. What two major challenges does weight pose?
5. What is an engine’s only job?
6. What happens when you increase engine power while in level flight?
7. Which three things determine the magnitude of drag?
8. Which two forms does drag come in?
9. What happens when the four forces of flight are unbalanced?
10. To maintain constant airspeed and constant altitude, what must happen?

APPLYING YOUR LEARNING

11. If an aircraft traveling at 200 knots has four times as much lift as an aircraft traveling at 100 knots, how much more lift does an aircraft traveling at 400 knots have as an aircraft traveling at 100 knots?