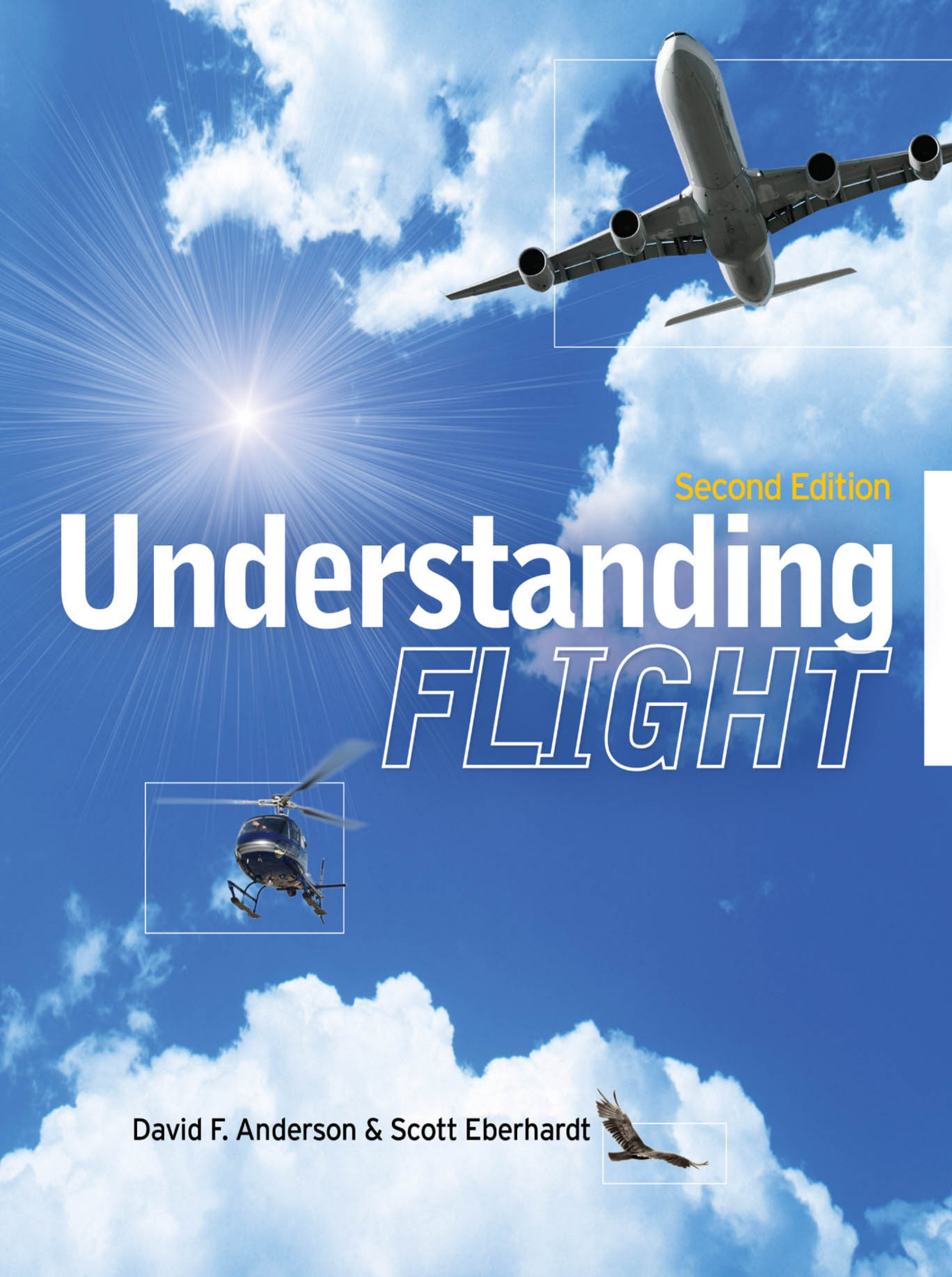
Second Edition
Understanding
FLIGHT
David F. Anderson & Scott Eberhardt

UNDERSTANDING FLIGHT

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UNDERSTANDING FLIGHT

David F. Anderson
Scott Eberhardt

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INTRODUCTION

Flight is a relatively simple and widely studied phenomenon. As surprising as it may sound, though, it is more often than not misunderstood. For example, most descriptions of the physics of lift fixate on the shape of the wing (i.e., airfoil) as the key factor in understanding lift. The wings in these descriptions have a bulge on the top so that the air must travel farther over the top than under the wing. Yet we all know that wings fly quite well upside down, where the shape of the wing is inverted. This is demonstrated by the Thunderbirds in Figure I.1, with wings of almost no thickness at all. To cover for this paradox, we sometimes see a description for inverted flight that is different than for normal flight. In reality, the shape of the wing has little to do with how lift is generated, and any description that relies on the shape of the wing is misleading at best. This assertion will be discussed in detail in Chapter 1. It should be noted that the shape of the wing does has everything to do with the efficiency of the wing at cruise speeds and with stall characteristics.

Let us look at three examples of successful wings that clearly violate the descriptions that rely on the shape of the wing as the basis of lift. The first example is a very old design. Figure I.2 shows a photograph of a Curtis 1911 Model D type IV pusher. Clearly, the air travels the same distance over the top and under the bottom of the wing. Yet this airplane flew and was the second airplane purchased by the U.S. Army in 1911.

During World War II, the length of a belt of 50-caliber machine gun bullets was 27 feet. When a pilot emptied his guns into a single target, he was giving it the "whole nine yards."

Figure I.3 shows the symmetric wing on an aerobatic airplane. The wing is thick and has a great deal of curvature on the top and bottom to give it good stall characteristics and to allow slow flight. The jets in

FIGURE I.1 Two Thunderbirds in flight. (Photograph courtesy of the U.S. Air Force.)

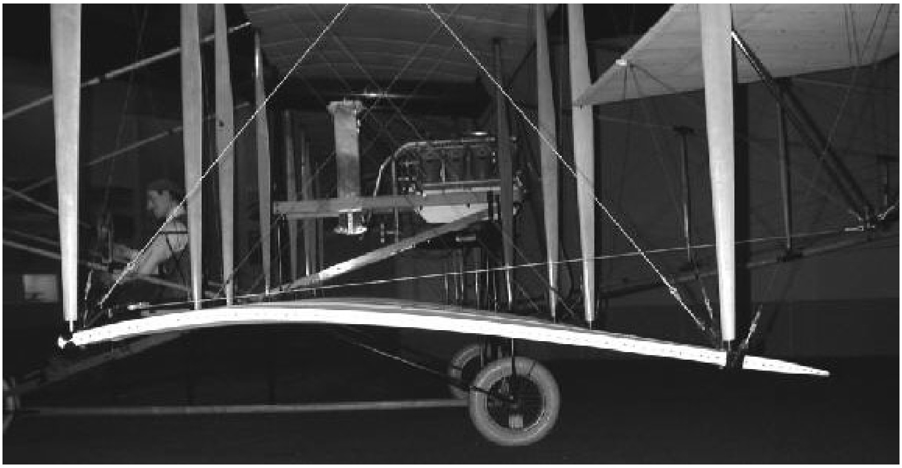

FIGURE I.2 Curtis 1911 Model D type IV pusher. (Photograph courtesy of the U.S. Air Force Museum.)

FIGURE I.3 **Symmetric wing on an aerobatic airplane.**

Figure I.1 have extremely thin, symmetric wings to allow them to fly fast but at the price of very abrupt stall entry characteristics.

The final example of a wing that violates the idea that lift depends on the shape of the wing is of a very modern wing. Figure I.4 shows the profile of the Whitcomb Supercritical Airfoil [NASA/Langley SC(2)-0714]. This wing is basically flat on top with the curvature on the bottom. Although its shape may seem contrary to the popular view of the shape of wings, this airfoil is the foundation of modern airliner wings.

The emphasis on wing shape in many explanations of lift is based on the *principle of equal transit times*. This assertion mistakenly states the air going around a wing must take the same length of time, whether going over or under, to get to the trailing edge. The argument goes that since the air goes farther over the top of the wing, it has to go faster, and with Bernoulli's principle, we have lift. Knowing that equal transit times is not defensible, the statement is often softened to say that since the air going over the top must go farther, it must go faster. Again,

FIGURE I.4 **Whitcomb Supercritical Airfoil.**

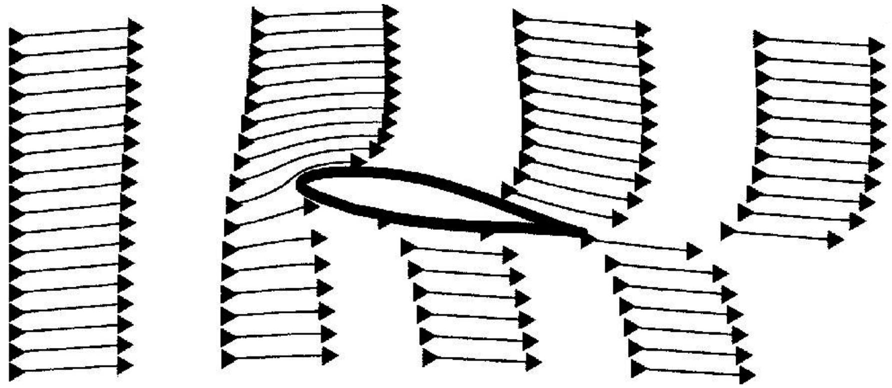

FIGURE I.5 Airflow around a wing with lift.

however, this is just a variation on the idea of equal transit times. In reality, equal transit times holds only for a wing without lift. Figure I.5 shows a simulation of the airflow around a wing with lift. It is easy to see that the air going over the wing arrives at the trailing edge before the air going under the wing. In fact, the greater the lift, the greater is the difference in arrival times at the trailing edge. Somewhere around World War II this popular assertion began to be taught from grade school to flight training classes. Before this idea permeated flight instruction, the correct idea of a lift as a reaction force was used.

Another erroneous argument that leads one to believe that the shape of the wing is responsible for the generation of lift is the argument that a wing is a half-venturi. The venturi (shown in the top of Figure I.6) works by constricting airflow. As the airflow constricts, it speeds up, much like putting your thumb on the end of a garden hose. Using the Bernoulli principle, the pressure (perpendicular to the flow) in the constriction decreases. This clever device is used to create low pressure to draw fuel into automobile carburetors. The argument for a wing goes like this: Remove the top half of the venturi, and you have a wing, as shown at the bottom of Figure I.6. The problem, as any physics student can tell you, is that there can be no net lift in the picture. If the air enters horizontally and leaves horizontally, how can there be a vertical force? This will be discussed in Chapter 1.

The air behind the wing is going almost straight down when seen from the ground.

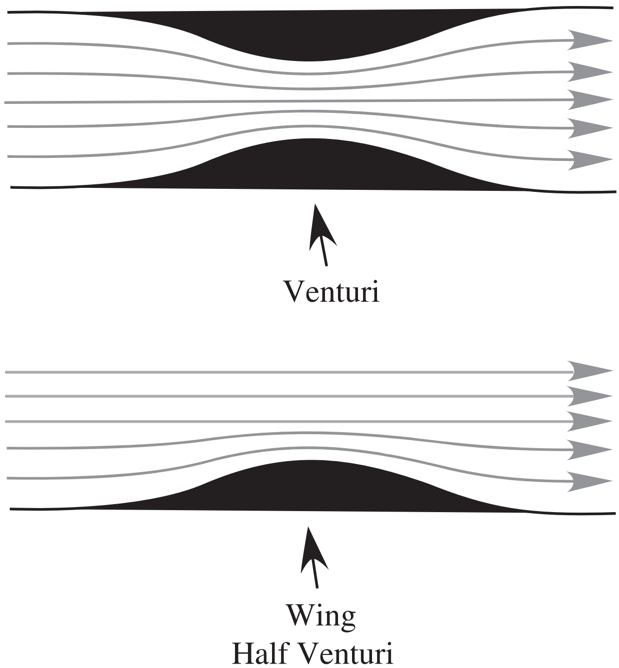

FIGURE 1.6 A venturi and a half-venturi.

We were motivated by these misleading and incorrect descriptions and others to write this book. Starting with lift as a reaction force, a consistent and physically correct description of lift is presented. While the foundation of this description was used commonly over a half-century ago, we have expanded on this simple description to describe many other aspects of flight.

The objective of this book is to present a clear, intuitive description of the phenomenon of flight and of aeronautics without complicated mathematics. This work will be presented on two levels. The bulk of the material will be addressed to the general reader. Here, a minimum of experience will be assumed. At times, it will be desirable to make clarifying comments by insertion of a short topic that may be somewhat removed from the main train of thought. These insertions will be printed on a colored background. These insertions may be skipped over without any loss of continuity or under-

Unlike previous versions, the tail-plane structure of the Boeing 747-400ER (Extended Range) houses extra fuel.

standing of the main text, although we will try to keep them of interest to the majority of readers.

Chapter 1, "Principles of Flight," is where we get into lift and flight. We believe that this chapter gives the most complete and correct physical description of lift to date. Like many before us, we describe lift using Newton's three laws. Unlike anyone else, to our knowledge, though, we take this description and use it to derive almost all aspects of flight. It allows one to intuitively understand aspects of flight that often are only explained mathematically. It will become clear to the reader why one increases the angle of the wing when the airplane slows down and why lift takes less power when the airplane goes faster. It will be obvious why airplanes can have symmetric wings and can fly upside down.

In the first edition of this book, there was a chapter entitled "Basic Concepts" that was an introduction to a basic set of terms and concepts of aircraft. This gave the reader and the authors a common set of tools with which to begin the discussion of flight and aeronautics. It was found to be too much information all at once and an unnecessarily complicated beginning to an otherwise readable book. We have made this chapter Appendix A in this edition. If the reader is a novice in the field of flight, he or she should read it through quickly and then use it as a reference while reading the book.

A Cessna 172 at cruise is diverting about five times its own weight in air per second to produce lift.

Two chapters have been added to this edition. The first is a chapter on helicopters and autogyros. We were unable to find a complete and readable discussion of these topics under one cover. Works were either too mathematical and too detailed or very incomplete. Such topics as the physical description of a helicopter's power curve were never discussed in physical terms.

The final chapter is a short discussion of airplane structures. The purpose of this chapter is to give the reader a brief introduction into how airplanes are constructed.

In the end, this book is a complete course in the principles of aeronautics, presented in straightforward, physical terms. We believe that the information will be accessible to nearly all who read it.

CHAPTER

1

Principles of Flight

Physical Description of Lift

A jet engine and a propeller produce thrust by blowing air back. A helicopter's rotor produces lift by blowing air down, as can be seen in Figure 1.1, where the downwash of a helicopter hovering over the water is clearly visible. In the same way, a wing produces lift by diverting air down. A jet engine, a propeller, a helicopter's rotor, and a wing all work by the same physics: Air is accelerated in the direction opposite the desired force.

This chapter introduces a physical description of lift. It is based primarily on Newton's three laws. This description is useful for understanding intuitively many phenomena associated with flight that one is not able to understand with other descriptions. This approach allows one to understand in a very clear way how lift changes with such variables as speed, density, load, angle of attack, and wing area. It is valid in low-speed flight as well as supersonic flight. This physical description of lift is also of great use to the pilot who desires an intuitive understanding of the behavior and limitations of his or her airplane. With the knowledge provided in this book, it will be easy to understand why the angle of attack must increase with decreasing speed, why the published maneuvering speed

The characteristic of fluids to have zero velocity at the surface of an object explains why one is not able to hose dust off a car.

FIGURE 1.1 A helicopter pushes air down. (Photograph courtesy of the U.S. Air Force.)

(maximum speed in turbulent air) for an airplane decreases with decreasing load, and why power must be increased for low-speed flight.

Lift is a reaction force. That is, wings develop lift by diverting air down. Since we know that a propeller produces thrust by blowing air back and that a helicopter develops lift by blowing air down, the concept of a wing diverting air down to produce lift should not be difficult to accept. After all, propellers and rotors are simply rotating wings.

One should be careful not to form the mental image of the air striking the bottom of the wing and being deflected down to produce lift. This is a fairly common misconception that also was held by Sir Isaac Newton himself. Since Newton was not familiar with the details of airflow over a wing, he thought that the air was diverted down by its impact with the bottom of a bird's wings. It is true that there can be some lift owing to the diversion of air by the bottom of the wing, but most of the lift is due to the action over the top of the wing. As we will see later, the low pressure that is formed above the wing accelerates the air down.

Newton's Three Laws

The most powerful tools for understanding flight are Newton's three laws of motion. They are simple to understand and universal in application. They apply to the flight of the lowly mosquito and the motion of the galaxies. We will start with a statement of Newton's first law: *A body at rest will remain at rest, and a body in motion will continue in straight-line motion unless acted on by an external applied force.*

In the context of flight, this means that if a mass or blob of air is initially motionless and starts to move, there has been some force acting on it. Likewise, if a flow of air bends, such as over a wing, there also must be a force acting on it. In the context of a continuum such as air, the force expresses itself as a difference in pressure.

The lift of a wing is proportional to the angle of attack. This is true for all wings, from a modern jet to a barn door.

Going out of order, Newton's third law can be stated: *For every action there is an equal and opposite reaction.*

This is fairly straightforward. When one sits in a chair, you put a force on the chair, and the chair puts an equal and opposite force on you. The force you put on the chair is the action, whereas the force the chair puts on you is the reaction. That is, the chair is reacting to the force you are putting on it. Another example is seen in the case of a bending flow of air over a wing. The bending of the air requires a force from Newton's first law. By Newton's third law, the air must be putting an equal and opposite force on whatever is bending it, in this case the wing. When the air bends down, there must be a downward force on it, and there must be an equal upward force on the wing by Newton's third law. The bending of the air is the action, whereas the lift on the wing is the reaction.

Newton's second law is a little more difficult to understand but also more useful in understanding many phenomena associated with flight. The most common form of the second law, which students are taught in early physics courses, is

$$F = ma$$

or force equals mass times acceleration.

The law in this form gives the force necessary to accelerate an object of a certain mass. For a description of the movement of air, we use an alternative form of this law that can be applied to a jet engine, a rocket, or the lift on a wing. The alternate form of Newton's second law for a rocket can be stated: *The force (or thrust) of a rocket is equal to the amount of gas expelled per time times the velocity of that gas*.

Newton's second law tells us how much thrust is produced by the engine of a rocket. The amount of gas expelled per time might be in units such as pound mass per second (lbm/s) or kilograms per second (kg/s). The velocity of that gas might be in units such as feet per second (ft/s) or meters per second (m/s). To double the thrust, one must double the amount of gas expelled per second, double the velocity of the gas, or a combination of the two.

Let us now look at the airflow around a wing with Newton's laws in mind. Figure 1.2 shows the airflow around a wing as many of us have been shown at one time or another. Notice that the air approaches the wing, splits, and re-forms behind the wing going in the initial direction. This wing has no lift. There is no net *action* on the air, and thus there is no lift, or *reaction* on the wing. If the wing has no net effect on the air, the air cannot have any net effect on the wing. Now look at another picture of air flowing around a wing (Figure 1.3). The air splits around the wing and leaves the wing at a slight downward angle. This downward-traveling air is the *downwash* and is the action that creates lift as its reaction. In this figure, there has been a net change in the air after passing over the wing. Thus there is a force acting on the air and a reaction force acting on the wing. There is lift.

If one were to sum up how a wing generates lift in one sentence, it would be that the wing produces lift by diverting air down. This statement should be as easy to understand as saying that a propeller produces thrust by pushing air back.

FIGURE 1.2 **Based on Newton's laws, this wing has no lift.**

FIGURE 1.3 **The airflow around a real wing with lift.**

Air Bending Over a Wing

As always, simple statements result in more questions. One natural question is, Why does the air bend around the wing? This question is probably the most challenging question in understanding flight, and it is one of the key concepts.

Let us start by first looking at a simple demonstration. Run a small stream of water from a faucet, and bring a horizontal water glass over to it until it just touches the water, as in Figure 1.4. As in the figure, the water will wrap partway around the glass. From Newton's first law, we know that for the flow of water to bend, there must be a force on it. The force is in the direction of the bend. From Newton's third law, we know that there must be an equal and opposite force acting on the glass. The stream of water puts a force on the glass that tries to pull it into the stream, not push it away, as one might first expect.

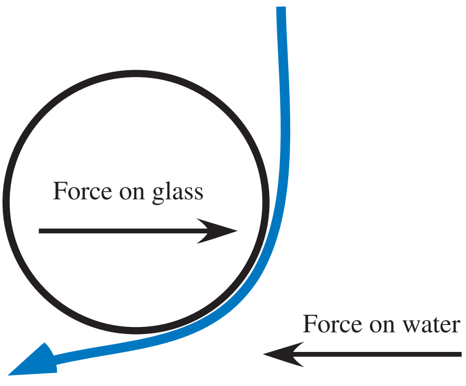

FIGURE 1.4 **Water wrapping around a glass.**

So why does the water bend around the glass or air over a wing? First, consider low-speed flight (subsonic). In low-speed flight, the forces on the air and the associated pressures are so low that not only is the air considered a fluid but it is also considered an incompressible fluid. This means that the volume of a mass of air remains constant and that flows of air do not separate from each other to form voids (gaps).

One out of every 11 airplanes registered in the United States flies to Oshkosh every year.

A second point to understand is that streamlines communicate with each other. A streamline, in steady-state flight, can be looked at as the path of a particle in the moving air. It is the path a small, light object would take in the airflow over the wing. The communication between streamlines is expressed as pressure and viscosity. Pressure is the force per area that the air exerts on the neighboring streamline. Viscosity in a gas or liquid corresponds to friction between solids.

Think of two adjacent streamlines with different speeds. Since these streamlines have different velocities, forces between them try to speed up the slower streamline and slow down the faster streamline. The speed of air at the surface of the wing is exactly zero with respect to the surface of the wing. This is an expression of viscosity. The speed of the air increases with distance from the wing, as shown in Figure 1.5. Now imagine that the first non-zero-velocity streamline just grazes the high point of the top of the wing. If it were to go straight back initially and not follow the wing, there would be a volume of zero-velocity air between it and the wing. Forces would strip this air away from the wing, and without a streamline to replace it, the pressure would lower. This lowering of the pressure would bend the streamline until it followed the surface of the wing.

The next streamline above would be bent to follow the first by the same process, and so on. The streamlines increase in speed with dis-

FIGURE 1.5 **The speed variations of a fluid near an object.**

tance from a wing for a short distance. This is on the order of 6 in (15 cm) at the trailing edge of the wing of an Airbus A380. This region of rapidly changing air speed is called the *boundary layer*. If the boundary layer is not turbulent, the flow is said to be *laminar*.

Thus the streamlines are bent by a lowering of the pressure. This is why the air is bent by the top of the wing and why the pressure above the wing is lowered. This lowered pressure decreases with distance above the wing but is the basis of the lift on a wing. The lowered pressure propagates out at the speed of sound, causing a great deal of air to bend around the wing.

Two streamlines communicate on a molecular scale. This is expressed as the pressure and viscosity of the air. Without viscosity, there would be no communication between streamlines and no boundary layer. Often, calculations of lift are made in the limit of zero viscosity. In these cases, viscosity is reintroduced implicitly with the *Kutta-Joukowski condition*, which requires that the air come smoothly off at the trailing edge of the wing. Also, the calculations require that the air follows the surface of the wing, which is another introduction of the effects of viscosity. One result of the near elimination of viscosity from the calculations is that no boundary layer is calculated.

The Wright brothers did not fly from October 16, 1905, to May 6, 1908, to protect their pending patent.

It should be noted that the speed of the uniform flow over the top of the wing is faster than the *free-stream velocity*, which is the velocity of the undisturbed air some distance from the wing. The bending of the air causes a reduction in pressure above the wing. This reduction in pressure causes an acceleration of the air. It is often taught that the acceleration of the air causes a reduction in pressure. In fact, it is the reduction of pressure that accelerates the air, in agreement with Newton's first law.

Let us look at the air bending around the wing in Figure 1.6. To bend the air requires a force. As indicated by the colored arrows, the direction of the force on the air is perpendicular to the bend in the air. The magnitude of the force is proportional to the tightness of the bend. The tighter the air bends, the greater is the force on it. The forces on the wing, as shown by the black arrows in the figure, have the same magnitude as the forces on the air, but in the opposite direction. These

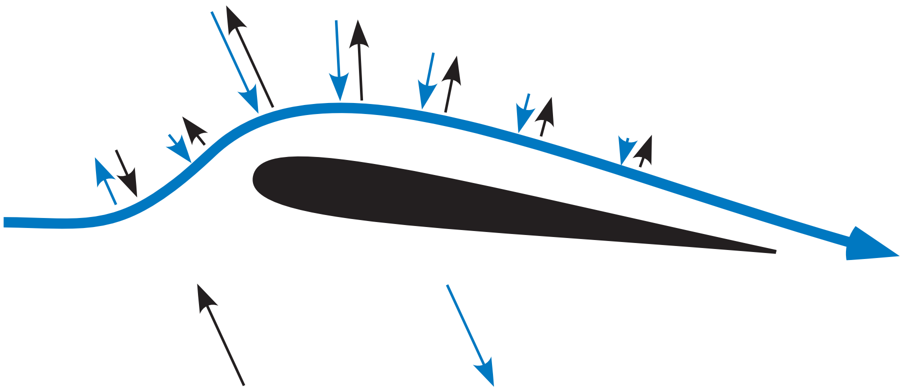

FIGURE 1.6 Forces on the air and the corresponding reaction forces on the wing.

forces, working through pressure, represent the mechanism in which the force is transferred to the wing.

Look again at Figure 1.6 while paying attention to the black arrows representing the forces on the wing. There are two points to notice. The first is that most of the lift is on the forward part of the wing. In fact, half the total lift on a wing at subsonic speeds typically is produced in the first one-fourth of the chord length. The *chord* is the distance from the leading edge to the trailing edge of the wing. The second thing to notice is that the arrows on the leading part of the wing are tilted forward. Thus the force of lift is pulling the wing along as well as lifting it. This would be nice if it were the entire story. Unfortunately, the horizontal forces on the trailing part of the wing compensate the horizontal forces on the leading part of the wing.

> **Because of the oil embargo, the price of 1000 gallons of Jet A1 fuel went from $100 in 1970 to $1100 in 1980.**

We now have the tools to understand why a wing has lift. In brief, the air bends around the wing, producing downwash. Newton's first law says that the bending of the air requires a force on the air, and Newton's third law says that there is an equal and opposite force on the wing. That is a description of lift. The pressure difference across the wing is the mechanism by which lift is transferred to the wing owing to the bending of the air.

Downwash

In the simplest form, lift is generated by the wing diverting air down, creating the downwash. Figure 1.7 is a good example of the effect of downwash behind an airplane. In the picture, the jet has flown above the fog, not through it. The hole caused by the descending air is clearly visible. As we will see, it is the adjustment of the magnitude of the downwash that allows the wing to adjust for varying loads and speeds.

From Newton's second law, one can state the relationship between the lift on a wing and its downwash: *The lift of a wing is proportional to the amount of air diverted per time times the vertical velocity of that air.*

FIGURE 1.7 **A jet flying over fog demonstrates downwash. (Photograph by Paul Bowen; courtesy of Cessna Aircraft Co.)**

Similar to a rocket, the lift of a wing can be increased by increasing the amount of air diverted, the vertical velocity of that air, or a combination of the two. The concept of the vertical velocity of the downwash may seem a little foreign at first. We are all used to thinking of the airflow across a wing as seen by the pilot or as seen in a wind tunnel. In this *rest frame*, the wing is stationary, and the air is moving. However, what does flight look like in a rest frame where the air is initially standing still and the wing is moving? Picture yourself on top of a mountain. Now suppose that just as a passing airplane is opposite you, you could take a picture of all the velocities of the air. What would you see? You might be surprised.

The first thing you would notice is that the air behind the wing is going almost straight down when seen from the ground. Because of friction with the wing, the air has, in fact, a slight forward direction. So how do we reconcile the two rest frames: the wing stationary and the air moving and the wing moving and the air stationary? Take a look at Figure 1.8a. The arrow labeled "Speed" is the direction and speed of the wing through the air. The arrow labeled "Downwash" is the direction and speed of the air as seen by the pilot or the engineer in the wind tunnel. The colored arrow labeled "V_v" is the vertical velocity of the air seen by the observer on the mountain. V_v is the vertical velocity of the downwash and represents the component that produces lift. In this figure, the letter α indicates the angle of the wing's downwash with respect to the relative wind, which is related to the *effective angle of attack* of the wing. Effective angle of attack will be discussed in the next section.

The engines on a Boeing 777 have a diameter that is within inches of the fuselage diameter of a Boeing 737.

The plausibility of the statement that the air comes off the wing vertically when the wing flies by is fairly easy to demonstrate. Turn on a small household fan, and examine the tightness of the column of air. If the air were coming off the trailing edges of the fan blades (which are legitimate wings) other than perpendicular to the direction of the blade's motion, the air would form a cone rather than a tight column. This also can be seen in a picture of a helicopter hovering above water (see Figure 1.1). The pattern on the water is the same size as the rotor blades. It is fortunate that nature works this way. If the air behind the propeller of an airplane came off as a cone rather than a column, pro-

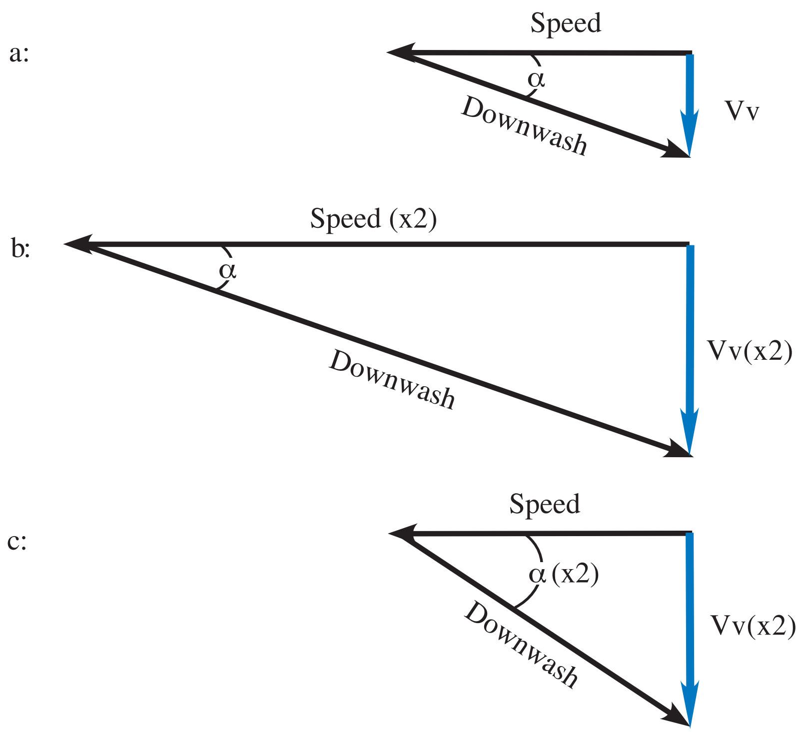

FIGURE 1.8 **Effects of speed and angle of effective attack on downwash.**

pellers would be a much less efficient means of propulsion. Only the component of thrust in the direction of motion of the airplane would be of use, and the rest of the thrust would represent wasted energy. Likewise, since the force of lift is up, one would expect the accelerated air that generates it to be down. Any other direction also would represent wasted energy.

The wing develops lift by transferring momentum to the air. Momentum is mass times velocity. In straight-and-level flight, the momentum is transferred toward the earth. This momentum eventually strikes the earth. If an airplane were to fly over a very large scale, the scale would weigh the airplane. The earth does not become lighter when an airplane takes off. This should not be confused with the (wrong) concept that the earth somehow supports the airplane. It does not. Lift on a wing is very much like shooting a bullet at a tree. The lift is like the recoil that the shooter feels, whether the bullet hits the tree or not. If the bullet hits the

DOES THE EARTH SUPPORT THE AIRPLANE?

Some people insist that since the airplane exerts a force on the earth, in straight-and-level flight, the earth is somehow holding the airplane up. This is definitely not the case. The lift on the wing has nothing to do with the presence of the surface of the earth. Examining two simple examples can show this.

The first example is to consider the thrust of a propeller, which is just a rotating wing. It certainly does not develop its thrust because of the presence of the surface of the earth. Neither could the presence of the earth provide the horizontal component of lift in a steep bank.

The second example to consider is the flight of the Concorde. It cruises at Mach 2 (twice the speed of sound) 55,000 ft (16,000 m) above the earth. The pressure information of the jet cannot be communicated to the earth and back faster than the speed of sound. By the time the earth knows the Concorde is there, it is long gone.

tree, the tree experiences the event, but that has nothing to do with the recoil of the gun.

The Adjustment of Lift

We have said that the lift of a wing is proportional to the amount of air diverted per time times the vertical velocity of that air. And we also have stated that in a rest frame where the air is initially at rest and the wing is moving, the air is moving almost straight down after the wing passes.

So what would happen if the speed of the wing were to double and the angle of attack were to remain the same? This is shown in Figure 1.8b. As you can see, the vertical velocity V_v has doubled. As we will soon see, the *amount of air diverted also has doubled*. As will be discussed shortly, the amount of air diverted is proportional to the speed of the airplane. Thus, in this case, *both the amount of air diverted and the vertical velocity of the air have doubled* with the doubling of the speed and keeping the angle of attack constant. Thus the lift of the wing has gone up by a factor of 4.

In Figure 1.8c, the wing has been kept at the original speed, and the relative angle of attack has been doubled. Again, the vertical velocity of the air has doubled, and since the amount of air diverted has not been affected, the lift of the wing has doubled. What these figures show is that the vertical velocity of the air is proportional to both the *speed* and the *angle of attack* of the wing. Increase either, and you increase the lift of the wing.

The pilot has controls for both airspeed and angle of attack. The airspeed is controlled by the power setting, along with the rate of climb or descent. The angle of attack is seen as a tilt of the entire airplane relative to the direction of flight and is controlled with the elevator, usually on the rear of the horizontal stabilizer, as shown in Figure A.1 (in Appendix A). The elevator works just like the wing in that it pushes air up or down to create a downward or upward lift, thus tilting the airplane.

Angle of Attack

Now let us look in more detail at the angle of attack of the wing. The *geometric angle of attack* is defined as the angle between the *mean chord* of the wing (a line drawn between the leading edge and the trailing edge of the wing) and the direction of the relative wind. This is what aeronautical engineers are referring to when they discuss angle of attack. For our discussion, we are going to use the *effective angle of attack*. The effective angle of attack is measured from the orientation where the wing has zero lift. The difference between the geometric angle of attack used by most people and the effective angle of attack used here should be emphasized to prevent potential confusion by the reader. Figure 1.9 shows the orientation of a cambered wing (see also Figure A.4 and text) with zero *geometric* angle of attack and the same wing with zero *effective* angle of attack. A cambered wing at zero geometric angle of attack has lift because there is a net downward diversion of the air. By definition, the same wing at zero effective angle of attack has no lift and therefore no net diversion of the air. In the case of a symmetric wing, the geometric and effective angles of attack are, of course, the same.

Harriet Quimby was the first U.S. woman to earn a pilot certificate, and in 1911 she was the first woman to pilot a plane across the English Channel.

For any wing, from that of a Boeing 787 to a wing in inverted flight, an orientation into the relative wind can be found where there is zero

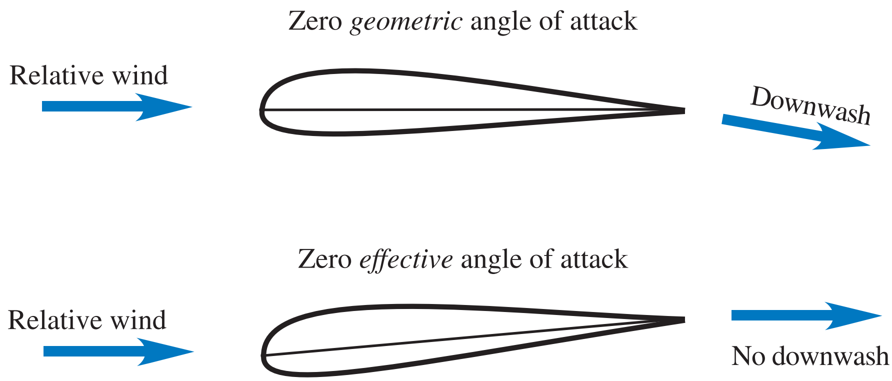

FIGURE 1.9 **Definition of geometric and effective angles of attack.**

lift. As stated earlier, this is zero effective angle of attack. Now, if one starts with the wing at zero degrees and rotates it both up and down while measuring the lift, the response will be similar to that shown on the graph in Figure 1.10. One can see that the lift is directly proportional to the effective angle of attack. The lift is positive (up) when the wing is tilted up and negative (down) when it is tilted down. When corrected for area and aspect ratio, a plot of the lift as a function of the effective angle of attack is essentially the same for all wings and all wings inverted. This is true until the wing approaches a stall. The stall begins at the point where the angle of attack becomes so great that the airflow begins to separate from the trailing edge of the wing. This angle is called the *critical angle of attack* and is marked in the figure. For two-dimensional (or infinite) wing simulations, lift as a function of effective angle of attack is identical for all airfoils.

Figure 1.10 also shows cross sections of the wings. A sharp, symmetric wing stalls earlier and more abruptly than a thick, asymmetric wing, but for smaller angles, the lift is the same for both. Turn the figure over, and you have the two wings' lift characteristics in inverted flight. Thus, as stated in the Introduction, any explanation of lift on a wing that depends on the shape of the wing is misleading at best. Such explanations also have trouble with explaining inverted flight, symmetric wings, and the adjustment of lift with load and speed. Again, it should be noted that the shape of the wing does affect the stall and drag characteristics of the wing.

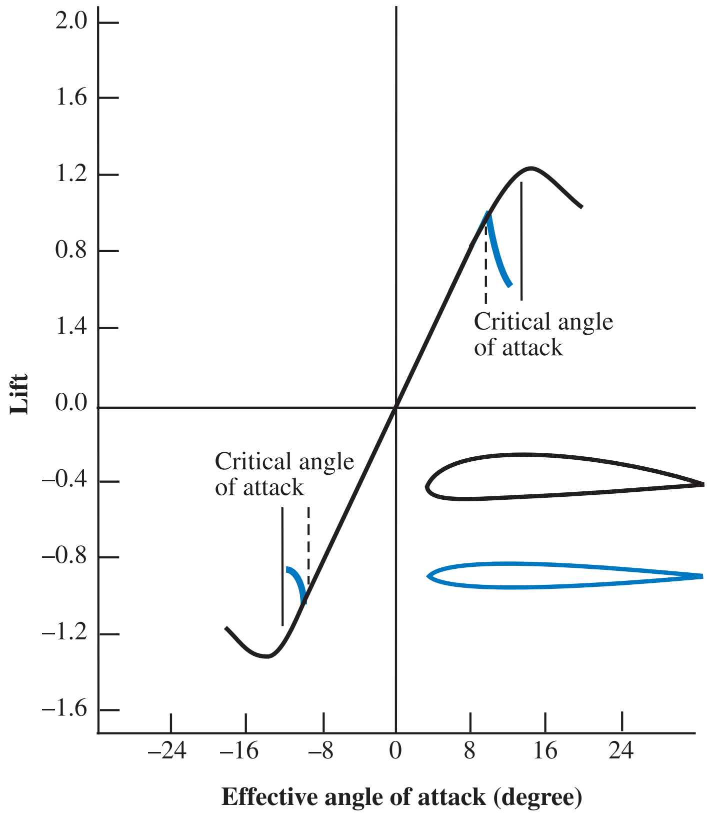

FIGURE 1.10 **Lift as a function of angle of attack.**

This is an extremely important result. It shows that the lift of a wing is proportional to the effective angle of attack. This is true for all wings: those of a modern jet, wings in inverted flight, a flat plate, or a paper airplane—or, for that matter, a bird's wing, as can be seen in the photo of a tern in Figure 1.11.

As can be seen in Figure 1.10, the relationship between lift and the angle of attack breaks down at the critical angle of attack. At this angle, the forces become so strong that the air begins to separate from the wing, and the wing loses lift while experiencing an increase in drag, a retarding force. At the critical angle, the wing is entering a stall. The subject of stalls will be covered in detail in Chapter 2.