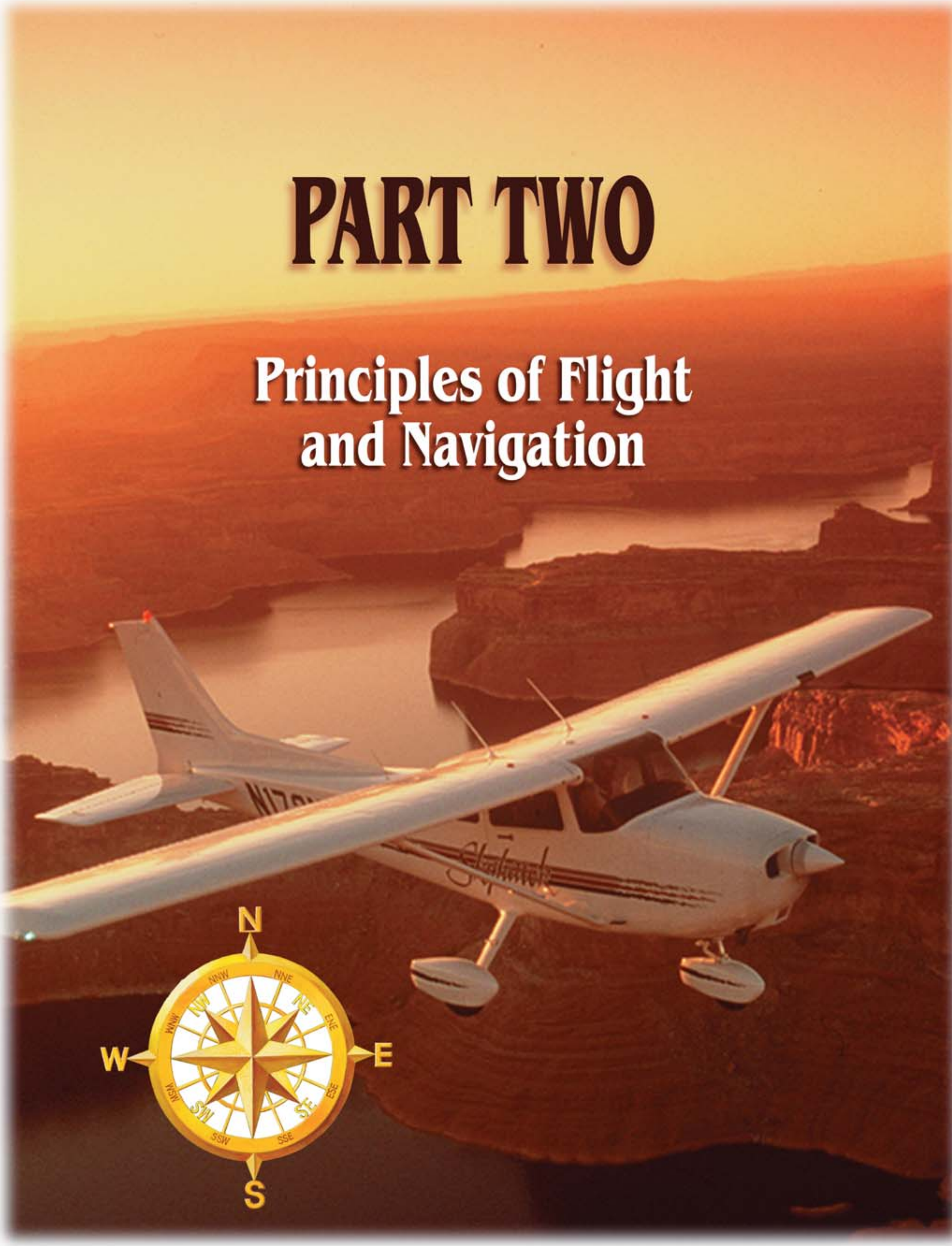
PART TWO

Principles of Flight and Navigation



Chapter 7 BASIC AERONAUTICS AND AERODYNAMICS

Objectives

Explain the difference between Aeronautics and Aerodynamics. Understand the properties of air that are important to flight.
Understand why scientists use simplifying assumptions during study.
Define airfoil.
Know the parts of an airfoil.
Describe the concepts of relative wind, angle of attack and streamlines.
Describe Bernoulli's Principle.
Describe the four forces of flight.
Give examples of aircraft characteristics that can improve each force.
Explain how the loss of one force affects the other three forces.
Describe the real world effects of viscosity and compressible airflow.
Name two effects wings have on airflow not accounted for by airfoils.

The Realm of Flight

The science and art of flight through the atmosphere is known as aeronautics. Aerodynamics, on the other hand, is the science relating to the energy of gases in motion.

To understand the science of aeronautics and aerodynamics, you must study the air and the machine that operates in it. Once you gain an understanding of the machine and its environment, you can appreciate the technological marvel of flight. One has only to watch a bird in flight for a short while and it becomes obvious that this living machine is capable of using the energy of the atmosphere to defy gravity.

The science of aerodynamics involves many investigations. Besides the study of airflow around an aircraft, it also includes the passage of air through a jet engine and even the expulsion of energy from a rocket motor. The common denominator of each of these examples is fluids in motion.

The Composition and Properties of Air

The atmosphere is a mixture of several gases. For practical purposes in the region where most flight occurs, it is a homogeneous mixture of one-fifth oxygen and four-fifths nitrogen. The atmosphere extends upwards to about 100 miles and can be compared to a pile of blankets.

Pressure

Air at the higher altitudes, is like the top blanket of the pile; it is under much less pressure than the air at lower altitudes. At the bottom of the atmosphere, say sea-level, the weight of all the layers of air above it press the bottom layer down at a pressure of 0.07651 lb/ft^3 (for dry air at 59°F, 40° latitude). That gives you a standard day pressure of 14.7 psi, or 29.92 on a mercury barometer.

The *Great Lakes Biplane* typifies the wonderful airplanes built in aviation's Golden Era.

Temperature

Temperature is a measure of the energy within a gas. The hotter the air, the more energy it has internally, and the faster its molecules move around.

The temperature of the atmosphere decreases at a rate of about 3-1/2 degrees, Fahrenheit, per 1,000 feet increase in altitude. This decrease in temperature continues up to about 38,000 ft MSL. You should remember, however, that the temperature of the air is under no contract to actually follow the standard. Sometimes, the temperature actually increases with altitude for a short distance.

Density

The density of air is essentially how many molecules are squeezed into a given volume. Higher density air is squeezed together more tightly than lower density air. From this, it can be assumed then, that air is compressible.

Because the air at higher altitudes has less pressure, it is also less dense. At sea level, on a cool day, the air is dense and airplanes perform very well.

Density is also related to temperature. As the air is heated, the molecules move farther apart and this means there is a decrease in density. On a hot day, at a high elevation, such as the airport in Leadville, CO (over 9000ft. MSL), some airplanes have difficulty taking off because the air is too thin.

Viscosity

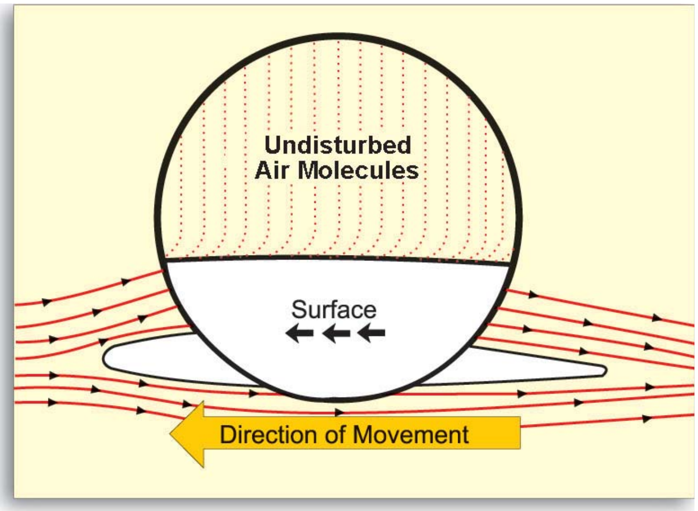
Viscosity is defined as a fluid's resistance to flow. An easy comparison would be water and honey. Honey is more viscous.

Since air is a fluid, it also has a resistance to flow. This is because of (1) the attraction between the molecules of the air and (2) the attraction between the air and the molecules of whatever it touches.

If a force is applied to air, its molecules resist a tendency to flow. The greater the density of the air, the greater the resistance.

A phenomenon known as **viscous drag** occurs when an object is placed in the path of moving air. The mutual attraction of molecules slows the rate of flow. This form of drag is transmitted to other air molecules that are not actually touching the surface over which they are flowing.

This transmission of drag is the result of a mutual attraction between molecules within the airstream, but it is not transmitted to all the air molecules. At some point away from the surface, the effect of viscous drag is lost.



Viscous Drag

Laminar Flow

As an object moves through the air, there is a flow **pattern** around it. This flow pattern is either smooth or turbulent. The smooth, and more desirable flow, is known as laminar.

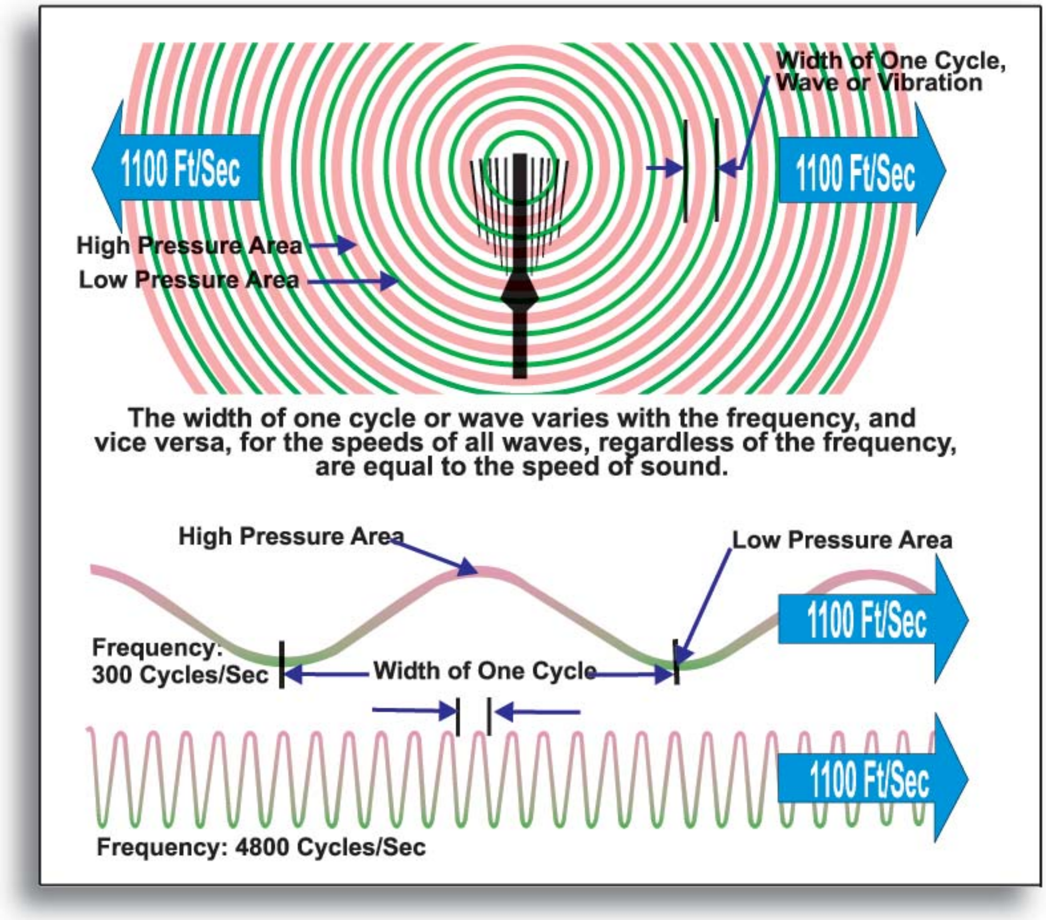
In actual flight, an airfoil may experience both laminar and turbulent flow patterns. Aeronautical engineers are, therefore, constantly searching for ways to improve performance and laminar flow is given careful consideration in the design of new aircraft.

The *P*-51*D Mustang* shown here had a very efficient laminar-flow wing.

The Speed of Sound in Air

If a pebble were dropped in a lake, ripples would spread out from the point where it impacts the water. This is a visualization of how sound waves travel away from the source that is making the sound.

In this example, the rock had to push against some water molecules, and they in turn push against other molecules. If another rock were placed in exactly the same location as the first one, another wave would be created. The “sound source” of energy does this.



Sound Wave Radiations

A disturbance with enough energy to produce a sound causes a reaction that is transmitted from molecule to molecule **in all directions**. These collisions of molecules cause small, local pressure changes within the gas, and it appears to radiate outwardly in a series of waves from the source. The speed at which the disturbance travels in air is called the speed of sound.

The Austrian physicist Ernst Mach, (1838-1916) is given credit for determining the correct mathematical value for the speed of sound. His last name and the number "one" after it represents the speed of sound through a medium—as in "Mach One."

The speed of sound varies with altitude because temperature generally decreases with an increase in height. For example, the speed of sound in air is about 761 mph when the air temperature is 59° F. If the air temperature is lowered to 30°F, the speed of sound drops to approximately 692 miles per hour.

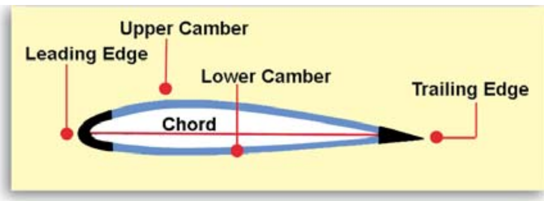
In the mid-Forties, it was thought that the speed of sound couldn't be attained. It was called the "sound barrier." The Bell Aircraft Corporation built an airplane, called the X-1, to break this barrier. It was a known fact that a 50-caliber rifle bullet could exceed the speed of sound and the Bell engineers used this shape as the basis for the fuselage of the X-1. After extensive testing, it exceeded the speed of sound on October 14, 1947 with Air Force test pilot, Charles E. "Chuck" Yeager, at the controls.

Airfoil—Designs that Capture the Energy of the Wind

An airfoil is designed specifically to cause a dynamic reaction from the air through which it moves. Those parts of the airplane specifically designed to react with the air include the wing and tail surfaces. Likewise, propellers are airfoils, by design, and their rotation through the relative wind creates a "forward lift."

Airfoil Design

This illustration shows the cross section of a wing, but it could be a tail surface or a propeller, because they are all essentially the same.



Airfoil Cross-section

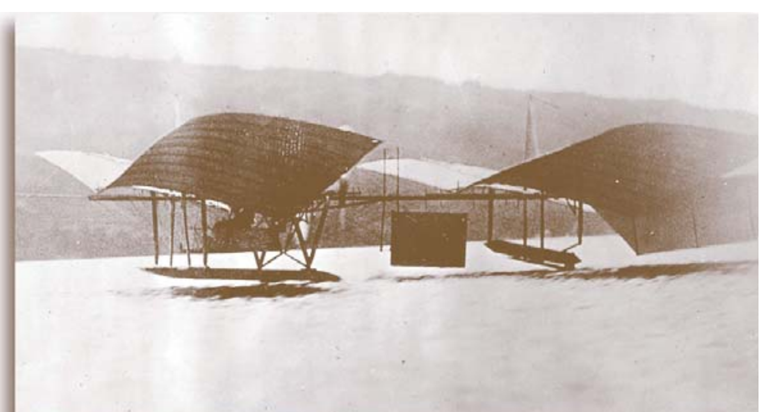
Going Supersonic! *F/A* 18 breaks the sound barrier.

Leading Edge. The leading edge of an airfoil meets relative wind, first. The shape at this location depends upon the intended use of the airfoil. If the airfoil is designed to be flown at high speeds, its leading edge will be sharp such as those found on the wings of jet fighters. The leading edges of the wings on slower training and pleasure-type aircraft (such as the single-engine trainers and gliders) are more rounded and thicker.

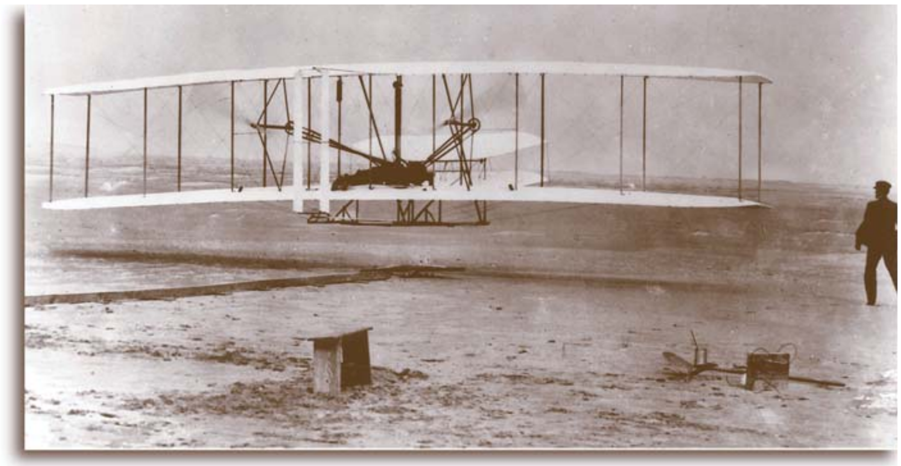
Camber. Immediately behind the leading edge, there is the upper and lower camber. This curvature determines the airfoil's thickness. Camber can be either positive or negative. Positive camber **curves aw**ay from the centerline while negative camber moves **toward** the centerline of the airfoil.

Early airfoils, such as the ones used on the Langley Aerodrome, were similar to the wings of birds. In aerodynamic terms, this means that the wing has a positive upper camber and negative lower camber.

A close examination of the Wright Flyer will show that it too has a positive-upper, negative-lower camber.



The Langley *Aerodrome*



The *Wright Flyer*

When the Wright brothers found that their calculations were not providing the expected lift for their gliders, they built a wind tunnel and experimented with small-scale airfoils. These experiments proved invaluable in achieving success on December 17, 1903. The airfoil that was eventually used on the Flyer was only a part of their successful design. The key ingredient to their achievement was **control**. Others had achieved varying degrees of success with lift from primitive designs; however, the Wrights were able to control their craft once it was aloft.

Trailing Edge. Whether the camber is pronounced, thin, positive, or negative, the upper and lower surfaces must come together at the rear of the wing. This thin junction is called the trailing edge. The trailing edge area is where the air stream rejoins after having been separated at the leading edge and directed over, and under the airfoil surface.

Chord. A very important part of an airfoil is its chord. This imaginary line is shown in the illustration of the airfoil cross-section on page 177. It connects the leading with the trailing edge. It is used in the scientific explanation of several aerodynamic functions. One of the most important is the concept of angle of attack .

The Relative Wind is opposite the flight path and impacts the airfoil at any angle to the chord line. Even though the air at an airport may be calm, when the airplane moves down the runway for takeoff, a "relative wind" starts blowing over the wing. At some point in the takeoff roll, the pilot increases the angle between the chord line and the relative wind. At that moment, a substantial amount of lift is created and the airplane takes flight. Pilots call this rotation.

Angle of Attack. The angle created by the pilot during takeoff is known as the angle of attack. By definition, it is the angle between the chord line and the oncoming relative wind.

It must be noted that angle of attack is not the same as the **Angle of Incidence**. The incidence angle is between the chord and the centerline of the aircraft.

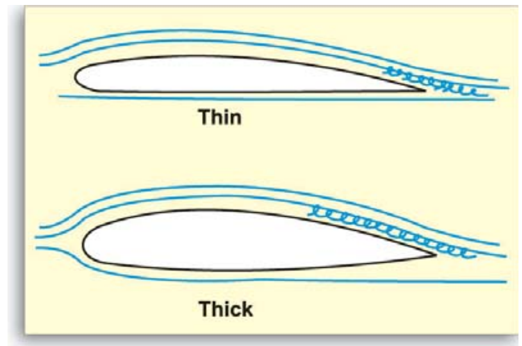
In the world of automobile racing, airfoils also play an important role. If a race car builder wants to improve traction, it is a common practice to mount an airfoil somewhere on the car. If properly designed and mounted, an airfoil can create a substantial amount of down force.

Angle of attack is also expressed in negative terms and when a car-mounted wing is angled with its leading edge lower than its trailing edge, a "negative lift" is created. An extreme example of this is found on oval track racers. Their airfoils often cover nearly 50% of the car! Some of the most sophisticated aerodynamic designs are found on the international grand prix and Indianapolis "500" race cars.

Who is Daniel Bernoulli?

In 1738, Daniel Bernoulli, a Dutch-born physicist, was given credit for developing the laws that explain how a wing lifts. What Bernoulli discovered was a relationship between the pressure and speed of a fluid in motion. More specifically, *as the velocity of a fluid increases, the pressure decreases.*

This illustration shows the flow of air, called streamlines, over an airfoil. They show air that is moving at the same velocity. Streamlines help visualize the fact that as the airfoil moves through the air, the air must go around the shape.



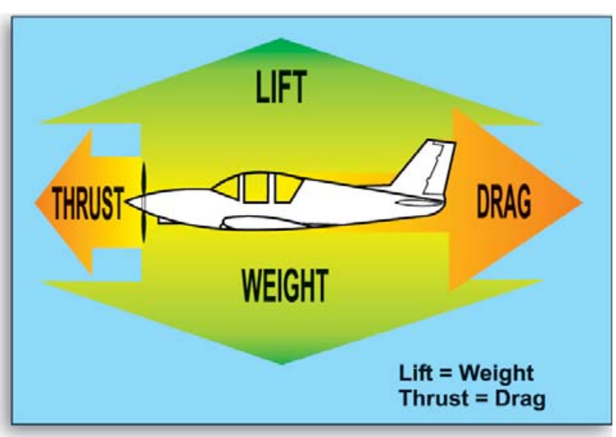
Streamlines Around an Airfoil

Because the air flow separation must have continuity, it splits at the leading edge and comes together once again at the trailing edge of the airfoil. The air that goes over the top of the airfoil must travel a greater distance than the air, which goes under the bottom; this is because the upper camber is designed to have a greater curvature.

Bernoulli's principle states, once again, "as a fluid's speed increases, the pressure within the fluid decreases." So the pressure of the air on top of the airfoil must be less than the pressure below. If the pressure above is less, and the pressure below is greater, the airfoil has no choice but to move upward, toward the lower pressure. It is literally a "suction" on top and "push" from underneath.

To a great extent, the camber determines the amount of lift that a wing will produce at a given speed. The thicker, or more pronounced, camber generally produces the most lift because it makes the airflow travel faster over the upper surface. This accelerated flow rate produces a much lower pressure. The more negative pressure induced to the upper camber, the more lift produced. At low speeds, it is desirable to have a high-lift airfoil. This is particularly evident in STOL, or **short takeoff and landing aircraft.**

The Forces of Flight



The Four Forces of Flight in Balance

The four forces of flight represent centuries of study by many historic figures. Leonardo DaVinci's detailed notes of his nature observations lead to the idea that lift could be produced by flowing air. Sir Isaac Newton's study of classical mechanics led to the mathematical explanations of gravity. Octave Chanute and Otto Lilienthal developed mathematical equations for lift. These were used although later disproved by the Wright Brothers.

These forces are *lift*, *drag*, *thrust*, and *weight*. By definition, the lift force acts perpendicular to the relative wind or the line of flight. The drag force acts parallel to the relative wind. The thrust force usually acts parallel to the centerline of the fuselage and the weight always acts in the direction of gravity.

First, think about the forces that oppose one another: Lift vs. Weight, Thrust vs. Drag. If you can get more lift and less weight, then your air vehicle will be able to fly. More thrust and less drag would allow the airplane to move forward.

Taking Flight

In this section we are ready to take the next step in understanding how airplanes fly. First, we must introduce the rest of the aircraft surrounding the airfoil. Without getting too deep into parts, we can add a third dimension to the airfoil and get a **wing**.

In the photo here, the airplane is in straight-and-level, unaccelerated flight. That means nothing is changing. It does not accelerate, go up, down, or turn. This, of course, is another simplifying assumption.

Early biplanes had a great deal of lift...and a great deal of drag. *(EAA)*

In straight-and-level, unaccelerated flight the thrust force balances the drag force and the lift force balances the weight. More thrust than drag would make the airplane accelerate. More lift than weight would mean the aircraft would climb in altitude.

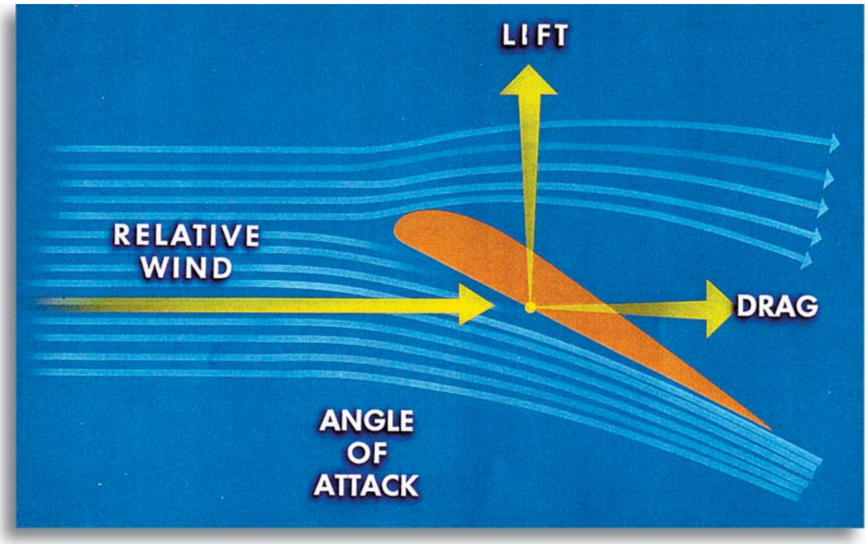
Vectors

A vector is a graphic mathematical illustration showing both direction and magnitude. There is a force moving in a vertical direction from the wing. This is an illustration of lift. The amount of lift being produced is the magnitude and its direction is upward.

Lift Overcomes Weight

It is obvious that increased lift and decreased weight are objectives in both the designing and flying of aircraft.

Lift can be increased, as has been mentioned before, by changing the camber, or curvature, of the airfoil shape of the wing. This type of lift is called **Induced Lift** because of the induced lower pressure on the top of the wing due to the camber.



Lift and Angle of Attack

Also important is the angle of the wing as it encounters the relative wind. That, we learned earlier, was called angle of attack. Lift is increased as the angle of attack is increased for two reasons. First, as the angle is increased relative to the wind, the air has to go a further distance over the top of the wing. That means a lower pressure above the wing and therefore, greater induced lift. Secondly,

NASA's Dryden Flight Research Center, Edwards, California, is using this modified *F*-18 aircraft to explore an area of flight called angle of attack. During maneuvers, pilots often fly at extreme angles of attack with the nose pitched up while the aircraft continues in the original direction. This can lead to conditions in which the airflow becomes separated from the airfoils, resulting in insufficient lift to maintain altitude or control. This project by NASA is creating a data base on aerodynamics at high angles of attack to help engineers and designers develop more maneuverable aircraft in the future. A thrust vectoring system has been installed on the F-18's two engine exhaust nozzles to redirect the exhaust flow to enhance control and maneuverability for this research project. The thrust vectoring system allows the research aircraft to fly at steep angles of attack for long periods of time to collect aerodynamic data. Future aircraft to benefit from this program are expected to be highly maneuverable fighters, hypersonic vehicles and high performance civilian aircraft.

because there is more relative wind striking the wing's bottom surface at higher angles of attack, the pressure created on the wing's bottom surface is higher. This is the same feeling you get when you put your hand out of the car window while driving. because the dynamic pressure of the air on the lower hand surface causes it.

Notice that there is a large increase in lift as angle of attack is increased. This is because changing angle of attack gains you both induced and dynamic lift. It should come as no surprise to you that the lift produced by the wing also depends upon the air.

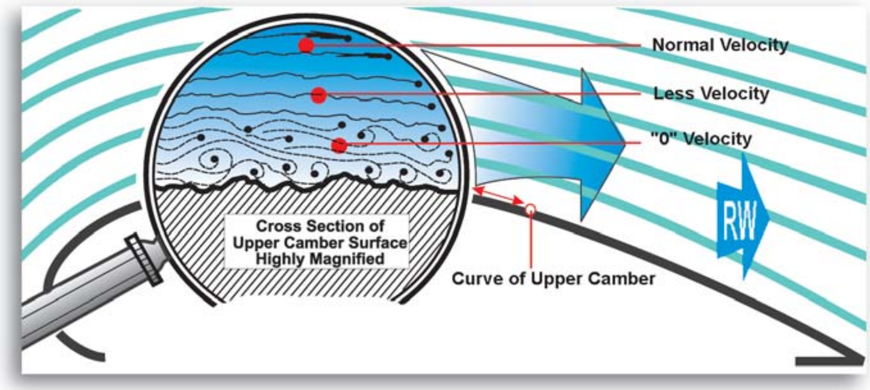
Remember the air's characteristics of pressure, temperature, density, and viscosity? Each can affect the ability of a wing to create lift. High-pressure air at sea level is more dense than at higher altitudes. Colder air is more dense than hotter air. Denser air flowing over the wing means more mass. More mass means more molecules and this translates to greater lift.

Weight

It's amazing how this much weight can fly! *(EAA)*

Since weight directly opposes lift in straight-and-level, unaccelerated flight, weight is a problem to be overcome. How is the problem of weight managed? First of all, the airplane must be constructed of the lightest-weight materials that can be used. Today, most airplanes are built of aluminum alloys. These are used extensively in aircraft construction because of their strength and light weight. The use of composite materials is making an impact too. Composites can be shaped easily and some have strength that exceed metals.

The weight of the airplane's cargo also receives very careful consideration. Each airplane has a total weight limitation called the maximum gross weight. Anything above this limit is considered unsafe for flight. It is possible to keep putting luggage or other cargo into an airplane until it is so heavy it will not fly. Since the pilot cannot put the airplane on a scale to make certain that the airplane is within its weight limits, another approach must be used. This approach is for the pilot to consult documents produced by the manufacturer of the airplane. These documents (which must remain in the airplane) will contain the maximum gross weight and the empty weight. All the pilot has to do is subtract the empty weight from the maximum allowable weight to find out how many pounds may be loaded into the airplane. This is called the **Useful Load**.



Friction Drag

Thrust and drag

Thrust is the force that propels the aircraft forward. The ultimate goal is to design an engine that produces a lot of thrust on a machine that weighs very little. This gives the pilot more speed, more lift, and less weight.

Drag is the force that opposes all motion through the atmosphere and is parallel to the direction of the relative wind. Drag is created because of the airplane's motion through the air.

There are many "components" of drag. Part of the total drag is caused by the friction of air particles rubbing against the parts of the airplane. An illustration of **Friction Drag** is dragging your hand across a smooth surface and then a piece of sandpaper. The movement of your hand over the sandpaper simulates the effects of friction drag.

Another type is **Form Drag**. The very shape of something may create turbulence as the aircraft flies. In this turbulence are pockets of low and high-pressure air leaving a wake behind the airplane. This turbulence disrupts the flow of air over the wing and reduces how well it creates lift. The smooth, low-pressure air over the top of the airfoil is pushed by the turbulence at the trailing edge. This pushing back upstream against the flow slows the airflow over the airfoil and causes the streamlines to separate away from the wing. As a result, a force vector trails the airplane and works against its forward motion. Streamlining the aircraft will reduce form drag. Parts of an aircraft which do not lend themselves to streamlining are enclosed in covers called fairings.

Drag is almost always detrimental to aircraft performance. Because it works to slow the airplane as it moves through the air, the engine must make more thrust to go faster. More thrust usually means a bigger engine and more weight.

Sometimes, however, drag is useful. When you want to slow down quickly you can deploy a speedbrake. This is usually a big plate that sticks out into the wind and creates an enormous amount of form drag. In a dogfight the speedbrake can be used to quickly slow down and force your enemy to fly past you.

Airliners also use speed brakes to slow their airspeed in preparation for landing.

In the old days there were wires, wings, large front ends and the pilot's headsticking out in the wind . All of these created a great deal of drag.
(San Diego Aerospace Museum)

Real World Lift and Weight

The last few pages defined the four forces of flight. Now, let's talk about them in practical terms, in the real world.

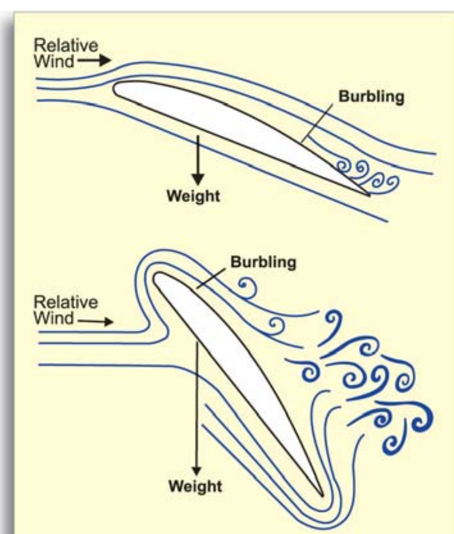
If the atmosphere and its characteristics are what allow us to fly, and we change those, then our forces of flight must be affected. Additionally, if we remove some of the simplifying assumptions and start looking at the whole airplane in flight, we will see that there is more to flying than we thought earlier.

Lift was broken down into induced and dynamic lift components. Induced lift came from the low-pressure air on the top of the wing and dynamic lift came from the high-pressure air on the bottom. Here are two examples of how the lift force works in the real world.

Turbulence. Air flowing over the surface of an airfoil is rarely very smooth. Streamlines do form as the air separates around the wing, but those streamlines are not very smooth close to the surface of the aircraft. This is because air is not really viscous. As it flows over the wing's surface it scrapes against the rough metal and is slowed down and churned up. The churning of air is called **turbulence** and reduces the efficiency of the airfoil. Therefore the lift created by the cambered wing is somewhat less than the ideal design prediction.

There are 4 forces at work...all the time in every airplane. ***(EAA)***

Stalls. There is a point where the streamlines, located in the **boundary layer** of air right next to the wing's surface, will separate from the airfoil. Once separation occurs, the air begins to flow more slowly and the lift producing low-pressure on the top of the wing is lost. The aircraft begins to sink, and if the stall becomes serious enough, departs controlled flight and plummets to the earth.



An airfoil approaching and entering a stall.

Aeronautical engineers try to design aircraft that stall predictably. They design the wings and fuselage so that the burbling of air shakes the aircraft and tells the pilot that a stall is imminent. When that cannot be done they build mechanical and electronic devices that warn the pilot of the stall. And if all else fails, they try to make the stall easily recoverable so that the pilot can regain control of the aircraft.

You might wonder why the force of power from the engine couldn't take the place of the loss of lift from the airfoil. Very simply, there just isn't enough of this force available from a conventional aircraft's engine. Some of the more powerful jet fighter and aerobatic sport airplanes can, for a short time and distance, climb straight up without any significant help from their airfoils, but these airplanes will eventually stall and start to fall toward Earth.

Gravity, or weight, always pulls the aircraft toward the earth, but its location in the air vehicle is extremely important. Here is an example of how the weight force can affect flight in the real world.

Weight Distribution. Where the weight, or useful load, is placed in the airplane has a pronounced effect on how well an airplane will fly. Recall that a moment is created when you exert a force on a body at some distance from its center of gravity? For an airplane that means it would rotate around the center of gravity in the direction of the moment. The pilot would have to use the control stick to counter the rotation. The danger of poorly placed weight in the aircraft is that the control surfaces may eventually not be able to counter the rotation. This would cause the aircraft to fly out of control. Although flight out of control is sometimes fun in a stunt plane, airline passengers and attendants generally frown upon it.

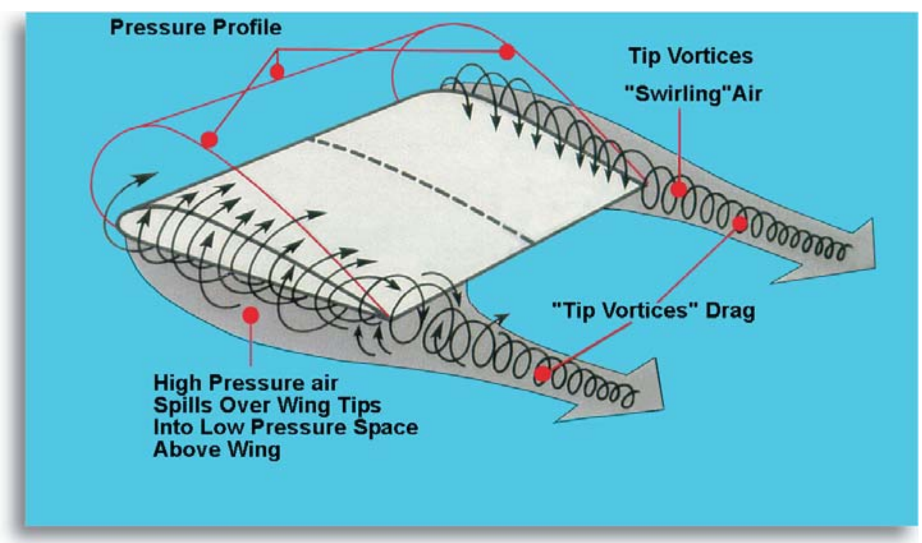
Real World Thrust and Drag

If the ideal were possible our air vehicles would have infinite thrust and negligent drag. You could go as fast as desired in any direction and never slow down if you did not want to.

Of course, this is not the case in the real world. Thrust from an engine has some limitations and can be used to the aircraft's advantage as these examples show.

Thrust Vectoring. Thrust on an aircraft is normally used to generate forward motion through the air so that the airfoil-shaped wings can develop enough lift to counter the aircraft's weight. If the thrust force could be pointed in any direction then it could assist in maneuvering as well. That is what thrust vectoring allows.

Engines are designed so that their thrust forces can be pointed along a direction other than the aircraft's longitudinal axis. This is done by pointing the engine's exhaust using mechanically driven plates or special exhaust ports called directional nozzles.



Wingtip Vortices Causing Induced Drag

Thrust vectoring can be used to assist lift, reduce the chance of a stall, or allow the aircraft to fly at extremely high angles of attack and very slowly. This might allow the use of very short runways or make a jet fighter very maneuverable.

Like the other forces, drag becomes a greater problem as our assumptions are eliminated and we consider the whole aircraft. Here is an example of a real world drag effect.

Induced Drag. If lift always acted in an upward direction it would be ideal because it would always help us get to a higher altitude.

The winglets on this *Learjet* help reduce induced drag.

The flow across a wing does not move only from the leading edge to the trailing edge. It also moves toward the wingtip and, sometimes, toward the fuselage. This spanwise flow on the top of the wing eventually must join the spanwise flow on the bottom of the wing. When they do, they form a swirling vortex. This vortex causes the lift vector of the wing to be slanted toward the rear of the aircraft. The slant results in a component of the lift vector pointing in the same direction as the drag vector. This component of lift adds to the drag and is called the **induced drag**.

Supersonic Aerodynamics

For flight at slow speeds, below about 260 knots, air was assumed to be an incompressible fluid. However, as speed increases, air at the leading edges of the vehicle can actually be compressed. Airflow over the surfaces is no longer represented by smooth orderly streamlines. The air is simply moving so fast that it cannot turn around edges very easily. Instead, at leading edges it compresses and at trailing edges it expands.

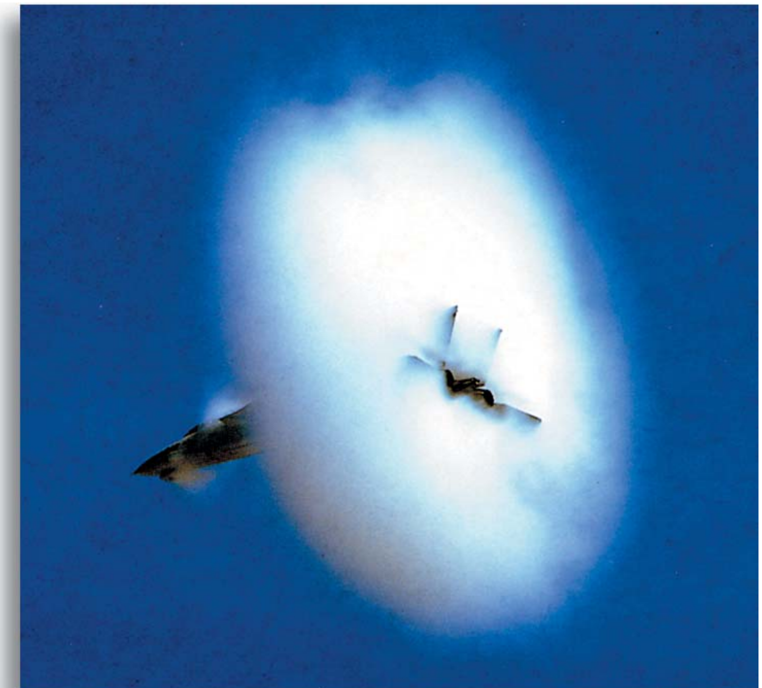
Supersonic Flow

When an airplane flies at subsonic speeds the air ahead is "warned" of the airplane's approach by a pressure change in front of the aircraft. Remember the pebble dropped in the pond creating a wave that tells the rest of the water to move out of the way? That wave in the air moves at the speed of sound, or "Mach One."

The pebble-pond analogy provides a very good picture of what is happening when an airplane flies at supersonic speeds. If a person drops pebbles into a smooth pond, each pebble will make a wave. This would be similar to the pattern of sound waves made by the aircraft's engine as it sits still on the airfield.

Now suppose we start dropping the pebbles one each second as we run along the bank. Each pebble still produces a circular wave, but the circles are crowded together on the side toward which we are moving. If we now move around the pond at a speed greater than the wave's speed, the pattern looks different than those previously formed. Smaller circles, or those made more recently, are no longer completely inside the next larger ones. Now all the circles are jammed into a wedge-shaped region.

This is similar to the sound-pressure wave pattern for an airplane flying at supersonic airspeeds. The leading edges of the airplane are a continuous disturbance in the air that leaves behind a wedge shaped wave.



A ring of condensation occurs in the wave as this *F*-14 goes supersonic. *(US Navy)*

This wave pattern would be similar to the pattern of engine sound as the airplane flies at subsonic airspeeds. It also is the pattern made by the pressure change at the aircraft's leading edges. At the leading edges the air is being pushed forward and this push is sent upstream of the airplane at the speed of sound, telling the rest of the air to get out of the way. The air ahead of the airplane is warned of the arrival, and the warning time is decreased as the airplane's speed approaches the speed of sound. The warning time is zero when the airplane flies at Mach One, and has a wave pattern.

If the airplane travels at supersonic speeds, the air ahead receives no warning of the airplane's approach because the airplane is outspeeding its own pressure wave. Because the air is unprepared for the airplane's arrival, it must move aside abruptly to let the airplane pass. This sudden displacement and resulting wedge shaped wave is called a **shock wave**.

There are two types of shock waves. Those formed when the air must move aside as a leading edge passes and those formed when the air must fill back in as the trailing edge passes. The first is called a **compression wave** and the second an **expansion wave**.

Supersonic aerodynamics requires different designs than those used on subsonic aircraft. This is a conflict with the fact that our aircraft still have to take off and land, and those are usually done subsonic.

Wave Drag. When air flows across a shock wave it undergoes a change in temperature, pressure, and velocity. These changes result in another component of drag called **wave drag**. Although the exact description of this drag is complex, it is really the result of lost energy.

The air that moves across the shock waves is being violently altered. These changes take some energy to produce, since you never get something for nothing. The loss in energy is depicted as additional drag on the air vehicle that would require more thrust (positive energy) to overcome.

The Concorde aircraft daily takes passengers across the Atlantic Ocean at a speed of Mach 2. They sit enjoying the comfort of first class for a period of three hours. All this time, all the violent forces of supersonic flight are present, but the passengers are not aware of it. Isn't this wonderful technology?!!

Key Terms and Concepts

- aeronautics and aerodynamics
- properties and characteristics of gases: pressure, temperature, density, viscosity
- laminar vs turbulent air flow
- Mach number, speed of sound, supersonic
- airfoil design: leading edge, camber, trailing edge, chord
- relative wind and angle of attack
- Bernoulli's Principle
- Four forces of flight: lift, drag, thrust, weight
- induced lift and dynamic lift
- useful load and load distribution
- types of drag: friction drag, form drag, induced drag, wave drag
- turbulence
- stall
- thrust vectoring
- shock wave, compression wave, expansion wave

? Test Your Knowledge ?

MATCHING

1. *Movement of objects through the atmosphere*
2. *Science relating to the energy of gases in motion*
3. *Decreases with an increase in altitude*
4. *Measure of how much energy the gas has*
5. *The measure of how many molecules are squeezed into a defined space*
6. *Resistance to the flow of a liquid or gas*
7. *The smooth or rough flow of air over an object*
8. *The ratio of the speed of an object to the speed of sound in air*

a. pressure
b. temperature
c. laminar or turbulent flow
d. viscosity
e. aeronautics
f. Mach number
g. aerodynamics
h. density

FILL IN THE BLANKS

9. *The part of the airfoil that meets the air first is the _________.*
10. *The area determining the airfoil's thickness and thus its lift is the _________.*
11. *The _________ is the rear junction where the upper and lower parts of the airfoil meet.*
12. *The _________ is the imaginary part of the airfoil that is the starting point for designing an airfoil in cross section.*
13. *Ideally, when a plane is in smooth flight, the force of the total lift equals the force of the total _________ and the force of _________ equals the force of drag.*
14. *Lift and weight are in opposition to each other. Induced lift can be increased by changing the _________ of the _________.*
15. *A _________ occurs when lift is destroyed and the force of weight takes over.*
16. *The sudden displacement of air and the resulting wedge-shaped wave is called a ___________ __________.*
17. *Each airplane has a total weight limitation called _________.*
18. *If a pilot subtracts the empty weight from the maximum gross weight the result is how many pounds can be loaded into the airplane. This is called the _________.*

TRUE OR FALSE

19. *Mach is the ratio of the speed of an object to the speed of sound in air.*
20. *All fluids possess viscosity which is a resistance to flow, but air is not included here.*
21. *Slowing the flow rate is known as viscous drag.*
22. *On an in-flight aircraft, laminar and turbulent flow are found at the same locations.*
23. *The angle formed by the airfoil chord and the relative wind direction is the angle of attack.*
24. *Induced lift is caused by the angle of attack.*
25. *Dynamic lift is caused by camber.*
26. *Positive atmospheric pressure at the bottom of the wing only increases the induced lift.*
27. *Generally, the less dense the air, the less lift is available.*

SHORT ANSWER

28. *In one sentence define relative wind, including the words speed, direction, and lift.*
29. *What's the difference between airspeed and ground speed?*
30.. *If drag is decreased, what happens to thrust?*
31. *Name two ways that drag can be decreased.*
32. *What is unique about supersonic aerodynamics?*