

This material can be found in more detail in *Understanding Flight* 1st and 2nd editions
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A Physical Description of Flight; Revisited ©

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Almost everyone today has flown in an airplane. Many ask the simple question "what makes an airplane fly?" The answer one frequently gets is misleading and often just plain wrong. As an 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. 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 everything to do with efficiency in cruise and stall characteristics. Any description that relies on the shape of the wing is wrong.

Let us look at two examples of successful wings that clearly violate the descriptions that rely on the shape of the wing. The first example is a very old design. Figure 1 shows a photograph of the Curtis 1911 model D type IV pusher. Clearly the air travels the same distance over the top and the bottom of the wing. Yet this airplane flew and was the second airplane purchased by the US Army in 1911.

The second example of a wing that violates the idea that lift is dependent on the shape of the wing is of a very modern wing. Figure 2 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. Though its shape may seem contrary to the popular view of the shape of wings, this airfoil is the foundation of the wings modern airliners.



Figure 1. Curtis 1911 model D type IV pusher



Figure 2. Whitcomb Supercritical Airfoil

The emphasis on the 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. But, this is again just a variation on the idea of equal transit times. In reality, equal transit times holds only for a wing without lift. Figure 3 shows a simulation of the airflow around a wing with lift.

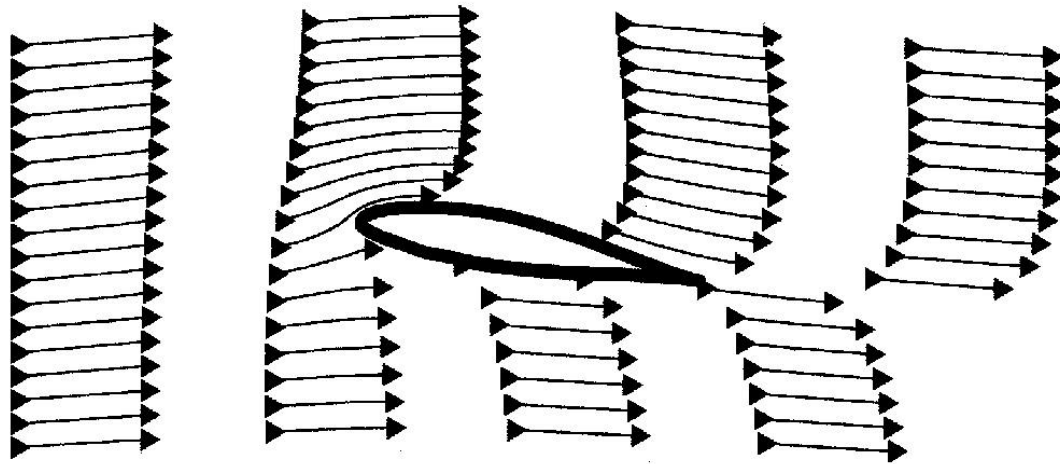


Figure 3 Air over a wing with lift.

The Bernoulli equation is a statement of the conservation of energy. It is correct, but not applicable to the description of lift on a real wing. The wings of an 800,000 pound airplane are doing a great deal of work to keep the airplane in the air. They are adding a large amount of energy to the air. One of the requirements of the application of the Bernoulli principle is that no energy is added to the system. Thus, the speed and pressure of the air above a real wing in flight are not related by the Bernoulli principle. Also, descriptions of lift that evoke the Bernoulli principle depend on the shape of the wing. As already stated, the shape of the wing affects the efficiency and stall characteristics of the wing but not the lift. That is left to the angle of attack and speed.

Newton's laws and lift

So, how does a wing generate lift? To begin to understand lift we must review Newton's first and third laws. (We will introduce Newton's second law a little later.) Newton's first law states:

A body at rest will remain at rest, or a body in motion will continue in straight-line motion unless subjected to an external applied force.

That means, if one sees a bend in the flow of air, or if air originally at rest is accelerated into motion, a force is acting on it.

Newton's third law states that:

For every action there is an equal and opposite reaction.

As an example, an object sitting on a table exerts a force on the table (its weight) and the table puts an equal and opposite force on the object to hold it up. In order to generate lift a wing must do something to the air. What the wing does to the air is the action while lift is the reaction.

Let's compare two figures used to show streamlines over a wing. In figure 4 the air comes straight at the wing, bends around it, and then leaves straight behind the wing. We have all seen similar pictures, even in flight manuals. But, the air leaves the wing exactly as it appeared ahead of the wing. There is no net action on the air so there can be no lift! Figure 5 shows the streamlines, as they should be drawn. The air passes over the wing and is bent down. Newton's first law says that there must be a force on the air to bend it down (the action). Newton's third law says that there must be an equal and opposite force (up) on the wing (the reaction). To generate lift a wing must divert lots of air down.



Figure 4. Common depiction of airflow over a wing. This wing has no lift.



Figure 5. True airflow over a wing with lift showing upwash and downwash.

The lift of a wing is equal to the change in momentum of the air it is diverting down. Momentum is the product of mass and velocity (mv). The most common form of Newton's second law is $F = ma$, or force equal mass times acceleration. The law in this form gives the force necessary to accelerate an object of a certain mass. An alternate form of Newton's second law can be written:

The lift of a wing is proportional to the amount of air diverted down times the vertical velocity of that air.

It is that simple. For more lift the wing can either divert more air (mass), increase its vertical velocity or a combination of the two. This vertical velocity behind the wing is the vertical component of the "downwash". Figure 6 shows how the downwash appears to the pilot (or in a wind tunnel). The figure also shows how the downwash appears to an observer on the ground watching the wing go by. To the pilot the air is coming off the wing at roughly the angle of attack and at about the speed of the airplane. To the observer on the ground, if he or she could see the air, it would be coming off the wing almost vertically at a relatively slow speed. The greater the angle of attack of the wing the greater the vertical velocity of the air. Likewise, for a given angle of attack, the greater the speed of the wing the greater the vertical velocity of the air. Both the increase in the speed and the increase of the angle of attack increase the length of the vertical velocity arrow. It is this vertical velocity that gives the wing lift.

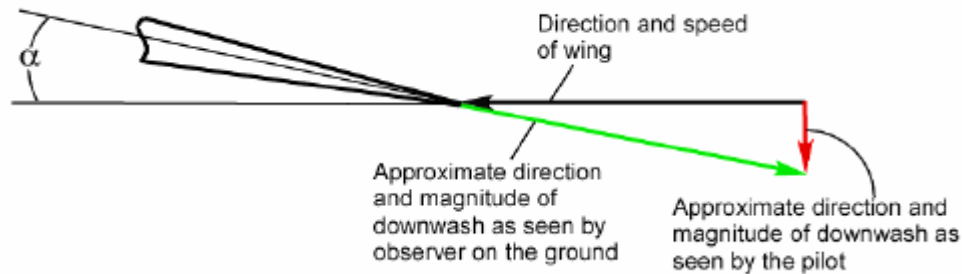


Figure 6. How downwash appears to a pilot and to an observer on the ground.

As stated, an observer on the ground would see the air going almost straight down behind the plane. This can be demonstrated by observing the tight column of air behind a propeller, a household fan, or under the rotors of a helicopter; all of which are rotating wings. If the air were coming off the blades at an angle the air would produce a cone rather than a tight column. The wing develops lift by transferring momentum to the air. For straight and level flight this momentum eventually strikes the earth. If an airplane were to fly over a very large scale, the scale would weigh the airplane.

Let us do a back-of-the-envelope calculation to see how much air a wing might divert. Take for example a Cessna 172 that weighs about 2300 lb (1045 kg). Traveling at a speed of 140 mph (220 km/h), and assuming an effective angle of attack of 5 degrees, we get a vertical velocity for the air of about 11.5 mph (18 km/h) right at the wing. If we assume that the *average* vertical velocity of the air diverted is half that value we calculate from Newton's second law that the amount of air diverted is on the order of 5 ton/s. Thus, a Cessna 172 at cruise is diverting about five times its own weight in air per second to produce lift. Think how much air is diverted by a 250-ton Boeing 777.

Diverting so much air down is a strong argument against lift being just a surface effect (that is only a small amount of air around the wing accounts for the lift), as implied by the popular explanation. In fact, in order to divert 5 ton/sec the wing of the Cessna 172 must accelerate all of the air within 18 feet (7.3 m) above the wing. One should remember that the density of air at sea level is about 2 lb per cubic yard (about 1kg per cubic meter). Figure 7 illustrates the effect of the air being diverted down from a wing. A huge hole is punched through the fog by the downwash from the airplane that has just flown over it.



Figure 7. Downwash and wing vortices in the fog.

So how does a thin wing divert so much air? When the air is bent around the top of the wing, it pulls on the air above it accelerating that air downward. Otherwise there would be voids in the air above the wing. Air is pulled from above. This pulling causes the pressure to become lower above

the wing. It is the acceleration of the air above the wing in the downward direction that gives lift. (Why the wing bends the air with enough force to generate lift will be discussed in the next section.)

Normally, one looks at the air flowing over the wing in the frame of reference of the wing. In other words, to the pilot the air is moving and the wing is standing still. We have already stated that an observer on the ground would see the air coming off the wing almost vertically. But what is the air doing below the wing? Figure 8 shows an instantaneous snapshot of how air molecules are moving as a wing passes by. Remember in this figure the air is initially at rest and it is the wing moving. Arrow "1" will become arrow "2" and so on. Ahead of the leading edge, air is moving up (upwash). At the trailing edge, air is diverted down (downwash). Over the top the air is accelerated towards the trailing edge. Underneath, the air is accelerated forward slightly. Far behind the wing the air is going straight down.

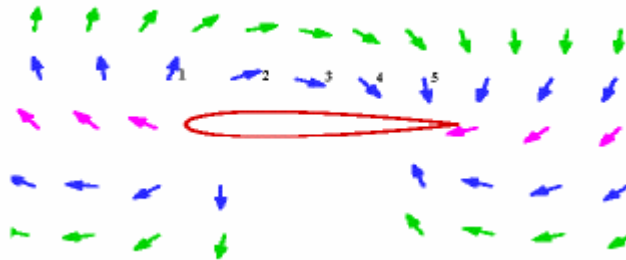


Figure 8. Direction of air movement around a wing as seen by an observer on the ground.

So, why does the air follow this pattern? First, we have to bear in mind that air is considered an incompressible fluid for low-speed flight. That means that it cannot change its volume and that there is a resistance to the formation of voids. Now the air has been accelerated over the top of the wing by the reduction in pressure. This draws air from in front of the wing and expels it back and down behind the wing. This air must be compensated for, so the air shifts around the wing to fill in. This is similar to the circulation of the water around a canoe paddle. This circulation around the wing is no more the driving force for the lift on the wing than is the circulation in the water drives the paddle. Though, it is true that if one is able to determine the circulation around a wing the lift of the wing can be calculated. Lift and circulation are proportional to each other.

One observation that can be made from Figure 8 is that the top surface of the wing does much more to move the air than the bottom. So the top is the more critical surface. Thus, airplanes can carry external stores, such as drop tanks, under the wings but not on top where they would interfere with lift. That is also why wing struts under the wing are common but struts on the top of the wing have been historically rare. A strut, or any obstruction, on the top of the wing would interfere with the lift.

Air Bending Over a Wing

As always, simple statements often 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 9. 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.

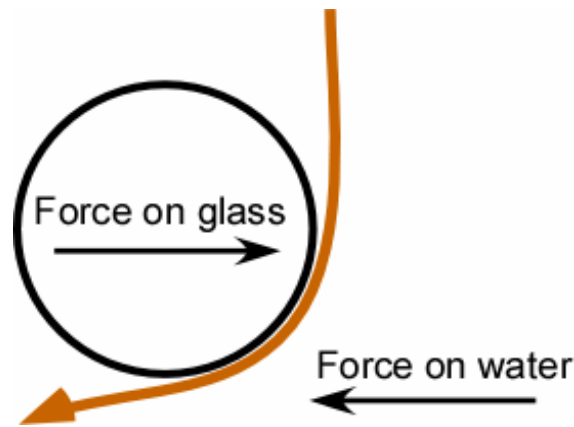


Figure 9. Water wrapping around a glass

So why does the water bend around the glass, or air over a wing? First consider low-speed flight. In low-speed flight the forces on the air and the associated pressures are so low that the air is not only considered a fluid but 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).

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 an expression of 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 trying 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 10. Now imagine the first non-zero velocity streamline that just grazes the highpoint of the top of the wing. If it were initially to go straight back 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.



Figure 10. The variation of the speed of a fluid near an object

The next streamline above would be bent to follow the first by the same process, and so on. The streamlines increase in speed with distance from the wing for a short distance. This is on the order of 6 inch (15 cm) at the trailing edge of the wing of an Airbus A380. This region of rapidly changing air speed is 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 decrease 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 an expression of the pressure and the viscosity of 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 re-introduced 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 there is no boundary layer calculated.

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 the 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 11. 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 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 forces, working through pressure, represent the mechanism in which the force is transferred to the wing.

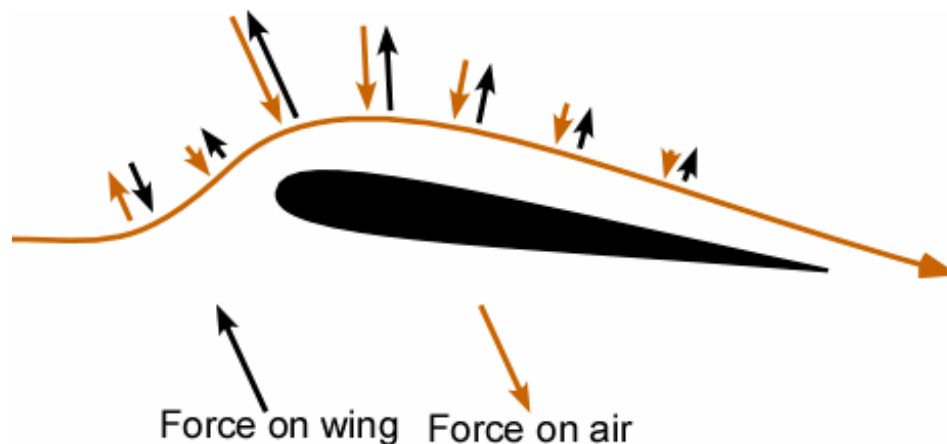


Figure 11. Forces on the air and the corresponding reaction forces on the wing

Look again at Figure 11, 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 of the total lift on a wing at subsonic speeds is typically 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.

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 in which lift is transferred to the wing due to the bending of the air.

Lift as a function of angle of attack

There are many types of wing: conventional, symmetric, conventional in inverted flight, the early biplane wings that looked like warped boards, and even the proverbial "barn door". In all cases, the wing is forcing the air down, or more accurately pulling air down from above. (although the early wings did have a significant contribution from the bottom.) What each of these wings has in common is an angle of attack with respect to the oncoming air. It is the angle of attack that is the primary parameter in determining lift.

To better understand the role of the angle of attack it is useful to introduce an "effective" angle of attack, defined such that the angle of the wing to the oncoming air that gives zero lift is defined to be zero degrees. If one then changes the angle of attack both up and down one finds that the lift is proportional to the angle. Figure 12 shows the lift of a typical wing as a function of the effective angle of attack. A similar lift versus angle of attack relationship is found for all wings, independent of their design. This is true for the wing of a 747, an inverted wing, or your hand out the car window. The inverted wing can be explained by its angle of attack, despite the apparent contradiction with the popular explanation of lift. A pilot adjusts the angle of attack to adjust the lift for the speed and load. The role of the angle of attack is more important than the details of the wings shape in understanding lift. The shape comes into play in the understanding of stall characteristics and drag at high speed.

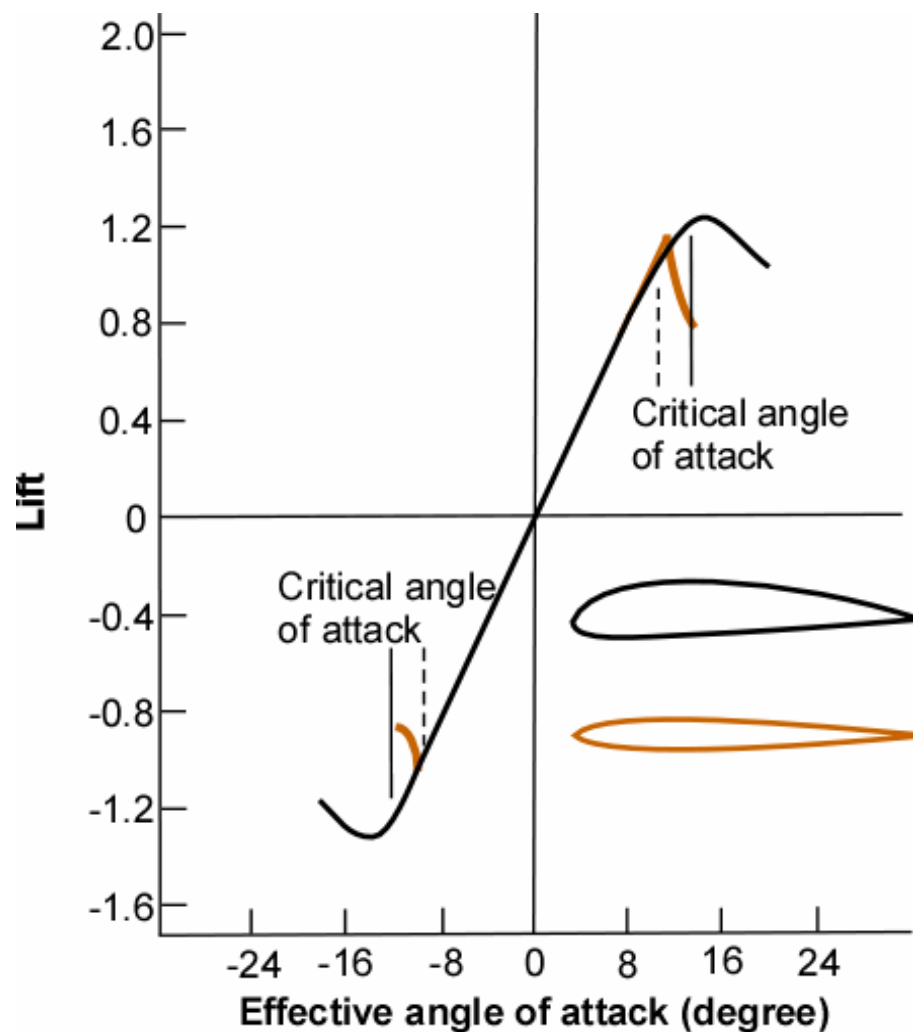


Figure 12. Lift as a function of angle of attack

One can see in the figure 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 on the figure. This separation of the airflow from the top of the wing is a stall.

The wing as air "virtual virtual scoop"

We now would like to introduce a new mental image of a wing. One is used to thinking of a wing as a thin blade that slices through the air and develops lift somewhat by magic. For this we would like to adopt a *visualization aid* of looking at the wing as a *virtual scoop* that intercepts a certain amount of air and diverts it to the angle of the downwash. This is not intended to imply that there is a real, physical scoop with clearly defined boundaries, and uniform flow. But this visualization aid does allow for a clear understanding of how the amount diverted air is affected by speed and density. The concept of the virtual scoop does have a real physical basis but beyond the scope of this work.

The virtual scoop diverts a certain amount of air from the horizontal to roughly the angle of attack, as depicted in Figure 13. For wings of typical airplanes it is a good approximation to say that the area of the virtual scoop is proportional to the area of the wing. The shape of the virtual scoop is approximately elliptical for all wings, as shown in the figure. Since the lift of the wing is proportional to the amount of air diverted, the lift of is also proportional to the wing's area.

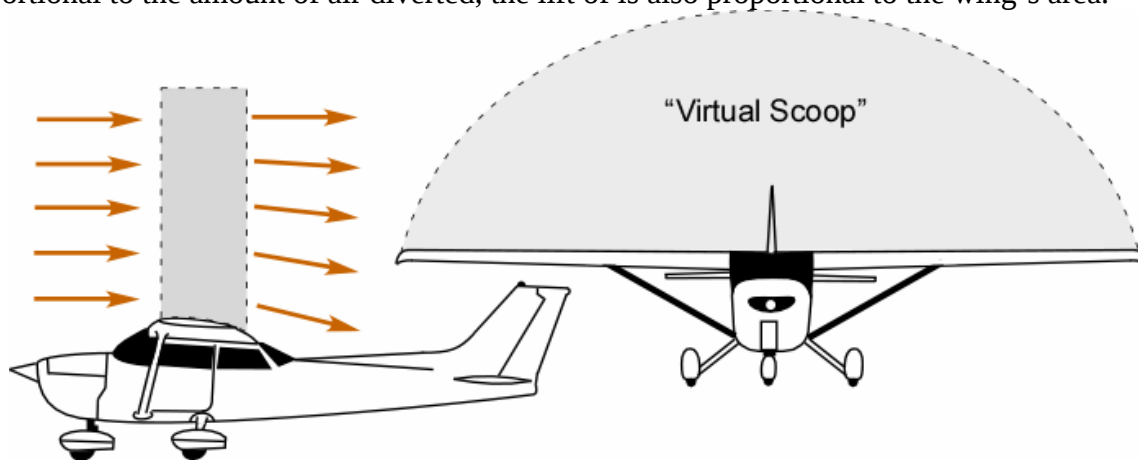


Figure 13 The "virtual scoop" as a visualization tool

As stated before, the lift of a wing is proportional to the amount of air diverted down times the vertical velocity of that air. As a plane increases speed, the virtual scoop diverts more air. Since the load on the wing does not increase, the vertical velocity of the diverted air must be decreased proportionately. Thus, the angle of attack is reduced to maintain a constant lift. When the plane goes higher, the air becomes less dense so the virtual scoop diverts less air at a given speed. Thus, to compensate the angle of attack must be increased. The concepts of this section will be used to understand lift in a way not possible with the popular explanation.

Lift requires power

When a plane passes overhead the formally still air gains a downward velocity. Thus, the air is left in motion after the plane leaves. The air has been given energy. Power is energy, or work, per time. So, lift requires power. This power is supplied by the airplane's engine (or by gravity and thermals for a sailplane).

How much power will we need to fly? If one fires a bullet with a mass, m , and a velocity, v , the energy given to the bullet is simply $\frac{1}{2}mv^2$. Likewise, the energy given to the air by the wing is proportional to the amount of air diverted down times the vertical velocity squared of that diverted air. We have already stated that the lift of a wing is proportional to the amount of air diverted times the vertical velocity of that air. Thus, *the power needed to lift the airplane is proportional to the load (or weight) times the vertical velocity of the air*. If the speed of the plane is doubled, the amount of air diverted down also doubles. Thus to maintain a constant lift, the angle of attack must be reduced to give a vertical velocity that is half the original. The power required for lift has been cut in half. This shows that the power required for lift becomes less as the airplane's speed increases. In fact, we have shown that this power to create lift is proportional to $1/\text{speed}$ of the plane.

But, we all know that to go faster (in cruise) we must apply more power. So there must be more to power than the power required for lift. The power associated with lift is often called the "induced" power. Power is also needed to overcome what is called "parasite" drag, which is the drag associated with moving the wheels, struts, antenna, etc. through the air. The energy the airplane imparts to an air molecule on impact is proportional to the speed² (from $\frac{1}{2}mv^2$). The number of molecules struck per time is proportional to the speed. The faster one goes the higher the rate of impacts. Thus the parasite power required to overcome parasite drag increases as the speed³.

Figure 14 shows the "power curves" for induced power, parasite power, and total power (the sum of induced power and parasite power). Again, the induced power goes as $1/\text{speed}$ and the parasite power goes as the speed³. At low speed the power requirements of flight are dominated by the induced power. The slower one flies the less air is diverted and thus the angle of attack must be increased to increase the vertical velocity of that air. Pilots practice flying on the "backside of the power curve" so that they recognize that the angle of attack and the power required to stay in the air at very low speeds are considerable.

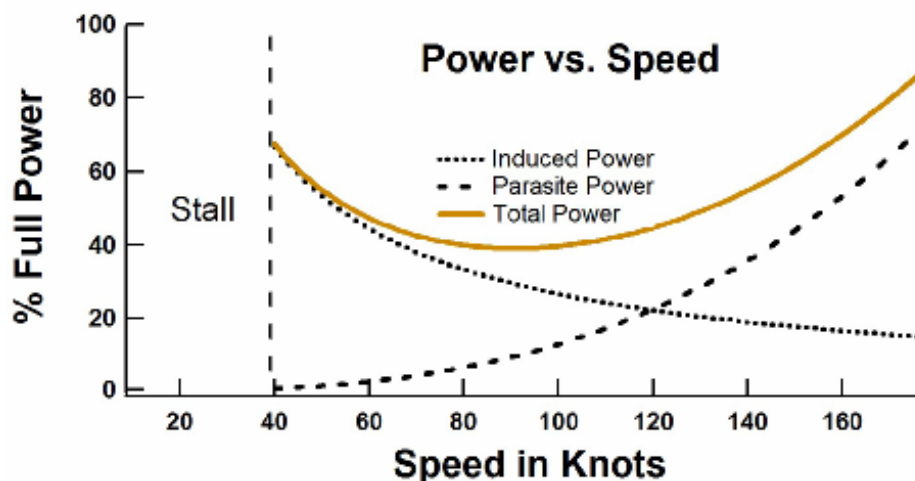


Figure 14. The power required for flight as a function of speed

At cruise, the power requirement is dominated by parasite power. Since this goes as the speed³ an increase in engine size gives one a faster rate of climb but does little to improve the cruise speed of the plane. Doubling the size of the engine will only increase the cruise speed by about 25%.

Since we now know how the power requirements vary with speed, we can understand drag, which is a force. Drag is simply power divided by speed. Figure 14 shows the induced, parasite, and total drag as a function of speed. Here the induced drag varies as $1/\text{speed}^2$ and parasite drag varies as the speed². Taking a look at these figures one can deduce a few things about how airplanes are designed. Slower airplanes, such as gliders, are designed to minimize induced power, which dominates at lower speeds. Faster propeller-driven airplanes are more concerned with parasite power, and jets are dominated by parasite drag. (This distinction is outside of the scope of this article.)

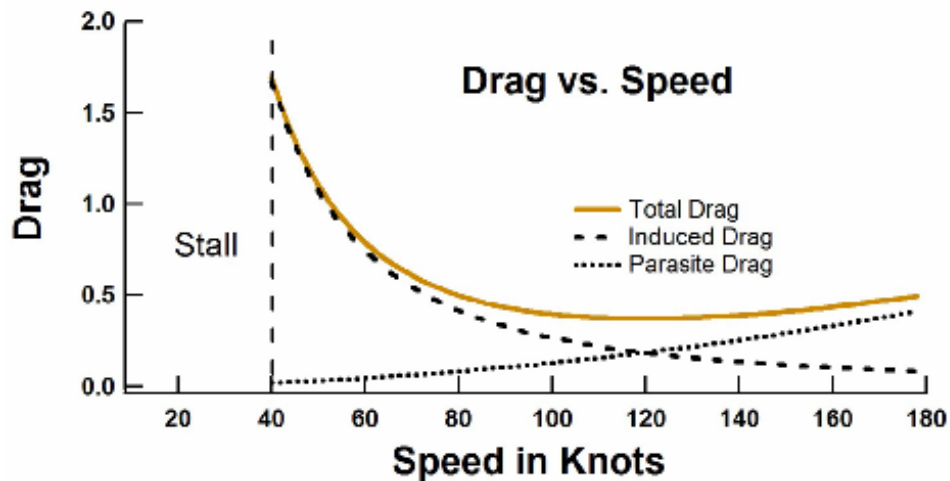


Figure 15. Drag as a function of speed

Wing efficiency

At cruise, a non-negligible amount of the drag of a modern wing is induced drag. Parasite drag of a Boeing 747 wing is only equivalent to that of a 1/2-inch cable of the same length. One might ask what affects the efficiency of a wing. We saw that the induced power of a wing is proportional to the vertical velocity of the air. If the area of a wing were to be increased, the size of our virtual scoop would also increase, diverting more air. So, for the same lift the vertical velocity (and thus the angle of attack) would have to be reduced. Since the induced power is proportional to the vertical velocity of the air, it is also reduced. Thus, the lifting efficiency of a wing increases with increasing wing area. The larger the wing the less induced power required to produce the same lift, though this is achieved with an increase in parasite drag.

There is a misconception by some that lift does not require power. This comes from aeronautics in the study of the idealized theory of wing sections (airfoils). When dealing with an airfoil, the picture is actually that of a wing with infinite span. We have seen that the power necessary for lift decreases with increasing area of the wing. A wing of infinite span does not require power for lift since it develops lift by diverting an infinite amount of air at near-zero velocity. If lift did not require power airplanes would have the same range full as they do empty, and helicopters could hover at any altitude and load. Best of all, propellers (which are rotating wings) would not require much power to produce thrust. Unfortunately, we live in the real world where both lift and propulsion require power.

Power and wing loading

Now let us consider the relationship between wing loading and power. At a constant speed, if the wing loading is increased the vertical velocity of the downwash must be increased to compensate. This is accomplished by increasing the angle of attack of the wing. If the total weight of the airplane were doubled (say, in a 2g turn), and the speed remains constant, the vertical velocity of the air is doubled to compensate for the increased wing loading. The induced power is proportional to the load times the vertical velocity of the diverted air, which have both doubled. Thus the induced power requirement has increased by a factor of four! So induced power is proportional to the load².

One way to measure the total power is to look at the rate of fuel consumption. Figure 16 shows the fuel consumption versus gross weight for a large transport airplane traveling at a constant speed (obtained from actual data). Since the speed is constant the change in fuel consumption is due to the change in induced power. The data are fitted by a constant (parasite power) and a term that goes as the load². This second term is just what was predicted in our Newtonian discussion of the effect of load on induced power.

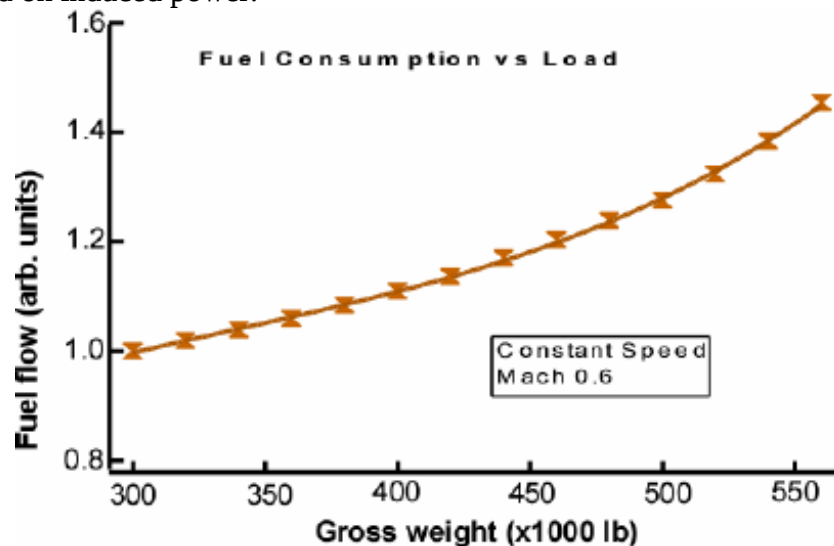


Figure 16. Fuel consumption as a function of weight for large jet at a constant speed

The increase in the angle of attack with increased load has a downside other than just the need for more power. As shown in Figure 12 a wing will eventually stall when the air can no longer follow the upper surface. That is, when the critical angle is reached. Figure 17 shows the angle of attack as a function of airspeed for a fixed load and for a 2-g turn. The angle of attack at which the plane stalls is constant and is not a function of wing loading. The angle of attack increases as the load and the stall speed increases as the square root of the load. Thus, increasing the load in a 2-g turn increases the speed at which the wing will stall by 40%. An increase in altitude will further increase the angle of attack in a 2-g turn. This is why pilots practice "accelerated stalls" which illustrates that an airplane can stall at any speed, since for any speed there is a load that will induce a stall.

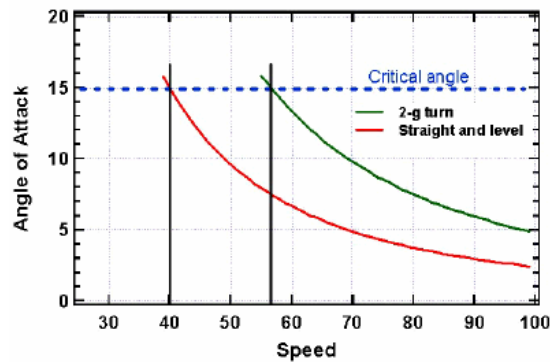


Figure 17. Angle of attack versus speed for straight and level flight and for a 2-g turn.

Wing vortices

One might ask what the downwash from a wing looks like. The downwash comes off the wing as a sheet and is related to the details on the load distribution on the wing. Figure 14 shows, through condensation, the distribution of lift on an airplane during a high-g maneuver. From the figure one can see that the distribution of load changes from the root of the wing to the tip. Thus, the amount of air in the downwash must also change along the wing. The wing near the root is "virtual scooping" up much more air than the tip. Since the wing near the root is diverting so much air the net effect is that the downwash sheet will begin to curl outward around itself, just as the air bends around the top of the wing because of the change in the velocity of the air. This is the wing vortex. The tightness of the curling of the wing vortex is proportional to the rate of change in lift along the wing. At the wing tip the lift must rapidly become zero causing the tightest curl. This is the wing tip vortex and is just a small (though often most visible) part of the wing vortex. Returning to Figure 7 one can clearly see the development of the wing vortices in the downwash as well as the wing tip vortices.



Fig 14. Condensation showing the distribution of lift along a wing.

Winglets (those small vertical extensions on the tips of some wings) are used to improve the efficiency of the wing by increasing the effective length, and thus area, of the wing. The lift of a normal wing must go to zero at the tip because the bottom and the top communicate around the end. The winglet blocks this communication so the lift can extend farther out on the wing. Since the efficiency of a wing increases with area, this gives increased efficiency. One caveat is that winglet design is tricky and winglets can actually be detrimental if not properly designed.

Ground effect

The concept of *ground effect* is well known to pilots. This effect is the increase in efficiency of a wing as it comes to within about a wing's length of the ground. The effect increases with the reduction in the distance to the ground. A low-wing airplane will experience a reduction in the induced drag of as much as 50 percent just before touchdown. This reduction in drag just above a

surface is used by large birds, which can often be seen flying just above the surface of the water. Pilots taking off from deep-grass or soft runways also use ground effect. The pilot is able to lift the airplane off the soft surface at a speed too slow to maintain flight out of ground effect. This reduces the resistance on the wheels and allows the airplane to accelerate to a higher speed before climbing out of ground effect.

What is the cause of this reduction in drag? There are two contributions that can be credited with the reduction in drag. The ground influences the flow field around the wing which, for a given angle of attack, increases the lift. But, at the same time, there is a reduction in downwash. It can be surmised that this additional lift must come from an increase in pressure between the wing and the ground. In addition, since lift is increased for a given angle of attack, the angle of attack can be reduced for the same lift, resulting in less downwash and less induced drag.

Ground effect introduces a fundamental change from the discussion of flight at altitude. When no ground is present, the relationship between lift, drag and downwash is straight forward. But, near the ground, there is an action-reaction between the wing, the air and the ground. At altitude the ground is so distant that this effect does not exist. Near the ground this interaction helps produce lift and reduce downwash due to an increase in pressure below the wing. The details of ground effect are extremely complex. Most aerospace texts devote a paragraph or two and don't attempt to describe it in depth. The truth is that so much is changing in ground effect that it is difficult to describe by pointing to a single change in the air flow or a term in an equation. There is no simple way to describe how the airflow adjusts to satisfy the change in conditions.

Conclusions

Let us review what we have learned and get some idea of how the physical description has given us a greater ability to understand flight. First what have we learned:

- The *amount of air* diverted by the wing is proportional to the speed of the wing and the air density.
- The *vertical velocity* of the diverted air is proportional to the speed of the wing and the angle of attack.
- The *lift* is proportional to the amount of air diverted times the vertical velocity of the air.
- The *power* needed for lift is proportional to the lift times the vertical velocity of the air.

Now let us look at some situations from the physical point of view and from the perspective of the popular explanation.

- The plane's speed is reduced. The physical view says that the amount of air diverted is reduced so the angle of attack is increased to compensate. The power needed for lift is also increased. The popular explanation cannot address this.
- The load of the plane is increased. The physical view says that the amount of air diverted is the same but the angle of attack must be increased to give additional lift. The power needed for lift has also increased. Again, the popular explanation cannot address this.
- A plane flies upside down. The physical view has no problem with this. The plane adjusts the angle of attack of the inverted wing to give the desired lift. The popular explanation implies that inverted flight is impossible.

As one can see, the popular explanation, which fixates on the shape of the wing, may satisfy many but it does not give one the tools to really understand flight. The physical description of lift is easy to understand and much more powerful.