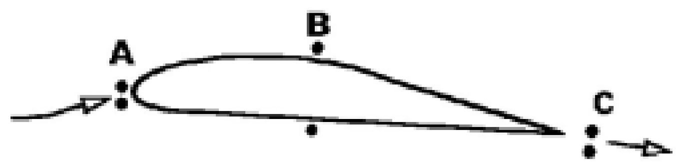
PHYSICAL PRINCIPLES OF WINGED FLIGHT

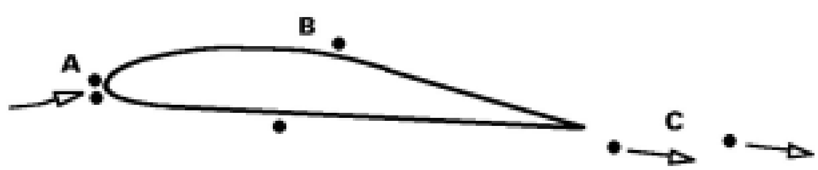
PLAUSIBLE FALSEHOOD

Popular explanations of how wings work are often erroneous and scientifically unsound. Wrong explanations may be given by well-meaning teachers and others, but false teaching may sometimes be just for convenience. Many years ago, a famous aerodynamicist, Dr. Theodore Von Karman, instructed his assistant: "When you are talking to technically illiterate people you must resort to the plausible falsehood instead of the difficult truth." (From Stories of a 20th Century Life, ISBN 0-915760-04-5, by W.R. Sears, former assistant to Von Karman). Falsehood, whether intentional or not, is still being taught.

The most popular theory of wing operation, which we may call "hump theory" because it requires a wing to have a more convex upper surface as compared to the lower, is easily shown to be false. Hump theory is based on an assumption of equal transit times, that air passage over a curved upper wing surface must occur in the same length of time as air passage below, where the surface is more flat, and hence of a shorter path length. In order to have the same transit time, flow at the longer path upper surface must be of greater velocity than that at the lower surface. Thus, in accordance with Bernoulli's law, it is reasoned that upper surface pressure must then be less than at the lower surface, thereby producing upward lift. Equal transit time is sometimes illustrated by representing adjacent bits of passing flow as being parallel ahead of and behind an airfoil or wing as shown above.



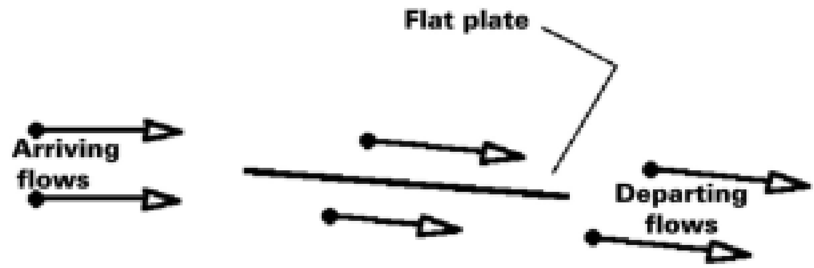
Although Bernoulli's law is sound and well proven, experiment proves this popular explanation of wing operation is false. Upper surface flow of a lifting wing is indeed faster than the lower, so much so that *upper surface transit time is normally less than the lower.*



Although the assumption of equal transit time is proven wrong and has no basis in known physics, it can be found in books from otherwise reputable publishers such as National Geographic, Macmillan and others in this country and abroad. Higher level teaching of aerodynamicists and aeronautical engineers does not include equal transit time, which cannot survive mathematical investigation

The fallacy of equal transit time can be deduced from consideration of a flat plate, which will indeed produce lift, as anyone who has handled a sheet of plywood in the wind can testify.

As indicated in here, air approaching an inclined flat plate, such as a sheet of plywood, accelerates into the reduced above-plate pressure with increasing velocity, while air approaching below is slowed in the increased pressure, in accordance with Bernoulli. Thus faster upper surface flow can be described as a result of pressure difference rather than the cause of it. Bernoulli's "principle," or "law," states that velocity varies in inverse relation to pressure but does not assign cause-and-effect. Unfortunately a great amount of confusion has been generated by abuse of Bernoulli's law in erroneous cause-and-effect explanations.



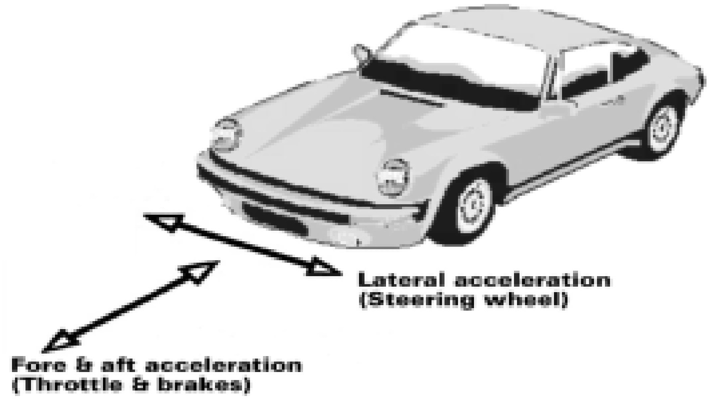
PHYSICAL REALITY

Basic Newtonian principles of aerodynamic lift and propulsion include:

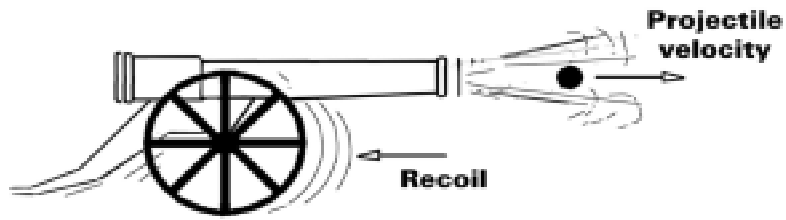
1. Upward lift is derived by accelerating air mass downward.
2. Forward propulsion, of propellers and jets, is gained by accelerating air mass rearward.
3. Drag is incurred through accelerating air mass forward, as by viscous coupling. For the most part this is undesirable but unavoidable.
4. Air mass recirculates upward at a rate equal to the rate at which it is displaced downward in the lift process, thus normal atmospheric mass distribution is maintained.

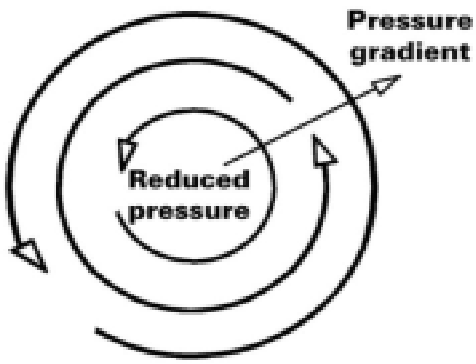
Sir Isaac Newton (1642-1727) provided for us laws of physics which govern aerodynamic lift. His first law is that velocity of an object, or bit of mass, changes only when the mass is acted upon by applied force. The second law states that when force is applied to a mass, it accelerates, meaning changes velocity, at a rate equal to the force-to-mass ratio. The term "velocity" includes both speed and direction.

Force is required to change direction or speed of an object. We drive our cars by operating a system of accelerators. These include throttle, brakes and steering wheel, as indicated here.



Newton's third law states that mass resists acceleration with equal and opposite force. Thus when a cannon accelerates a missile forward the cannon recoils in rearward direction in response to equal opposite force.





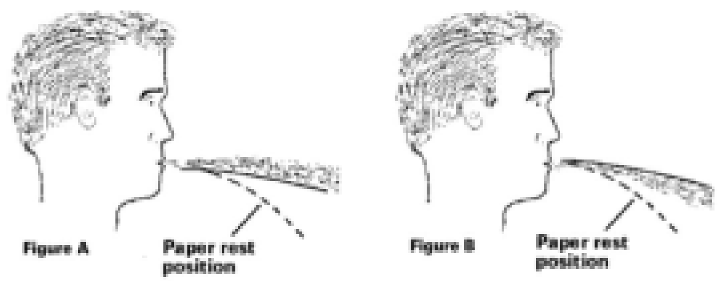
In air, or other fluid, force is exerted in pressure difference. Pressure difference between two positions in air is distributed across the distance between positions as a *pressure gradient*, equal in magnitude at any point to the ratio of pressure difference increment, dp, to distance increment, ds, at that point. Direction of the pressure gradient is toward the position of greater pressure. The direction of air acceleration is toward lower pressure and thus opposite to the direction of pressure gradient. A tornado has reduced air pressure at its center. Air moving around it is accelerated toward reduced center pressure (centripetal acceleration) so that it continuously curves around the center. In opposition with equal counter-centripetal force, air pushes outward from the center, producing an outward pressure gradient, which we may refer to as a "centrifugal pressure gradient."

In a demonstration sometimes wrongly described as showing lift due to pressure reduction in moving air, or pressure reduction due to flow path restriction, a ball or balloon is suspended by a jet of air. Such demonstration may be designed for the purpose of attracting attention to the vacuum cleaner section of a department store.

In reality, flow follows the surface of the ball, in a phenomenon known as "surface attachment" or "Coanda effect," producing, in the curving flow, an outward pressure gradient opposing atmospheric pressure and reducing surface pressure at the ball so that the ball is drawn into the flow. Coanda effect can be demonstrated by the device shown in the photograph below.

In demonstration the coffee can is removed and the candle lighted. The small blower is then energized, blowing air above the candle with no significant effect on the flame. The blower is then stopped and the coffee can is inserted as shown. When the blower is again energized, flow follows the can surface downward and extinguishes the candle flame. The blower shown was found in an electronics flea market. Perhaps a small hair dryer operating at low speed would suffice for one wishing to produce a similar demonstration.

A popular classroom demonstration of aerodynamic lift involves a drooping sheet of paper, as in figure A, which lifts when air is blown over it. This is often mistakenly described as pressure reduction in moving air according to "Bernoulli principle." In reality it is another demonstration of pressure reduction in a centrifugal pressure gradient. The upward pressure gradient in downwardly accelerating flow opposes atmospheric pressure, resulting in upper surface pressure reduction and lift.



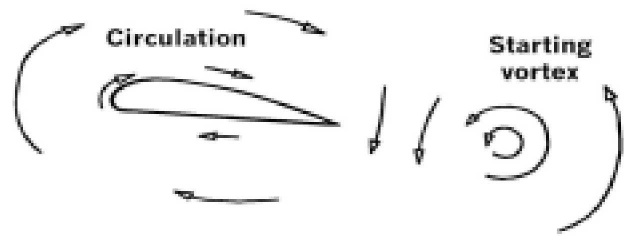
If the lift in figure A were caused by "Bernoulli principle," then the paper in figure B should droop further when air is blown beneath it. However, as shown, it raises when the upward pressure gradient in downward-curving flow adds to atmospheric pressure at the paper lower surface. Curvature of flow and resulting pressure gradients is the source of lift for heavier than air aerodynamic flight. Description of lift as due to pressure gradients in curvature of above-wing and below-wing flows was given by Otto Lilienthal in his 1889 book titled *Birdflight as the Basis of Aviation.* Unfortunately that has been neglected for well over a century in favor of pseudoscientific descriptions. Lilienthal found that wing curvature from leading edge to trailing edge improved efficiency by adapting to the required curvature of flow.

CONSERVATION OF ANGULAR MOMENTUM

In basic physics, angular momentum, the mass times velocity movement around a position or axis is said to be "conserved," meaning unchanged in absence of applied torque and rotation. Here we have water rotations caused by movement of a canoe paddle which does not rotate, and therefore cannot produce net angular momentum. It can, however produce dual rotations of equal but opposite angular momenta, adding to zero net angular momentum change. In the right photo rotations are around the paddle and around a vortex left behind. These are caused by recirculation of water in reaction to pressure differences caused by paddle movement. In classical aerodynamics teaching, Helmholtz' vortex theorems similarly require equal and opposite vorticity.

Comparable rotations in air are caused by beginning wing or airfoil movement, as illustrated here, where upward recirculation is produced from increased pressure below toward reduced pressure above. Ludwig Prandtl (1875-1953), an important aerodynamics pioneer, photographed and published such recirculation movements around an airfoil in water.

CIRCULATION

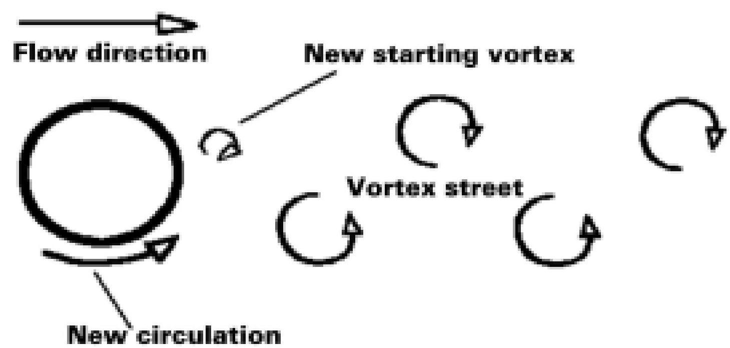


Upward recirculation in response to downward displacement produces rotational patterns of recirculation around an airfoil and around a "starting vortex" left behind. The recirculation around an airfoil or wing is termed "circulation," and is, in classical theory, the cause of faster above-wing flow as compared to below-wing flow. As described by Lanchester (1868-1945) in his 1907 book, *Aerodynamics*, circulation is essential to lift.

Because of downward air acceleration, pressure below the airfoil or wing is increased and pressure above it is decreased. In beginning response upward recirculation occurs around the leading and trailing edges. Then, as forward airfoil movement continues, downward movement left behind the trailing edge divides, forward and rearward, into patterns of circulation around the airfoil and around a "starting vortex." The starting vortex is left behind while circulation travels with the airfoil.

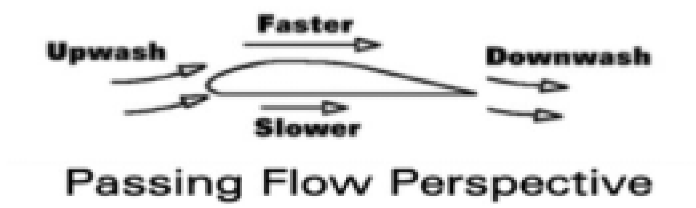
Circulation is regenerative. Pressure difference produces circulation, and as circulation upward movement ahead of the leading edge is intercepted by wing forward movement, and accelerated downward in following the surfaces, more pressure difference is produced. Thus circulation increases regeneratively until reaching the limit at which it provides downward movement at the rear for flow to depart the trailing edge in the pointed direction. Circulation in excess of this would be opposed by airfoil direction. With mature circulation providing downward movement matching the need for flow departure in the pointed direction at the trailing edge, participation of the starting vortex is no longer needed or accepted, and as growths of starting vortex and forward circulation cease, the starting vortex is left behind.

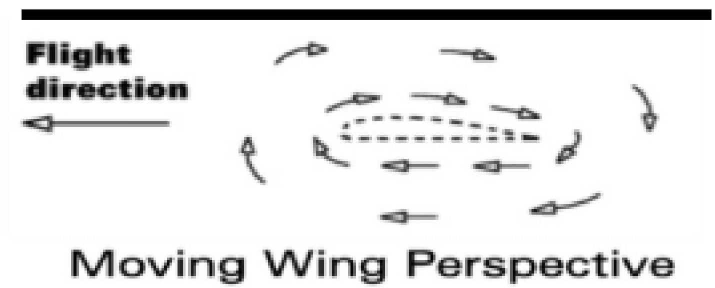
In this mature and stable circulation state, called the "Kutta condition," theoretical lossless two-dimensional lift of an airfoil is equal to the rate of circulation downward momentum produced plus an equal rate of upward recirculation momentum intercepted by airfoil forward movement.



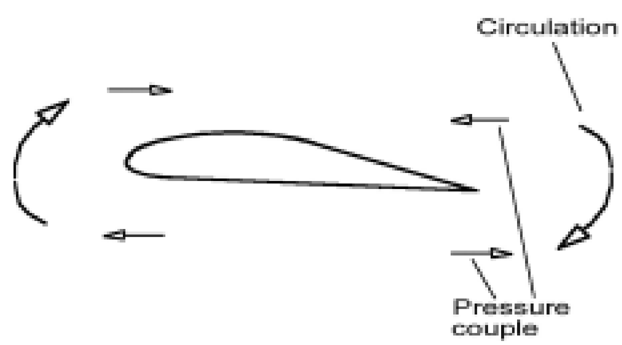
Evidence of the regenerative nature of circulation and lift can be sometimes be seen in flow downstream from bridge pilings. A round piling has no departing flow direction limiting feature. This allows circulation and lift to increase until stall occurs, followed by lift reversal due to effects of residual boundary layer and pressures. A trail of alternating vortices occurs as circulation and lift periodically produce stall and reversal. In each reversal of circulation and lift a new starting vortex is carried downstream.

Circulation is sometimes described as a rotational movement added to, or superimposed on, passing flow. With the added rotational component, oncoming flow can be described as rising upward ahead of an airfoil or wing, descending behind, having increased velocity above-wing and decreased velocity below. Alternatively circulation can be considered as a transitory rotation of air which travels with the airfoil or wing through otherwise relatively still air, in a manner somewhat analogous to movement of water as it is parted laterally by a ship bow and rejoins at the stern in outward and inward movements. The water movements travel with the ship even though the water does not. The concept of superimposed circulation may seem a bit abstract but circulation is a real rotational movement that travels through the air with the wings of an airplane in flight. Alternate perspectives, of fixed wing in passing flow and moving wing through still air, are illustrated here.





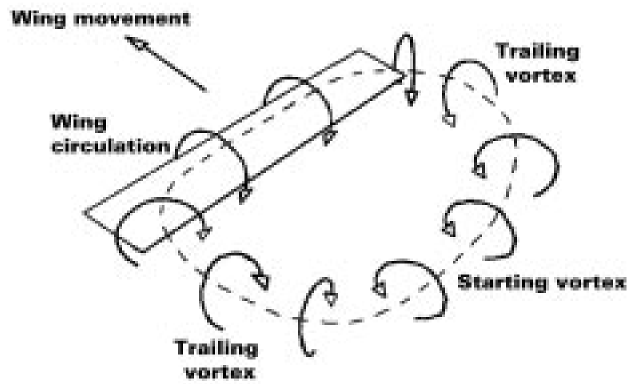
In passing flow perspective, flow curves upward ahead of the lifting wing or airfoil toward reduced pressure above, and away from increased pressure below, accelerates rearward into reduced above-wing pressure with increased rearward velocity and decreases rearward velocity below in response to increased pressure. At the trailing edge upper and lower flows merge to leave in downward direction pointed by the airfoil. Downward departing flow curves upward toward being parallel to the path of flight, again in response to gradients of decreased above-wing pressure and increased below-wing pressure. In stable flight, circulation kinetic energy is recovered from flow left behind and imparted to oncoming flow ahead, through fore and aft pressure gradient couples and Bernoullian process.



In moving wing perspective, as we normally think of airplanes moving through still air, circulation is carried with the wing. Upward movement of air ahead is driven by pressure force coupled from gradients of increased pressure below-wing and reduced pressure above. Gradients of the same pressures, oppose circulation at the rear and recover circulation kinetic energy, though not all of it. In stable lift condition, equal and opposite pressure couples cancel in effects on overall circulation, leaving angular momentum constant. This stable condition is known as the “Kutta condition.”

If angle of attack is increased, downwash demand is increased for reestablishing the Kutta condition. Increase or decrease of downwash is shared between circulation and a new starting vortex. Circulation angular momentum increase is matched by equal and opposite angular momentum in the new vortex. Growths of starting vortex and circulation cease when the Kutta condition is again established and the starting vortex, no longer involved with circulation, is left downstream. In the opposite case, of decreased angle of attack, a portion of airfoil circulation, in excess of that permitted by the Kutta condition, is deflected by the airfoil and carried downstream as a new vortex of angular momentum equal in magnitude to that of circulation reduction and of same direction as circulation.

In two-dimensional flow of wind-tunnel wall-to-wall confinement of an airfoil section, circulation and starting vortex develop as two opposite-direction vortices formed in equal division of downwardly driven air into forward and rearward paths of upward recirculation. In this case the stabilized rate of upward recirculation ahead is equal to the rate of downward displacement left behind. In the case of a real wing beginning lift in open air, where there is no barrier to lateral loss around wing ends, circulation, starting vortex and wing end vortices are all part of a closed recirculating vorticity loop, as indicated here, driven by air acceleration downward behind a wing. Conservation of angular momentum is maintained as angular momentum on one side of the vortex loop is matched by equal and opposite direction angular momentum on the other side.



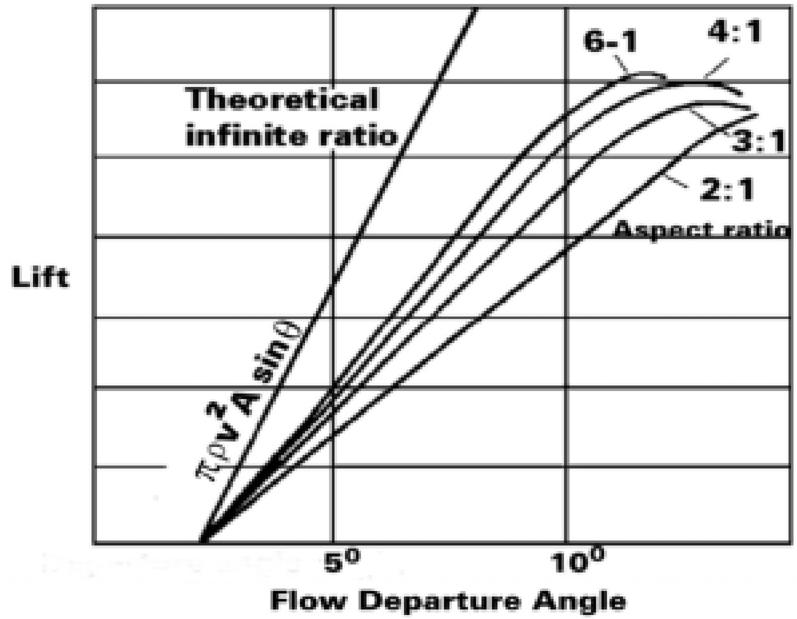
For our purposes, air driven downward by a wing or airfoil will be termed “downwash” and upward recirculation will be termed “upwash.” For a real wing in stable flight, recirculation is also driven around wing ends by pressure difference between above-wing and below-wing regions. In combination with downwash left behind the wing, upwash around wing ends produces twin vortices which trail behind. The starting vortex portion of the initial loop, left behind at the beginning of trailing vortices, has virtually no lasting involvement in stabilized lift.

Continuous production of trailing vortices involves continuous energy loss. A helicopter, which also derives lift from producing downwash, leaves a similar pair of trailing vortices behind, but helicopters can fly much slower than fixed-wing craft of comparable weight and thus can leave much more intense vortices. This picture, courtesy of NASA, shows a vertical column of red smoke drawn into the recirculating downwash vortex left behind a slow flying fixed-wing cropduster.

The body of air included in continued downward acceleration and upward recirculation is extensive, involving a large rate of air mass in circulation and wing end vortices. Inertial opposition of the large rate of air mass involvement to downward acceleration allows the required rate of downward air mass acceleration required for lift to be achieved with a sufficiently low effective downward velocity that the rate of kinetic energy input, proportional to mass times velocity squared production, is small enough for practical flight.

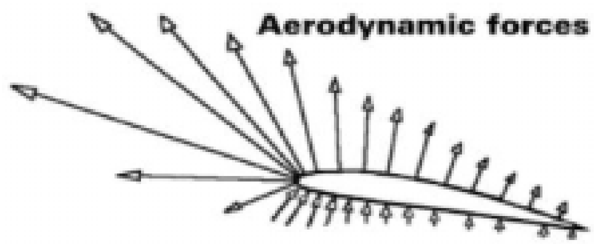
In level flight downward momentum produced in lift is ultimately intercepted by the Earth’s surface, thereby transferring airplane weight to the surface. However, a steeply banked turn may produce mostly horizontal momentum which would be retained in continued atmospheric movement. That wing lift can be effective in maneuvers of any attitude demonstrates the fact that lift at altitude is in reaction to acceleration of a large mass of circulation, not necessarily dependent on weight force transfer to the ground.

In wind tunnel two-dimensional flow airfoil tests, trailing vortices are prevented by confinement of tunnel walls. For a wing operating in open air, limited confinement is effected by inertial resistance to acceleration of surrounding air mass. Longer wingspan produces greater lateral path length with greater mass inertial resistance to lateral acceleration and associated performance loss. This graph indicates relative lift vs flow departure angle, q, performances of wings with differing “aspect ratio,” the ratio of span to chord. Pressure gradients which produce rising circulation ahead of a wing also produce upward recirculation around wing ends, leaving trailing vortices behind. In wind tunnel two-dimensional flow airfoil tests, trailing vortices are totally prevented by confinement of tunnel walls. For a wing operating in open air, limited confinement is effected by inertial opposition of surrounding air mass to acceleration.



“INDUCED” DRAG

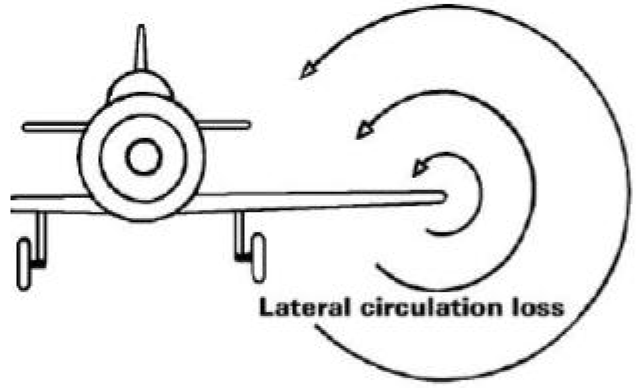
The lift process also produces forward and rearward thrust components, as force vectors here indicate. Forward thrust is associated with pressure reduction in rearward acceleration of circulation rising around the leading edge. Leading edge pressure reduction, known as “leading edge suction,” varies with the ratio of lift to airspeed, and on some airplanes is piped from a leading edge port, as shown below, to a pneumatic stall warning horn in the cabin. Another type of stall sensor actuates when intense circulation around the wing leading edge lifts a small vane, also shown, which operates a switch connected to an electrical warning horn.



Stall warning suction port

Stall warning switch vane

In addition to lift, rearward thrust is produced in reaction to downward and forward acceleration of circulation as it is redirected at the rear of a wing. If there were no losses, the rearward thrust would be equal to the forward thrust generated in leading edge suction. However, because of partial upward circulation loss into lateral paths around wing ends, the rate of rising air mass ahead of a wing is less than that of descending air mass behind . The thrust difference appears as drag, known for historical reasons, as "induced drag."



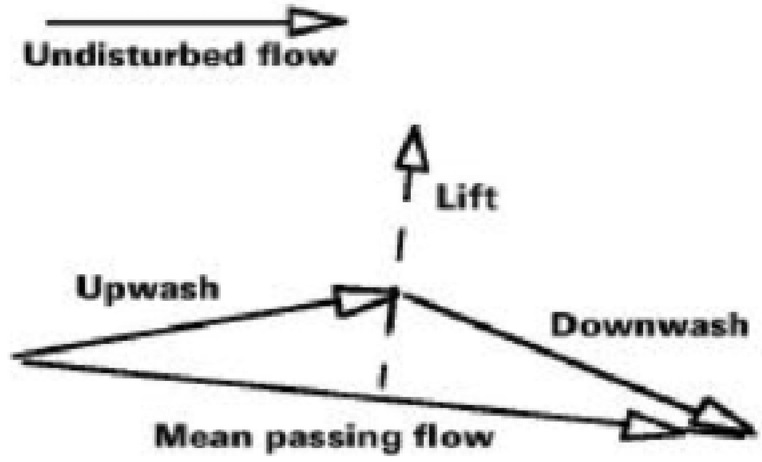
Longer wing spans, which provide greater air mass inertial opposition to lateral loss, are aerodynamically desirable, but limiting factors include stress due to bending moments, and space requirements for ground operations and hangaring. For special airplanes like "Voyager," which flew around the world nonstop and unrefueled, and the U2 spyplane, which flew long high altitude missions, long spans were vital.

Trailing vortices behind wing ends became described as "induced" when it was found that mathematical expression of vortex flow velocity in relation to radius involved the same equation as that expressing magnetic field strength induced by electrical current through a wire. The actual physical basis for describing flow velocity as "induced" is elusive, and authors have written different concepts of it based on differing interpretations of a statement of Ludwig Prandtl.

Prandtl stated: "The wingtip vortices cause a downward motion of air at the wing, which will be shown to be responsible for the drag." (From Prandtl-Tietjens *APPLIED HYDRO-AND AEROMECHANICS* ISBN 0-486-60375-X). Clark Millikan, in *Aerodynamics of the Airplane,* (Wiley and Sons 1941) states: "The numerical computations in Prandtl's theory are identical with calculations developed long ago in the theory of electromagnetic induction, so that the adjective "induced" has been taken from the electrical field and introduced into aerodynamics. John D. Anderson, Jr., in *Fundamentals of Aerodynamics,* 2nd edition, 1991, ISBN 0-07-001679-8, says of trailing vortices: "The two vortices tend to drag the surrounding air with them and this secondary movement induces a small velocity component in the downward direction at the wing." Krisnamurty Karamcheti, in *Principles of Ideal Fluid Aerodynamics,* 1996, ISBN 0-089874-113-0, writes: "It is customary to refer to the velocity at any point in the vortex flow as the velocity induced by the vortex. It must be understood that this is simply a matter of convenience and does not mean that the vortex is actually causing the flow, for they just coexist." Clearly there is no common understanding of what "induction" or "induced" really means in aerodynamics context. Reasonably that is because the concept is, at best, an analogy.

TILT OF LIFT DIRECTION

In classical aerodynamics, which regards trailing vortices as "induced" from central cores, rather than caused by lateral loss of circulation upward movement, addition of "induced downwash" is said to cause downward tilt of flow passing the wing. With lift being aerodynamic force perpendicular to relative flow, downward tilt of passing flow can be said to cause rearward tilt of lift, illustrated symbolically below. The rearward component of tilted lift appears as drag, known as "induced drag," because it is said to be caused by induction effects. The concept of drag due to downward tilt of passing flow has merit, but the tilt can better be described, not as due to addition of induced downwash but due to loss of circulation upwash ahead of the wing, partially diverted into lateral paths around wing ends, making the upwash arrival angle at the wing leading edge less steep than the downwash angle at the trailing edge.

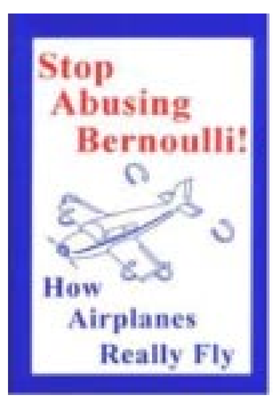


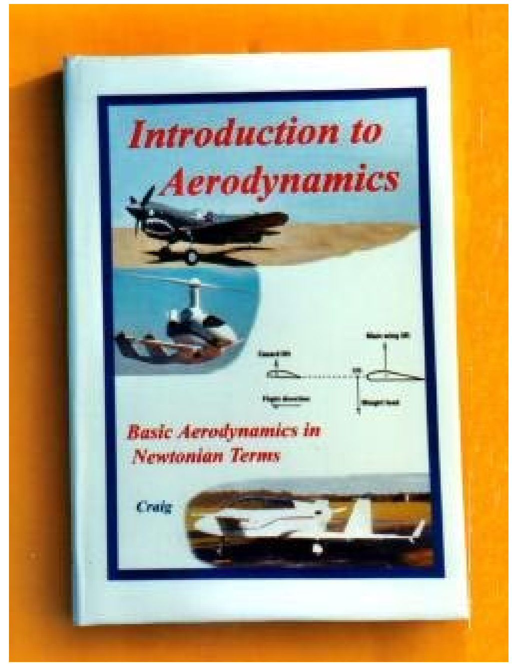
A MODEST PROPOSAL

Some obfuscation might have been avoided, if the electromagnetism analogy of induced flow had not been so convenient as a substitute for Newtonian reasoning. Trailing vortices, as well as other aspects of aerodynamic lift, should be accounted for in Newtonian terms, as proposed by Dr. Jaako Hoffren, of Helsinki University of Technology, in paper, AIAA 2001-0872, *Quest for an Improved Explanation of Lift,* presented at the Aerospace Sciences Meeting & Exhibit in Reno in 2001. If aerodynamics were commonly described in Newtonian terms, regarding all air mass accelerations as associated with forces of pressure difference, then high school and early college physics and mathematics courses might be enriched with basic aerodynamics topics, and false teaching of equal transit time, half-venturi theory and electromagnetism-like induction might be abandoned.

Another questionable point in classical teaching is that of describing circulation as a reaction to the starting vortex, which is usually said to be caused by viscous drag at the wing trailing edge. The reasoning involves Helmholtz' theorems of vorticity, which require that creation of any vortex be accompanied by other opposite and equal vorticity. This is equivalent to the Newtonian principle of conservation of angular momentum. This requirement does not justify assumption that one vortex causes another of opposite rotation, as indicated by some authors. Starting vortex and circulation can readily be explained as created simultaneously in equal and opposite reactions to pressure gradients occurring when air mass is displaced by airfoil movement.

Two books by this author present basic aerodynamics in terms of Newtonian principles, as taught in high schools and college, with circulation but with less mathematical complexity than usually associated with circulation teaching. Soft cover, *Stop Abusing Bernoulli!- How Airplanes Really Fly,* ISBN 0-9646806-2-9, 160 pages and 100 illustrations, as shown on the left, was published in 1999. The book has sold to many countries around the world, and as shown on the right, has been translated into Korean by Dr. S.K. Lee for use in Pusan National University.





Peter Garrison's review of Stop Abusing Bernoulli! in July 1999 FLYING MAGAZINE, recommends it "to all pilots and would-be pilots." However, it is no longer in print, although, as of this writing, a few copies are still on the shelf at Academy of Model aeronautics (AMA) museum, phone 765-289-4236. A second book, with more detail, better illustrations and hardcover, incorporates the Stop Abusing Bernoulli information, and more.

The second book, Introduction to Aerodynamics, ISBN 0-964680637, published in January, 2003, with 224 pages and 167 illustrations, begins with applicable principles of Newtonian physics explained in aerodynamics context, followed by aerodynamics of wings, airplanes, helicopters and surface effect craft explained in Newtonian context. Reviews are posted on Amazon.com.

Introduction to Aerodynamics, list $29.50, is available from Amazon.com, from Academy of Model Aeronautics (AMA) Museum bookstore at Muncie, Indiana, Phone 765-289-4236, and from DAR Corporation in Lawrence, KS, phone 785-832-0434, e-mail info@darcorp.com. For further information contact the publisher:

Regenerative Press
1900 Romine Road
Anderson, IN 46011

Discount available for libraries and educational institutions. e-mail regenpress@aol.com, Phone 765-642-4349

Author Gale Craig is retired from 35 years in General Motors Research and development. Licensed to teach high school physics and mathematics, he holds the MS degree in physics, is named as sole inventor in sixteen U.S. patents in widely varied areas and is a licensed pilot of 1700 hours who owns and flies a Cessna 182.