Flight

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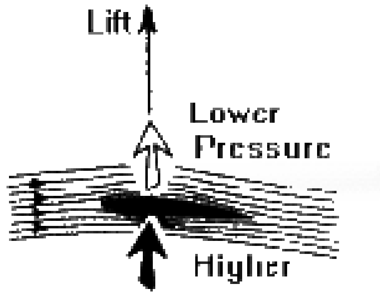
INTRODUCTION

When one thinks of a bird one invariably thinks of flight, since the behaviour of the vast majority of birds is usually connected to the benefits and problems of flight. Flight enables birds to cover large areas in a short period, and to migrate thousands of kilometres between two different habitats in one year. Some birds use their wings in courtship displays, some herons employ them as sunshades to better see fish when fishing, and rails use them for clambering through branches. Birds cannot use their forelimbs for holding, or carrying, and so use either their beak or feet.

The mechanics of bird flight are more complicated than for an aeroplane with fixed wings. When gliding, a bird wing behaves like an aeroplane wing and lift is generated by its forward movement through the air. In flapping flight the wing is acting both as a lifting surface and as a means of propulsion. In level or horizontal flight, the relative airflow is horizontal and lift acts vertically upwards. In non-horizontal flight (in a dive, with the head down, or in a climb, with the head up) lift still acts at right-angles or perpendicularly to the relative airflow, but, because the relative airflow is not horizontal, lift does not act vertically upwards.

How is Lift Produced?

To get "lift" from a wing in an airflow, we need two conditions. Firstly, the airflow must flow around the object in smooth, unbroken "streamlines". Luckily, air flows smoothly in "streamlines" or layers around any object that is streamlined. These are the streamlines or layers of air that we see flowing in the accompanying figure. An airflow that does not flow in streamlines develops eddies and burbles, which we call turbulence. Turbulence upsets a smooth airflow, causes a loss of lift, and increases the drag of the object, which is its resistance to its passage through the air. We may still get lift, but less of it.

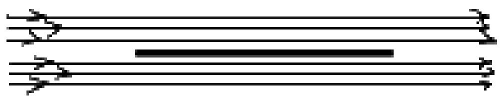


Secondly, in getting lift, we need a higher air pressure on one surface of the wing and a lower air pressure on the other surface. Water flows downhill, from a higher level to a lower level. If we push on a chair, we have a higher pressure on the side we are pushing, and a lower pressure on the other side. The chair will then move away from our push towards the side of lower pressure. It is the same with an object in an airflow that has two different air pressures about it - it will tend to move away from the area of high pressure towards the area of the lower pressure.

When flying straight-and-level, the bird needs a higher air pressure on the under-surfaces of the wings, and a lower air pressure over the top surface. The difference of pressures has a resultant force acting upwards. This force is LIFT.

If the bird is to maintain its height, the force of LIFT must be sufficiently great to support and balance the bird's WEIGHT

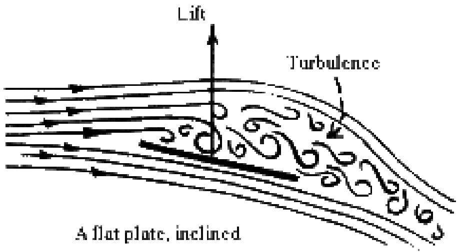
A flat plate would be unsuitable as a wing, because air does not flow smoothly around its surfaces when it is inclined or tilted against the airflow. The air eddies and burbles in turbulence, which destroys some of the streamlines and reduces Lift. Turbulence disturbs the area of lower pressure and the pressure is then not as low as it would be if the airflow was streamlined.



A flat plate edge on to the airflow:
No lift at all

A flat plate perfectly edge on to the airflow would give no Lift at all, because the air would flow **equally and smoothly** over the top and underneath, and so the air pressures above and below would be the same. For lift, we need the pressures to be different. Therefore, what happens if the plate is tilted?

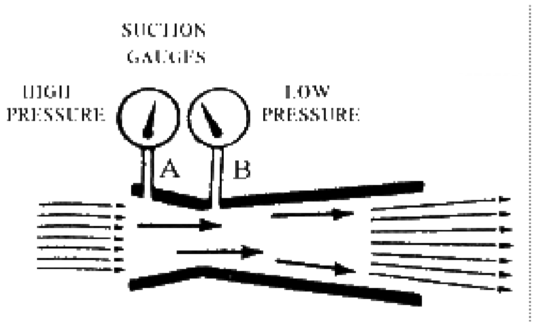
First, the airflow strikes the bottom surface of the plate and is deflected downwards. It therefore changes direction, which causes it to lose some of its kinetic energy, and it slows down. This is good, because as we shall see later, slower moving air has a higher pressure. As this is on the lower surface of the plate, it helps lift - the plate forces the air down, but in doing so enjoys an upward reaction. However, in tilting the plate, lets see what happened to the smooth streamlines that flowed so evenly over the plate when it was edge on to the airflow. Look at all the turbulence over the top surface in the accompanying figure. Turbulence occurs on the top surface because the top surface is not streamlined and the air has to change direction sharply and not smoothly. Turbulence disturbs the smooth airflow and its streamlines, slowing the airflow, which increases the pressure where we want a lower pressure to give lift. In addition, turbulence increases the backwards drag of the plate, hindering its forward motion through the air. Therefore a flat plate is "out". What is needed is a wing with a streamlined shape (cambered top surface) which maintains the streamlining of the airflow, and which causes the airflow on the lower surface to travel slower than the airflow on the upper surface.



Why does a cambered or curved top surface reduce the pressure in an airflow? In 1738, Daniel Bernoulli gave the world his famous Bernoulli's theorem. This theorem explains the changes in air pressure obtained when air flows over an aerofoil. Stationary or static air has its **static** pressure, which is the ordinary or stationary pressure which air possesses due to its **weight**. This pressure comes from the weight of all the air above us, and it grows less as we ascend higher in the atmosphere - the higher we go, the less air there is above us pressing down and around us.

When air moves, it develops a new pressure called **dynamic pressure** or pressure due to movement. It is the air's dynamic pressure you feel when you walk into a stiff breeze. The faster you go, the greater the dynamic pressure. However, moving air still possesses static pressure, and so we say that moving air possesses static pressure, dynamic pressure and **total pressure** (the sum of static and dynamic). Bernoulli found that when air or fluid move in a streamlined flow, the total pressure remains the same so that if either static or dynamic pressure increase, the other must decrease.

Bernoulli's theorem states that *in a streamlined flow, the sum (or total) of the dynamic pressure and static pressure in a fluid remains constant*. This is important on a wing, since if we have a streamlined flow of air moving **faster** over the top surface, the static or stationary pressure there will be **less** than what it is on the lower surface. Thus the static pressure underneath the wing will be greater, and we will have LIFT acting towards the area of lower pressure. Thus the greater the velocity and dynamic pressure, the less the static pressure.



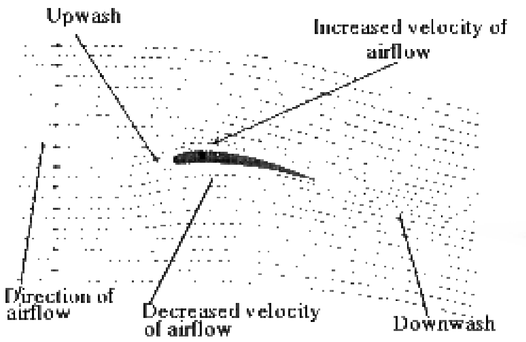
A venturi tube has a wide mouth or inlet, a **narrower** throat, and a gradually widening outlet. C The tube inside is circular and smooth to ensure a smooth, streamlined flow of air. When air is passed through the tube, the same amount of air must pass through the narrow throat as enters the inlet. Since the throat is **narrower**, the air must flow faster. The manometers will indicate that there is a high pressure at the inlet, where the air flows slower, and a low pressure at the throat, where the air flows faster. Look again at the tube - if we throw away the top portion, and close in the bottom portion to give a lower surface, we have the shape of an aerofoil with a curved top surface for a **faster** flow of air, a lower static pressure, and the beginnings of lift!

Pressure Distribution Around a Wing

Pressure acts all round a wing, top and bottom, but NOT at the same value. Air pressure is **less** all over the top surface; pressure is slightly greater all **underneath**; and pressure is least of all over the highly curved anterior section of the top surface. The top surface contributes about 75% of the Lift of the wing, and the bottom surface about 25% of the lift. There is NOT a partial vacuum over the lower-pressure area of the top surface. The lower pressure over the top surface is only slightly less than normal atmospheric pressure, while the higher pressure below the wing is only very little above normal atmospheric pressure.

Airflow Around the Wing

When the wing moves forward through the air at a small angle of attack, the air is parted some distance ahead of the leading edge. The air rising over the leading edge is called the UPWASH. The rising air meets the camber or curvature of the top surface; the airflow is speeded up; the streamlines come closer together and the pressure is reduced. The top surface then curves the airflow downwards over the rear of the wing, which is helped to some extent by the lower surface. This downward wash of air is called the DOWNWASH. Downwash contributes to lift.



The more the wing is tilted against the airflow, that is, the **greater the angle of attack** of the airflow against the wing, the greater the curvature of the airflow over the top surface, the greater the deflection downwards underneath, and the greater the lift.

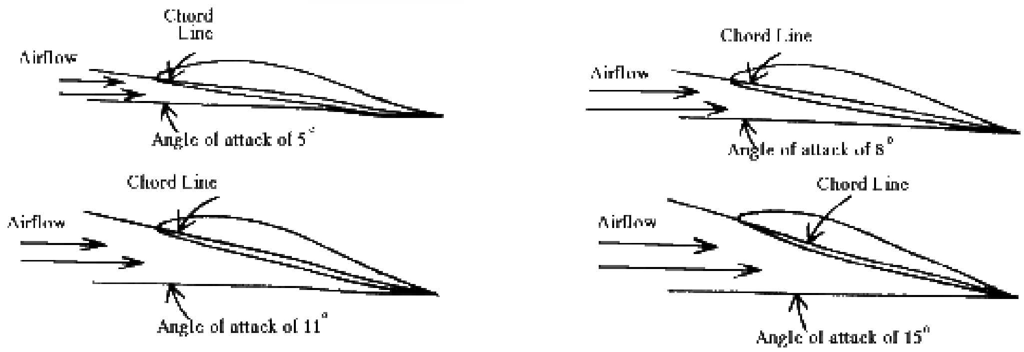
Lift also depends on **air density**. If the air is thin and light, as on a hot day, there is less air by weight passing over the wings than on a day when the air is heavy and more dense.

Next, after angle of attack and air density, comes **airspeed** - the speed of the airflow over the wing. The faster the airflow, the less the pressure and the greater the lift. If the bird doubles its airspeed, it quadruples the lift - lift varies as "speed squared".

Finally, lift depends on the **surface area** of the wings. More air is able to act on and develop more lift from a big wing than a small wing; thus, the greater the wing area, the greater the lift.

ANGLE OF ATTACK

The Angle of Attack (AOA) is the angle between the Chord of the wing and the direction of the airflow. This angle of attack is measured in degrees, and on a wing looks like this: A bird may fly straight-and-level at an AOA as low as -1° or 0°, or at 15°. Neither attitude is economic, the best AOA being 4°. At small angles of attack, drag is low, because the wings present an attitude of minimum resistance to the relative airflow, but lift is also small. As the AOA increases, then lift increases. However, large AOA's mean that the wings and body of the bird jut into the airflow, presenting a large frontal surface to the airflow, causing more resistance, and so more drag. In fact, lift falls off dramatically above AOA's of 15-16°, because the airflow then ceases to flow smoothly in unbroken streamlines over the top of the wing, and eddies and turbulence occur over most of the top, greatly reducing lift.



Beyond 15-16° AOA, the wing is said to STALL. This means that the wing loses lift and will no longer support the body of the bird. Thus lift varies as the AOA, air density, speed-squared, and wing area. The bird has control over the AOA and its speed through the air.

In cross-section, an aeroplane's wings are similar to a bird's wings - convex above, concave below, the leading edge blunt and rounded, and the trailing edge narrowing to a point. The upper and lower surfaces are unequal are unequal in length; air flowing over the upper surface travels farther and hence faster, so that pressure is reduced. Air travelling under the wings does not have to travel so far, and so travels slower, and pressure is increased. The result is the upward force of lift which increases with the angle of attack, reaching a maximum when the AOA is 15°. Above this, lift disappears suddenly and the wing stalls. A wing is said to **stall** when the airstream over the top of the wing breaks up, becomes turbulent, increasing pressure in proportion to that beneath the wing (because the turbulent air above the wing now travels slower than that beneath the wing) and so the wing is forced **downwards**.

The magical difference about a bird's wing is that the shape of the flight feathers can change through the wingbeat cycle. The trailing edge of the vane of each primary feather is broader and more flexible than the leading edge. On the downstroke, the vane twists, the trailing edge goes up and air is forced backwards to produce forward thrust. To fly faster the bird flaps its wings faster to make the primaries twist more and increase thrust. On the upstroke, the carpus rotates and the elbow flexes so that the outer part of the wing folds and separates the primaries, allowing the airflow to pass through and so avoiding the wing (and the attached body) pushing the bird down. A small backward sweep of the wing as it comes up forces the primaries against the air and they act like a paddle to give the bird an extra push forward.

TAKING OFF

To commence flight a bird needs to "take off". When taking off or hovering, the bird loses the lift generated by forward movement through the air. The wings will generate lift as long as the relative airflow over the upper and lower surfaces is below 15° AOA, and the bird is travelling at sufficient speed through the air. The simplest way many birds achieve this is by opening their wings into a sufficiently strong headwind, shaping and angling the wing into an appropriate AOA, and rising with the lift generated. Another way is to jump from a height, folding the wings slightly to allow the body to fall through the air (losing potential energy to gain kinetic energy), and opening the wings once sufficient speed is attained. Swifts have difficulty in taking off in any way other than this. In other circumstances, taking off is a strenuous, energy-demanding procedure, and in order to lift straight up the bird must generate enough power to get it airborne without the help of airflow over the wings to give it lift. Thus most birds jump into the air to give the wings room to beat fully to the downstroke. The tail is fanned outwards and forwards to deflect the airstream downwards, and it may beat shallowly up and down to increase the lifting effect. During this take-off procedure the wingtips (primaries) may hit each other above the body and travel well below the body in order to get the maximum downstroke. The loud "claps" made by a dove taking off in a hurry are caused by the wingtips hitting at the end of the upstroke. At the end of the downstroke, the carpus rotates and the elbow flexes so that the primaries are turned upwards and the wing partly folds. The wing is then pushed sharply back, separating the primaries to let the airflow through. At the end of the upstroke, the wing is given a backward flick as it straightens out and the primaries give the bird a boost forwards and upwards.

When headwind takeoffs, dropping or leaping are not possible, takeoff can be achieved by running, just like an aeroplane accelerating down the runway. Some ducks and geese can

leap straight into the air but swans, cormorants, auks, flamingoes and petrels patter their feet over the surface, their wings beating rapidly but shallowly, until flying speed is reached. If they face into a headwind, this will increase the airflow over the wings and so generate extra lift, and the birds will not have to achieve as high a speed before they become airborne. A wandering albatross cannot take off in a flat calm and, if chased, will fail to become airborne. A strong headwind will lift it off after a few steps.

FLYING

In order to maintain stability, a bird needs its tail. A bird can fly without a tail, but expends considerable energy in maintaining stable flight. *Archaeopteryx*, the earliest-known bird fossil, had a long, reptilian-like feathered tail, which acted as a stabiliser, but would have hampered manoeuvrability. This bird could probably only glide from tree to tree. Modern birds have reduced the tail to a stump with a fan of feathers, and stability is achieved by movements of the wings and tail.

A gliding bird can maintain its course by steering with its tail; to dive it folds its wings to the body (reducing drag) and maintains its dive by steering with the tail (so that relative airflow will keep the head down), thus increasing speed. To rise nose-up, the wings are pushed forward and straightened and the tail is raised slightly. Most birds control stability by raising the wings in a shallow V and moving the tail from side to side to counteract momentary threats to instability. Steering can also be accomplished by altering the AOA of one wing, thus increasing or decreasing lift and rotating the bird back to an even keel. The tail continually reinforces any actions of the wings, especially at slow forward speeds. When flying slowly, a bird's wings can stall. The bird must keep the relative airflow over the top of the wing smooth and faster than that beneath the wing. This becomes very difficult at low forward speeds. The AOA can become so large that the wing stalls and the bird falls from the sky (hopefully pushing its nose down, shifting its tail to the dropped wing, increasing its speed and slowly pulling out of the dive). The alula, or bastard wing, has a bunch of three or four remiges attached to it. It performs the same function as the slot on the leading edge of an aeroplane wing. If the wing is in danger of stalling, the alula is raised and directs rapidly moving air over the upper surface of the wing, thus avoiding turbulence. Herons and storks have a very large alula which allows them to obtain maximum lift at landing, when they almost hover and gently touch down. The alula allows a wing to generate lift even though the AOA exceeds 15°.

SOARING

Once airborne, a bird may glide, a procedure in which forward motion comes from losing potential energy (that due to height) for gain of kinetic energy (speed). Thus altitude is lost. However, altitude can be regained if the bird soars. Soaring allows the bird to exploit upwardly directed air currents, such as occur near cliffs (updrafts) or over hot ground (thermals). These air currents can buoy up the bird's body without it moving the

wings (energy soaring).

There are two main ways a bird may exploit air currents to achieve energy soaring:

a) **Static soaring**. One way birds may utilise this type of soaring is to exploit airflow being deflected upwards by an obstacle. A cliff, hill, large building or other large object such as a ship, provides an opportunity for soaring in the airflow blowing up its face. Gulls use this phenomenon to soar and hover along cliff faces. Ships provide an opportunity for gulls and albatrosses to "gust soar", seeming to hover over the stern of a ship, making use of the eddies of air swirling around it. Ocean swell provides a similar updraught for seabirds, and albatrosses can soar along them, travelling with the swell even in calm weather.

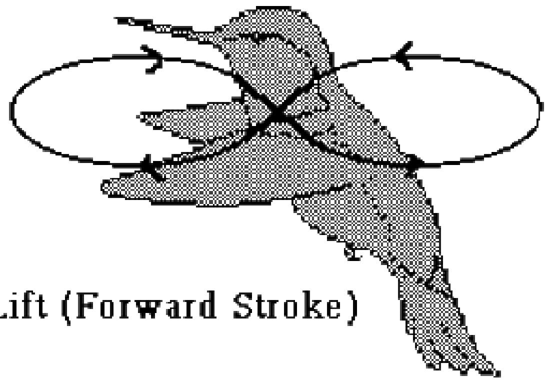
   A second source of energy for static soaring is provided by air rising as it is warmed. When the ground warms in the sun, the air close to it heats and rises as a thermal. Expanses of rock, tall buildings and expansive buildings with metal roofs generate thermals, just as do the oil-field flares used by storks migrating across the Sahara. In all types of thermal there is a rising current of air in the centre which birds use for soaring. Most of the birds which use this type of static soaring to advantage are heavily built with short, broad wings - eagles, hawks, storks, cranes, pelicans and vultures. They all have the ability to turn in tight circles, soaring to the top of one thermal, then gliding to the next, which might be several kilometres distant, to soar again.

b) **Dynamic soaring** takes advantage of the differences in the velocity of air currents which occur at differences in height. Thermals cannot form over the sea, but this is the home of a second group of great soaring birds: the albatrosses. Albatrosses are fast gliders with streamlined bodies and long slender wings to reduce drag. Over the sea surface, in conditions of steady wind, the layer of air in contact with the sea surface is slowed by friction, and full wind speed is only reached at about 30 metres above the sea. Albatrosses use this wind gradient to gain energy for soaring. They glide downwind, picking up speed and losing height, then turn into the wind and rise. Thus as it rises, the kinetic energy it gained on its "downhill run" is converted to potential energy, and its speed relative to the surface decreases. However, as it climbs higher, it meets a stronger wind. The bird exploits this stronger wind to rise higher (this potential energy being gained from the kinetic energy of the faster wind at higher altitude). It thus gains altitude for no input of energy from itself! When the wind gradient drops and the bird cannot climb any more, it turns downwind again and glides

downward, gathering momentum ready to repeat the cycle. An albatross may get 20% of its gained height from dynamic soaring, the remainder coming from static soaring along a wave.

HOVERING

Many birds can hover for a short time, but few can sustain it for long since it is an energy-draining exercise. Some birds such as kestrels appear to hover for prolonged periods. However, in reality they are only flying steadily into a headwind, and their wings are just at the point of stalling. The hummingbirds are the most specialised of hovering birds; in order to hover "on the cheap", they have developed a wing structure different from all other birds, except the closely related swifts. The elbow and carpal joints are immobile, and the wing is a rigid paddle which rotates around a flexible shoulder joint. When hovering, the body is held at an angle of 45° and the wings sweep through a narrow figure-of-eight in a horizontal plane. On the downstroke, the wings are angled to provide lift, and at the end of the beat the wing turns over, so presenting the same angle of attack and obtaining the same lift. The thrust on up down strokes is equal and opposite, so the hummingbird stays in the same place, while a slight change in the angle of attack on either stroke will send the hummingbird forwards or backwards.



To land, a bird must lose height and slow down in a controlled manner, so that it does not crash. Fanning the tail and changing to deep wingbeats, increase drag, slow the bird and generate extra lift. Additional braking can be achieved by approaching the landing point from below and gliding up so that gravity is used to slow the bird. Ducks and geese can lose altitude suddenly by "whiffling" (side-slipping). They use their wings to turn one way and counteract this by using their tails to turn in the opposite direction. They alternate this action and so tumble from side to side, allowing air to spill between widely

spread primaries. This causes a shrill tearing sound, and lift is shed allowing the birds to lose height quickly. At the last moment they use the wings as airbrakes before hitting the ground. Sometimes they twist onto their backs, fold their wings, and so lose lift altogether.

POSTSCRIPT

While on fish disease excursions I have spent hours watching dragonflies. Seemingly without effort, they can rise like an elevator, then hover, make right-angled turns, fly backward, turn around on a point and alight like a feather. The design of dragonflies has changed little since Paleozoic times, 260 million years ago, millions of years before dinosaurs walked the planet. Although early dragonflies were as big as seagulls and today's are much smaller, they still have four wings.

Airplanes with the highest performance generate only 1.3 times their weight in lift. Scientists working at the University of Colorado have determined that dragonflies generate lift amounting to seven times their body weight. They have found that the front wings feed vortices to the rear wings, and these slowly travel from the leading to the trailing edge. The swirling of air in vortices drops pressure at the vortex's centre, and so a moving vortex lowers the pressure on the top of a wing, increasing its lift. We may one day have aircraft that look like, and emulate the flight of, dragon flies.