Second Level Technologies
Benchmark SCN 2-20a

Physics of Flight Pt 5

Exploring the science of the force of aerodynamic lift.

Exploring how Aerodynamic Lift is produced.

The force we call lift can be generated by shapes, called aerofoils, moving in air and shapes, called hydrofoils, moving in water.

When early man saw birds, bats and butterflies moving around in the sky he had no idea how they could do that. Of course he did not even know that there was such a thing as air. Birds, some mammals, some insects and even some fish had found the secret of flight and it was all to do with having some kind of wing that could produce an upward force which was at least equivalent to the weight of the animal.

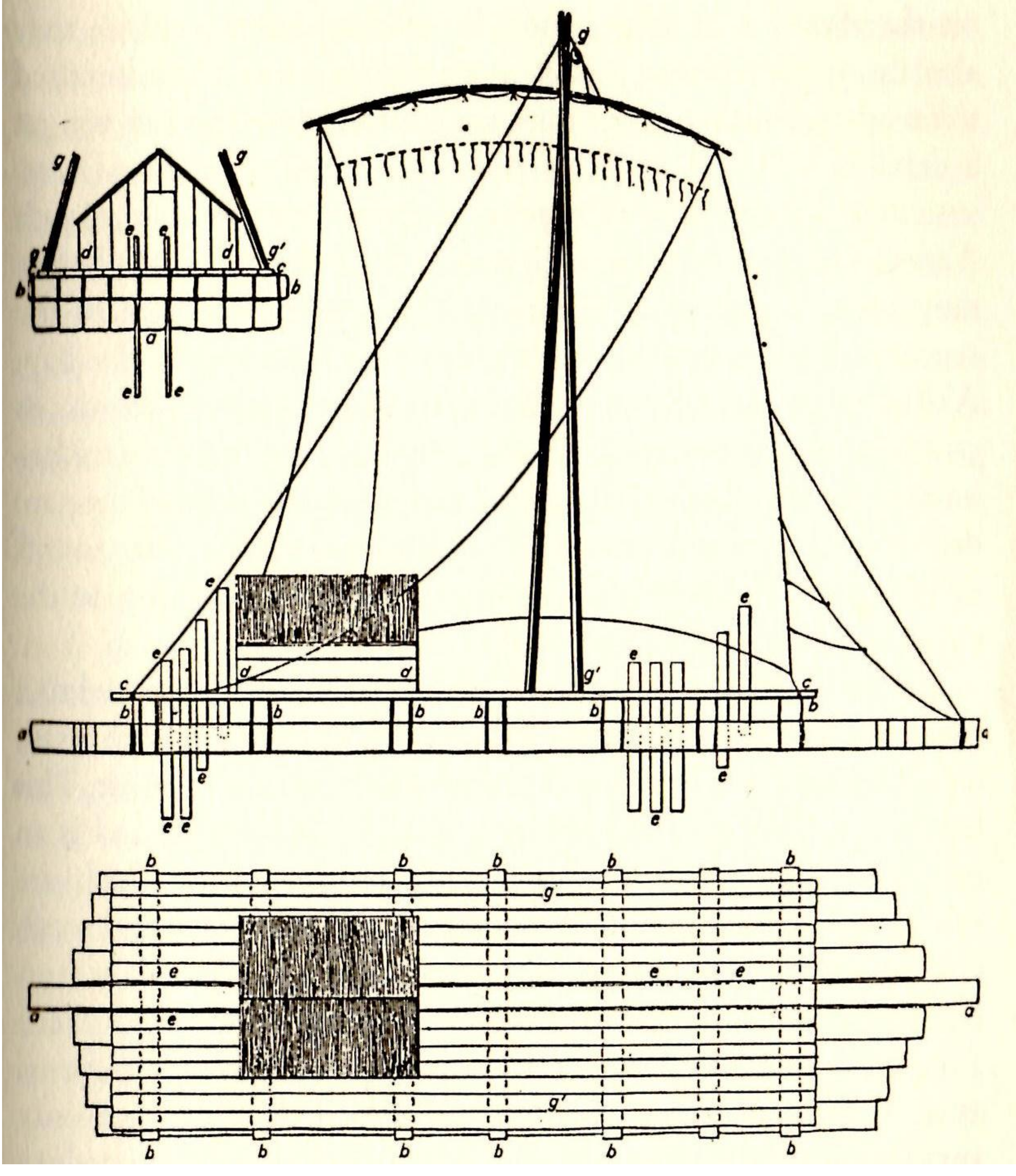
Men could see that wings were obviously the means of flight but when men experimented with wings covered with feathers they did not work. So there was more to it than just a shape like a bird's wing.

The best brains of the physicists and engineers tried to solve the puzzle but it was not until quite recently at the end of the 19th century that the explanation was found.

It was only then that it became clear that man had actually invented aerofoils and hydrofoils hundreds of years earlier.

Polynesian sailing catamaran

In the Science of Flight Pt 3 presentation we saw that the islanders of the South Pacific had been building boats for many centuries that used fore-and-aft sails. This type of sail allowed the boat to travel into the wind but specifically was very good at powering the boat along quickly when sailing at right angles to the prevailing wind. Although the islanders did not know it at the time, they had invented a wing that developed aerodynamic lift.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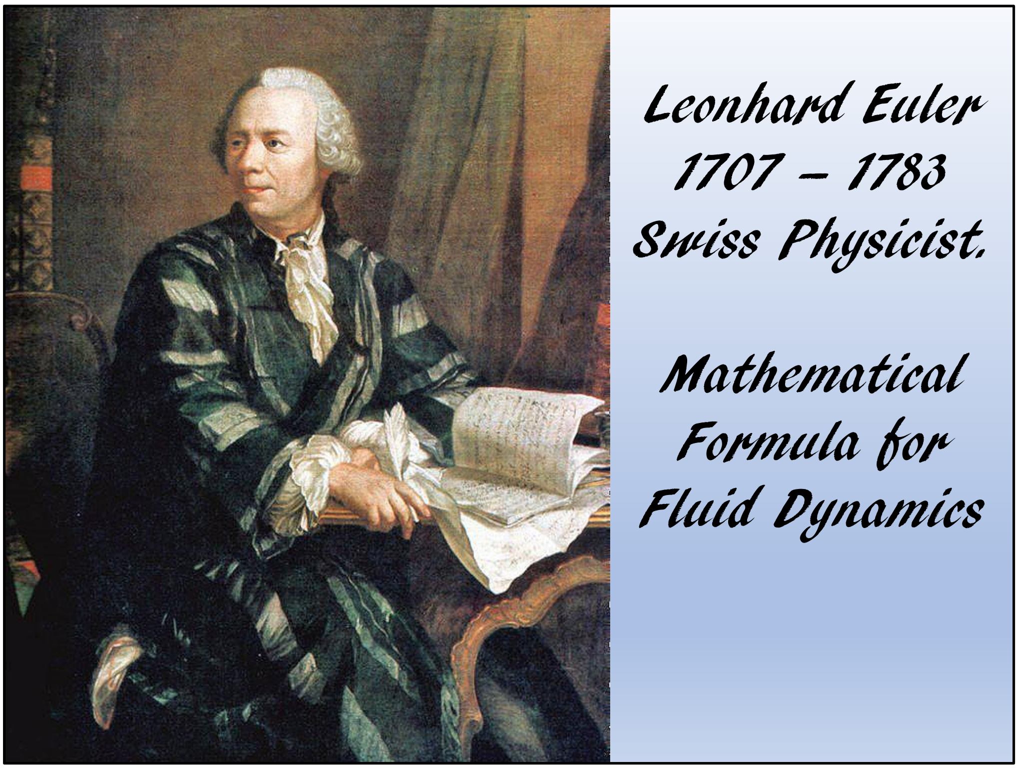
We saw how the sails and keels of modern racing catamarans are designed to be almost the same as an aircraft wing and are able to generate a large lift force to power the boat at high speed. These catamarans also have very sophisticated keels which provide the side force to prevent the boat from being pushed sideways through the water. Although the original inventors of the centre-board and fore-and-aft sail may not have understood how they worked we now know that both these devices developed the force that we would now call “lift”, one working in air, an aerofoil, and the other working in water, a hydrofoil.
Our modern understanding of aerodynamics and hydrodynamics allows us to build very fast racing yachts that can reach very high speeds. The world record speed for a sailing boat is 75 mph in a 30 mph wind.
So now we have found out about devices that provide lift on boats we now have to find out how the principle was applied to aircraft wings.



To understand what happens when we cause a fluid to move we have to go back to the theories and laws set out by Bernoulli and Euler and to look at one of the first practical applications of their work.

Giovanni Venturi was trying to solve the problem of how to find out how much water was flowing in a pipe without opening up the pipe to see. He knew of the Bernoulli experiments and the curious effect of reducing the pressure by speeding up a flow of water. Venturi surmised that if he could make a device to speed up the flow of water in a pipe he could somehow measure the reduction in pressure and, from that, deduce the flow rate. He eventually designed a device that achieved the result he was looking for and it bears his name to this day.

The basic idea was simple enough, it was just a section of the pipe that was smaller than the rest of the pipe, but the shape of the entry and exit from this small section was a bit more tricky to design. The following diagram shows a typical section through a “Venturi”.

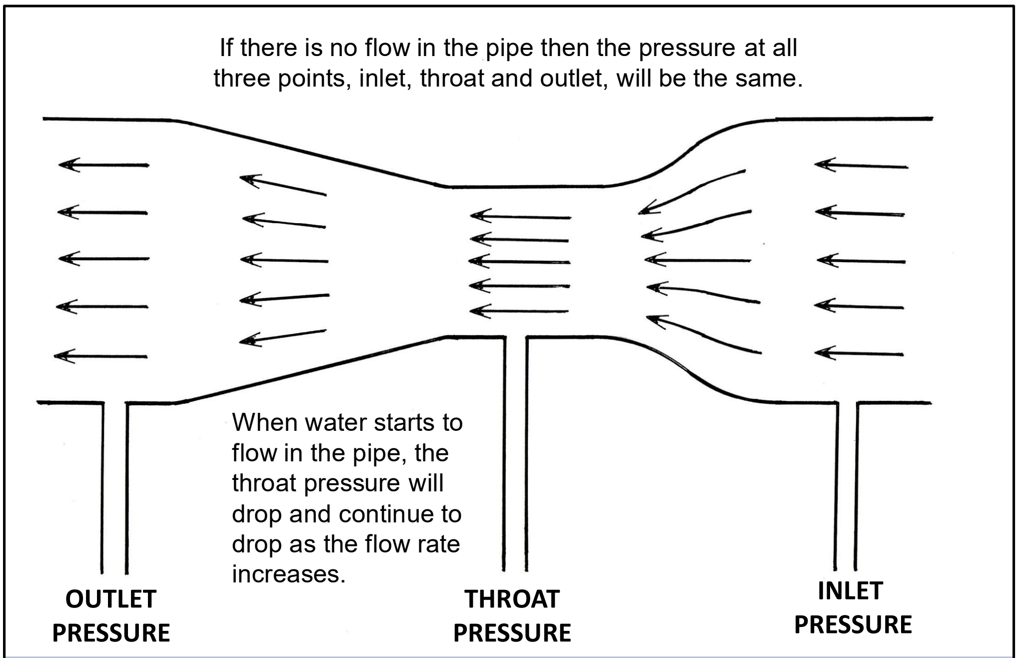
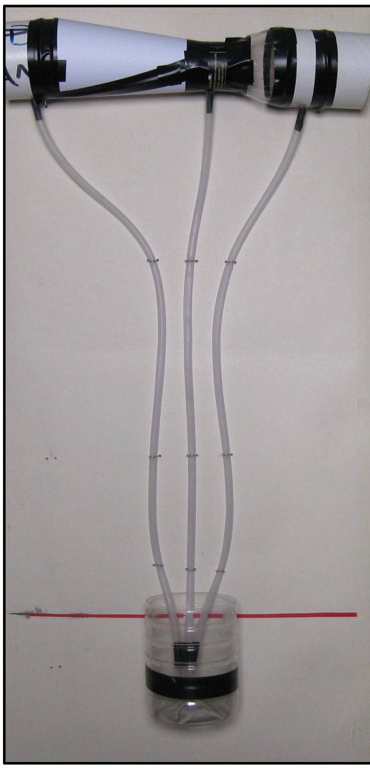


Diagram of a Venturi

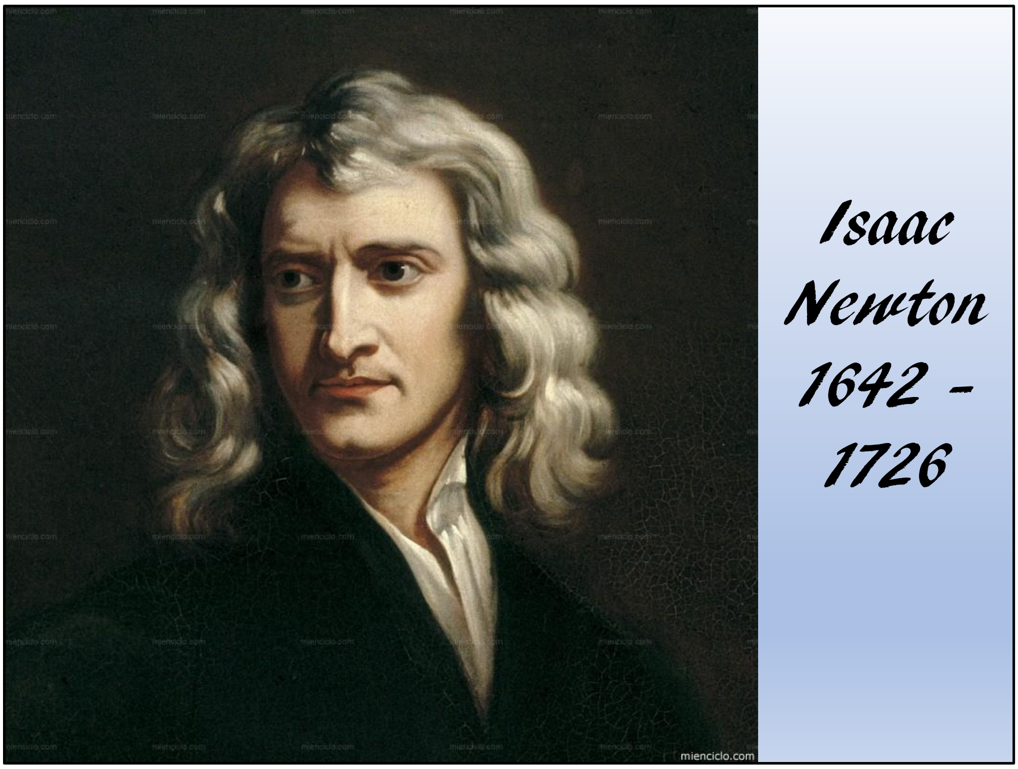
This diagram of a Venturi shows how the flow of water has to speed up to get through the smaller section of the tube. As a result, the pressure drops in this smaller section and, as a result, the rate of flow can be deduced from the difference in the pressure readings.



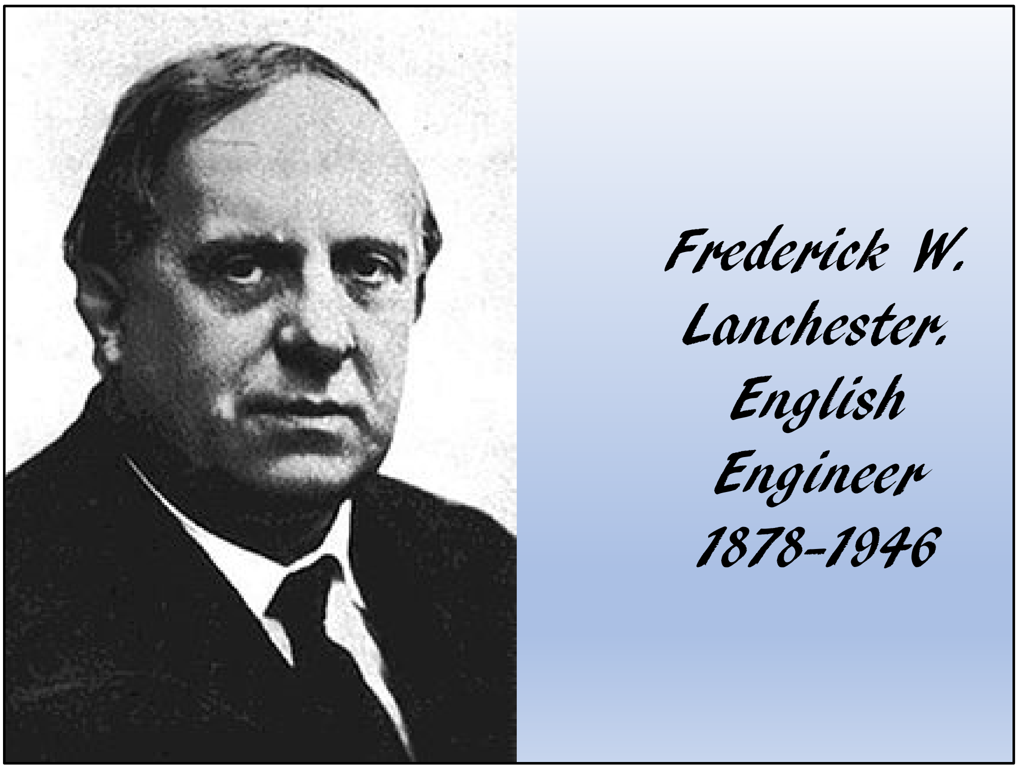
Air is blown in here.

A simple home-made Venturi that was constructed to show how it works.

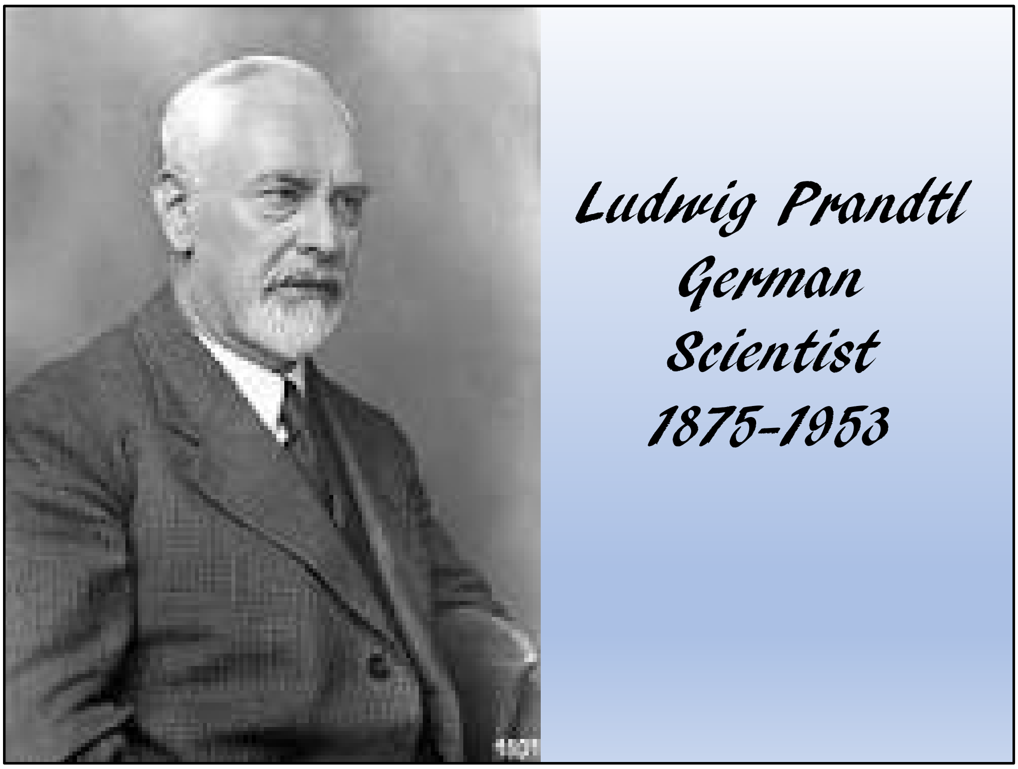
This simple model of a Venturi was made from pieces of plastic drinks bottles, cardboard, adhesive tape and plastic tubes. Water is added to the tank at the bottom and air is blown through the Venturi by an electric hair dryer.
When air is blown through the Venturi the water level in the three tubes is affected by the pressure in each section of the Venturi. The inlet and outlet pressures will be the same but the low pressure in the throat of the Venturi will lift the water level in the central pipe showing that air is indeed flowing.
When a real Venturi is manufactured it is tested with varying flows of air and it is calibrated so that when it is fitted into a pipeline it is able to show the amount of flow in the pipe.



Newton’s Second Law of Motion states that:- **Force = Mass x Acceleration**



Frederick Lanchester studied the flight of birds but, since it was too difficult to visualise what happened when a bird flapped its wings, he concentrated on trying to figure out how seagulls managed to glide on air currents with their wings held stiffly out. Lanchester knew that air was heavy, it had mass, and so he assumed that somehow the wing was accelerating air downwards and generating a force that was equivalent to the weight of the bird. Isaac Newton's 2nd law of motion said that:- Force = Mass x Acceleration so Lanchester proposed the theory that the wing was accelerating the air downwards with enough force to support the bird. He decided that the wing shape caused the air that it passed through to circulate, like a mini tornado, and that as long as the wing moved forward, this circulation was maintained and was constantly produced by the wing. Lanchester proposed this theory to his engineering peers but his idea was not accepted.



.However, in Germany, Ludwig Prandtl realised that Lanchester had hit on the right idea and set about trying to develop the theory of the creation of lift.
Prandtl refined Lanchester's theory and went on to add his own insight as to how the circulation around the wing was formed and could be quantified. In so doing he set the rules for modern aerodynamics and the analysis of fluid mechanics.
Nowadays, with the aid of wind tunnels exploring the flow around aerofoils, and the use of powerful computers that can calculate the local flow and pressure in great detail, the science of aerodynamics has reached a very advanced state. The basic theory however remains the same.

The following examples of aircraft all have lift generated by wings using the circulation theory even although their weight and flying speeds may be very different.

A typical light aircraft, the Piper Cub, designed to cruise at 90 mph at 5,000 ft.

This is a small light aircraft and the wing has to be able to support the aircraft during take-off and landing at a slow speed of 48 mph.

A light twin-engine aircraft designed to cruise at 200mph at 8,000 ft.

This light twin-engine aircraft may be able to cruise at 200 mph but the wing still has to be able to support the aircraft at take-off and landing at about 60 mph.

The Airbus A350 designed to cruise at Mach 0.85, 540 mph, at about 35,000 ft.

The designers of this big modern airliner still had the problem of getting the wing to support the aircraft at take-off and landing speeds. To do this the wing had to be fitted with clever flaps and slats to change the shape of the wing and allow it to continue to provide enough lift at about 120 mph.

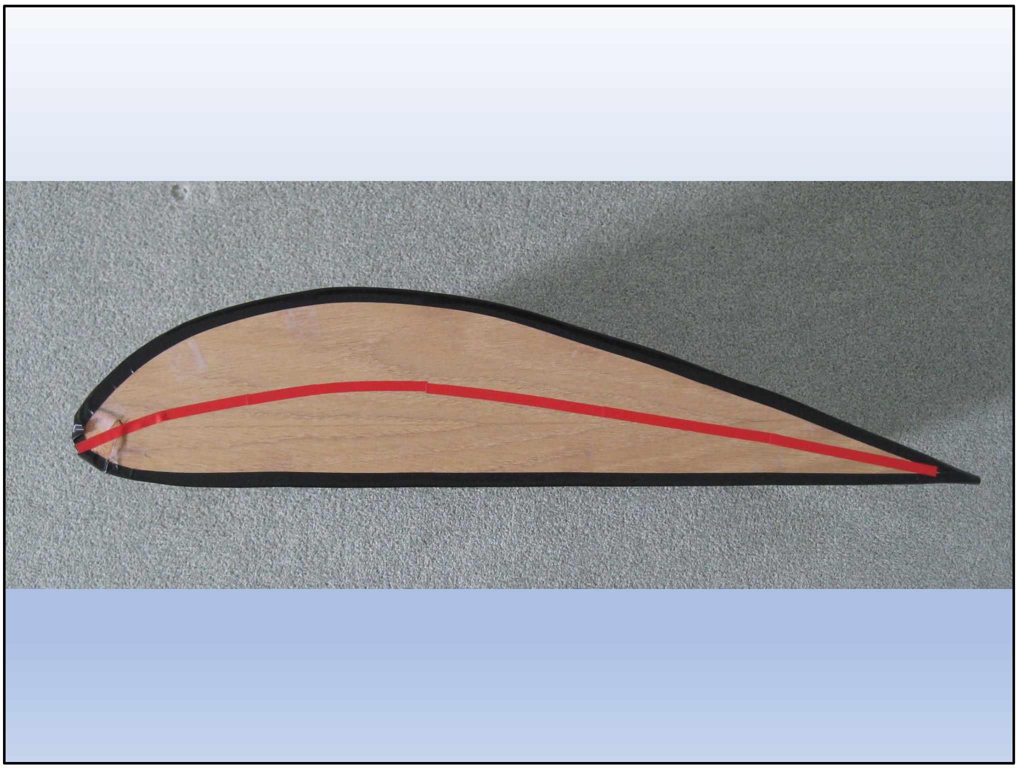
The huge 600 ton Antonov An225 is the heaviest aircraft in the world.
Designed to cruise at 500 mph at 35,000 ft carrying a load of 245 tons

The wing of this huge aircraft has to be able to support the 600ton weight during the 130 mph take-off.

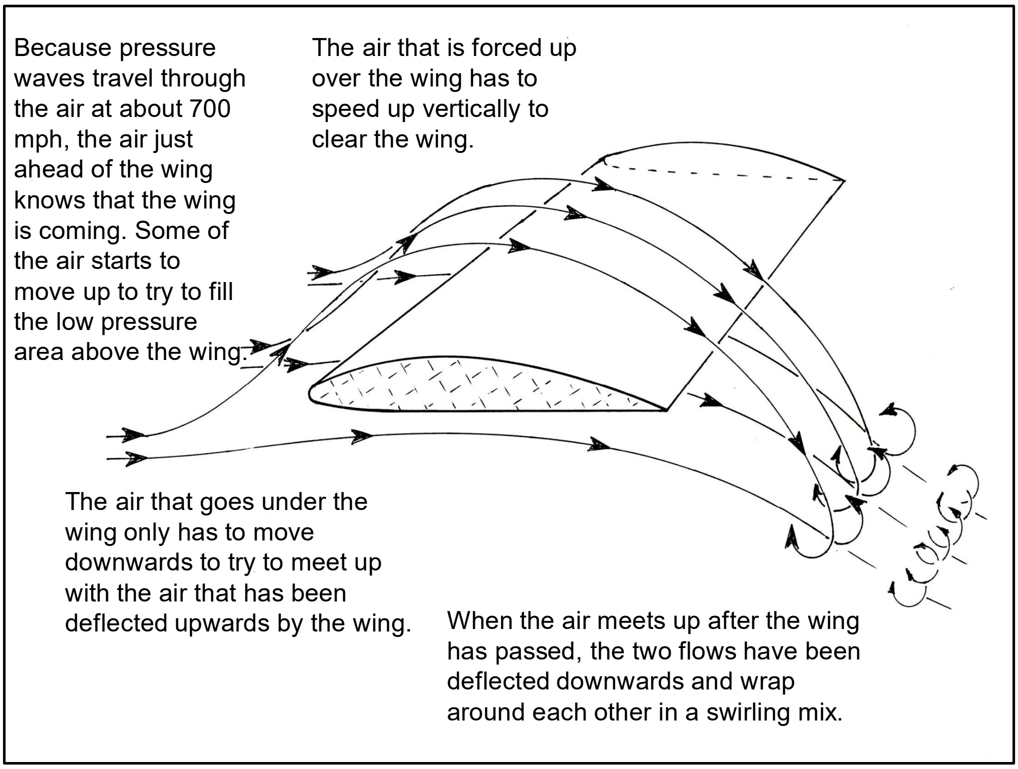
The Aerospatiale Concorde designed to cruise at Mach 2.02, 1,300 mph, at 60,000 ft.

This aircraft has a very special type of wing that is able to support the aircraft during take-off at 250 mph but also continue to work when the aircraft is cruising at twice the speed of sound.

We now need to understand how wings develop the lift that allows aircraft to fly.



This is a model of a typical section through a wing. This represents only one aerofoil shape of the many types that are used in the design of aircraft. Slower speed aircraft tend to have relatively thick sections and high speed aircraft tend to have thin sections. All the aerofoil sections that are designed to produce efficient lift have the characteristic mid-section curve, shown by the red line, to give the best lift at their operating speeds. This curve is called the “camber” of the section.



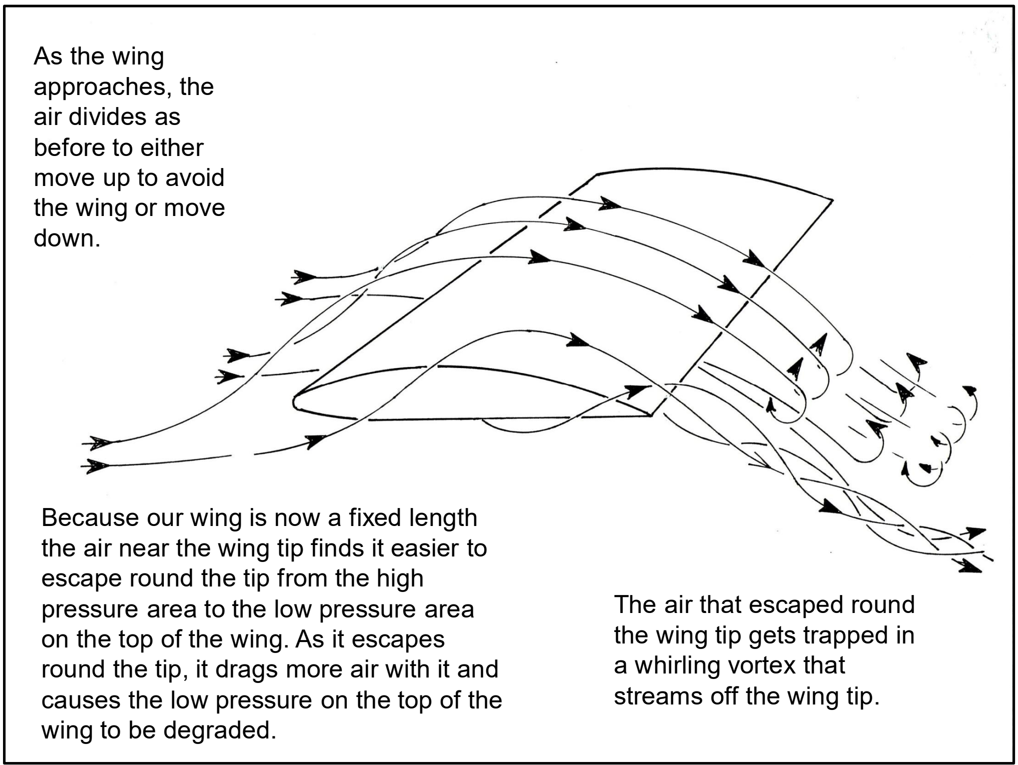
This diagram shows that when a wing travels through the air it causes the molecules of air to move into a rotating flow that forms a lengthwise whirlpool around the wing.
This does two things:-

1] The air that was ahead of the wing is rotated so that it now meets aft of the wing but lower than it had been before. This is called “downwash”. Isaac Newton showed that if the wing accelerates a weight of air downwards the wing will be forced upwards.

2] The air that travelled over the wing had to accelerate upwards up to avoid the wing.
Bernoulli showed that if the air is speeded up then the pressure would drop.

So now we can see that the wing has been forced up because it forced the air down and also the air above the wing is at a lower pressure than the air below the wing and this pressure difference is also forcing the wing upwards.

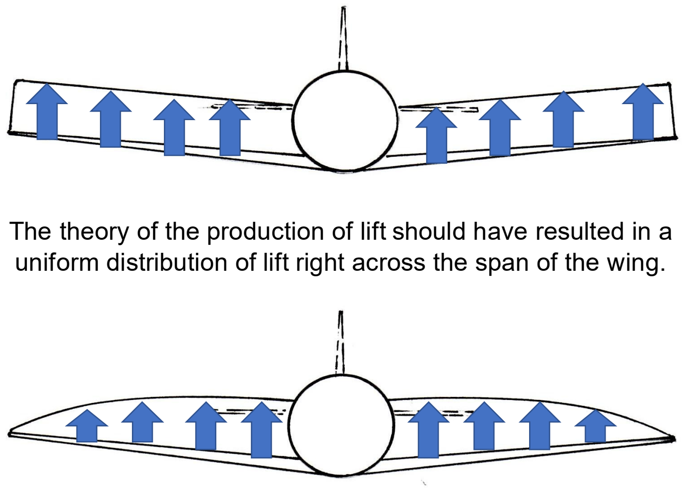
This is the theory but this does not entirely work in practice.



The theory of how lift is developed only holds true if the wing is of infinite length but, unfortunately, aircraft wings are designed to have a limited span and that means they have wing tips. The problem with wing tips is that the air always tries to take the shortest route from high pressure to low pressure and that means that some of the air near the wing tip, that was supposed to travel under the wing, finds it easier to escape round the wing tip to the low pressure that is on top of the wing.

Not only does this upset the flow over the whole wing but the air that escaped round the tip drags in other air and the mixed air streams off the wing tip in a tight vortex like a mini whirlwind.

The air in this vortex does not create lift and prevents the rest of the wing from generating a constant lift force right out to the tip.



The theory of the production of lift should have resulted in a uniform distribution of lift right across the span of the wing.

However, because of the leakage of air around the wing tips, the distribution of lift across the span of the wing assumes an elliptical shape with the maximum lift close to the body of the aircraft and almost none at the wing tips.

If you go to an Airport on a wet day and watch the aircraft taking-off you may see the air doing as we have shown. As the aircraft climbs away from the runway you may see a cloud of condensation forming on the top surface of the wing which shows the area of low pressure that has been generated by the wing. Also you may see the ribbons of vapour streaming from the wing tips that shows how the air is leaking round the tips and rolling up into a vortex with a low pressure centre.

You might also see that modern airliners all seem to have odd shapes on their wing tips. These shapes are put there by the aircraft designers to try to stop the air escaping around the wing tips and also to try to recapture some of the lift that was lost and also reduce the drag caused by the loss.

Of course, as usual, the birds had solved the problem a few million years ago and it is only recently that aircraft designers have started to take some lessons from the birds.

The beautiful Wandering Albatross flying effortlessly near the surface of the sea.

The beautiful Wandering Albatross solved the problem by putting its wing tips as far away as possible from it's body. It's wing span can be up to 12 feet [3.5 meters]. This wing allows it soar effortlessly in steady winds near the surface of the water. It can only do that if it lives in an area of the world where there is a steady strong wind. The albatross is only found in the southern hemisphere of the globe in the latitudes know by sailors as the “Roaring Forties”.

The graceful shape of a modern high-performance glider.

This modern glider does the same thing as the Albatross by having very long thin wings. These high performance competition gliders are the most efficient aircraft that man has devised so far.

The Golden Eagle can soar on air currents for hours without having to flap its wings but is very manoeuvrable when diving to catch prey on the ground.

Other big heavy soaring birds do not use very long wings since they need to manoeuvre at high speed in limited spaces. So birds, like the Golden Eagle, found another solution. It has special long separated tip feathers. As each one sheds its tip vortex the next feather behind twists to partly unwind the vortex. The special tip feathers fool the air into thinking that the wing span is greater than it really is.

The modern and very efficient airliner, the Airbus A 350

Modern airliners are usually fitted with similar devices to try to unwind the tip vortex. These specially shaped wing tips again increase the effective span of the wing allowing a more even distribution of lift and a reduction in drag.

Now let us see if we can use the theories and formulae devised by Bernoulli and Euler to work out how big a wing an aircraft would need.

This photo shows a small two-seat light aircraft called the Piper Super Cub. We can do a calculation to find out how big a wing that this aircraft needs. Since the aircraft is well known we can check our answer against the actual size of the wing.

$$S = \frac{W}{\frac{1}{2} \rho V^2 C_L}$$

S -- Is the wing area that we want to calculate.
W - Is the weight of the aircraft.
ρ - Is the density of the air that we are flying through.
V - Is the slowest speed that we want to fly at.
C_L - Is the co-efficient of lift of the wing shape.

If we rewrite one of Euler's formulae we can calculate how big a wing we will need to be able to fly the aircraft at the slowest speed possible with full control. This would be the safe landing speed of the aircraft.

By adding up the mass of the engine and propeller, the structure of the aircraft, the fuel and the pilot we find that a typical maximum weight of a Piper Super Cub is 795 kg multiplied by the acceleration force of gravity 9.8 M/sec^2.

We want to be able to fly as slowly as 22.9 M/sec [48 mph] to be able to safely land the aircraft.

We can assume that we will be flying the aircraft near the ground to land so we will assume that the density of the air is 1.225 Kg/m^3.

The aerodynamic efficiency of the type of simple wing section used on light aircraft is well known from experience and wind tunnel testing so we will assume the coefficient of lift is 1.5.

You can probably see the similarities between these values and the ones that we used when working out the drag and maximum speed of a skydiver.

When we worked out the speed of a sky diver we needed to know the coefficient of drag which is a measure of how streamlined a shape is. In this calculation we need to know the coefficient of lift which is a measure of how good the wing section is at producing lift.

If we add the known facts into the formula, it will look like this:-

$$\text{Wing Area} = \frac{795 \text{ Kg} \times 9.8}{0.6125 \times 22.9 \times 22.9 \times 1.5}$$

The answer is 16.20 Square metres.

The actual wing area of the Cub is 16.58 m^2 so our answer agrees quite well with the actual aircraft.

Perhaps the actual Cub has a slightly bigger wing to allow it to operate safely at higher altitudes.

If we do the same calculation for the 600 ton Antonov AN225 we find that it has a huge wing area of nearly $930m^2$ and even then it has to use special aerodynamic devices on the wing to be able to fly as slowly as about 130 mph.

So, by using the formulae that Euler devised from the work that Bernoulli carried out over three hundred years ago, we have found that we can get a good estimate of the drag of a body and the lift that a wing can generate.

However, lift and drag are not the only parts of the problem of getting aircraft to fly safely under control. All the parts that make up a complete aircraft generate aerodynamic forces and it is how these forces are balanced that we will look at next.