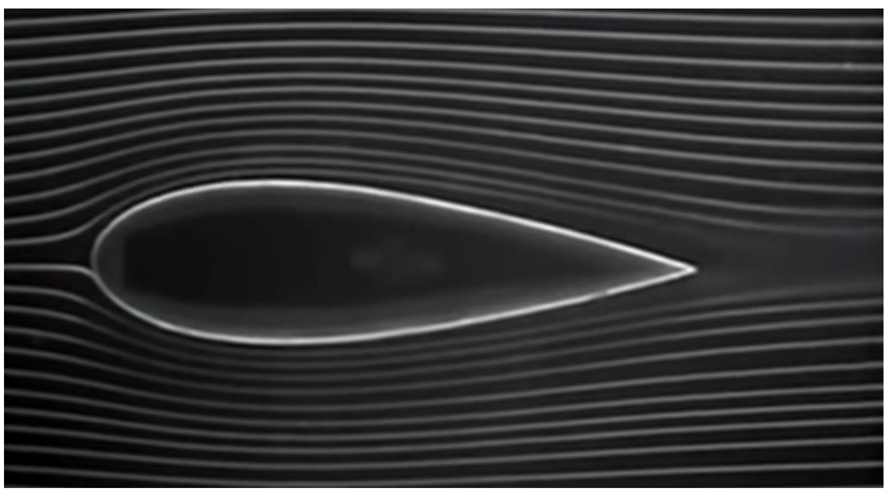
How the Wing Got its Lift

P. Marchal

In this note, we'll provide a qualitative explanation of why wings generate lift, based on sound physical principles.

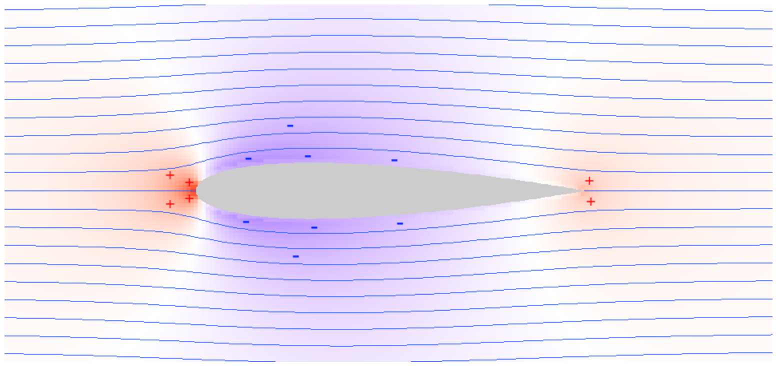
Let's start by investigating the actual flow of air around a symmetrical airfoil (the cross-section of a wing) immersed in a uniform flow, at zero angle of attack. By design, an airfoil is *streamlined*, that is, it is of such a shape that the flow will closely follow its contour, without any separation (a.k.a., stall).

The picture below displays a flow visualization corresponding to that situation, obtained in a wind tunnel. The air flows from left to right, and smoke injected at regularly spaced intervals upstream of the airfoil allows us to observe the trajectories of fluid "particles" as they pass near the airfoil—the *streamlines*.

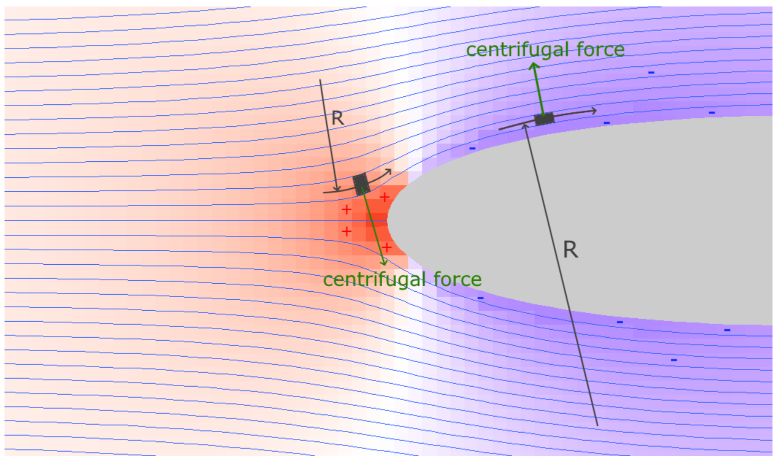


In the absence of any obstacle, the streamlines would be equidistant horizontal lines. The presence of the airfoil forces the streamlines to part away shortly upstream of it, and they rejoin downstream. Far from the airfoil, the streamlines are mostly undisturbed from uniform flow, but close to it, they curve to follow the contour.

The following figure shows a simulated version of the flow. In addition to the streamlines, it shows areas of pressure higher and lower than ambient (red shading and "+" signs indicate pressure higher than ambient, blue and "–" signs pressure lower than ambient). How come the pressure changes as the air passes around the airfoil?

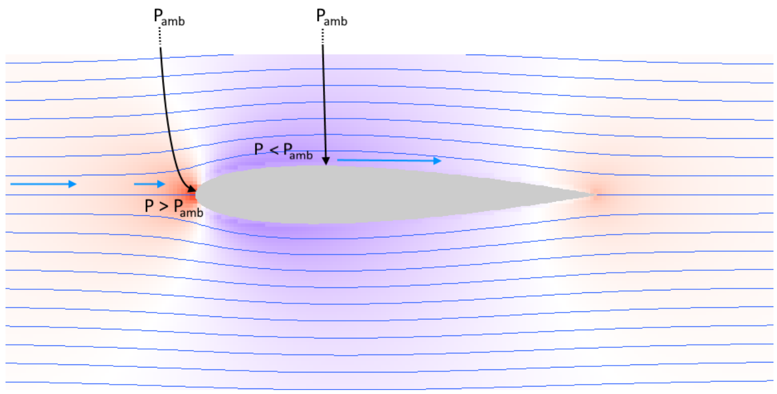


Let’s zoom in, and look in more details at what is happening.



Consider the small air particle on the left, near the leading edge. It is moving along a curved path of radius R, in the direction of the arrow. Just like an aircraft in a turn, it will be subjected to a centrifugal force pointing away from the center of curvature, “pushing” against the leading edge, increasing the air pressure in that direction. Similarly, the air particle on the right is subjected to a centrifugal force pulling it away from airfoil surface , creating a “suction” force (decrease in pressure) between itself and the airfoil.

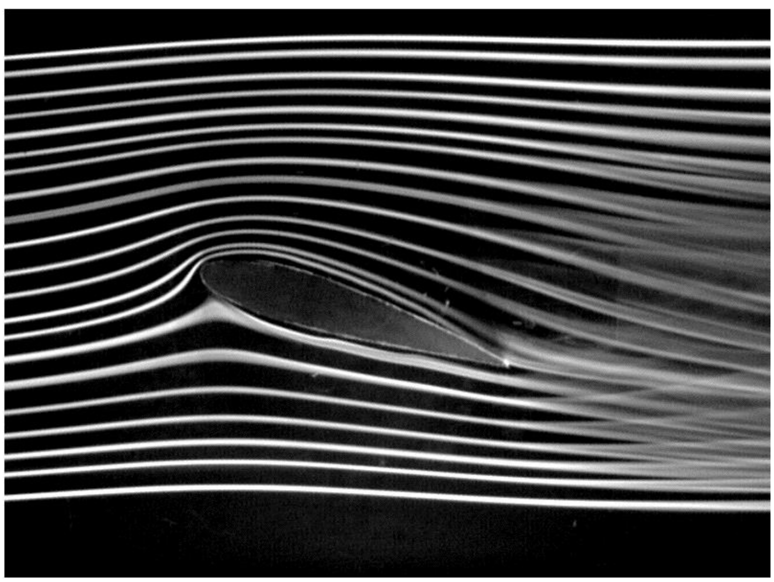
So, ***any time streamlines are curved, there will be a pressure difference across them***, the pressure increasing in the direction of the centrifugal force. From the streamline pattern, it is easy to deduce the pressure changes around the airfoil. We know that, far away from the airfoil, the pressure is the ambient (atmospheric) pressure. If, as illustrated in the next figure, we follow a path across the streamlines in a direction *away* from the center of curvature (i.e., in the direction of the centrifugal force), the pressure will *increase* along the path. If we follow a path across the streamlines in a direction *towards* the center of curvature (i.e., in the direction opposite to the centrifugal force), the pressure will *decrease* along the path.



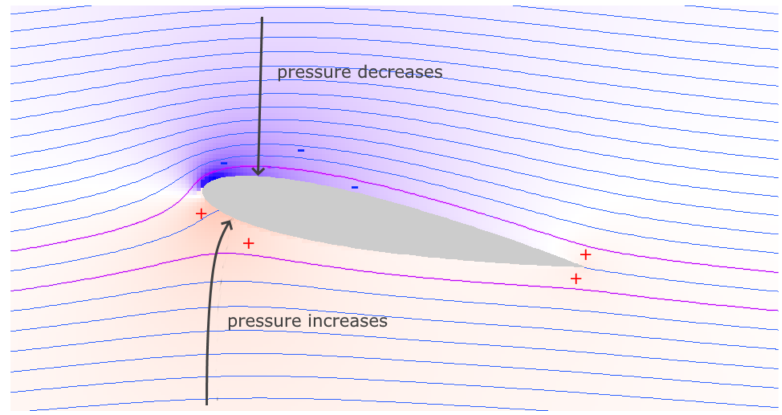
(The blue arrows represent air velocity—by Bernoulli's law, the velocity will be lower in the region of relatively high pressure around the leading edge, and higher in the region of relatively low pressure on top of the airfoil).

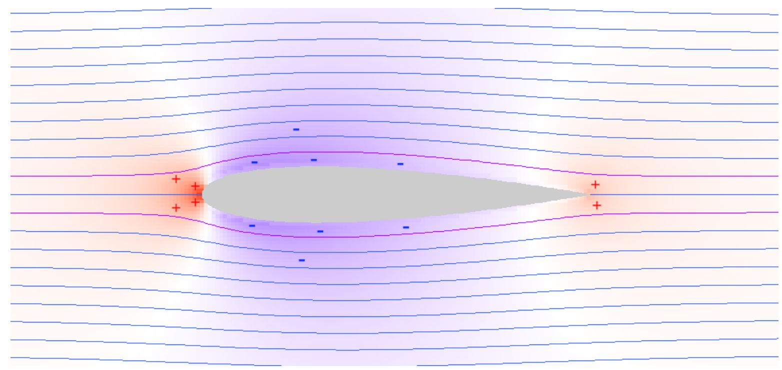
Since the airfoil is symmetrical, and at zero angle of attack, the flow pattern, and thus the pressure pattern, is symmetrical at the top and bottom of the airfoil, and the net lift will be zero.

What happens if we now place the wing at a small positive angle of attack (e.g. 10 degrees)? Once again, let's turn to flow visualization.

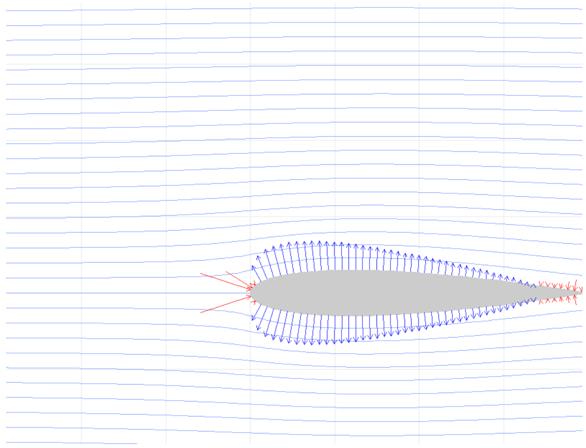


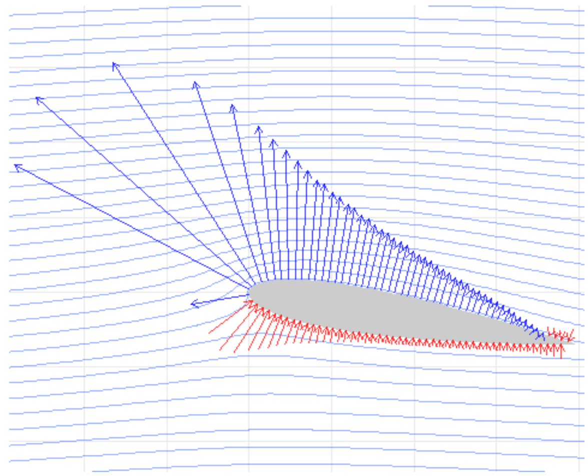
We notice that the streamlines from top and bottom of the airfoil join smoothly at the trailing edge, and leave it in a direction tangent to the chord of the airfoil, thus inclined downwards. The corresponding simulated flow, including the pressure differences from ambient, is as follows (two streamlines close to the surface of the airfoil are highlighted for emphasis).



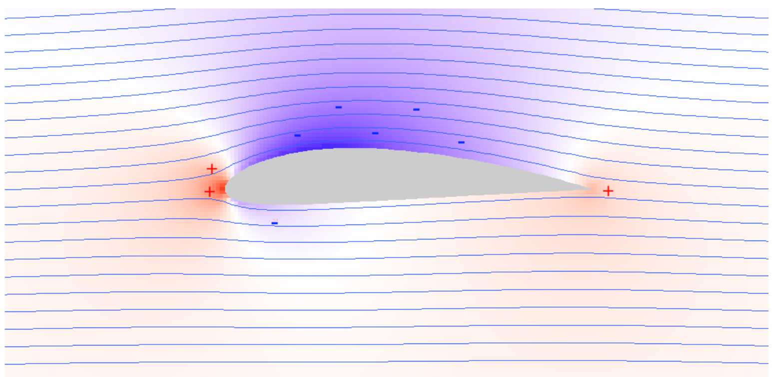


Compared to the original configuration (zero angle of attack, shown below the new figure for ease of comparison), the positive angle of attack has the effect of increasing the curvature of the streamlines on top of the airfoil, thus making the pressure more negative there. At the bottom of the airfoil however, the downward direction of the flow as it leaves the trailing edge changes the curvature of the streamlines—while the original (zero angle of attack) streamlines were *convex* downward for most of the length of the chord, they are now mostly concave downward. This leads to a positive pressure (above ambient) along the entire length. Lower pressure and the top, and higher pressure at the bottom—we have lift! Even though the wing section is symmetrical—what matters is that the increase in angle of attack increases the curvature of the flow on top, and inverts it at the bottom. To illustrate the difference in a more quantitative fashion, the pressure difference from ambient on the surface of the airfoil is compared below for the two conditions—zero angle of attack on le left, and 10 degrees angle on the right. Red arrows pointing into the airfoil indicate a pressure higher than ambient, and blue arrows pointing away indicate a lower pressure. Both diagrams use the same scale. The pressure is very sensitive to the curvature of the streamlines!!





What about a non-symmetrical airfoil? Let's have a look at a cambered airfoil more typical of a general aviation aircraft, placed at zero angle of attack..

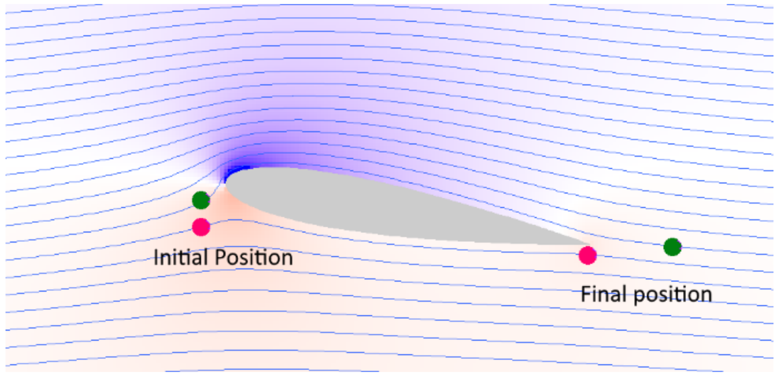


The geometry of the airfoil is such that the bottom is almost flat, while the top is more curved than the corresponding symmetric airfoil. Consequently, the streamlines (even at zero angle of attack) exhibit more curvature at the top than at the bottom, compared to the symmetric airfoil at zero angle of attack. As illustrated in the figure, the pressure is consequently lower at the top than at the bottom, and net lift is generated.

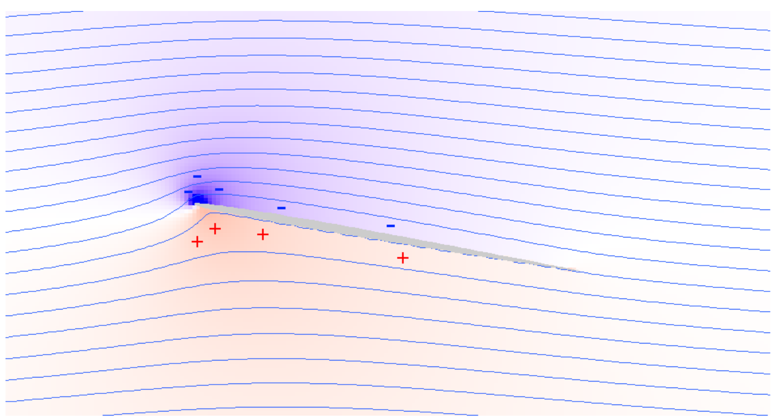
In summary, *flow curvature* holds the key to the pressure distribution around a wing section, and thus the generation of lift.

Notes

1. A popular theory of lift states that air particles have to travel faster over the top of the airfoil to meet at the trailing edge the particles traveling at the bottom. There is no physical reason for adjacent particles at the leading edge to meet at the trailing edge—it can actually be shown that a particles traveling at the top will arrive at the trailing edge *ahead* of the particle traveling at the bottom if the airfoil generates lift, as illustrated below. According the Bernoulli's law, the air travel faster on top because of the lower pressure there than at the bottom.



2. Another popular theory is that at least part of the lift, the one contributed by the bottom of the airfoil, is due to the incoming flow impacting the bottom of the wing. The argument is that the wing pushes the fluid downward, and that by reaction, according to newton's third law, the fluid pushes the wing upward, thus generating lift. The general idea of this theory is of course correct—the "bending" of the flow is what indeed generates lift. The notion of air particles "impacting" the bottom of the airfoil is however an over-simplification. Let's consider a very thin airfoil (essentially a flat plate) at a positive angle of attack.



It is clear from the picture that no air particle away from a very thin layer flowing along the bottom of the airfoil will ever be able to impact the bottom of the airfoil—air is a continuous medium, and the place is already occupied! The only way the air flowing below the airfoil can exert a force on the airfoil is through pressure, which has we have seen above is generated by the curvature of the streamlines. So, the mechanism is—the presence of the airfoil (flat plate in this case) forces the flow to curve downwards, the curvature creates an area of higher pressure on the bottom of the airfoil, which in turn exerts an upward force on the airfoil. This mechanism is *the same* as the one generating a lower pressure at the top of the wing section--Newton's third law applies exactly the same way to the top and bottom. We should also observe that the condition that the flow smoothly exits the trailing edge influences the general shape of the streamlines around the airfoil, top and bottom, determining the pressure distribution on its surface, and thus lift. Everything is connected—we should not consider the flows on the top and bottom of the airfoil independently and describe them according to different principles.

3. The fact that the flow leaves the trailing edge smoothly in a direction tangent to the camber line is critical to the shape of the streamlines, and thus to the generation of lift. That flow pattern is known as the “Kutta condition”, and while it seems fairly intuitive, it is physically not obvious. It depends on a surprising way of the fact that air has a small amount of viscosity—if the flow over a wing were truly frictionless, there would be no lift! The curious reader is invited to consult the expanded version of this document, which details the physics of the phenomena.