Bernoulli? Perhaps, but What About Viscosity?

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Abstract

Bernoulli's principle is being misunderstood and consequently misused. This paper clarifies the issues involved, hypothesises as to how this unfortunate situation has arisen, provides sound explanations for many everyday phenomena involving moving air, and makes associated recommendations for teaching the effects of moving fluids.

> *"In all affairs, it's a healthy thing now and then to hang a question mark on the things you have long taken for granted."* Bertrand Russell

I was recently asked to teach Bernoulli's principle to a class of upper primary students because, as the Principal told me, she didn't feel she had a sufficient understanding of the concept. While during my 20 years as a secondary science teacher I had never needed to teach this topic, and hence think deeply about it, from my general reading I was aware of the existence of a plethora of interesting, everyday phenomena involving moving air that had been explained in terms of

Bernoulli. I thought I could probably do a good job of teaching it, readily accepted the invitation, and eagerly began searching for lesson ideas.

However, as I read and questioned, I quickly found my initial eagerness being replaced by confusion and disbelief. I found myself constantly asking "but why should that be so?" and thinking along the lines of "but surely that cannot be the case?" A new form of eagerness dawned; an eagerness to better understand the issues involved. Deeper investigation was needed, but to my great surprise, I found the literature plagued by incorrect physics and misleading logic. In this paper, I share my deliberations.

A Typical Example

Consider the situation represented in Figure 1, where a strip of paper hanging over a finger adopts a curved shape. When air is blown across the top of the paper, as shown, the part of the curved paper that is free to move will rise. A typical explanation for this observation is that the pressure of the air moving along the top surface of the paper is less than the pressure of the stationary air beneath the paper strip and, as a result, the paper strip experiences a net force upwards; which is fine. Such a pressure difference is commonly justified, on the basis of Bernoulli's Principle, by statements such as "when air sweeps across a surface at high speed the pressure on that surface is lowered" ("Bernoulli Station," 1989, p. 308) or "as the speed of a moving fluid increases, the pressure within the fluid decreases" (Mitchell, n.d., ¶ 1), or it is implied on this basis (e.g., Brusca, 1986b). This reasoning for the pressure difference, found not only in popular writings but also in specialist, peer-reviewed journals (e.g., see also Bauman & Schwaneberg, 1994; Holmes, 1996), is wrong.
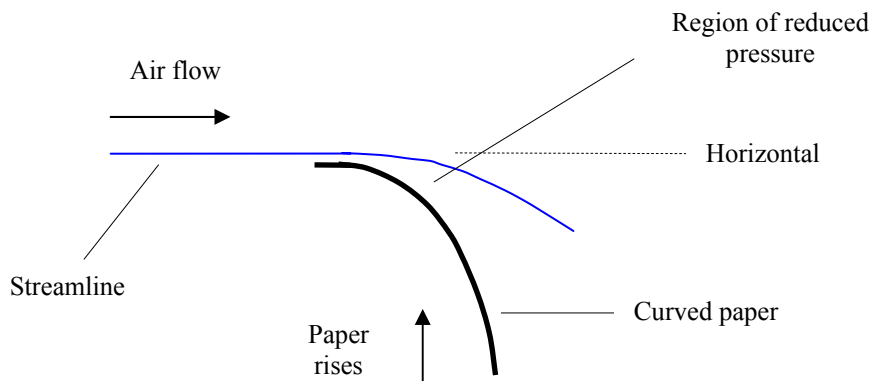

Figure 1. Blowing air across the top of a curved object.

As I will show, air does not have a reduced lateral pressure (or static pressure, as we will see it can be called) simply because it is caused to move, the static pressure of free air does not decrease as the speed of the air increases, it is misunderstanding Bernoulli's principle to suggest that this is what it tells us, and the behaviour of the curved paper is explained by reasoning other than Bernoulli's principle. Demonstrating how confusing, confused, and just plain wrong the literature can be, we even find Denker (2005b) claiming that blowing across the top of the paper as in Figure 1 won't cause it to rise. I can only presume that Denker either wasn't blowing sufficiently strongly and/or that the paper used was too heavy for the blowing speed used.

Static Pressure and Speed

Let's use a couple of ways to dispel the myth that the faster air moves along a surface, the less it pushes on that surface. First, Weltner and Ingelman-Sundberg (1999a) show how a sensitive manometer may be readily constructed to investigate this situation experimentally, as shown in Figure 2. The end of the manometer comprises a thin disk with a small hole in it, connected to tubing. When positioned in stationary air, the manometer reads atmospheric pressure. Then, a stream of free air is caused to flow across the surface of the plate, and the manometer used to measure the pressure of the moving air.
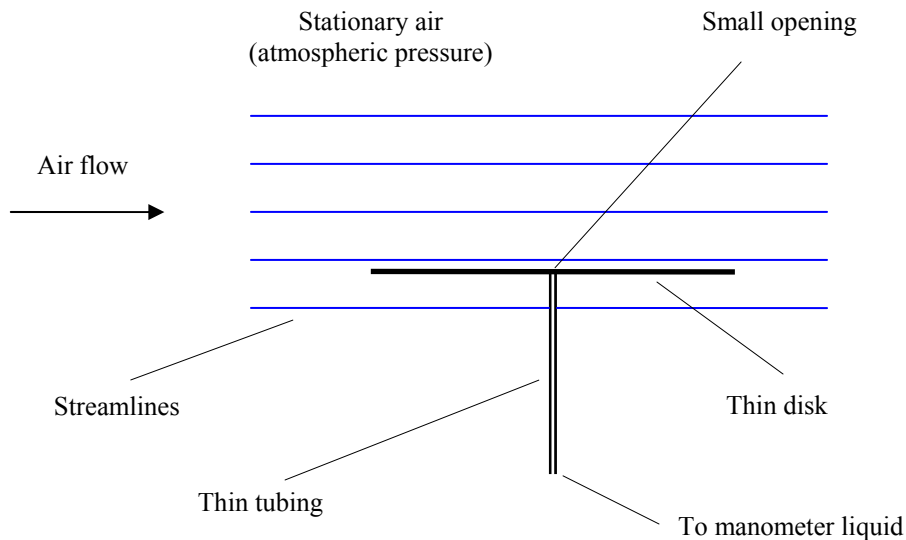

Figure 2. Using a manometer to measure static pressure.

To clarify, the pressure of moving air can actually be measured in different ways. The static pressure of a stream is the pressure measured by a manometer moving with the flow, and is also the pressure at the surface of a plane parallel to the flow, as in Figure 2. If we were to rotate this manometer plate 90° anticlockwise, so that the air was colliding with the plate surface, we would measure the impact (or ram) pressure, which is different. As an aside, elementary texts generally do not address this difference between static and impact pressure explicitly and therefore miss an opportunity to clarify what is a common source of confusion (Martin, 1983). It is static pressure that interests us here, and when this experiment is performed, Weltner and Ingelman-Sundberg (1999a) assure us that the static pressure of the moving air is always atmospheric pressure, regardless of the speed of the moving air.

Babinsky (2003) suggests that this result may be demonstrated by holding a strip of paper so that it hangs straight and vertically downwards, blowing air vertically downwards along one side of the paper, and noting that the paper does not move. However, I doubt that this is a valid test, as any tendency of the paper to bend towards the air stream would result in the paper experiencing some direct impact from the moving air (i.e., an effect due to impact pressure), hence changing the situation that is trying to be studied (i.e., changes in static pressure only).

This result also makes sense theoretically. Since perpendicular vectors are independent, any net force that changes the motion of air particles in one direction (e.g., speeds up the air) will have no effect on the speed of these particles in a perpendicular direction.

Those trying to justify the incorrect notion that free moving air does have reduced static pressure have therefore set themselves quite a challenge. The only way to explain something that is false is to use false reasoning, as in the following examples. One finds the argument that, when air is caused to move in one direction, the particles are somehow so occupied with moving in that direction that they now no longer have time to push as hard laterally (e.g., Niven, 1999). This idea might be intuitive to some, but it has no basis in science.

Mitchell (2003) uses the analogy of moving children. A room full of children (representing air particles) running around and colliding quite forcefully, with both one another and the walls, represents a high pressure situation. However, when these same children are asked to run down a hallway (simulating the movement of bulk air), the collisions are much more gentle (i.e., the pressure is lower.) This analogy is invalid, because the students running down the hallway have lost their lateral motion, which air particles do not after bulk air begins to move. The twists, turns, evasions, and incorrect physics in Brusca's responses (Brusca, 1986a, 1987) to readers' criticisms of the content of his earlier article (Brusca, 1986b) demonstrate just how tenacious we can be, though, in "hanging on" to wrong ideas.

Bernoulli's Principle

To distinguish between situations in which Bernoulli's principle does, and does not, provide a suitable explanation for everyday phenomena involving moving air, let us first revise what Bernoulli's principle tells us. Consider Figure 3, which represents fluid moving along streamlines in a horizontal tube of varying cross-sectional area. The flow needs to be steady, nonviscous, and incompressible. (It also needs to be irrotational, but this need not concern us for present purposes.) Steady flow means that, at any particular point in the stream, the velocity of passing fluid does not change with time. Viscosity in fluid motion is analogous to friction in the motion of solids, where tangential forces between layers of fluid in relative motion results in dissipation of mechanical energy.
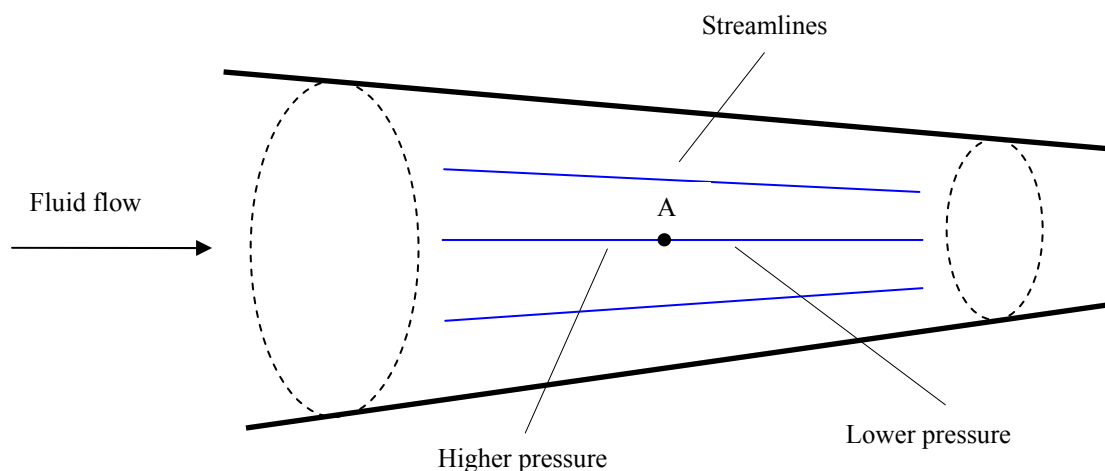

Figure 3. Fluid moving through a tube of changing cross-sectional area.

For continuity of flow, as the fluid moves from left to right in Figure 3 it must speed up, because the same volume of fluid needs to move through a smaller cross-sectional area per unit time.

Take, for example, a small volume of fluid at point A. What is causing this volume to speed up to the right? There must be a net force to the right, and this force is provided by a static pressure differential in the fluid; that is, the pressure just to the left of A must be higher than the pressure just to the right of it. So, if the pressure drops along a streamline, the speed of the flow increases. The reverse is also true (i.e., the faster moving fluid will have a lower static pressure), but the former seems a preferred statement because it expresses cause and effect, and the widespread use of the reverse form has probably been a source of so much misunderstanding. So, pressure gradients cause fluids to accelerate. Note also that, in Figure 3, more closely spaced streamlines indicate lower static pressure and higher fluid speed.

Bernoulli's principle can also be considered an expression of the law of conservation of energy. With no energy being added to, or taken from, the fluid by an external influence, Bernoulli's principle is concerned with internal relationships in a fluid. The sum of the kinetic energy (represented by the speed of the fluid) and potential energy (as represented by pressure) remains constant. Any decrease in static pressure must be associated with an increase in kinetic energy (and vice versa). (Note that for present purposes, by restricting the discussion to horizontal fluid flow, we can omit a consideration of any changes in the gravitational potential energy of a fluid.)

In everyday contexts, Bernoulli phenomena typically involve fluids moving into a constriction, as in Figure 3. For example, squeeze a flexible hose from opposite sides and release it. Provided the flow is sufficiently strong, the constriction will remain, even if the hose would normally spring back to its normal shape, because atmospheric pressure outside the hose is greater than the reduced static pressure of the fluid through the constriction. Other applications of Bernoulli's principle are the Venturi, Pitot tube, carburettor, jet pump, foam firefighting nozzles and extinguishers, blowing through a funnel containing a ping-pong ball and finding that the ball is not forced from the funnel, blowing through the hole in a cotton reel with a flat card across the opposite edge and observing that the card "sticks" to the reel, and noting how two rowing boats moving parallel to one another in the same direction are pushed towards one another. I experience a similar effect on the highway when my vehicle towing a horse float is being overtaken by a large truck with closed sides, as the air in front of us is forced to move through the narrow space between the vehicles and my unit is pushed towards the truck!

Entrainment

Returning to the situation of Figure 1, one may now ask how applicable Bernoulli's principle is in explaining the observed behaviour. The flowing air may be considered incompressible because, unless air speed is near, or above, the speed of sound, the density of moving air changes very little with speed (Bauman & Schwaneberg, 1994; Denker, 2005a; Resnick & Halliday, 1966). However, this is about as far as the similarities between the situations in Figures 1 and 3 goes.

In Figure 1, the effect of viscosity is important. In a gas like air, viscosity is caused practically entirely by collisions between the air particles (rather than the attraction between them due to Van der Waals forces, which can be ignored) (Field, n.d.). On the far side of the paper (relative to the person blowing the air), the stream of air will sweep away air from the adjacent still air, giving rise to the region of reduced pressure shown. Friction is said to entrain the adjacent air, in a process known as entrainment, and two things follow. Because the pressure of air below the curved paper is greater than the pressure just above it, the paper will be pushed upwards. Similarly, the air particles moving along the streamline shown will be pushed downwards (i.e., the streamline will be deflected downwards), because the static pressure in the air stream above the streamline will be greater than the pressure in the depleted region below it. (Note that while, for

clarity, a lower streamline only has been drawn in Figure 1, further streamlines could be drawn above and below it.)

An explanation based on Bernoulli's principle is not applicable to this situation, because this principle has nothing to say about the interaction of air masses having different speeds (i.e., viscous flow, which results in turbulence, where the velocity of passing fluid at any particular point in the stream varies with time). Also, while Bernoulli's principle allows us to compare fluid speeds and pressures along a single streamline and, as we will do later when the behaviour of aerofoils is considered, along two different streamlines that originate under identical fluid conditions, using Bernoulli's principle to compare the air above and below the curved paper in Figure 1 is nonsensical; in this case, there aren't any streamlines at all below the paper!

So, when moving air interacts with an object, such as a curved plane, viscosity causes regions of differing pressures to result, and this concept can be used to explain many other everyday phenomena that include the following:

- Watch a paper tunnel collapse when air is blown through the tunnel.
- Use a straw to blow air near a candle flame and observe the flame bend towards the airstream.
- Hold a strip of paper so it hangs straight and vertically downwards, use a straw to blow air vertically downwards a little distance away from the strip, and note that this time the paper does move towards the moving air.
- Blow across touching pages in a book to separate them.
- Be frustrated, while driving, by how readily a piece of paper lying near an open window will "fly" out the window. (Similarly, it is important that the hole in the thin disk forming the end of the manometer in Figure 1 is not too large.)
- Notice the upward movement of an umbrella in strong wind.
- Suspend a ping-pong ball or beach ball in a stream of air, or levitate an M&M above your mouth.
- Demonstrate the operation of an evaporator by standing a short length of straw in a liquid, use another straw to blow across the opening of the short straw, and watch the liquid rise in this straw.

Ever been irritated, when showering, by the shower curtain continually moving in towards you? It was an issue that had been "in the back of my mind" for many years, due to the fact that it kept "popping up" in the literature from time to time, albeit each time accompanied by what I now think was a partial treatment only of the variables involved; which probably explains why it kept popping up. Until recently, though, I had never been in a position to investigate experimentally. While travelling in a remote location, the fuel pump in my car ceased to function and I found myself taking unscheduled accommodation while I waited for a new pump to arrive. I wasn't too pleased about having my return to home delayed in this way, though, until I saw the shower provided; this investigator's dream! The set-up allowed for the effect of the variables that interested me to be investigated, because I could change the distance between the showerhead and the curtain (which is usually not possible in showers), the height of the curtain from the floor (the curtain needs to be free to swing), and the temperature of the water. In accord with the above description of the entrainment of air, cold water streaming a moderate distance from the curtain caused the curtain to move inwards. Also, as expected, having the stream beside, or too far away (i.e., too far away to have any influence at all) from the curtain produced no such movement. Then, with the water again flowing a moderate distance from the curtain and the curtain swinging inwards, I changed to hot water and noticed an even greater inward deflection of the curtain. This

additional effect appears to be due to convection of the air, with the air in the shower space being heated by the water, having its density decreased, and hence rising as cold air enters from outside below the bottom of the curtain. Bartlett (1996) reported observing an effect using hot water but not with cold, so I can only conclude that he didn't have the cold stream from the showerhead at an appropriate distance from the curtain.

The Coanda Effect

Let us return to Figure 1 and modify the situation slightly by replacing the curved paper strip with a curved object that cannot straighten, such as the outside surface of a standing, plastic soft drink bottle, now viewed from above. The moving air will again be deflected and begin to follow the surface of the bottle (later separating from it with increasing turbulence). The bottle will also experience a net force in the opposite direction and, if it is resting on a slippery surface, might begin to slide. However, if the surface is not so abruptly curved, as in the case of an aerofoil, the moving air does not separate from the surface, thereby following the geometrical shape of the surface. This tendency of a fluid to follow the shape of an obstacle, as a result of entrainment, is called the Coanda effect.

The bending of air around an object in this way is readily observed by hanging a narrow strip of paper out-of-sight behind the edge of a standing, plastic soft drink bottle, using a straw to blow air across the edge of the bottle, and observing the paper strip behind the bottle move. Curiously, neither entrainment nor the Coanda effect, concepts critical to an understanding of so many everyday phenomena, are typically found in the common literature dealing with the subject. It appears that, compared with Henri-Marie Coanda (1885-1972), Daniel Bernoulli (1700-1782) has benefited from a far better "publicity machine"! Also, the commonly used demonstration of the Coanda effect, in which a stream of water falling vertically from a tap is observed to bend along the surface of a curved spoon (e.g., Raskin, 2005) is inappropriate, because the forces of adhesion between the water particles and the spoon are responsible for the deflection in this situation.

Now that we understand why blowing air beside a standing plastic bottle can make it move, let's go one step further and stand two such bottles side-by-side and blow air through the constriction between them. Depending upon how slippery the surface upon which the bottles are standing is, the bottles will either slide or topple towards one another. However, far less blowing effort is required to get bottle movement when two bottles are so used rather than one only. With two bottles, both entrainment and Bernoulli's principle appear to be at work simultaneously, so rather than providing alternative explanations for the two-bottle situation, as suggested by Swartz (2003) in relation to an analogous situation using bowling balls, these two effects reinforce one another. For this reason, it is also not only easy to lose paper out the window of a moving car, but even easier when a large, closed-sided truck is overtaking at the same time.

The Aerofoil

How it works. Returning to Figure 1, let's give the curved object a more gentle curvature (to ensure no flow separation) and consider it to represent an aerofoil, thereby requiring us to also have air flowing, from left to right, under the aerofoil. This air moving below the aerofoil will effectively collide with the underside surface, pushing the aerofoil upwards, and there is no other option for the moving air itself than to be deflected downwards. Previously, we have understood how the air moving over the top of the aerofoil has the same effect; that is, causing the aerofoil to rise with the air being deflected downwards. Combine these two reinforcing effects and we have an explanation for the lift of an aerofoil.

The fact that the aerofoil of Figure 1 is a very thin one should not be of concern, because thin aerofoils work just fine, as demonstrated by the flight of birds and the effectiveness of the thin, cloth membranes used for sails on boats. In practice, for structural strength the wings of an aircraft do need a wider cross section, as shown in Figure 4, which also depicts the general pattern of streamlines around a typical aerofoil. However, the general principles explaining lift remain the same as for a thin aerofoil, also applying to things like rudders, propellers, oars, and helicopter blades.
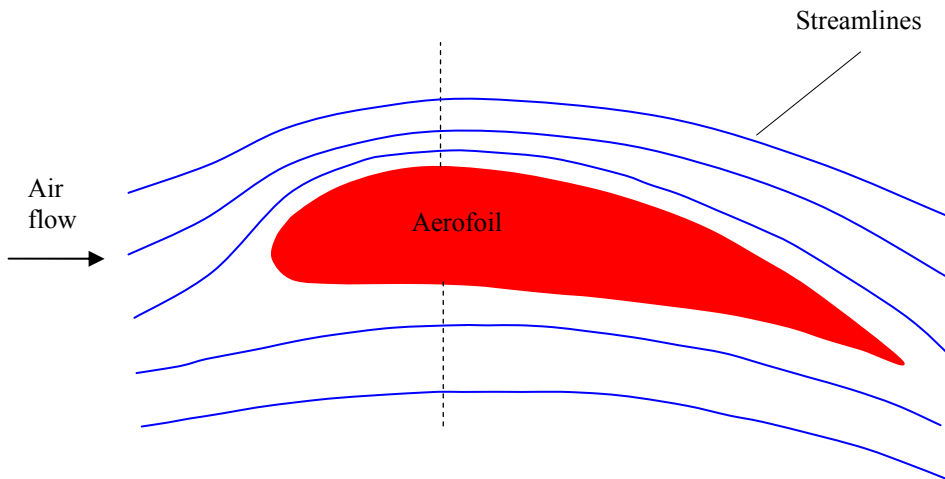

Figure 4. General pattern of streamlines around an aerofoil.

I find the foregoing explanation for aerofoil lift satisfying, because it reasons from first principles. In other words, if something changes its motion, I like to know what is doing the pushing and/or pulling, and how it is doing it, and that is what has been provided. At the same time, there are other more abstract ways to describe aerodynamic lift, and I will now consider two. While I consider them more descriptions than explanations, they are none-the-less valuable since they bring additional features to the discussion. They are also not alternatives, but simply different and compatible ways of thinking about the same phenomenon.

A Newtonian perspective. Newton's third law tells us that for every action, there is an equal and opposite reaction. So, in an overall sense, if an aerofoil forces air downwards (both the air that moves across the top of the aerofoil and the air that moves across the bottom), the deflected air must push the aerofoil upwards. As shown in Figure 4, for small angles of attack (i.e., small angles between where an aerofoil is pointing and where it is going), the streamlines adopt an overall shape that follows the geometrical shape of the aerofoil (i.e., a line drawn through the middle of the aerofoil cross section). It follows that, in a diagram like that of Figure 4, it is impossible for the streamlines to have the same direction (e.g., be horizontal) both in front of, and behind, the aerofoil, as commonly depicted in textbooks (Smith, 1972). According to Beatty (1996), the upper surface of a typical aircraft wing deflects more air than the bottom surface, and so contributes more to the lift. Crop-dusting aircraft make good use of this downwash, injecting spray into it and sending the spray downwards rather than having it trail behind.

Bernoulli's principle. Bernoulli's principle can be used to describe the flow of air in Figure 4, albeit not in the fallacious way so commonly found in the literature that will be discussed in the next section. In Figure 4, the flow is steady, frictional forces may be neglected, and, since general aviation speeds are around Mach 0.2 or 0.3, the air can be considered incompressible. It is

somewhat interesting that, while friction forces are negligible (from the point of view of Bernoulli's principle being applicable to the flow of practically all of the air, since the boundary layer of air--the layer between the aerofoil surface and the air flowing like an ideal fluid, to which Bernoulli's principle will not apply--is relatively very thin and negligible), without them the air moving over the top of the aerofoil would not be deflected downwards and hence not contribute to lift.

The static pressure of the air to the left of the diagram in Figure 4 is atmospheric pressure. As we follow the streamlines from left to right, we notice that the lines above the aerofoil become more closely spaced, indicating (as we have noted previously) lower static pressure and higher air speed. Conversely, the streamlines under the aerofoil separate somewhat, indicating increased static pressure and lower air speed. This pressure difference above and below the aerofoil produces lift and, as confirmed by wind tunnel photographs that use pulses of smoke in the airstreams (Beatty, n.d.; Weltner & Ingelman-Sundberg, 1999b), air actually takes less time to move across the top of an aerofoil (i.e., from the leading edge to the trailing edge) than to move across the bottom of it.

There is another way to think about Bernoulli's principle applying to the flow of air in Figure 4. As we follow the streamlines across the top of the aerofoil, we notice that they bend downwards. What could be causing such a deflection? We have seen previously how a pressure gradient will cause a fluid to either speed up or slow down, but a pressure gradient (just like a net force) can also cause something to change direction. The reason that each streamline above the aerofoil curves downward is that the static pressure above each streamline is greater than the pressure below it. Well above the aerofoil, the pressure is atmospheric pressure. So, as we move from this region towards the top surface of the aerofoil along the dotted line shown in Figure 4, the static pressure must be continually decreasing. The static pressure of the air at the top surface of the aerofoil must therefore be less than atmospheric pressure. If we now follow a streamline across the top of the aerofoil, we see that it begins, on the left of Figure 4, in a region where the static pressure is atmospheric pressure and moves into a region of lower static pressure. According to Bernoulli's principle, the air must speed up. A similar analysis can be performed for the streamlines under the aerofoil, which bend downwards. Well below the aerofoil, the static pressure will be atmospheric pressure and, as we move along the dotted line towards the bottom surface of the aerofoil, the static pressure must increase. Air moving under the aerofoil will therefore move from a region of atmospheric pressure to a region of higher static pressure and, according to Bernoulli's principle, must slow down. So, just as in the previous paragraph, the speed of the air above the aerofoil is greater than the speed below.

While Bernoulli's principle is at work in Figure 4, it is operating more in a secondary sense than in the sense of providing an explanation for aerodynamic lift from first principles. The analysis in the previous paragraph can also be applied to the earlier cases of Figure 1 involving curved paper and a plastic soft drink bottle, but I chose not to do so earlier in an attempt to avoid unnecessary complication at that time.

Some fallacies. We are now in a position to appreciate how Bernoulli' principle has been so inappropriately used, in much of the literature, in relation to aerofoils. According to Weltner and Ingelman-Sundberg (1999b), the origin of the classic incorrect explanation can be traced to a 1921 report by Prandtl. If Bernoulli's principle was to account for aerodynamic lift, a reason had to be found for why the upper surface of an aerofoil experiences reduced pressure. What was needed, then, was a cause for increased air speed above an aerofoil, because Bernoulli's principle equates higher fluid speed with lower static pressure. So, the classic explanation goes something like this:

Because of continuity of flow, two small, adjacent parcels of air that begin at the leading edge of an aerofoil and move to the back of it, one across the top surface of the aerofoil and the other across the bottom surface, must arrive at the trailing edge at the same instant in time. Because the aerofoil is curved upwards, the parcel of air moving across the top surface has a greater distance to travel and therefore must travel faster.

This explanation is attractive because it is simple, quick, and predicts correctly. However, it is also an example of how two wrongs can make a right, and is as satisfying as simplifying 16/64 by cancelling the *6* in the numerator and denominator and arriving at the correct answer; ¼ ("Did you Know?" 2005).

Fallacy 1: *Air takes the same time to move across the top of an aerofoil as across the bottom.* While using terms like "continuity of flow" to support this notion might sound authoritative, there is no reason for why it should be the case. Continuity of flow (e.g., the notion that, in a tube of varying cross-sectional area, the same volume of fluid must move through any cross-section per unit time) is a recognized scientific principle, but applies as used earlier in this paper to situations like that in Figure 3 rather than to flow around an aerofoil. Besides, as mentioned previously, wind tunnel experiments show clearly that a parcel of air that moves across the top of an aerofoil arrives at the trailing edge before an initially adjacent parcel of air that moves across the bottom.

Fallacy 2: *The distance across the top of an aerofoil must be greater than the distance across the bottom.* Or, *an aerofoil must be curved on top and flat underneath* Aerofoils need to provide lift, and can take a variety of shapes. Many have no path length difference between top and bottom surfaces, as in aerofoils that are thin and curved, or cambered (i.e., curved) top and bottom) and symmetrical; even thin, cambered, and symmetrical. Examples include early aircraft, kites, hang gliders, sails, aerobatic aircraft, and rubber-powered balsa gliders. Some aerofoils that do have a path difference can fly upside down. The NASA "supercritical" wing designs are flat on top and more curved underneath (Beatty, 1996). Even a flat "barn door" will fly although, because the air cannot flow smoothly over the top surface (because the point at the top is too sharp), it separates from the surface and, due to entrainment, produces a region of turbulent, reduced-pressure air behind the wing that reduces lift and increases drag. Indeed, given an appropriate angle of attack, any shape that causes streamlines to curve downwards can generate lift. The typical aerofoil shape shown in Figure 4 just happens to be very effective at doing this, at the same time changing the speed of the air (i.e., the air flow above the aerofoil is faster than below it).

Stall and house roofs. While a higher angle of attack will deflect an airstream more and hence produce greater lift, too high an angle and the flowing air will separate from the aerofoils of an aircraft, similar to the barn-door behaviour mentioned in the previous paragraph. The aircraft can suddenly lose sufficient lift and begin to fall, and is said to have stalled (Nave, n.d.). This term should not be interpreted to mean that the engine has stopped working, nor that the aircraft is not still moving forward, and pilots are trained to correct stall. Rather than creating lift, designing wing shapes for aircraft is more about avoiding stall. For a similar reason, skilled sailors need to keep the airflow across a sail smooth to avoid separated flow, turbulence, and drag.

This consideration of separated flow can be applied to wind blowing across a peaked house roof, as depicted in Figure 5. The turbulent, lower-pressure region behind the peak allows the air inside the house (which is at a higher pressure; atmospheric pressure) to cause a net force upwards on this part of the roof behind the peak. To guard against losing the roof, one might reduce the flow

of air over the roof by opening front and back doors and/or windows, although there will need to be a trade-off with the amount of damage the wind through the house might cause. However, this is an extremely cursory and limited discussion of the effect of wind on a roof because, for example, in practice the presence of eves and overhangs can actually result in greater lift being experienced by the windward side of a roof than the leeward side (Rowe, 2003).
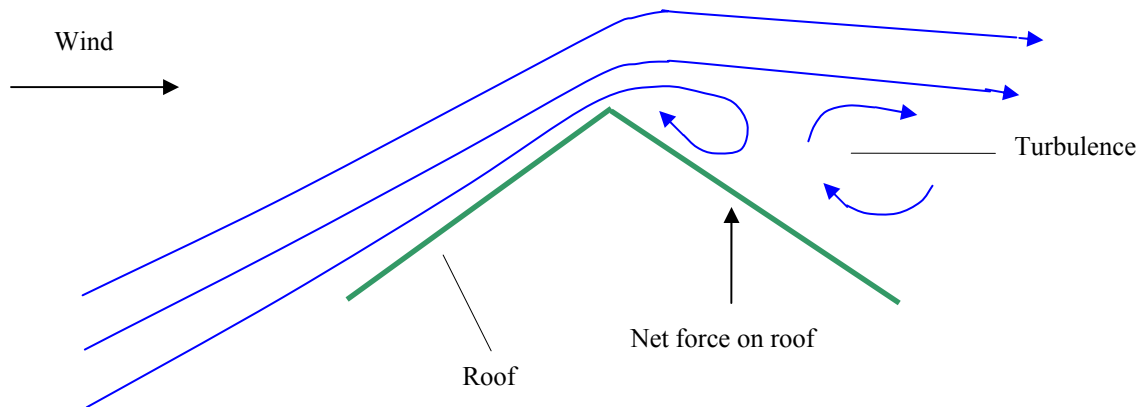

Figure 5. Wind blowing across a house roof.

Complexities. The behaviour of real aircraft wings in three dimensions, which actually produce a vortex downward wash, is complicated, and we have no simple mathematical solutions to explain flow attachment and turbulence. There is still much to learn about aerodynamics, and the concepts involved continue to be argued. Heisenberg (1901-1976), the celebrated German physicist and Nobel laureate, was supposedly hoping to ask God how turbulence works after he died.

Conclusions and Recommendations

Bernoulli's principle has been, and continues to be, misunderstood and misused. Why is this the case, and why have incorrect Bernoulli explanations survived for so long in the literature? I offer the following possible reasons:

- Simplified Bernoulli explanations are quick, sound logical, and make correct predictions. As Brusca (1986b) said with a sense of satisfaction, the prediction is "in complete agreement with what happens in practice" (p. 15). This would be fabulous if it wasn't for the fact that these explanations are also wrong!
- Statements like "as the speed of a moving fluid increases, the pressure within the fluid decreases" facilitate a misunderstanding of Bernoulli's principle and, when used in a sweeping sense and therefore out of context, are wrong.
- Viscosity, entrainment, and the Coanda effect are not to be found in lower-level literature, despite the fact that such literature deals with phenomena that rely on these concepts.
- There appears to be a desire to have a single, best explanation for an observed behaviour when in fact a combination of factors may be "at play."

There is a need to introduce the ideas of viscosity and entrainment at primary and middle school levels, and to use these ideas to explain the numerous everyday phenomena that are based upon them, including aerofoil lift, and a teacher without a more advanced scientific background might achieve this by reading selected sections only of this article. Henri Coanda's work has been

marginalized, and it is a shame that for far too long it has found a place in advanced literature only instead of being included in school textbooks and the general literature.

While a derivation of Bernoulli's principle is not appropriate at primary and middle school levels, might Bernoulli-based phenomena still be discussed with younger students? I think this is possible, although it would be necessary to ask students to accept, without understanding, something along the lines of: "When air is squeezed through a space, it doesn't push as hard sideways." While this approach is in accord with Bruner's view that "anything can be taught to anyone at any stage, in an intellectually honest way" (Y. Hadzigeorgiou, personal communication, May 7, 2007), it also represents teaching for shallow understanding and, as such, will undoubtedly appeal to some less than others. For this reason, I purposely used the term *discussed*, rather than *taught*, in the question at the beginning of this paragraph.

Finally, when Bernoulli's principle is derived at a higher level, the conclusion needs to avoid statements like "as the speed of a moving fluid increases, the pressure within the fluid decreases," because this conveys the misconception that a change in speed causes a change in static pressure. Rather, the reverse form should be used, as in: "A difference in static pressure will cause a fluid to accelerate."

The Curve Ball: A Reader Exercise

Another everyday phenomenon involving moving air is the observation that a spinning ball will follow a curved path as it moves through air, a behaviour that is exploited in a variety of ball games. Rather than explaining this effect here, I wish to leave this task as an exercise in critical reading for the interested reader. By performing a web search on relevant keywords, reading selected documents that are found, and analysing them using the thinking developed in this article, you should arrive at a satisfactory explanation for a curving ball. I will be disappointed if you are now deceived by explanations based on Bernoulli's principle, as in Brusca (1986b). Also, you will find that frictional effects are critical, because a perfectly smooth ball cannot be made to curve.

References

Babinsky, H. (2003). How do wings work? *Physics Education*, *38*, 497-503.
Bartlett, A. A. (1996). The curious case of the well-behaved shower curtain. *The Physics Teacher*, *34*, 444.
Bauman, R. P., & Schwaneberg, R. (1994). Interpretation of Bernoulli's Equation. *The Physics Teacher*, *32*, 478-488.
Beatty, W. (n.d.) *Airfoil diagrams*. Retrieved April 25, 2007, from http://www.amasci.com/wing/airgif2.html .
Beatty, W. (1996). *Airfoil lifting force misconception widespread in K-6 textbooks*. Retrieved April 25, 2007, from http://www.amasci.com/wing/airfoil.html .
Bernoulli station. (1989). *The Physics Teacher*, *27*, 308-310.
Brusca, S. (1986a). Bernoulli effect (S. Brusca replies). *Physics Education*, *21*, 262-263.
Brusca, S. (1986b). Buttressing Bernoulli. *Physics Education*, *21*, 14-18.
Brusca, S. (1987). Bernoulli bunkum (S. Brusca replies). *Physics Education*, *22*, 9-11.
Denker, J. (2005a). *Airfoils and airflow*. Retrieved April 26, 2007, from http://www.av8n.com/how/htm/airfoils.html .
Denker, J. (2005b). *Stalls and spins*. Retrieved April 26, 2007, from http://www.av8n.com/how/htm/spins.html#sec-teaspoon-effect .
Did you know? (2005). *The Science Education Review*, *4*, 1.
Field, S. O. (n.d.). *Chapter 6: Aerodynamics*. Retrieved May 3, 2007, from http://sci-toys.com/scitoys/scitoys/aero/aero.html .
Holmes, B. W. (1996). My teacher is a blowhard. *The Physics Teacher*, *34*, 362.

Martin, D. H. (1983). Misunderstanding Bernoulli. *The Physics Teacher*, *21*, 37.

Mitchell, M. (n.d.). *Animated demonstration of Bernoulli's principle*. Retrieved April 25, 2007, from
http://home.earthlink.net/~mmc1919/venturi.html#animation .

Mitchell, M. (2003). *Bernoulli's principle: Introductory discussion*. Retrieved April 27, 2007, from
http://home.earthlink.net/~mmc1919/venturi_discuss_nomath.html .

Nave, R. (n.d.). *Airfoil*. Retrieved April 27, 2007, from http://hyperphysics.phy-astr.gsu.edu/hbase/pber.html .

Niven, A. (1999). *Why aircraft don't always fly*. Retrieved May 4, 2007, from
http://www.ul.ie/~childsp/elements/issue4/niven.htm .

Raskin, J. (2005). *Coanda effect: Understanding why wings work*. Retrieved May 2, 2007, from
http://jef.raskincenter.org/published/coanda_effect.html .

Resnick, R., & Halliday, D. (1966). *Physics*. New York: John Wiley & Sons.

Rowe, M. (2003). *Roof damage by hurricane force winds in Bermuda*. Retrieved April 29, 2007, from
http://www.gov.bm/portal/server.pt/gateway/PTARGS_0_2_2637_0_0_43/http%3B/portalcontent.gov.bm%3B70
87/publishedcontent/publish/dept___environmental_protection___hurrican_fabian_roof_damage_report/articles/h
urricane_fabian_roof_damage_report_3.pdf .

Smith, N. F. (1972). Bernoulli and Newton in fluid mechanics. *The Physics Teacher*, *10*, 451-455.

Swartz, C. (2003). Bernoulli and Newton. *The Physics Teacher*, *41*, 197.

Weltner, K., & Ingelman-Sundberg, M. (1999a). *Misinterpretations of Bernoulli's law*. Retrieved April 25, 2007,
from http://user.uni-frankfurt.de/~weltner/Mis6/mis6.html .

Weltner, K., & Ingelman-Sundberg, M. (1999b). *Physics of flight: Revisited*. Retrieved April 25, 2007, from
http://user.uni-frankfurt.de/~weltner/Flight/PHYSIC4.htm .