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Ideas for enhancing primary and high school science education

Did you Know?

Fish Likely Feel Pain

Studies on Rainbow Trout in the United Kingdom lead us to conclude that these fish very likely feel pain. They have pain receptors that look virtually identical to the corresponding receptors in humans, have very similar mechanical and thermal thresholds to humans, suffer post-traumatic stress disorders (some of which are almost identical to human stress reactions), and respond to morphine--a pain killer--by ceasing their abnormal behaviour.

How, then, might a freshly-caught fish be treated without cruelty? Perhaps it should be plunged immediately into icy water (which slows the metabolism, allowing the fish to sink into hibernation and then anaesthesia) and then removed from the icy water and placed gently on ice, allowing it to suffocate.

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, hypotheses 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.

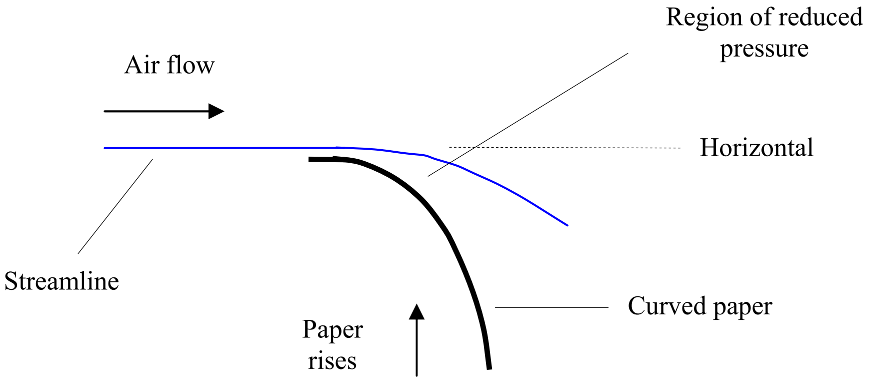

Figure 1. Blowing air across the top of a curved object.

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.

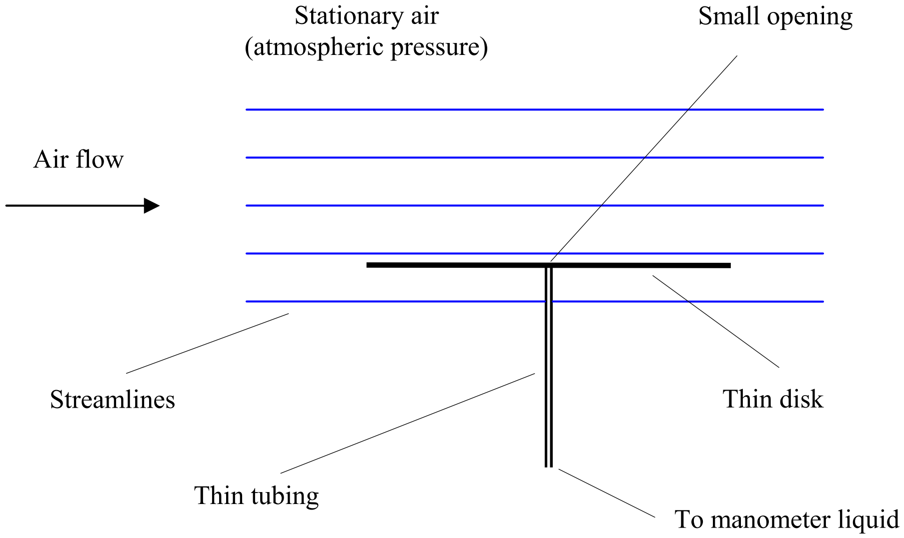

Figure 2. Using a manometer to measure static pressure.

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.

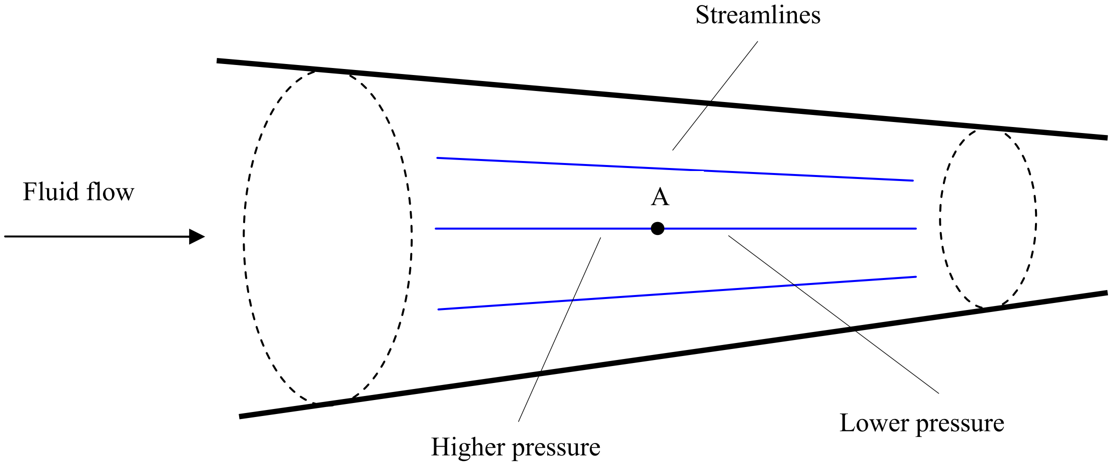

Figure 3. Fluid moving through a tube of changing cross-sectional area.

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 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.

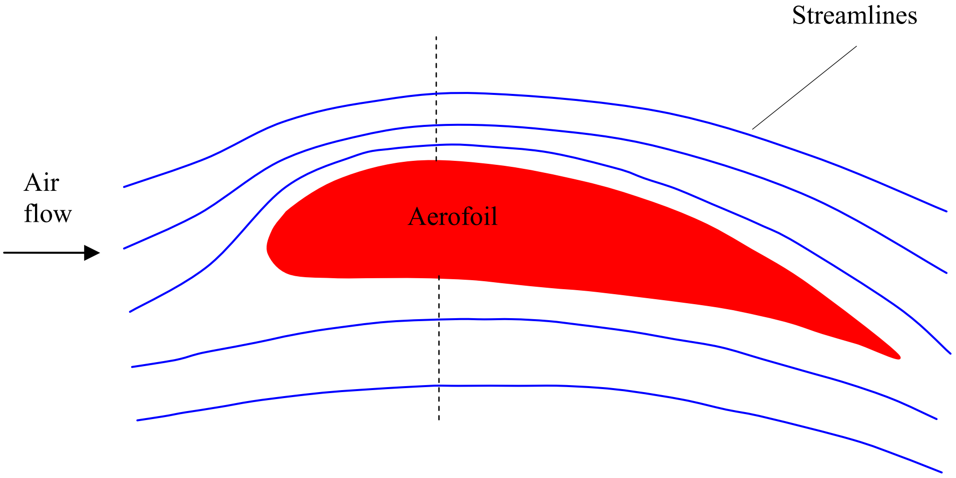

Figure 4. General pattern of streamlines around an aerofoil.

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).

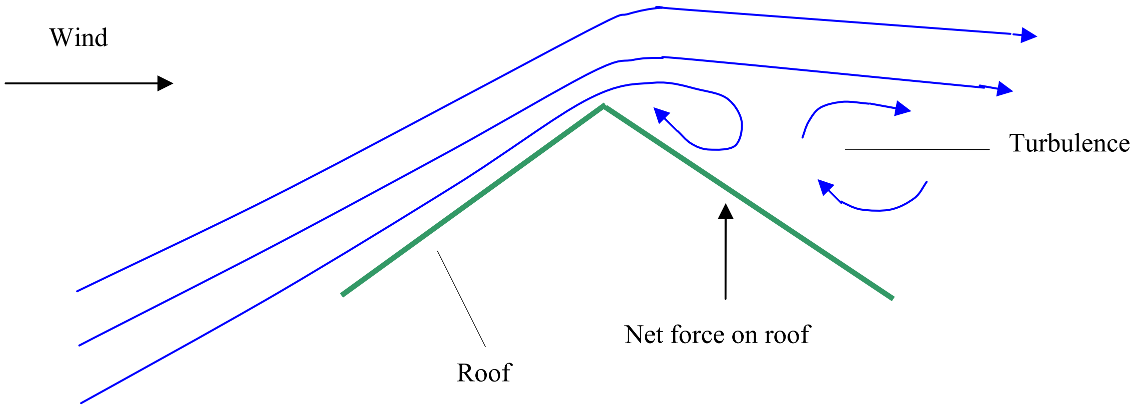

Figure 5. Wind blowing across a house roof.

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.

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Demonstration

While the activities in this section of *SER* have been designated demonstrations, some might easily be structured as hands-on student learning experiences. Although some sample lesson sequences may be included, the notes provided both here and in the *Student Activity* section of the journal are meant to act primarily as stimuli for classroom activities and to provide teachers with background information, so please modify any sample pedagogy as you see fit.

Centripetal Force and the Bowling Ball

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Needed. Bowling ball, wooden plank, gloves, and level floor space.

One of the most difficult subjects in introductory physics is centripetal acceleration, and the associated centripetal force. A mass moving at constant speed in a circle is being accelerated, because the direction of the velocity is always changing. The direction of the velocity vector is tangent to the circle at the point where the mass is instantaneously located, but the direction of the acceleration vector is along a radius, toward the center of the circle; that is, perpendicular to the velocity vector. The magnitude of the acceleration is equal to v^2/r, where v is the speed of the mass and r is the radius of the circle. Given this acceleration, it follows from Newton's second law that there must be a net force (the vector sum of all the forces on the body) pointing toward the center of the circle and equal in magnitude to the acceleration times the mass; this is the centripetal force.

There are various ways to demonstrate these principles to students, including calculus-based or more geometrical analyses on the blackboard, student-constructed vector diagrams on paper, swinging a tennis ball on the end of a string around a circle, and discussing the orbits of earth satellites and planets. But whether one is teaching at the level of a quantitative, problem-oriented course for top science students, or at the conceptual level for a general audience, it is clear that many students lack an intuitive grasp of what is happening in this kind of motion and, in particular, of the direction of the acceleration. Even students who succeed quite well at complex problems on this subject will quietly come up at the end of class and say: “Really, why doesn’t the moon fall into the earth?”

At the same time, uniform circular motion is, at least in my opinion, the most essential part of introductory physics (for any audience), since it lies behind Newton’s explanation of the motion of the planets and the moon, where the centripetal force is supplied by gravitation. And this accomplishment, after all, is what made Newton the superstar of the 17th century.

Several years ago, I decided to try to reinforce the idea of center-directed force by asking students to imagine a bowling ball rolling on the floor and being struck sideways by a wooden plank. The force doesn’t result in the ball suddenly beginning to move in the sideways direction, but rather changes its straight-line motion through a small angle, with the ball continuing with about the same speed as it had before. Then, I would say, suppose a second person hit the ball sideways, making it bend again through a small angle. Now suppose we continue this procedure on a big floor, with enough students standing around to hit the ball perpendicular to its velocity each time after it rolls a short distance. The ball would eventually describe a polygon, and come back close to its starting point. Then it is hit again, and begins to follow a second polygon, around the same path as the first. It is not too much of a stretch then to say that the polygonal path looks something like a circle and, if one used many small forces, the path would be a polygon with a very large number of sides, which would approach a circle. The force is always directed toward the center.

After a few semesters, I thought that since this is supposed to be a physics course, why shouldn’t I get a real bowling ball and actually do this in the lecture room? Bowling balls are expensive. However, I found that some sporting goods stores drill bowling balls to fit the hands of a purchaser, and that they sometimes have cheap balls (20 US dollars or less) that have been drilled for a customer who then decided the ball was unsatisfactory and didn’t take it.

I have space in front of my lecture room about 9 meters wide, with a little less than 2 meters between the students in the front row and the demonstration tables. This gives me room for two, or sometimes three, impacts. The ball rolls about a meter between each hit and the time between hits is about 1 second. Due to irregularities in the floor, a lower speed would allow the ball to wander a bit from its constant-velocity trajectory. The path bends about 10 degrees with each impact. A plank of wood is good for making the hit, but I use gloves to avoid splinters. Every once-in-a-while, the wood splits and I need a new plank.

Once the students see what happens with two or three hits, it is not difficult for them to imagine 10 or 20 successive hits, and a closed polygon. I show this with a diagram on the blackboard. Sometimes I have student volunteers come up to hit the ball, although I have to make clear that it is just a slap; they can’t drag the ball. The point is for them to get a physical and visceral feeling about which way the force has to go in order for the ball to move in a circle (approximately). Indeed, it would be nice to take the class somewhere with a lot of space--outdoors or to a gym--and have a group of students create one or more complete closed paths. I haven’t had a chance to try that, but I’m sure it would create an indelible recollection of the dynamics of circular motion. (Swinging a tennis ball in a circle also gives one some feeling of the centripetal force. I have students try it, but there just isn’t the same unambiguous feeling about the direction of the force as there is in whacking the bowling ball.)

Having the ball in my office also led to its use earlier in the course. Just as centripetal acceleration is a tricky concept, Newton's second law itself, and the distinction between acceleration and velocity--even in one dimension--can be subtle. I let the ball roll to the right, and I hit it with the plank toward the left. The ball does not turn around and go left, but continues to the right at a slightly slower speed. Similarly, a single sideways impact can be used to demonstrate the law of compound motion. According to this venerable theorem, in two-dimensional motion, say, the component of velocity in a particular direction will be affected only by the component of a force in this same direction; it will not be affected by a force acting in a perpendicular direction. Students can hit a moving bowling ball side-on as hard as they want, but they cannot give it a final velocity in the direction of the strike, because the force being applied has no component in the original direction of motion and hence cannot change that component of velocity. These simpler observations precede, and lead up to, the demonstration of centripetal force and the polygon-circle. In all these cases, the large inertia of the bowling ball makes it an effective demonstration tool, and this property directs attention to the inertial character of Newton's first law.

Readers may not be aware that Newton, giving credit to Huygens, uses the kind of polygonal motion described here to derive the equation for the magnitude of centripetal acceleration. This argument, based on elastic collisions with the interior of a cylindrical wall, is given in modern terminology by Arons (1990).

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Imaginative Thinking and the Learning of Science

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Abstract

This article discusses the role of imagination in science education. It provides a justification for imaginative thinking in the context of school science, as well as some strategies that can be implemented by science teachers in their classrooms.

No doubt one would feel more comfortable about discussing the role of imagination in subjects such as literature and the fine arts, rather than science education. And it would not be an exaggeration to say that, for some, imagination should be considered a blasphemy in science education. But before making such a judgement, they should seriously ask the question: Is imagination important in science? Certainly the answer to this question cannot be found in journals where scientists report their research (i.e., their methods and results). It can be found, though, in books, where scientists, in speaking "autobiographically," make an explicit or implicit reference to the role of imagination in their own work or in the work of others. Van't Hoff, for example, in a letter to his father, wrote: "The fact is the basis, the foundation. Imagination the building material, the hypothesis the ground to be tested, and reality is the building" (Van't Hoff, 1967, p. 2). Maxwell, in admiring Faraday's exceptional imaginative thought, said: "Faraday, in his mind's eye, saw lines of force, traversing all space, where the mathematicians saw centres of force attracting at a distance. Faraday saw a medium where mathematicians saw nothing but distance" (cited in McAllister, 1996, p. 54). And Planck (1933) remarked: "Imaginative vision and faith in the ultimate success are indispensable. The pure rationalist has no place here [in modern physics]" (p. 215). The history of science, of course, provides many examples that testify to the importance of imagination (Di Trocchio, 1997).

It appears that if the true image of science is to be presented to pupils, then imagination should become the ubiquitous element in the teaching-learning process. However, research based on the life stories of scientists (e.g., Einstein, Maxwell, Faraday, Watts, and Feynman) provides evidence that imaginative skills are not developed by formal schooling. Shepard (1988) has pointed out that "their development occurs before, outside of or perhaps in spite of such schooling - apparently through active but largely solitary interaction with physical objects of one's world" (p. 181). So it appears that the development of imagination in the context of formal education is a real challenge. Fortunately, though, science is a subject that can provide opportunities for free exploration, for self-directed inquiry, and for taking science outside the classroom and the school. And, even more fortunately, science is a subject that can inspire pupils by making them feel the mystery and wonder inherent in its very ideas (Hadzigeorgiou, 1999, 2005). However, more than being just a challenge, imaginative thinking is crucial in the wider context of science education, and there are a number of reasons to justify this.

A Justification for Imaginative Thinking

If we realize that imagination is not simply a capacity to form mental images, but a capacity to think in a particular way--that is, a way that involves our capacity to think of the possible rather than just the actual (Egan, 1990)--then its significant role in science education can be easily comprehended. It must have been in the aforementioned sense that Einstein considered imagination more important than knowledge. For he is reputed to have said that, while knowledge points to what there is, imagination points to what there can be. And he also urged people who want to become scientists to take 30 minutes a day and think like non-scientists (Di Trocchio, 1997)! However, as has been pointed out, there are a number of reasons that justify the importance of imaginative thinking in the context of science education.

The first reason emerges from the notion of scientific literacy. Although the debate about that notion is not exactly settled, there is an agreement that a person who is scientifically literate should be able to apply scientific knowledge for both personal and social purposes (OECD, n.d.; UNESCO, 2000). It is quite evident that the ability to apply scientific knowledge can, by itself, justify the use of pupils' imagination. Given that the application of knowledge to novel situations, to real world problems, requires both convergent and divergent thinking, and that creativity and imagination are intricately linked, the development of scientific literacy requires imaginative thinking.

The second reason is provided by the notion of narrative thinking. This term was proposed by Bruner (1986), who argued that there are two distinct but complementary modes of thinking: the paradigmatic (or logico-mathematical) and the narrative mode. The former is concerned with the formation of hypotheses, the development of arguments, and generally with rational thought. The latter, on the other hand, is concerned with verisimilitude (i.e., life-likeness or truth-likeness and the creation of meaning) and it employs similes, analogies, metaphors, and even irrational thinking (e.g., paradoxes). Because these two modes are complementary, such processes as hypothesis formation, generation of analogies, and modeling--central processes in the development of scientific knowledge--cannot rely exclusively on the paradigmatic mode. Therefore, in the context of science education, pupils should be given opportunities to use their two modes of thinking. Bruner's hypothesis is certainly very bold but it sheds light on the fact that the development of scientific knowledge cannot be explained solely in terms of paradigmatic thinking. Both the irrational character of scientific thinking (Di Trocchio, 1997; Feyerabend, 1993) and the idea that scientific theories start their life as myths (Popper, 1972) support Bruner's theory about the two modes of thought. Story-telling can be considered a good means for helping pupils understand science ideas, if these are embedded in the plot of a story (Banister & Charly, 2001; Egan, 1986; Hadzigeorgiou, 2006a), and story-telling can also help pupils convey their thoughts (Bruner, 1986). There is even evidence that scientists' personal stories (i.e., stories based on events from their everyday lives) can help scientists think about their own work (Martin & Brouwer, 1991).

It deserves to be pointed out that such notions as myth, story-telling, and narrative thinking may make some scientists and science educators raise their eyebrows. Given that rationality and reality are closely intertwined in our mental lexicon (Egan, 1997), a story or myth could be viewed as the cause of the construction of unreal or even impossible worlds. Yet it is important to consider two points here. First, narrative thinking is not unconstrainedly imaginative, since there is the paradigmatic or logico-mathematical mode of thought which complements, and therefore restrains, the former. Second, there is historical evidence that contemporary science is built upon yesterday's science, and yesterday's science upon the oldest scientific theories which, in turn, are built on pre-scientific myths (Hadzigeorgiou & Stefanich, 2001). In fact, Bruner (1986) did point out that "many scientific theories . . . start their life as myths or metaphors" (p. 12).

The third reason comes from the nature of science itself. Over the past 3 decades, work in the philosophy of science has led to a reconsideration of what could be called the scientific method and the view of science as a rational activity (Duschl, 1994; Trefil, 2003). Gell-Mann, a Nobel laureate in Physics, said: "Rationality is one of the many factors governing human behaviour, and it is by no means always the dominant factor" (cited in Jenkins, 1996, p.147). Although the effort by philosophers of science to arrive at a satisfactory definition of science has not been fruitful, there has been agreement that imagination is an important ingredient of the scientific process, complementing observation, reason, and experiment (Hadzigeorgiou, 2005). This imaginative element is stressed by Richard Feynman (1995):

> The test of all knowledge is experiment. Experiment is the sole judge of scientific "truth." But what is the source of knowledge? Where do the laws that are to be tested come from? Experiment, itself, helps to produce these laws, in the sense that it gives us hints. But also needed is imagination to create from these hints the great generalizations – to guess at the wonderful, simple, but very strange patterns beneath them all, and then to experiment to check again whether we have made the right guess. (p. 2)

Although science is a social activity--"constitutively social," as Woolgar (1993, p. 13) put it--the personal, imaginative dimension of science needs to be recognized (in the same way that we need to recognize the elements of chance and serendipity and their role in scientific discovery). This dimension should also be sought in the area of aesthetics. Science, in fact, might have a greater commonality with art than was originally thought in a more positivist era (Tauber, 1996). The philosopher and historian Thomas Kuhn (1970) has stressed the importance of the aesthetic element in scientific revolutions: "Aesthetic considerations can be decisive. Though they often attract only a few scientists to a new theory, it is upon those few that its ultimate triumph may depend" (p. 156). The history of science provides evidence that aesthetic factors did play a major role in theory construction and in influencing scientific practice in general (Hadzigeorgiou, 2005).

In connection with these ideas, romantic understanding can be offered as another reason for justifying imaginative thinking. Although the idea of romance in the context of education appears to have made a debut with the philosopher Alfred North Whitehead (who argued that pupils need first to engage in any subject in a romantic way, before they can study its details and before they go into some depth), the notion of romantic understanding was introduced by Kieran Egan (1990) as one of the various forms of understanding that people have developed in the course of cultural history (with the other forms being somatic, mythic, philosophic, and ironic). The educational process can be conceived as a process of recapitulating these forms of understanding. Egan, although not giving a definition of romantic understanding, argued for a number of features associated with it: preoccupation with the extremes of reality, desire to transcend everyday reality, mystery, wonder, meaning, and inspiration. These features point to the fact that romantic understanding is not achieved by just mastering any particular body of knowledge. The following quotation is an example of Richard Feynman's experience of romantic understanding:

> The world looks so different after learning science. For example, trees are made of air, primarily. When they are burned, they go back to air, and in the flaming heat is released the flaming heat of the sun which was bound in to convert the air into tree. [A]nd in the ash is the small remnant of the part which did not come from air, that came from the solid earth, instead. These are beautiful things, and the content of science is wonderfully full of them. They are very inspiring, and they can be used to inspire others. (cited in Girod, Ran, & Schepige, 2003, p. 575)

Feynman’s ideas, no doubt, point to how science can inspire pupils to see the world differently. But does this inspiration lead to a conceptual, and not simply a romantic, understanding? The answer is not simple, since there are differences between these two forms of understanding. But a philosophical exploration of the notion of *wonder*, and some historical evidence, can lead one to consider romantic understanding as a prerequisite for conceptual understanding (Hadzigeorgiou, 2005). Wonder, in fact, can be seen as a connecting ring between these two forms of understanding. It is interesting to note that many renowned scientists (e.g., Einstein, Schrodinger, and Dirac) did say that their work was driven and sustained by both an appreciation of beauty and a sense of awe and wonder (Tauber, 1996). Although it is beyond the scope of the present paper to explore the nature of wonder, it is important to stress that a *wonder at* attitude or state of mind, which a) signals the limitations of one’s present understanding (Opdal, 2001), b) makes one aware of the mysterious nature of some phenomena or ideas (Hadzigeorgiou, 1999), and c) makes one aware that some phenomena exist at all (Hadzigeorgiou, 2006b) does excite the imagination. It is no wonder then that such a wonder at attitude is recommended for the teaching and learning of science (Goodwin, 2001; Hadzigeorgiou, 2001).

Capturing and Developing Imagination in the Science Classroom

Despite the blows that empiricist and logical positivist philosophies have suffered during the last 3 decades (Duschl, 1994), it is still difficult for both pupils and science teachers to completely abandon such philosophies (Monk & Dillon, 2000). It is very common for them to be engaged in laboratory work involving the investigation of the relationships among various variables and, at times, the confirmation--through an experiment--of an idea (e.g., a law or principle). However, if a true constructivist philosophy was to be considered the foundation for science education, then pupils should be given opportunities to propose hypotheses and to test them and to be involved in modelling, problem solving, finding diverse connections among ideas, and generally opportunities for divergent thinking. From such a perspective, imagination, evidently, becomes an important factor to be considered. In science education, of course, thought experiments, modelling, and problem solving requiring divergent thinking (e.g., calculating the density of a proton or a black hole) can be considered good ways to develop pupils' imagination. However, there are other strategies to do so. In the light of what has been discussed so far, the following strategies/activities can be considered:

- *Presenting ideas that conflict with everyday common-sense* (e.g., the uniform, straight-line motion of a spaceship at thousands of kilometres per second in the absence of an external force, the equivalence of rest and straight-line motion at constant speed, the "emptiness" of solid matter, and the increase in mass of an object with an increase of its speed).
- *Presenting ideas through mysteries, paradoxes, and the extremes of reality* (e.g., the fate of the earth after the total disappearance of the sun, the mystery of universal attraction, the twins paradox in the special theory of relativity, the transmission of electromagnetic radiation through a freezing and empty space, radiation that penetrates matter and makes it visible, the smallest and the biggest molecule, and the fastest particle).
- *Investigating topics from everyday life that call for a creative approach to inquiry* (e.g., investigating possible factors that might have an effect on the illumination of a room, the construction of a flashlight from simple materials, ways to produce electricity for the house in a case of emergency, and ways to heat water in the absence of metallic containers).
- *Investigating topics and problems that might confront humankind in the future* (e.g., investigating alternative sources of energy, the possible effects of new technologies on the production of electricity, and ways to protect the planet from various kinds of dangers).
- *Presenting the great ideas of science through real events from the history of science and through story-telling* (e.g., the idea of the nature of electricity through the Galvani-Volta conflict, the idea of energy through a historical evolution of events that led to the abandonment of caloric theory, the idea of the atom, the discovery of X-rays, and the magnetic effects of an electric current).
- *Having pupils keep daily journals in which they record, and write about, their everyday experiences--their personal stories--which can illustrate science ideas* (e.g., the reverse thrust they experienced while riding the bus, the spectacular colours of a sunset, and the breathtaking twisting somersault of a gymnast).
- *Using questions that challenge pupils to find connections among apparently unconnected facts and ideas* (e.g., how would a thief, the police, and the speed of light be connected? What would be a connection between Newton's laws, a nurse, and a soccer player? Between light, electrons, and a surgeon? Between a glass of wine, the age of the universe, and the evolution of stars?).
- *Encouraging pupils to create their own analogies to understand phenomena and ideas* (e.g., the phenomenon of resonance and the ideas of nuclear fission, nuclear fusion, and chemical bonding).
- *Approaching the teaching and learning of science through the arts* (e.g., using photography and making a collage to present the different states of water or the effects of acid rain or modern technology on everyday life, using sculpture and technologies to construct scientific models, and using drawing to represent a phenomenon such as photosynthesis or the water cycle).
- *Approaching the teaching and learning of science through poetry* (e.g., writing a poem on the elements of the periodic table, conservation of energy, pollution, or action and reaction).
- *Using science fiction* (e.g., speculating about possible applications based on established principles).

Some strategies appeal more to the imagination than others. For example, speculating on new science ideas, constructing a scientific model, or investigating a problem that humankind might face in the near or distant future appear to be more appropriate than having pupils discuss some of their own experiences in connection with their science course. However, even in this case, both the narrative element and the attempt on pupils' part to try to identify from an everyday experience the application of a scientific idea (e.g., the law of conservation of energy or momentum) help develop their imagination.

Regarding the presentation of ideas, it would be naive on anyone's part to believe, for example, that the presentation of an idea alone, in a way that it conflicts with everyday experience, is of itself sufficient to develop romantic understanding. While conflict with everyday experience, or even conflict with accepted beliefs, is crucial in capturing the pupils' imagination, it is the discussion that will follow that will lead to an understanding. The way questions are posed, the opportunities given to pupils to respond, and the discussion that ensues are all crucial for romantic understanding. Any exciting experience, even at a science museum, will remain simply an experience if it is not followed by a discussion. The historical development of ideas, as presented through the various exhibits, should be followed by a discussion of the possibilities these ideas can open for humankind. For example, pupils should discuss the various possibilities of applying the idea of radio waves. If it was the possibility of sending messages to the other side of the Atlantic, or to the other side of the world, that had captured Marconi's imagination, and the imagination of people who had become aware of the power of the idea of radio waves, then pupils should also share in, and extend, that discussion.

Perhaps the most challenging idea in regard to capturing and developing imagination is the speculation about new ideas. How can these ideas be taken seriously? If the development of imagination is not an end in itself, as has already been pointed out, what point is there in encouraging the pupils to come up with "crazy" ideas? Two arguments can be advanced here. First, the history of the evolution of ideas in physics shows that ideas that appeared not simply revolutionary, but very irrational indeed, did prove to be great ideas. Planck had advised Einstein not to try to include gravity in his theory of relativity because that was an almost impossible task. He also told Einstein that even if such an attempt was to be successful, no one would pay any attention. Poincare did believe that the transmission of radio waves on the surface of the earth to a distance more than 300 km was impossible, and Lord Rutherford initially thought that the idea of deriving energy from splitting an atom was absurd (Di Trocchio, 1997). Second, the hypothetical ideas (or principles) can be introduced in such a way that they don't contradict accepted ideas or principles that have been directly tested (Schmidt, 1980).

In Conclusion

The strategies/activities proposed in this article to develop imaginative thinking have been implemented by 12 science teachers who work in suburban (primary and secondary) schools in a European capital, and who have formed an action group committed to the important role of imagination in the learning of science. Their action research (which is part of a larger international project on imaginative education directed by Professor Kieran Egan at Simon Fraser University in Canada) has reported changes in pupils' behaviour in connection with science leaning. These changes refer mainly to discussions outside the classroom, students' comments in their journals, and the seeking of opportunities to learn more about what was presented in the classroom. Female students, in particular, who were the "outsiders" in the science class, were motivated to participate in science activities, and especially those that connected science and the arts.

Of course, one might raise a question about the opportunities pupils have for improving their ability to learn science. It sounds quite reasonable that pupils' engagement in an activity connecting science and the arts or poetry is no guarantee for learning science. But what needs to be pointed out is that the activities proposed here, and which were implemented in real classroom settings (e.g., the use of photography and the making of a collage to present the different states of water, the effects of acid rain, or the effects of modern technology on everyday life, the drawing of models to represent phenomena such as photosynthesis and the water cycle, and the writing of a poem about action and reaction), apart from engaging pupils' imagination, did result in the acquisition of scientific knowledge (e.g., elementary school students did learn that water exists in different states and did learn about the chemical substances involved in photosynthesis), as this was assessed at the end of the unit. Even a poem on Newton's third law became the means through which pupils revised their view that action and reaction are exerted on the same object. An interesting finding by a ninth-grade teacher was that, although the pupils' initial motivation to compose a poem on Newton's third law, and the actual writing of that poem, did not result in a conceptual understanding of action and reaction, poetry did play a catalytic role in involving the pupils--especially the females--with both science, as an object of study, and the events of instruction. This finding provides evidence that school science can be both a scientific and a literary experience, an idea that should be given more thought by science teachers and science educators (Midgley, 2000; Watts, 2001).

What also needs to be pointed out is that activities connecting science with poetry or the arts represent immersion activities, which do not provide pupils simply with opportunities to approach science in a nontraditional way, but with opportunities for self-exploration and self-actualization. If we conceive of education as a possibility, as Maxine Greene (2000) has contended, and if in a school classroom all possibilities exist until a pupil decides to actualize one of them (Liston, 2001), then pupils should participate in activities that give them the opportunity to explore their "unexplored selves." Is it not possible for a girl engaging in the creation of a collage on the effects of a tsunami, or the effects of environmental pollution, to develop an interest in science? Is it not possible for a boy engaging in the creation of a collage on the states of water to become curious about whether ice floats in water or generally about whether matter in its solid state sinks or floats in its liquid state? If we conceive of education in general, and science education in particular, as a possibility, then these questions should always be raised.

A final point that deserves stressing is that giving imagination its proper place in science education helps reaffirm the value of liberal education. This is crucial, given that recent reform efforts in science education have placed an emphasis on the notion of the utility of science (OECD, n.d.; UNESCO, 2000). Although utilitarian aims of science are laudable, an appreciation of science as a way of knowing, an appreciation of its beauty, and an understanding of its great ideas should also be an important goal of science education (Girod et al., 2003; Hadzigeorgiou, 2005; Millar & Osborne, 1998). While the applications of science presuppose the workings of imagination, an emphasis on presenting science mainly through applications (technological and practical), because they are relevant to pupils' lives, might result in consolidating a positivist view of science. In reaffirming, of course, the value of liberal education, and in providing pupils with opportunities to connect science and the arts, science education can pave the way toward bringing the humanities and the sciences closer (Hadzigeorgiou, 2006b; Midgley, 2000). This is another reason why new holistic approaches to the learning of science should be welcome. These approaches, apparently, should not contradict what we know about the nature of scientific inquiry.

Although there are no recipes for how a pupil learns science, research suggests that certain ideas, such as misconceptions, social context, dialogue, and conceptual change should be considered in planning a curriculum and instruction. These, no doubt, are important ideas, but they have represented a limited view of how pupils learn science (Girod et al., 2003; Hadzigeorgiou, 2005). They should certainly be considered in developing more holistic models of learning, but they should also allow for a place for imagination. Kieran Egan's (1990) idea that the neglect of imagination might be a reason for pupils' failure in science should be given serious thought.

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Critical Incident

An Invitation

Readers are invited to send, to the Editor at editor@ScienceEducationReview.com , a summary of a critical incident in which you have been involved. A critical incident is an event, or situation, that marks a significant turning point, or change, for a teacher. The majority of critical incidents are not dramatic or obvious, but are rendered critical through the analysis of the teacher (see Volume 3, p. 13 for further detail). You might describe the educational context and the incident (please use pseudonyms), analyse the incident (e.g., provide reasons to explain your observations), and reflect on the impact the incident made on your views about the learning and teaching process. Upon request, authors may remain anonymous.

We have undoubtedly all done things about which we were very pleased, and perhaps done other things about which we did not feel so pleased, and we all need to remain reflexive of our practice. While teachers will view an incident through the lenses of their own professional experiences, and may therefore explain it differently, this does not detract from the potential benefits to be gained from our willingness to share our experiences and thus better inform the practice of other teachers.

Measuring Pi

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Once, when my younger son was in the fifth form, he came home from his school with the task from his mathematics teacher to measure pi. I proposed that he find a round object, take a thread, make several turns of the thread around the object, measure the length of the thread, and then determine the circumference of the object. After using the thread to also measure the diameter of the object, he could calculate the required ratio.

He went away to complete the task, but returned in tears. I inquired as to what had happened. He said that his result was 3.12, but that he knew from the book it had to be 3.14. I suggested he repeat the measurements with a different round object he could find in our flat. He obeyed, but came back in complete despair. Through more tears, he reported that he had got 3.16, but that it still had to be 3.14. I congratulated him with the results and said that both his numbers were right.

At first, he couldn't grasp the idea, so I informed him that the first number he got was used by ancient Egyptians, and the second one was in use in Mesopotamia. For everyday, practical purposes it is often quite sufficient to use 3.12 or 3.16; even today. The first theoretical value of 3.14 was obtained only by ancient Greeks (specifically, perhaps, by Archimedes), using mathematical reasoning rather than the measuring that had been used previously, and the kind of argument used is exemplified by O'Connor and Robertson (2001). Actual physical measurements in Archimedes time did not, and could not, furnish him the desired result.

We need to convey to physics students the important idea that all physical quantities are known with uncertainties, some of which are due to imperfect measuring tools whereas others are of a more fundamental nature. And, every physical quantity must be measured with a precision that reflects the physical phenomenon in question. For example, the height of a human being is measured to the nearest centimetre, and it is senseless to try to improve this precision because, during a day, a human's height naturally changes up to several centimetres. The same applies to measurements of blood pressure and other physical parameters.

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Science Poetry

Reading and/or listening to poems composed by other children their own age can inspire and reassure students as to their ability to understand and write poetry, and the science poems in this regular section of *SER* may be used for this purpose. Please find information about the *International Science Poetry Competition* at http://www.ScienceEducationReview.com/poetcomp.html .

My Science

(With apologies to Dorothea Mackellar)

The love of books and music
Of cultural pursuits
Of opera and the theatre
Can be traced back to your roots.
The words of Keats and Shakespeare
Have a truth that time defies
I know them, and respect them
But my love is otherwise.

I love the world of science
Its many different arms
Biology and physics
Each with their unique charms.
Geology, forensics
Marine biology
Environmental science
and anthropology.

Core of my heart, my science!
The lab and microscope
The single cell amoeba
The mighty isotope!

Science Saves Lives

Vaccinations save our lives
From Hep A, Tetanus, Flu and Hives
A shock in my arm, I'd much rather
Than die of smallpox like my grandfather.

Antibodies are what they inject
The needles are new and thrown in the bin
If it wasn't for vaccinations we wouldn't be here
The plague would have wiped the world clear!

What about Edison, and how about Florey?
Both of them have a hell of a story!
Florey discovered some great medicine
And the light was invented by Thomas Edison.

Science is a part of everyday life
Without it we would be in all sorts of strife
We wouldn't know about helpful yeast
Which makes beer a yummy feast!

I come to my conclusion that science is great
And I don't understand people who say science they hate?

I love its quiet grandeur
Each new discovery
Its ever changing boundaries
A scientist I'll be!

Jack Burnham, 12 years
Australia

Without these discoveries there will be no best mate
Because science makes up our world; science is great!

Emily Rocco, 15 years
Australia

Students' Alternative Conceptions

Students' alternative conceptions have been variously called misconceptions, prior conceptions, preconceptions, preinstructional beliefs, alternative frameworks, naive theories, intuitive ideas, untutored beliefs, and children's science. The tasks in this regular section of *SER* are based on the literature and may be used at the beginning of a constructivist learning segment to arouse the curiosity of students and to motivate them, while simultaneously eliciting their ideas or beliefs. They are designed to address areas about which students are likely to have an opinion, based on personal experiences and/or social interactions, prior to a specialist learning sequence, or areas that might be considered important for the development of scientific literacy.

Micro-organisms

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1. Where would you expect to find micro-organisms? (There may be more than one.)

   a. In hot sulphur springs.
   b. At the bottom of the ocean.
   c. In the freezer.
   d. In, or on, human beings.
   e. In volcanoes.
   f. In dirty and unhygienic places.

All answers are correct. The ubiquity of micro-organisms and their adaptability to survive in many hostile and difficult environments make them some of the most successful groups of living organisms on Earth. Children do associate micro-organisms with human beings and dirty or unhygienic places, as they have a predominantly negative view about micro-organisms and their location.

2. Most micro-organisms are:

   a. microscopic animal-like organisms.
   b. the same as specks of dirt.
   c. single-celled organisms.
   d. microscopic plant-like organisms.

The correct response is c. However, many children, including some secondary school pupils, associate micro-organisms especially with animal-like characteristics and will even anthropomorphise them.

3. Is the following statement true or false? "Micro-organisms cause all diseases."

False. Less than 1% of all micro-organisms are pathogenic, although many children do consider micro-organisms to be the cause of all diseases and think the presence of micro-organisms in, or near, human beings is a potential danger to their health.

4. Something (e.g., an apple) might decay because it is:

    a. old.
    b. damaged (e.g., squashed or bruised).
    c. being attacked by micro-organisms.
    d. damp.
    e. in a warm place.
    f. in a dirty place. (There may be more than one.)

To some extent all are correct; decay may be caused by a combination of physical, chemical, and biological factors, such as appropriate temperature and humidity to support microbial growth. Children tend to consider factors in isolation. The age of an item is regarded as a crucial factor and something being past its "sell by date" is a frequently mentioned reason for decay. Micro-organisms are associated with decay because the item has already "gone bad" or it is in a dirty place. Micro-organisms are thought "to eat" the items, multiply rapidly, and, due to the increase in numbers, pose a threat to human health.

5. Micro-organisms can be used to produce:

    a. lemonade.
    b. antibiotics.
    c. washing powder.
    d. yogurt.
    e. silage.
    f. ice-cream.
    g. bread.
    h. hormones.
    i. vaccines. (There may be more than one.)

All of the above; the potential applications of micro-organisms are vast. Applications include what might be regarded as traditional technologies that employ whole organisms (e.g., lactobacilli cultures to make yogurt) and the new biotechnologies which manipulate microbial genomes to manufacture products, most of which are not naturally produced by micro-organisms (e.g., the industrial production of insulin). Children have a poor understanding of the range and benefits of microbial applications.

Teaching Techniques

This regular section of *SER* describes thinking, cooperative learning, and other teaching techniques.

The RAFT Technique

The RAFT writing technique helps students understand:

- their ***R***ole as a writer (e.g., a victim, animal, scientist, or journalist),
- the ***A***udience (e.g., self, community, jury, or a fictional character),
- the writing ***F***ormat (e.g., a party invitation, Letter to the Editor, poem, or interview), and
- the ***T***opic (e.g., one of personal interest, or one relevant to a unit of study).

Given a topic, students might brainstorm various roles, audiences, and formats, and then each student might select one of each of these for their writing. Alternatively, the audience and/or format might be specified for them. *Instructional Strategies Online* (2007) contains further ideas, including a blank RAFT form and rubric for assessing RAFT presentations.

The RAFT technique occupies middle ground between standard essays (that can be somewhat dry) and free-for-all creative writing and, by providing students with choices about their writing, can motivate them to write and hence produce higher-quality work. Beginning with a topic of local importance helps students build connections with, explore, and understand their immediate surroundings.

Groenke and Puckett (2006) suggest that the products from a RAFT exercise (i.e., writings from a particular perspective) might be further used by students to share their different viewpoints in panel style, thus allowing a group to better appreciate the complexities and tensions associated with an issue. Following such a sharing of ideas, students might be invited to think about how a decision on a topic might be made.

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Group Work in a Classroom: An Analogy With Organisms in a Community

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Abstract

There is a large number of relationships between organisms in communities, and these relationships comprise the following types: predation and parasitism, commensalism, protocooperation and mutualism, neutralism, amensalism, and competition. The possible effects of the relationship between two species are that one or the other can benefit (+), lose (-), or neither benefit nor lose (0). By analogy, I have classified the behavioural relationships between students during group work. Different groups of students require different treatments. As a result, I propose a mixed approach to the formation of groups, careful observation of individuals, and the division of the work into smaller sections. In this way, low achievement of a group as a result of the uncooperative behaviour of some students can be prevented.

Introduction

Between teachers, at least on a declarative level, it is widely accepted that active methods with fully engaged students can lead to higher levels of student learning, and this is especially true in teaching science. Group and collaborative work is considered beneficial for students in many ways (Marentič-Požarnik, 2000; Peklaj, 2004). Through such work they can learn new facts and skills, reconstruct their knowledge, change attitudes, and best of all achieve all of this in a friendly environment, and it would be negligent for a teacher to ignore a method with such promise to elevate students to the highest peak of educational Olympus. However, in everyday reality, collaborative work does not suit all situations and some traps are hidden within, traps that include the grouping of students, fairness in grading, and absenteeism (Gupta, 2004).

In more than 20 years of teaching using group work, both in the classroom and in outdoor activities, I have observed that, under equal outer conditions, some groups work brilliantly but the outcomes of other groups performing the same task may not be so encouraging. In the same class, where work must follow a prescribed schedule, there are always groups that "work like a Swiss watch," with all work completed on time and almost without any intervention by the teacher. On the other hand, there are groups that are always late and where a lot of school time is lost simply by having to push them to work. In practice, these are well-known problems and there is no unique solution to overcome them. Some suggest forming groups by chance, while others allow students to form groups based on their own preferences. Some will suggest that work must be done, in the same group, from start to finish, while others prefer to vary group membership (Bahar, 2003; Mitchell, Reilly, Bramwell, Lilly, & Solnosky, 2004). I have observed that group work was sometimes improved with just the absence of a single student, or the presence of a formerly absent student, in a group. Out of curiosity, a colleague and I started to observe patterns of behaviour in groups and, with time, recognised an analogy between the interrelationships of students in a group and those of community members in an ecological system (a biocoenosis).

In every biocoenosis, there is a large number of relationships between species, and these relationships comprise the following types: predation and parasitism, commensalism, protocooperation and mutualism, neutralism, amensalism, and competition (Odum, 1971; Tarman, 1992). The possible effects of the relationship between two species are that one or the other can benefit (+), lose (-), or neither benefit nor lose (0), as shown in Table 1. Some species can experience one type of relationship with one species and a completely different relationship with another. For example, a sparrow can be commensal in a stork nest, a predator of seeds, the prey of a hawk, and neutralist with a hedgehog.

Table 1
Possible Types of Relationship Between, and Effects on, Two Species in an Ecological System

Type of relationship	Effect	
	Species A	Species B
Predation and parasitism	Benefit (+)	Lose (-)
Commensalism	Benefit (+)	Neither (0)
Protocooperation and mutualism	Benefit (+)	Benefit (+)
Neutralism	Neither (0)	Neither (0)
Amensalism	Neither (0)	Lose (-)
Competition	Lose (-)	Lose (-)

Methodology and Results

For more than 20 years, I and a colleague observed students as they participated in group work. When students work in groups, their teacher should not interfere and disturb them but slowly walk between groups to observe and listen to the students and wait on their call for help. As a result of our observations, we learned that each group works in a completely different fashion, with the work of a group largely dependent on the behaviour of group members. Knowing about the relationships between species in an ecological community mentioned previously, we recognised almost similar patterns for the students in a group.

For the analysis of possible relationships, we took each student to represent a member of a different species, and student behaviours were categorised. In an earlier attempt, we analysed a similar relationship pattern between teachers in team work (Šorgo & Logar, 2006), and we believe similar patterns can be recognised in almost every group which stays intact long enough and has some work to do. In the following, I commentate on the behaviours of different types of students during group work.

Predators and parasites. In both cases, one partner benefits and the other loses. Predation is a short-term process where the prey instantly dies. In contrast, parasitism is a long-term process and can even last a lifetime. Examples from nature are well known, and include foxes and owls as predators and mice as prey, and a cat that hosts fleas or tapeworm, both of which digest the cat's body fluids.

Typically, we recognise only parasitism in a student group, so there is no need to clean the bloody remains of a feast after a lesson! We can observe that some students constantly live at the cost of others. We can easily recognise them because they are constantly asking others for help before they have even tried to solve a problem. They consistently do not take notes, so they can be easily recognised via photocopies or scans of their peer's work. They rarely complete homework voluntarily, so the other group members must do more. Sometimes we can observe the bullying of peers. We can further divide parasitism into two subgroups. In the first, one of the students can be a parasite on several members of a group, just like a mosquito "sucking" blood in a herd of animals. Damage for every single animal is minor, unless there are too many parasites. A smart student can be a parasite for years and nobody would even recognise him as a parasite, because the loss for a single host student is small. We must not confuse parasitism with cooperation, when students help each other with the exchange of notes or other materials. The other kind of parasitism is one-on-one, like a tapeworm in a small intestine. In this case, one student parasitizes on a single student. In some cases, the relationship can last for their entire school career.

As a teacher, you need to have an eye on them all the time. They need strict control, and their work must be checked several times during a lesson. Sometimes it is good to give them some work which can be performed only individually, so they cannot escape or push others to do the rest. Because they are not immune to plagiarism, it is a good idea to check their homework and compare it with internet resources.

Competitors. In nature, competition is one of the most common relationships. We can observe competition within and between species. Organisms from different species can compete for food, nesting grounds, and so on. Within species, they can compete for everything, just like the situation between species, as well as for mating partners. In the long term, a species can benefit through evolution, but usually both partners lose because they must share a resource. In the absence of others, the whole resource will belong to just one species.

Competitors would prefer to work alone, and would gladly escape group work if that was possible. They are always first to take additional material after it is delivered, and will rarely bring it back to the others at the right time. You will recognise them as lords of a mouse or keyboard, and they are in the first row when there is a demonstration. They will rarely share their findings with others and, in the worst case, will try to produce everything on their own, not allowing others to participate in a session. To prevent competition within a group, it sometimes pays to ignite competition between groups. Under this circumstance, some competitors can be very co-operative just to taste the winner's glory. They like to be honoured at least every few minutes.

Amensals. In this case, one of the partners experiences neither a benefit nor loss, but the other partner loses. In nature, we can observe that some blue-green bacteria excrete poisons into the water. The result is dead fish, without any observable benefit for the bacteria. Another example is moulds that secrete antibiotics which stop reproduction in bacteria. It is unclear if moulds benefit, but bacteria definitely lose.

The best known situation in a school is vandalism. Students sometimes damage things, or sabotage the work of others, without any sane reason. More commonly, some students can destroy the working atmosphere in a group by making remarks about other members of the group.

Because of their destructive nature, amensals are the hardest people to work with. Because one eye is spared for parasites, the other eye belongs to them. Sometimes it is a good idea to give them some responsibility and remove them from a group for some time. If they are in a group with a student who is in one way or another different, then troubles can be expected.

Neutralists. Here, there is no direct relationship between species. This does not mean that they are not connected in some indirect way, though, or through some other species or ecological factor. In the jungle, for example, there is no direct connection between elephants and apes, but they do breathe the same air and can be hosts for the same blood-sucking insects.

Neutralists prefer to work alone. Even if they alone cannot produce great projects, they do not like to work with others. Unlike the competitors, they do not like attention. They prefer to take their patch of work, finish it, and present it to the others without a lot of argument. When they know what to do, you can leave them alone.

Commensals. While one of the partners benefits, the other neither benefits nor loses. So a bird can nest in a tree (i.e., benefits) without visible damage or surplus for a tree. Our houses and apartments are full of tiny animals eating our dandruff or scraps of food.

Commensals are easily recognised by their invisibility as quiet people who say something only if they are asked to, or do something when they are forced to. If you want something from them, you have to tell them directly. They do not take the initiative and do not disturb group work. If there is some physical work, they are normally in the second row; and on computers, they are peeking at the screen from the back. They will do exactly what they have to and nothing more. It is easy to miss them and they are only one step away from parasitism.

Protocooperates and mutualists. In this relationship, both partners benefit. The difference is that mutualism is obligatory for both partners and protocooperation is not. The textbook example for mutualism is cooperation between ruminants and microbes in their intestine. The great African herds are an example of protocooperation. In such a herd, there are animals with good sight, the others with excellent noses or ears. A panic run is the signal to every other animal that something is wrong.

It is easy to recognise the students who can, and are willing to, co-operate. They will sit around a table, listen to each other, and everyone will have a chance to talk. The work is divided into fair amounts. In a group with many co-operative students, commensals and parasites can mimic themselves for a long time. Ideally, all partners in a group recognise that through co-operation all of them can benefit. It is too optimistic, though, to say that the benefits must be totally equal, which would be an ideal situation. Rather, the benefit must correlate with the amount of work invested in the project.

Cooperators enjoy group work and prefer peers with similar attitudes. When working, they sometimes take a teacher as a partner. This is a potential trap, because you can spend all your time with such a group and forget the others. They can be very intolerant to uncooperative partners in a group. It is good to check their work because they often have long debates and they lose track of time.

Conclusions

After years of group and collaborative work with students, we recognised through careful observation that we can identify different types of students with different behaviours during group work, and knowing that students are different can make group work easier from a teachers point of view. Students’ behaviours are in many ways analogous to those between different species in a living community. As a result, work in some groups is better than in others, and different groups need different teacher assistance to reach the same goals.

There exists no such thing as a recipe to counteract all of the interactions that interfere with student learning and enhance the interactions that enable student learning. Even more, there is always the possibility that a teacher’s intervention in group work would produce unwanted side effects. But as far as is possible, we have reduced long-lasting, unwanted relationships between students with a mixed approach to the formation of groups. Work in a classroom, or in a group, has to be split into smaller parts, with varying criteria for group selection. The criteria include random selection, student choice, and either completely or partially teacher-directed selection. In this way, almost every student will work with others and can take different roles in different groups. The group work must be organised in such a way that every student depends on every other student, and they have to have full responsibility for the work. Some students need to be constantly observed and, if they are harmful to the group, neutralised. In the worst cases they must sometimes be removed from a group for a period of time, set an individual task, and then returned to the same or another group after their part of the work is done. If this procedure is performed carefully, and is not recognised as punishment, even so called problematic students can became valuable partners in a group.

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Ideas in Brief

Summaries of ideas from key articles in reviewed publications

Towards a Theoretical Framework for Teaching Controversial Socio-Scientific Issues

By: Ralph Levinson, University of London, UK
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Open any newspaper and you will find an increasing number of articles, many on the front page, dealing with public policy issues that have a strong basis in science. Glancing through the March 28, 2007 edition of our local, free newspaper, the *Free Metro*, one finds articles on the future of nanoscience, carbon emissions from power stations, a car that runs on air, cars converted to run on cooking fat, the effect of climate change on bird migration, CCTV cameras, beef as a possible cause of infertility, melting ice killing off baby seals, Toadzilla--a gargantuan cane toad--in Australia, near-identical twins, legislation on smoking and effect on cancer rates, and a couple of

New Zealand schoolgirls doing a classroom experiment to discover that false claims were being made for the amount of Vitamin C in ribena.

In addition, there are increasing efforts by governmental and semi-official bodies to consult lay people on scientific issues such as genetically modified crops and new forms of gene therapy. Extraordinary amounts of sophisticated, and not-so-sophisticated, information requiring interpretive skills and political literacy is being made available on the internet. There is an increasing emphasis being placed on the science curriculum to teach controversial socio-scientific issues, partly to address developments in public policy and information. *Twenty First Century Science* (2002), a new course for 14- to 16-year-olds in the United Kingdom, is a good example of this.

In Levinson (2006), I argue that teaching controversial socio-scientific issues is very difficult and, in fact, controversial. The problem is that there is very little consensus as to what is meant by a "controversial issue." For example, I happen to think that Tottenham Hotspur is the best soccer club on Earth, but there are many supporters of other soccer clubs who would disagree with me. Does that then become something we should teach in our schools? And issues deemed controversial in 2007 might be completely non-controversial in 2010. If we were to teach everything that was controversial, there would be no room in the curriculum to teach anything else. So, my main question is: Is it possible to have a theoretical framework for teaching controversial socio-scientific issues that will help teachers in schools?

In attempting to answer this question, I have drawn on three theoretical sources. The central source is based on Terence McLaughlin's categorization of the sources of disagreement in a liberal and pluralistic democracy (McLaughlin, 2003). McLaughlin himself draws most significantly on the political philosopher John Rawls, and also on Robert Dearden and David Bridges. McLaughlin formulates nine levels of disagreement, ranging from people agreeing about the criteria for judgement but waiting for the evidence to settle the matter, to people who have completely different world views. Examples of the first couple of levels are when people agree that a water course needs cleaning but still have not agreed about the evidence underpinning the best method. Examples of the ninth level of disagreement would be creationists disagreeing with those who think of evolution as a fact, and people for and against the use of embryos in stem cell research. Evidence is often deemed irrelevant in settling these cases of disagreement. The advantage of McLaughlin's formulation is that it allows teachers to focus on a particular aspect of a controversy rather than the whole complex topic, and helps people to identify what is important to know in a controversy. Thus in judging what evidence tells us about the best treatment for cleaning up a local stream, teachers would focus on the kinds of procedures that tell us what to look for in deciding what is the best evidence available.

The second theoretical source is the kinds of dispositions necessary to discuss controversial issues in the classroom. Rice and Burbules call these *communicative virtues* (Rice & Burbules, 1992). Disputants in a controversy need to agree to listen respectfully to each other, and to be open, truthful, and honest, as well as critical. These might seem obvious characteristics, but think of the difficulties when pupils get angry with each other and/or refuse to listen. Sometimes, of course, there is an early consensus and everybody forgets what the disagreement is about. That is why a critical approach is so important. Pupils don't just pick up these communicative virtues; they need to be taught and rehearsed. For example, in a recent discussion we had a number of people who thought of themselves as fundamental creationists and the other part of the group was committed to evolution. To get them talking, we asked those supporting creationism to convey their main arguments in 5 minutes. We then asked their interlocutors to relay back the argument to the creationists, but this time to make the creationist argument even stronger. This provides evidence as to whether the point has been understood. Then, the evolutionists put across their argument and the creationists had to respond in the same way. Time was then allowed for both sides to ask questions of each other. There was no need to change minds or come to a decision, but the point was to listen carefully and to be open and critical. A good phrase to express the way teachers might approach an issue is “to shed light on the matters of disagreement.”

Jerome Bruner is the third theoretical source. Bruner (1996) argues that there are two modes of thought in which we seek to convince others of the truth of our experiences. One mode is logico-scientific, comprising the making of valid generalisations and inferences, using evidence appropriately, and making truth claims. This demands rigorous thought and logical and scientific procedures. The second mode of thought is the narrative mode, where protagonists can tell stories about their experiences, thus giving the stories verisimilitude. Suppose a parent has a sick child. The doctor or specialist might be able to diagnose a problem, but the parent and child can give specificity and context to the diagnosis by talking about the way they feel, what happens in certain circumstances, and so on. Both modes of thought are important in helping to resolve the problem. Again, using these modes of thought requires practice. We need to tell stories which are appropriate to those who are listening, to structure them sensibly, and to relate the incidents which are relevant.

Thus, in teaching controversial socio-scientific issues, the levels of disagreement, communicative virtues, and modes of thought can be thought of as intertwining strands of a thread. I suggest that teachers should start by focusing on evidence and keeping matters relatively simple at first. For example, students might disagree about the reading on a burette. How can they decide which is the correct reading? They might decide to take the average of two different readings, but why should this be valid? Both readings might be inaccurate. Here students have to decide what data count as valid and how they can ensure it is as accurate as possible. They would have to listen to each other, work together, and be respectful and critical of what the other has to say. In this case, the mode of thought is predominantly logico-scientific, but there are plenty of issues where narrative is instrumental.

The main points are that controversy is too large a term and needs to be broken down, and that the theoretical thread I have tried to construct can provide a useful theoretical model. Now is the time to test it.

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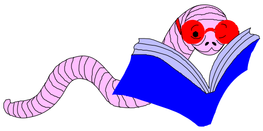

Research in Brief

Summaries of research findings from key articles in reviewed publications

What Does Out-of-School Learning Offer School Science?

By: Martin Braund, University of York, UK and Michael Reiss, University of London, UK
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In many countries of the developed world, there are concerns that science as taught in schools is not delivering and is unpopular; pupils are not interested in science, do not want to study it if they are given the option, do not see it as a worthwhile career, and so on (e.g., see the findings of *The Relevance of Science Education* [ROSE], n.d., research project). In contrast, places such as museums, botanic gardens, and exhibitions and films and television programmes about science are popular. Science as communicated and experienced in these places has therefore much to offer the development of school-based learning.

In our recent papers (Braund & Reiss, 2006a, 2006b) and our book (Braund & Reiss, 2004), we have discussed ways in which out-of-school science contributes to, and enhances, school science. Several can be identified:

By improved development and integration of concepts. For example, bird-watching and visiting zoos and museums have been found to have an impact on pupils' ability to classify living things; visiting industrial sites improves an understanding of chemical processes; studying energy changes and forces at a hands-on science centre provides a useful counterpoint to experiments in the school laboratory.

By providing opportunities for extended and more authentic practical work. There are science activities that, for safety and other reasons, can only be, or are better experienced, outside the classroom (e.g., water rockets, large-scale chemical reactions such as the thermit reaction, and ecological surveys). Residential fieldwork offers the opportunity for extended work over time (e.g., to explore populations or activity and interactions in a habitat over 24 hours). Sometimes it is the serendipitous experiences that have most impact: seeing rainbows or a beautiful sunset, seeing nocturnal animals, or even getting drenched in the pouring rain! We, and many teachers with whom we have spoken, have experienced some of the awe and wonder about the natural world that out-of-school learning can bring to both youngsters and older students. Such experiences are often the ones that stay in the mind and can even influence a choice of career.

By providing access to rare material or to "big" science. Objects telling stories about the history of science, or arranged so as to show the development of technologies, are hard for science teachers to access without visiting museums or hands-on galleries. Contact with real objects is valued much more by pupils than pictorial representations on the Internet. By "big science" we mean the sort of science that requires large or sophisticated equipment (e.g. radio telescopes, particle accelerators, and electron microscopes), often involving collaboration on an international scale. People can find big science inspirational and controversial. On the one hand, there is the excitement of research into big questions such as "what are we made of?" and "what will be the ultimate fate of the universe?” There are also questions about whether the financial costs of the enterprise can be justified.

As well as enriching the basic diet of learning at school, the world of learning beyond the classroom offers a more authentic model of the way science is done than the version that currently dominates school science. If someone who knew nothing about what scientists do based their ideas solely on what goes on inside a school, they might think that scientists spend most of their time experimenting in laboratories, whereas most of them do not. Modern science is carried out in a wide variety of locations and relies as much on reading, interdisciplinary debate, fieldwork, and computer modelling as it does on bench work. In a number of ways, the version of school science that is portrayed at the beginning of the 21st Century owes more to the science of the late 19th and early 20th Centuries than it does to science today. Science teaching has also had to take on board changes in the ways that we think about learning based on the findings in psychology and in the cognitive and neurosciences. Putting these thoughts together, we have devised a model of how we think science education in schools should develop to be more authentic. Being biologists interested in how things change (hopefully for the better), it is not surprising that we have called this an evolutionary model (Figure 1).

Museums and other informal sites of learning have had to work hard to attract visitors precisely because attendance at them is not compulsory. In almost all countries, school science has both the advantages and disadvantages of being a compulsory subject and one that is greatly valued by those who control the curriculum, albeit not always valued by those who sit in the resulting lessons. What is clear is that, in an increasing number of countries, the quality of presentations of science in the media (including television) mean that the days are long gone when pupils of secondary age will be impressed by a demonstration of a collapsing can when attached to a vacuum pump, the growth of copper sulphate crystals, or the meanderings of desiccated woodlice or dazzled maggots.

What we need is a great deal more thought about the potential for learning science outside the classroom. If we can get this right, there is every chance that out-of-school learning can make school science more attractive and authentic. If we get it wrong, not only may we continue to lose many of our best students from science, but the very worth of school science may increasingly be questioned by those in power who sanction the use of large amounts of money on school science laboratories, technicians, and teachers.

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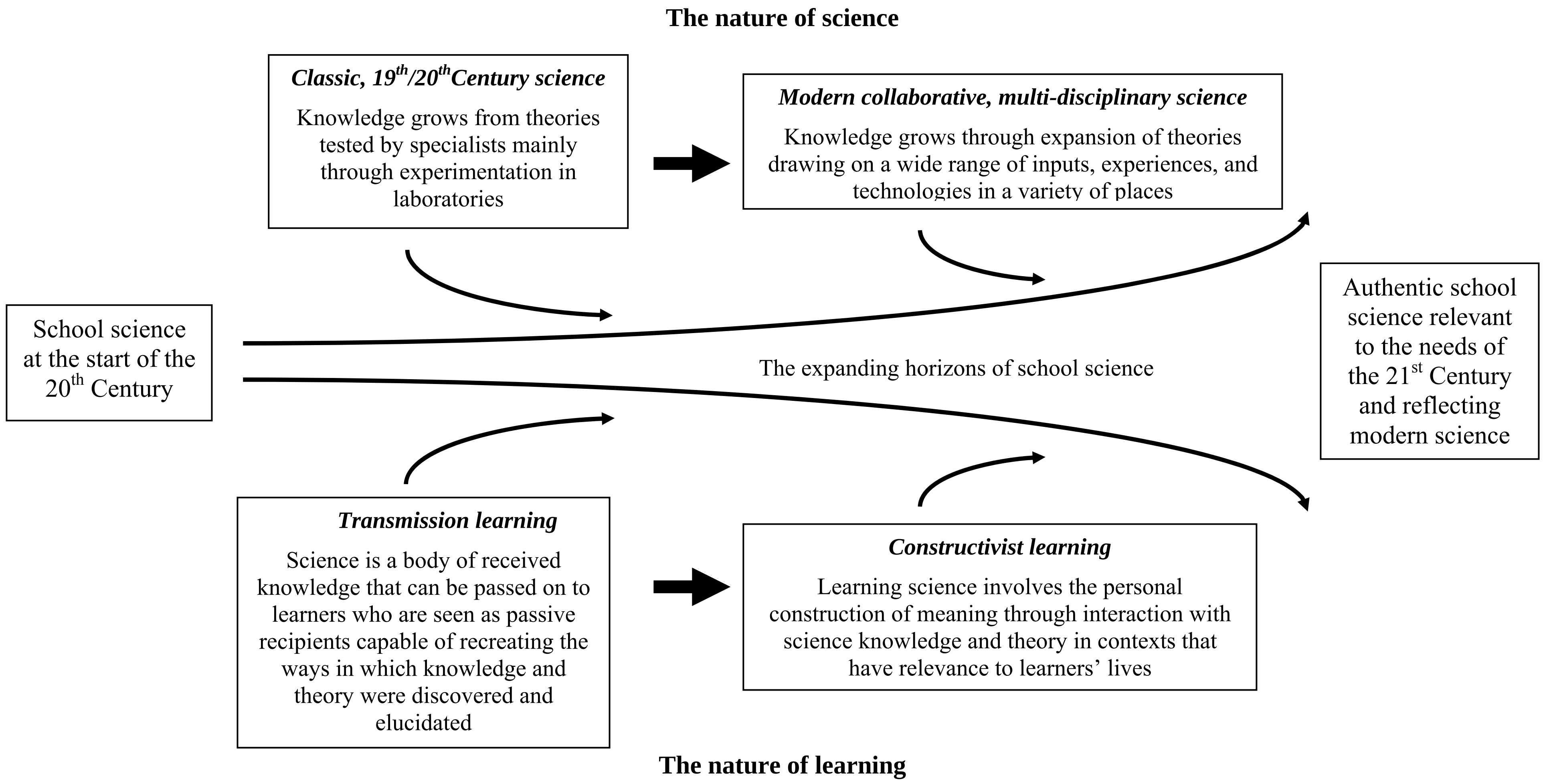

Classic, 19th/20th Century science

Knowledge grows from theories tested by specialists mainly through experimentation in laboratories

Modern collaborative, multi-disciplinary science

Knowledge grows through expansion of theories drawing on a wide range of inputs, experiences, and technologies in a variety of places

Transmission learning

Science is a body of received knowledge that can be passed on to learners who are seen as passive recipients capable of recreating the ways in which knowledge and theory were discovered and elucidated

Constructivist learning

Learning science involves the personal construction of meaning through interaction with science knowledge and theory in contexts that have relevance to learners' lives

Figure 1. Towards a more authentic school science: An evolutionary model.

Readers’ Forum

Vacuum Cleaner Advertisement

During recent months, I have been amused by a television advertisement for a vacuum cleaner that conveys a neat scientific misconception and would provide a great stimulus for student evaluation. The vacuum cleaner hose divides into 10 separate tubes, each with a “suction” cap on the end from which a bowling ball can be suspended. The presenter enthusiastically implies that, because the vacuum cleaner can hold 10 bowling balls aloft simultaneously, it is superior to other cleaners that presumably struggle to hold up far fewer bowling balls.

This conclusion is invalid. Once the vacuum cleaner reduces the air pressure in the tubes between itself and the balls, it will hold up 1, 2, 5, or 10 balls equally easily, because what is actually holding the balls up is the force due to the pressure of the atmosphere below each ball. A valid way to use bowling balls to test the relative effectiveness of vacuum cleaners to create a vacuum would be to determine how many bowling balls can be suspended from the same suction cap.

Peter Eastwell, Science Time Education, Australia

? ? ? ? ? Your Questions Answered ? ? ? ? ?

This section of *SER* responds to readers’ queries, so please submit your question to The Editor at editor@ScienceEducationReview.com . Have that long-standing query resolved; hopefully!

Top Research Need

What do you suggest is the most important science education matter in need of research?

I think the most important area of research in science education is how to best help teachers move from traditional to research-based, hands-on, inquiry activities with authentic assessment. Many science educators agree that the latter are one of the best ways for students to obtain a deeper understanding of the content and processes of science. It is at the implementation level that many teachers do not change significantly their traditional teaching and assessment approaches.

Wilson J. Gonzalez-Espada, Arkansas Tech University, Russellville, AR, USA

How do we draw a greater number of students, mentally and physically, to science learning at primary and secondary levels?

Bijay Parida, India

Given the number of teachers with alternative licensures and other routes to teaching science, I have been wondering about the impact of science methods courses on the quality of science teaching and learning. Is there research to support science-specific methods courses? Or, do general methods courses, or even absences of any kind of methods course, provide the same results?

Erica M. Brownstein, Capital University, Columbus, OH, USA

Over the last 2 decades, mainstream science education research focused on student thinking (i.e., on students' conceptual understanding of natural phenomena and the patterns of their thought in the process of understanding those phenomena), and that thinking was judged against scientists' thinking. Most of these studies did provide evidence that students' thinking differs considerably from scientists' thinking, and the studies served as a justification for the development of teaching interventions (i.e., strategies and models) that, in turn, would help students restructure their thoughts and ultimately develop a scientific understanding. In short, there was a focus on how students learn.

However, we need to recognize that such a focus shifted our attention from the heart of the problem. Those interventions were based on the belief, or tacit assumption, that the most important question science educators should ask is "how do students learn?" while, at the same time, they downplayed the importance of the question "what makes students want to learn?"

The fact that almost 2 decades of research were dedicated mainly to students' conceptual understanding can raise a number of questions on a number of grounds. But what I think is important to stress here is that a) these studies identified learning with "a rational activity" and therefore focused attention on what learning is, and not what learning depends on, and b) effective learning was associated with the "scientists' way of understanding."

Although affective factors were acknowledged, the identification of learning with a rational activity did result in an emphasis on the cognitive component of learning. But if the question "what makes a student want to learn?" is seriously considered, then effective learning cannot take place without considering the affective component of the learning process. In fact, such a consideration can raise a question concerning the validity of certain science education studies.

Although a number of relatively recent studies have reported on the effectiveness of alternative models of learning that take into account the affective dimension of learning (e.g., dramatization, narratives, poetry, and informal out-of-school experiences), what needs to be given priority in educational research is the role of self/personal identity on understanding and learning. There are a few studies, but the problem of learning, if the ecology of learning is taken into account, is a complex one, and needs to be carefully designed and researched in multiple contexts.

There is no doubt that the question "what makes a student want to learn" is a tough one to answer, since one will need to consider the whole learning--not just the conceptual--ecology. But a central factor in that ecology is the self/personal identity of the student. (One may very well suspect that science learning is ineffective not only because science is a difficult discipline but because there are factors associated with expectations, values, etc.)

In the light of this self/personal identity factor, what needs to given priority is the significance students attach to their object of study (and not science in general) and the purpose they have for learning something. These two notions need to be researched. And their findings can in turn shed light on the difficulties of learning science (which so far has been considered mainly from an epistemological perspective), and also on the problem of transference (i.e., what happens after students leave school? How effective is students' learning in everyday life contexts?).

A third area that needs to be researched is the aesthetic dimension of school science. Although there are very few studies, it is important for the science education community to realize that it is crucial for students to have an appreciation of what science is if they are to decide whether they want to become involved with it. Work here certainly exists (i.e., research on the nature of science), but the appreciation of science as an endeavour that is inspired by mystery and a sense of wonder is also crucial and needs to be researched.

Why am I saying this? Over the last decade the idea of science as another world, another culture (or subculture), has been stressed from the cultural perspective on science education. Although the teacher can be viewed as a "tour guide," who introduces students into the culture of science, the notion of teacher as someone who inspires may also be considered very useful. Teachers can inspire students by revealing the mysterious nature and wonder of both natural phenomena and scientific ideas, helping them see and appreciate their beauty. Why should any student decide to cross into a foreign land--that is, science--even when a tour guide is always available? Making the decision to cross into a new, unknown, and different territory requires some inspiration, and the teacher's role here is very important. If inspired, students can be empowered. Empowerment and inspiration can complement each other, an idea that needs to be taken into account even in the case of teaching marginalized groups of students.

It should be pointed out that the appropriation of concepts from cultural anthropology has helped science educators understand several problems associated with the teaching and learning of science as a culture. However, there are some questions to be asked: Is science a culture that is beyond most students' grasp? Are border crossings extremely difficult, if not impossible, for some students? Are the obstacles to learning science only cultural (or simply epistemological)? In the case of female students, for example, it is true that several factors can be identified in regard to their negative attitudes toward school science: less encouragement from teachers and parents, fewer out-of-school activities, lack of peer support, and lack of good role models. This means that if girls had more encouragement, more out-of-schools science-related activities, more peer support, and good role models, they could make the border crossing into the culture of science. The same, of course, could be true for some boys, although not to the same degree. But how about encouraging an existential relationship between those girls and their object of study? What about helping them feel a sense of wonder? What about inspiring them? What about helping them to become aware that scientific knowledge is not only for power--not only to dominate and control the natural world--but also for love? Empirical research to investigate these questions, and into the role of the teacher as one who inspires students to cross borders, is imperative.

Yannis Hadzigeorgiou, University of the Aegean, Rhodes, Greece

Laboratory Safety Guidelines

This section presents a series of 40 laboratory safety guidelines kindly provided by Dr James A. Kaufman, President, The Laboratory Safety Institute (LSI), USA. Please visit http://www.labsafety.org for further information, products, services, and publications.

#1 of 40. *Have a Written Safety Policy*

This is the cornerstone of a good safety program. It's a statement, endorsed and supported by the administration, that speaks to the fundamental responsibilities for health and safety in the academic institution or company.

For example: "It is the responsibility of [name of company or institution] and its employees to insure that our business activities [or educational programs and other activities] protect and promote the health and safety of our customers [students], our employees, and the environment."

Your department may want to draft a sample policy statement for recommendation to your administration or board of education. It is virtually impossible to have an excellent safety program without their support. Your written safety policy will provide the foundation of your safety program.

Policy statements of this type need to be signed by the highest ranking official of the organization, dated, laminated, and mounted in the entrance of every building.

When I was EH&S coordinator at Curry College, I got our president to sign a policy statement not unlike the one above. I made up seven framed copies, took them--with a hammer and nails--to the offices of the president and his direct reports, and asked them where (not if, but where) they wanted the college's new EH&S policy statement displayed. I hung them prominently, and especially so both the senior administrator and his/her visitors could see the policy every day.

What is your company's, or academic institution's, safety policy statement? Please send a copy to info@labsafety.org to share with our readers, and visit the LSI website to order a 16-page booklet containing a collection of 19 safety policy statements.

Further Useful Resources

Fieldwork Knowledge Library (http://www.fieldworklib.org) Describes itself as "the site for professional fieldwork and outdoor science activities." It may be browsed by discipline, and includes suggestions for overcoming the difficulty of fitting fieldwork into the curriculum, ideas for using the school grounds and for visits away from school, practical advice for implementing suggested activities, example itineraries, and health and safety considerations.

London Ideas Genetics Knowledge Park (http://www.londonideas.org) Games for teaching genetics in primary school.

EHP Science Education Program (http://www.ehponline.org/science-ed) Recent authentic scientific research is paired with complementary lessons to help keep students informed about hot-off-the-press science.

C.H.A.N.C.E. (https://teamworks.campuses.psu.edu/psu/lv/CHANCE/default.htm) Inquiry-based, research-oriented modules in environmental science and ecology incorporating current research data.

Moodle (http://moodle.org/) A free, open-source course management system (CMS) to help educators create an effective, online learning community (e.g., post assignments, lesson plans, announcements, and course documents and allow students to participate in discussions and chats and submit assignments).

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The Science Education Review (*SER*) is an international, peer-reviewed periodical aiming to provide primary and high school teachers with the latest, and best, ideas in science education from around the world. *SER* also publishes original articles, including research articles, and much more.

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