What is buoyancy force?
¿Qué es la fuerza de flotación?

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Abstract

The idea that liquids exert a force –called buoyancy force or up thrust– on objects immersed in them is part of a typical school science curriculum and is integral to explaining why some objects float. However, an explanation of how this force originates is often not provided at school level, and this may make its nature rather mysterious to students and give rise to difficulties in using the idea. In this article various kinds of explanation of buoyancy force available in the literature are explored, including the place of ARCHIMEDES' Principle. A way of simplifying fluid mechanics analysis of fluid pressure and pressing force is presented and suggested as a possible way of explaining buoyancy force at school level. Implications for teaching this area of physics are discussed.

Key Words*: flotation; buoyancy force; fluid mechanics; fluid pressure.*

Resumen

La idea que los líquidos ejercen una fuerza llamada fuerza de flotación sobre objetos sumergidos es parte del currículo de ciencia en la escuela y es esencial para explicar por qué flotan algunos objetos. Sin embargo, una explicación de cómo esta fuerza se origina no es proveída a menudo en el ámbito de la escuela, y por esta razón su naturaleza puede ser misteriosa a los estudiantes y aumentar las dificultades al usar este concepto. En este artículo son analizados varios tipos de explicación de la fuerza de flotabilidad disponible en la literatura, incluyendo el principio de ARQUÍMEDES. Se presenta una manera de simplificar el análisis de la presión de fluidos y la fuerza de presión, sugerida como una manera posible de explicar la fuerza de flotación en el ámbito de la escuela. Las implicaciones para enseñar esta área de física son discutidas.

Palabras clave*: flotación; fuerza de flotación; mecánica de fluidos; presión de fluidos.*

INTRODUCTION

On our initial teacher training courses in science, we include study of a phenomenon that continues to fascinate both children and adults and has an accepted place in the science curriculum: that of the floating and sinking of objects placed in water. We obviously want to include explanations of this and also to provoke student teachers to think through their own ideas. But what level of explanation is appropriate? KOLIOPOULOS *et al* (2004) make the useful point that floating is explained in terms of two quite distinct conceptual frameworks:

> "The first framework is connected with the comparison between the values of the forces and weights that act in the solid body. The second framework is connected with the comparison of densities of the solid body and the liquid in which the body floats / sinks."

Interestingly, research by my colleagues (Parker and Heywood, 2000) of sessions with student teachers identified some of the difficulties they had in coming to terms with the former framework; few, for example, initially thought in terms of a buoyancy force and

> "For many postgraduate student teachers viewing this situation from a forces perspective was something new" (page 102).

It was in this context that the topic for this paper arose: what is the nature of buoyancy force (also called up thrust)? Why and how is it exerted? In a teaching situation in which the existence of this force is being emphasized, it is a natural question to ask. Indeed it may be that difficulty in coming to terms with the place of buoyancy force in explaining flotation is linked with not having access to an explanation of why and how such force is exerted. During initial teaching sessions I had to confront the rather uncomfortable fact that I too was lacking an explanation of buoyancy force: I could think of no obvious way in which water could exert this kind of force. This led me to explore of a range of literature, from children's science information books to science textbooks at secondary school and undergraduate levels. This paper presents some thoughts that arose from this: not trying to find 'the' explanation but one that might be appropriate for secondary level – and for me!

THE CURRICULUM CONTEXT

A relevant example of the way that floating is approached at lower secondary school level is that of the science National Curriculum for England and Wales (DfEE, 2000) and its implementation described in the Qualifications & Curriculum Authority's science exemplar Scheme of Work for 11- to 14-year old students (DfES / QCA). Within this scheme buoyancy force / up thrust is included in a unit on 'forces and their effects', with study being focused on the weighing of objects in air and water. Pupils are instructed to weigh a denser-than-water object using a Newton meter and then to re-weigh the object when it is immersed in water. Pupils are taught the explanation of the lower reading of the meter in terms of the action of the buoyancy force exerted by the water. A useful extension to this (not suggested in the scheme) is for the container of water to be placed on a balance. It is then possible to see that as the reading of the Newton meter on which the object is hanging decreases when the object is immersed in the water, the reading of the balance increases by the same amount. In terms of my own thinking, this led me to understand the water as partially supporting the object. The QCA scheme goes on to get pupils to consider objects floating in water so that they should 'recognize that objects which float show a zero weight reading'. This strikes me as rather odd because the object is not in a meaningful way hanging from the meter. A possibly more convincing activity is for pupils to push a balloon into water and to feel the buoyancy force pushing back (Parker and Heywood, 2000).

The final stage of the scheme is through 'encouraging generalizations, *eg light for size*, showing how to calculate density, and using the displacement of water to measure volume (referring again to Archimedes)', pupils should come to 'state that an object will float in water if it is less dense than water'. The approach of the unit may therefore create the dilemma described above. Buoyancy force is first introduced as an important aspect of flotation but the reason for its existence is not provided. Explanation then shifts to relevant characteristics of the floating object. Archimedes' Principle - that the size of the buoyancy force is equal to the weight of the water displaced by a floating object – is given emphasis, and this is also true of a wide range of science information books and textbooks. However, the Principle, at least when stated in this form, is in itself an explanation of buoyancy force and indeed raises the further question as to why it holds true. One can in fact easily be misled into thinking that the water displaced by a floating object is the actual cause of buoyancy force. Indeed in some cases it seems that the author concerned actually believes this. For example:

> "Up thrust: When an object is placed in any liquid or gas, it pushes some of the liquid or gas out of the way. This liquid or gas pushes back on the object with a force called the up thrust. This force is equal to the weight of the liquid or gas that has been pushed out of the way." Riley (1999) p. 37.

A similar example is from an excellent review of explanations of floating by Selley (1993). In explaining why 'things float if their density is less than the density of the fluid', Selley follows the line of thinking that the water displaced by the object placed in the water is important:

> "Regardless of whether it (the object) floats or sinks, it will cause the water level to rise. So a certain mass of water is now situated *above* its original position; and that water, under the influence of the earth's gravity, has a tendency to fall back … the weight of the raised water will give rise to an uward force on the submerged object…" (p.58/9).

However, the fallacy or at least partial truth of this idea, becomes apparent when considering the situation where an object is placed in a container already full of water. As it is placed in the water, an appropriate volume of water is displaced and overflows from the container: it obviously can play no further part in causing the buoyancy force! Archimedes' Principle in itself does not, therefore, provide an explanation of buoyancy force. However, Selley's explanation does raise the possibility that the weight of water does somehow provide a balance to the weight of a floating object. This idea, albeit rather vaguely formulated, was at the back of my mind when consulting further literature.

Wang's discussion (Wang, 2004) of the floating of bodies consisting of solid material with fluid inside also raises interesting questions about how to interpret Archimedes' Principle, and brings out how the different components of such a body need to be considered separately.

FLUID MECHANICS ANALYSIS

Not finding relevant explanations at a school level, I had to investigate the more complex realm of undergraduate textbooks in fluid mechanics, which provide detailed accounts of the nature of buoyancy force. The reader is referred to these (for example, Fox *et al* 2003 and Bedford *et al* 1998) for such accounts, and I can here only briefly summarize some relevant points. They typically start from a Newtonian treatment of pressure within a fluid for situations where the fluid velocity is zero or constant, including the condition that there is no relative motion of adjacent layers and consequently the shear stresses are zero. For a situation in which gravity is the only force acting, a simple differential equation relates the change of pressure *(p)* to the specific weight of the fluid*(s)* and the change of elevation *(y)* and holds true for both compressible and incompressible fluids:

$$dp = - s\, dy$$

Further, for fluids which can be considered homogeneous and incompressible, *s* is constant and the above equation when integrated becomes:

$$p = -s\, y + c$$

in which *c* is the constant of integration. The hydrostatic law of variation of pressure is frequently written in the form

$$p = s\, h$$

in which *h* is measured vertically downwards from a free-liquid surface and *p* is the increase in pressure from that found at the free surface. (Streeter and Wylie, 1998). Buoyancy force is then presented as a specific application of this analysis. The buoyancy force on a submerged body is the difference between the vertical component of pressure force on its under side and the vertical component of pressure force on its upper side. For an object floating in a fluid such as water, buoyancy force is static fluid pressure on the lower surface of the object that is sufficient to cause the object to float provided its density is less than that of the fluid itself.

The mathematical analysis is rigorous but demanding: it did not provide the 'simple' explanation of buoyancy force I was hoping to find. On the other hand, the general picture that came across was an exciting one: within a seemingly inert body of still water, there is a dynamic pattern of forces that interact and balance each other - even when there are no objects floating in it! This suggested an alternative, qualitative way of understanding the forces involved. Mathematical analysis starts from consideration of cuboid-shaped elements of water, the forces exerted on the surfaces of such elements by adjacent elements and the forces exerted by each element on adjacent elements. While the mathematical development is to take the limit as the fluid element is reduced in size to zero so that the derived equation relates to 'points' in the fluid, it is useful to think further about the way that forces act on the larger fluid elements.

A surface force is easier to understand than a body force in this respect, so imagine a volume of water in a syringe that is sealed at its end; when the plunger is pressed, the force exerted tends to compress the water. The water resists being compressed and pushes back on the plunger. In fact, since water is not rigid but can flow in any direction, it also pushes in the opposite direction on the end wall and outwards on the side wall. Such forces are balanced by forces exerted by the container itself on the water. The action of the water in pushing back in this way does not come through clearly from textbooks' very mathematical explanations of fluid pressure; however, it is at the heart of understanding how buoyancy force originates.

With this picture in mind then, consider what is happening in a body of water on which the force acting is only that of gravity on the water itself. In figure 1 below, 'A' is a cylinder of water at the top and centre of a body of water in a cylindrical container. A is resting on, and is supported by, the water X, which itself rests on the bottom of the tank. The weight of A causes it to press down on the top of water X, tending to compress it. The water of X resists this and pushes back, just as in the example above of the water in the syringe. This 'push back' is of course the buoyancy force or up thrust. It is in turn in balance with the weight of A. However, X also pushes back in other directions, downwards and sideways, and if it is to provide a push back on A it must be contained by something that provides a force around it to balance the forces in these directions. At the bottom the wall of the container provides this, but what about around its sides? This force must be provided by the surrounding water. Consider the cylinder of water, Y, surrounding X. This presses inwards on X because it too is pressed on from above – by the weight of the cylinder of water, B, which is the same as the weight of water A. Y is in turn contained by the water surrounding it (with water pressing down on that, as well) and so on until there is the water that is adjacent to the wall of the container; the sideways push exerted by the container wall provides the ultimate support for the water. Remember, too, that since Y is hollow it needs supporting on its inside as well as on its outside: this is provided by X, which has the weight of A pressing down on it. X and Y thus provide reciprocal support for each other.

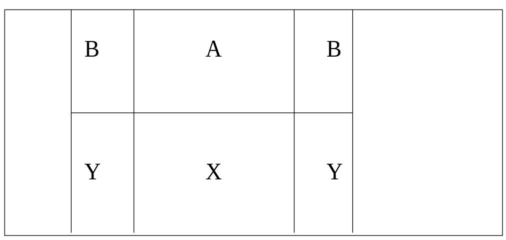

Figure 1
A body of water in a container

Despite the simplifications involved in this analysis, it does, I think, give a good insight, in a simple and striking way, into the process of pushes acting on, and balancing, one another throughout a body of still water. Whatever force is exerted at one place in the water needs to be understood in the context of the forces acting throughout the whole body of water. This applies as well to the buoyancy force exerted on a floating object.

To extend the discussion, consider now what would happen if an object were to occupy the space that the water A occupies in the above situation, an object that conveniently has the same density as water. It is an important insight that exactly the same forces, including buoyancy force, would be acting as when water occupied that space! The object could rest on, and be supported by, the water beneath it in exactly the same way as the water was supported.

Finally consider the situation if the object (O) had a density less than that of water (figure 2); in other words the force pushing down on X is less than it is in figure 1. This weight, and the forces exerted by the elements of water X, Y and B (and similar elements further away), would not be in balance with one another. Some water would then be pushed into X, pushing A upwards. The equivalent of B (B* now reduced in volume compared to B) would exert a smaller force on the equivalent of Y (Y*), which in turn would exert a smaller force on the equivalent of X (X*). The forces involved would now be closer to balance and the process of water movement would continue until they came into balance.

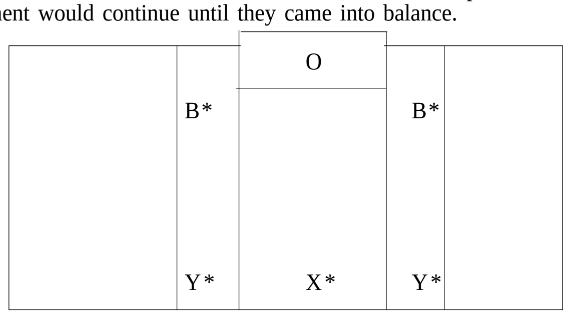

Figure 2
An object with a density less than that of water floating in water

The object and all the elements of water are in balance even though the top of the object is higher than the level of the water. How high the top of the object is above the level of the water depends, of course, on its density compared to that of water.

Closer inspection of the diagram of figure 2 also reveals a way of looking at Archimedes' Principle. Consider the space occupied by the immersed part of the floating object: if that space were occupied by water, then the body of water would be in balance. The weight of that water is also equal to the weight of the object, that is, both the immersed part and the part above the water; and in turn is also equal to the buoyancy force on the floating object.

CONCLUSIONS

Having worked my way through this line of thinking, I felt that I came to understand better the nature of buoyancy force as the outcome of fluid pressure caused by the weight of fluid itself. However, while it is satisfying as a teacher to feel that one has a grasp of wider implications of an idea, it is another matter whether they are relevant to the teaching of the topic concerned. It will require classroom investigation to determine the extent to which the above explanation is accessible to students, for example, through using a pretest/posttest technique to compare students' understanding taught the model with students' understanding taught traditional models of buoyancy.

The model is certainly challenging to understand, requiring imagination to visualize concentric cylinders of water in dynamic interaction. It may be more suitable for a later stage of physics education than the 11- to 14-year old stage from which my thinking started. But its accessibility may also be to do with how buoyancy force is linked to other parts of the physics curriculum. While the model ties buoyancy force closely with fluid mechanics, the England and Wales's QCA science scheme of work in contrast includes it in a unit on 'forces and their effects' while elementary fluid mechanics is part of another unit, 'pressure and moments'. The model is therefore more in tune with the views of Kariotogloy *et al* (1993) that floating and sinking should be put

> "in the context of a broader mechanics curriculum (and) should provide a link between solid and fluid mechanics since the phenomena obey the laws of solid mechanics but at the same time involve a force applicable specifically to fluids" (p. 166).

Kariotogloy *et al* also suggest giving emphasis to the distinction between pressure in a fluid and the pressing force which a fluid may exert on, say, the walls of a vessel containing fluid or, as buoyancy force, on the immersed surface of an object floating in the fluid. Buoyancy force (or more widely, pressing force) is a reactive force arising from a force being exerted on the fluid and tending to compress it. A similar reactive force arises when a force is exerted on a rigid solid (except that the push back is in one direction only). Encouraging students to recognize the similarity between these two situations might help their understanding of both.

A possible difficulty to developing this understanding is that in everyday thinking we usually think of, say, a table, with an object on it, as inertly 'supporting' the object (and having the 'strength' to do so) rather than providing a force that balances the weight of the object. This in turn raises the even broader matter of how reactive forces are explained in terms of particle theory. At what stage or age might it be most suitable to introduce the idea that reactive forces arise because of the repulsion that exists between atoms? Or that liquids and solids, though for practical purposes incompressible, are in fact very slightly compressed by forces pushing on them, bringing the constituent atoms very slightly closer together and hence increasing the force between them? These are relevant and interesting questions that are certainly part of understanding buoyancy force but go beyond the scope of the present article.

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