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Underwater laboratory: Teaching physics through diving practice

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Summary. — Diving education and diving science and technology may be a useful tool in teaching physics in non–physics-oriented High School courses. In this paper we present an activity which combines some simple theoretical aspects of fluid statics, fluid dynamics and gas behavior under pressure with diving experience, where the swimming pool and the sea are used as a laboratory. This topic had previously been approached in a pure experimental way in school laboratory, but some particular experiments became much more attractive and meaningful to the students when they could use their bodies to perform them directly in water. The activity was carried out with groups of students from Italian High School classes in different situations.

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1. – Introduction

Despite some recent signs of increase in the interest for hard science studies such as physics, mathematics and chemistry, teaching these subjects in Italy seems to be particularly unattractive. Nevertheless, the knowledge of such subjects could give students important professional skills for their future. One reason for the above-mentioned phenomenon is that scientific subjects are often perceived as too difficult by students; moreover in their opinion the presentation of the content, usually through frontal lectures, is not very attractive. On the other hand, the wonder and curiosity about natural phenomena and the discovery of the mechanisms that govern them are an inherent feature of all human beings, especially the younger ones. Many authors in educational research

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consider it necessary to identify innovative teaching methods and paths in the transmission of knowledge and expertise in natural science, encouraging the natural curiosity of students, by starting, for example, from the observation of natural reality by an intensive use of laboratory [1] and direct experience. Unfortunately, not all schools actually have the necessary equipment to implement laboratory teaching in science education. Thus the most driven teachers try to make their lessons more efficient with hands-on experiments.

The interest in sport-related examples supporting the teaching of elementary physics is well known [2]. Very often, a simple physical example taken from sports can be of great help in particle dynamics, fluid mechanics and thermodynamics lectures. This may be the case of diving. In recent decades, diving has become a popular and widespread leisure. Usual references to this sport in most elementary-physics textbooks deal with buoyancy equilibrium and with the limitations imposed by hydrostatic pressure [3-7]. Young people often approaching diving without a real comprehension of its physics principles, may turn this exciting sport into a dangerous activity. Actually, every diving course includes at least one lesson and some activities about physical concepts, but very often divers forget them or do not take them into account when diving. Divers use regulators, manometers, BCDs (Buoyancy Control Device), but they have poor understanding of the inner workings of these devices. In this paper a teaching path about fluid statics stemming from diving is described. A recreational sport like diving and a school matter often considered difficult are connected in this path, whose novelty is that some of the practical activities are performed in a swimming pool. These activities are described here with a particular attention to linking physical principles and diving skills together.

2. – Methodology

The path was performed in three different frameworks:the first time with 40 students of a Graphic Technical School during curricular lessons of physics, the second with 30 selected students during a Summer School, and the third in the framework of the project Piano Lauree Scientifiche (PLS) with 40 students. The latest experience is discussed in this paper. All the students, boys and girls, were attending the last two years of the high school, so they were 17-18 years old. The teaching path took 16 or 20 hours overall.

As indicated in Kresta's experience [8], the lessons were performed as seminar demonstrations providing hands-on experience of basic fluid mechanics principles, so the most important aspects of the course can be illustrated in a practical, relevant way. This makes the few hours of the course more effective. The demonstrations must be relevant and illustrative, not just visually appealing. They must be simple to run and easy to remember. Learning may be enhanced by increasing students engagement [9]. Students were requested not to passively observe demonstrations. Three different ways of presentation were performed during the lessons: *observe*, the traditional approach to demonstrations, in which students watch the demonstration and hear the instructor's explanation; *predict*, in which students record their predictions of the demonstration outcome, observe the demonstration, and hear the instructor's explanation; and *discuss*, in which students record predictions, observe the demonstration, discuss it with fellow students, and finally hear the instructor's explanation. During the lessons electronic presentation slides were used for the explanation of the specific physical theories. This tool was used to spare time.

Before developing the object of the study, students were surveyed by means of a preliminary entrance test not only to find out an overview of their previous knowledge, but also to raise more interest and expectation about the topics to be presented. A post-test was submitted to find out the achievements coming from the experience. The same test was used both before and after the experience. It consisted of eleven specific multiple-choice questions about the topics, some of which were contextualized. Between pre- and post-test no direct answers to the questions were given to the students and they had the chance to change their pre-test answers.

3. – Activities and experiments in the swimming pool

The activities in the pool were divided into two sessions: without and with SCUBA (Self Contained Underwater Breathing Apparatus) diving gear. During the pool sessions, students were divided into two groups: one half of the students carried out the activities without diving gear and the other half was introduced to diving techniques and equipment use in order to safely use the equipment and to feel comfortable during the experimental session with gear. The measurements performed during the activities are qualitative and the approximations do not permit any error estimations though some statistics considerations can be done.

3˙1. *Activities without diving equipment*. – The activities described in the following section deal with some preliminary knowledge or skills that can be useful while diving with the complete equipment in the final part of pool activities.After a brief description of the diving skills we refer to, the simple demonstrations performed with the students in the pool are described.

3˙1.1. Mask clearing. Although intentionally filling a well-sealed mask with water may seem counterintuitive to its purpose, the mask clearing skill is one of the most important skills of an open water diving course. All scuba divers will find water in their mask at some point of their diving career (usually sooner rather than later). They will need to be able to efficiently get the water out without surfacing and without panicking. This skill has some analogies with the attempt to get up or down the water level in a Torricelli tube experiment. Mask clearing consists in taking a deep breath from the regulator and exhaling it slowly but firmly through the nose while tilting your head up and pressing the top of the mask. Air from the nose bubbles upwards and fills the mask increasing the pressure inside and forcing water out from the bottom. It is important to maintain firm pressure on the upper frame of the mask, or the exhaled air will simply escape from the top of the mask. Is also important to look upwards while exhaling, otherwise the air will just flow out from the bottom and the sides of the mask. As mentioned earlier, we can create an analogue situation in the school laboratory. Take a glass test tube about $l = 20\,\text{cm}$ long with internal diameter a. Fill the tube with water. Plug the other end and invert the tube, placing the open end in a basin of water. Upon removing the plug, no matter the internal diameter, depth, angle of inclination of the tube, the height of water in the basin or whether you have partially filled the tube, the water level in the tube will come to rest at a certain height above the level of the water in the basin. The space in the tube above the column will be filled with air. Then you can inflate some air into the tube with the help of a thin cane and you will see the water level in the test tube going down. In the pool we have used a tank with a 10 liters volume. The tank, which was filled with water and turned upside down in the pool taking care to avoid water leakage, was maintained with the opening just few millimeters below the water level and a tube was inserted in it. What was observed is that water in the tank did not sink and come to rest at a certain height above the water level in the pool. Students were then invited

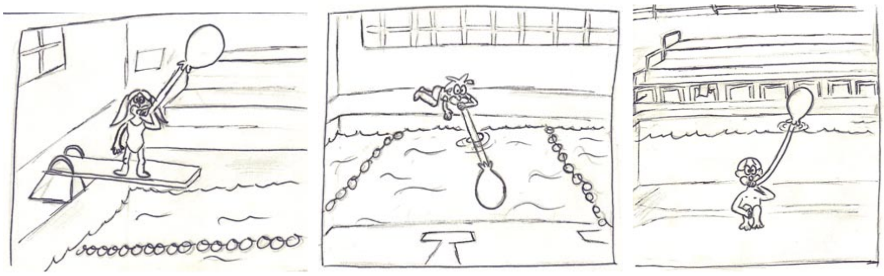

Fig. 1. – How to experience difference in breathing inside and outside the water.

to inflate air into the tank using a short hose. The water level in the tank decreased due to the pressure increase inside the tank. It is possible to calibrate the volume of the tank and mark a scale in liters. In this way, the vital capacity of lungs (the maximum amount of air a person can expel from the lungs after a maximum inhalation) can be measured. Total lung capacity and accordingly vital capacity, is dependent upon many factors such as weight, gender, age and activity. For example, females tend to have a 20–25% lower capacity than males [10]. In our measurement, we have found a mean value 3.5 L (0.5 L) for female students and 4.5 L (0.5 L) for male students.

3˙1.2. Pressure increases with depth. The weight of the water above divers exerts a pressure on their body. The deeper divers descend, the more water they have above them and the more pressure they feel on their body. The pressure a diver experiences at a certain depth is the sum of all the pressures above him, from both the water and the air. This is strictly related to Stevin's law for hydrostatic pressure. In a school laboratory we have proved Stevin's law with a funnel immersed upside down in a tall pot and connected to a pressure measuring device like a u-tube where the difference in fluid height in the liquid columns is proportional to the pressure difference. It is well known that in water, pressure increases by one bar every ten meters deep. In a school laboratory it is difficult to reach great pressure differences without using a vacuum pump. Divers do not feel the large pressure because the tissues of the human organism contain 65% of liquids that virtually do not shrink. In inner cavities, the pressure of the inhaled air counteracts the external pressure. During descent, divers usually do not feel the increasing pressure but in the ears, due to the air spaces in the middle ear. They only find breathing slightly more difficult because the gases they inhale have the same pressure of the surrounding water and thus a higher density. The increased pressure also acts on lungs during the inhalation making it more difficult to breath. Students can experience this difference in breathing in and out the water trying to blow a balloon fixed on the top of a 2 m rigid tube in three different situations. In the first, both the student and the balloon are outside the water. In the second, the student is outside and the balloon is in the water and finally the student is under water and the balloon in air (fig. 1).

This experiment demonstrats that it is very difficult to blow up the balloon if it is immersed more than 0.8–1 m under the water. In fact, to blow up the balloon not only the force due to the tension of the rubber wall of the balloon but also the pressure around the balloon must be won. During exhalation our lungs develop a pressure that can be measured with a simple U tube manometer. In our measurements we have found for males a mean pressure of 1.3 m and for females 0.8 m expressed in meters of water units.

It means that by our breathing apparatus we can produce the same pressure of a water column 1.3 or 0.8 m deep. Thus students experience that it is easier to blow up the balloon when they are under the water and the balloon is out, thanks to the pressure over their bodies.

3˙1.3. Drilling an oil well: a possible problem. It is known [11] that gas bubbles from the bottom of an oil well can dangerously raise the pressure at the well head: it is therefore a good practice not to completely shut all the valves (blowout preventers) at the top of the well. Let us consider a gas bubble trapped at the bottom of an oil well: its pressure corresponds to standard atmospheric pressure plus the hydrostatic pressure ρgh generated by the liquid column above it. The total pressure, in some cases, can reach the very high value of more than 700 atm [11]. If we can consider the closed pipe of an oil well ideally rigid, the liquid (petroleum) in it ideally incompressible, and the air ideally insoluble in the liquid, then we can say that the volume of the bubble remains constant as it rises through the liquid in the pipe and the gas pressure in the bubble at the top will be the same as it was at the bottom. Releasing a bubble brings the initial bottom pressure to the top. We can reproduce a similar event in the pool. A student, immersed down to a depth of 1 m or 1.5 m into the water, creates bubbles that, thanks to a funnel, are sent into a tube 2 m long (the pipe) at the end of which a rubber balloon is fixed (the valve). When the bubble reaches the top, the balloon easily blows up.

3˙1.4. Lung-regulated buoyancy control. Buoyancy control is a fundamental skill in diving practice. Underwater diving is a common example of the problem of unstable buoyancy due to compressibility. Divers, swimming in mid-water, desire neutral buoyancy, but this condition is unstable, so divers need to make constant fine adjustments through the control of lung volume, and through the adjustment of the contents of the buoyancy compensator (BCD) if the depth varies. Our lungs are a natural buoyancy compensator with about 5 kilograms of buoyant lift. A normal, resting breath expands our lungs by about one half liter, giving us half a kilo more buoyancy. By breathing in and out, our buoyancy fluctuates within a range of about half a kilo. So as long as we are nearly neutral with a half-breath, we can rise or fall at will just by controlling our lungs. Students know that buoyancy is due to an upward force exerted by a fluid that opposes to the weight of an immersed object. They also know that buoyancy depends on the volume of the displaced fluid. In this activity students experience the buoyancy law directly on their bodies. They have to keep arms, legs and feet still, than they exhale slowly and by doing that they begin to sink. This is also a basic skill in diving with equipment. We can observe that with completely filled lungs, the entire head emerges from the water. The rough estimation of the head volume fits lungs capacity.

3˙2. *Activities with diving equipment*. – For this part it is necessary to use a deep pool with at least 4 m depth to better understand and experience the effects of pressure difference. Students are involved in two different situations. At the beginning they are introduced to the safety rules and to the use of the equipment by specialized instructors. Although divers do not feel the absolute pressure at any depth, a rapid pressure change may cause different sicknesses. A quick decrease of pressure during ascent is particularly dangerous and may result in a serious disease called decompression sickness. With the activity in the swimming pool we performed dives in a 4 meter pool, so that the students experienced a pressure difference of about 0.3–0.4 bar, just enough to be constrained to equalize the ears and the mask too. After this theoretical introduction, the instructors guided the students to their first dive. Of course these brief lessons cannot be considered

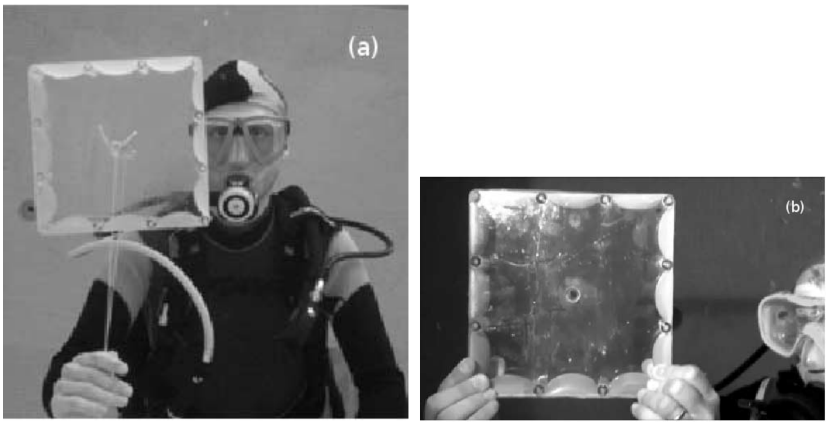

Fig. 2. – (a) Student during the dive with the box at 3 m depth down. (b) Box with the bent rubber wall. Note the different bending of the top side with respect to the bottom side.

equal to a SCUBA Open Water Diving course. They try the mask, the fins and the snorkel. They breathe through the regulator outside the water and then under the water. Many students experience ears pain due to pressure increase with the depth for the first time and the instructors explain them how to equalize the pressure inside the ears.

3˙2.1. Archimedes' Law. Archimedes's principle probably is one of the most famous physical principles. People are curious about floating and sinking and most of them believe that small objects float and large objects sink [12]. There are also some alternative conceptions that are generally resistant to change and are often incompatible with currently accepted scientific knowledge. For example, students at the primary grades often predict if an object sinks or floats basing their reasoning solely on its weight, without considering its volume. Many students also focus on specific features of objects, such as air trapped inside or holes in the object, and make predictions based on these features [13]. A typical explanation widely presented in Middle and High School is the bottom-up derivation [14] involving a balance between surface and body forces [15]. To explore the origin of Archimedes's force, let us consider a square shaped box completely immersed in water. The pressure P_1 on the top side S_1 of the box is less than the pressure P_2 on the bottom side S_2 since the surface S_2 is deeper than the surface S_1. Thus the force $F_1 = P_1S_1$ acting on the top surface is less than the force $F_2 = P_2S_2$ applied on the bottom surface. The Archimedes upthrust force originates from the difference between these two forces. In order to enhance the visibility of the theoretical explanation, we realized a simple device made of a Plexiglas box sealed with rubber lateral walls (fig. 2) following the suggestion of a didactic video from the 1980s [16]. As the box was completely immersed in water, the bottom rubber wall was bent more than that on the top (see fig. 2). As expected, the left and the right rubber sides were bent equally.

3˙2.2. Archimedes' Law and buoyancy. Does an air tank used by scuba divers sink or float? What is the weight of an empty or full tank in water and outside it? These questions are extremely important for divers who have to determine the proper weight.

During laboratory lessons we can use the well-known Cartesian diver demonstration to illustrate the relation between Archimedes' Law, buoyancy and Boyle's Law. In the

Fig. 3. – The author during simulation of the submarine.

pool, that relation can be illustrated by simulating how a submarine works. In order to float, a submarine must experience a buoyant force equal to its weight. In other words, the density of the submarine has to be equal to the density of the water around it for it to float, and greater than the density of water to dive. It is also necessary to control the density of the submarine so that it can surface and dive at will. In our simulation we use a graduated cylinder partially filled with air and immersed upside down in the pool. The cylinder being moved vertically up or down in the pool (fig. 3), the air volume inside changes according to Boyle's law in which the pressure is a function of the depth. In this way the total density of the submerged cylinder can be adjusted until we find the equilibrium. In this condition the cylinder density equals water density and the cylinder floats in middle water. A second exercise that is important to illustrate Archimedes' Law and buoyancy is the Fin Pivot. Fin Pivot is a simple buoyancy control skill where a scuba diver lays on the bottom of the pool, and elevates his torso by simply controlling the breathing. In a way, Fin Pivot is very similar to pushing up, but replacing the action of arms with the action power of lungs. In fact, by taking a deep breath our chest increases its volume and as a consequence the buoyant force increases. To perform the Fin Pivot these steps have to be followed.

1. Fully deflate the buoyancy compensator device (BCD).
2. Lay down on the bottom, face down. Spread legs and keep your knees straight.
3. Avoid using arms, just use the breath.
4. Inhale slowly and deeply from the regulator. Full lungs are more buoyant. If you are properly weighted, you should begin to rise off the bottom; if nothing happens after breathing, inflate the BCD slightly.
5. On a slow deep inhalation you will ascend, while on a slow exhalation you should descend and touch the bottom. As said above all these exercises have been performed under the supervision of the instructors.

3˙2.3. Boyle's Law and measurement of g. In this section a simple experiment carried out in the pool to verify the Boyle's Law and to determine the free-fall acceleration g is described. Divers enrolling in a recreational scuba diving course have to be able to learn some basic physical concepts and apply them to the underwater environment, which

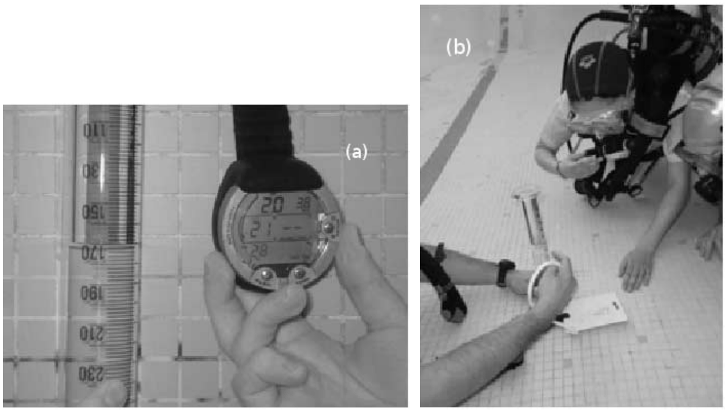

Fig. 4. – (a) Test tube and dive computer. (b) The author takes data at the bottom of the pool with two students.

could seem not particularly attractive. Boyle's law is one of these basic concepts. On the other hand, applying physics laws in sport activities may be extremely interesting for High School students. As we know Boyle's Law states the inverse pressure-volume relationship in an ideal gas as long as its temperature is kept constant. This means that as pressure increases the volume of the gas considered decreases. This law has physiological consequences for the body: although we are mostly liquid, and liquid is incompressible, human bodies have several areas that are air filled, such as the thorax, the middle ear, the sinuses, the intestines; as gases expand and contract, these are the parts that will be affected. The pressure inside any gas space must match the surrounding pressure. During descent gas-filled spaces within body increase their pressure by decreasing their volume; upon ascent these gas spaces lower their pressure by expanding their volumes. Barotrauma is the damage inflicted on the body by changes in pressure, or more precisely, the pressure differences between the gas spaces and the surrounding water. In the pool activities we wish to verify Boyle's Law. Actually we can only indirectly verify it since we do not have any pressure gauge. To this purpose we assume Stevin Law for the hydrostatic pressure determination, so that we can express the volume V of the gas in the test tube as a function of the depth in the pool.

From the following two equations:

$$P(h) = P_0 + \rho g h, \tag{1}$$

$$P(h)V(h) = P_0 V_0, \tag{2}$$

we obtain the expression for the Volume,

$$V(h) = \frac{V_0}{1 + (\rho g / P_0) h}\,, \tag{3}$$

where P_0 = atmospheric pressure (Pa), V_0 = initial volume (m^3), ρ = water density (kg/m^3), g = acceleration of gravity (m/s^2), h = depth (m).

We performed the experiment starting from the bottom of the pool. We used a 200 ml (± 2 ml) test tube for the volume measurement and a Suunto Vyper 1 dive computer to obtain the depth values with a resolution of ± 0.1 m (see fig. 4).

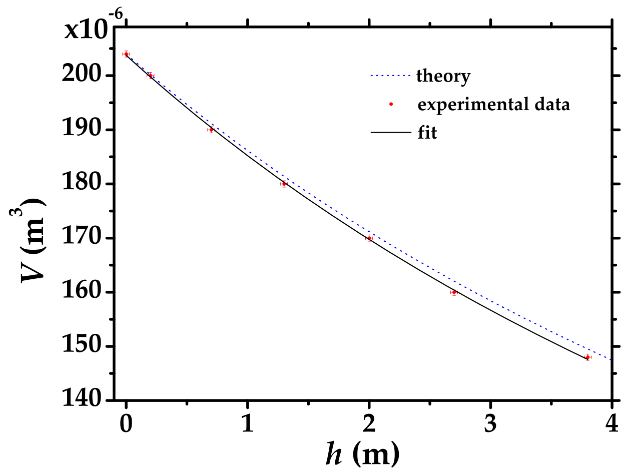

Fig. 5. – Plot of the volume of air inside test tube as a function of the depth.

Figure 5 represents the theoretical values (dashed line) of volume *vs.* depth, our measured data (dot points) and the fit of our data to eq. (3). As we can see, measured values are consistent with expected values. From the parameters of the fitting it is possible to get the value of the acceleration of gravity. The value we obtained is $(g = 10.25 \pm 0.09)\,\mathrm{m/s^2}$ We highlight that in spite of the very simple nature of our experiment, we obtained a g value of $10.25\,\mathrm{m/s^2}$ which differs only by 4% from the standard value $9.806\,\mathrm{m/s^2}$. It is possible to perform a similar experiment in High School laboratories by using an Alexander's diving bell which consists of some sort of glass bell pushed straight down into the water [17].

4. – Conclusions

The teaching path proposed in the previous pages, was highly motivating for all kind of students and especially for students with non–science-oriented curricula. The statics of fluids might look easy, but it is not, as highlighted by research [18]. The topic under study is very close to students' everyday life and, like other sport-related educational paths, it is useful for a better comprehension of this simple but not trivial physics subject. The course consists of solid physics background and gives many ideas for further in-depth analysis. Furthermore, the direct experience of the effects of pressure and pressure variations on the body might prevent students' misconceptions and naive ideas about fluid behaviour. Unfortunately some constraints must be taken into account. It is important to provide a training period for the teachers if they are not already divers. It is also important to have a good feeling with the diving instructors. Although all the demonstrations during class lessons and pool activities are performed with cheap material, the access to swimming pools and the instructors' presence may generate some difficulties. It is important, especially in pool activities, to go beyond excitement by helping students to understand and learn as much as possible from the simple experiences they perform. Further development of the presented path will be aimed at performing more accurate measurements.

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