Abstract
We present a series of experimental activities, based on super-hydrophobic toys, allowing high school students to get in touch with a class of phenomena, concerning water properties, which are very relevant in an interdisciplinary perspective. In particular, important topics (such as surface tension, hydrophobicity, wettability of a surface, self-aggregation) are usefully illustrated in an appealing context, making use of self-made devices. Furthermore, the use of commercial grade high-speed cameras, together with freely available software, allows teachers to improve proposed experiments, making them quantitative.

Keywords
Interdisciplinary learning, laboratorial activities, properties of water, video analysis.

Introduction
The increasing complexity and pervasiveness of technological applications of the empirical sciences more and more suggests the opportunity of finding significant moments of integration of the physics' teaching/learning process with that of other sciences, especially chemistry and biology. There is no doubt that, in such a context, physics preserves a peculiar epistemic status, as it provides to the other empirical sciences the key, both conceptual and instrumental, for the success of the reductionist approach often taken by these sciences. In this context, great importance is assumed by the identification of teaching topics, within the physics curriculum, that lend themselves well to the preparation of interdisciplinary learning paths allowing learners to grasp a unitary perception of science.

In this perspective, a very interesting argument is represented by the physical properties of water, in particular those concerning its interaction with a large class of surfaces known as “hydrophobic” surfaces. Hydrophobicity, in fact, is a kind of “emerging” force driving many important processes, either in the biological realm (let’s think as an example to the self-aggregation of molecules giving rise to cells membranes) or in the development of technological applications (let’s think to the development of water-repellent clothing).

In this work we describe a consistent series of activities, based on super-hydrophobic toys (and on cheap components easily obtainable by these toys), allowing high school students to get in touch with unusual phenomena concerning water properties, such as those related to: i) surface tension, ii) self-aggregation of macromolecules driven by hydrophobic/hydrophilic character, iii) wettability of a surface; just to cite some.
The experiments we propose can be carried out with simple teaching equipment and are well suited to undergraduate students. Moreover, some well-known toys (the “Aqua Drop” and the “Magic Sand” games) inspire our didactical activities, whose playful nature allows teachers to construct learning paths at different levels, ranging from undergraduate students to primary school pupils. On the other hand, the use of commercial grade photo/video cameras, together with freely available video analysis software, allows undergraduate learners to explore unfamiliar phenomena related to fluids, allowing them to get in touch with the principal theoretical concepts and practical applications pertaining a context located at the crossway among physics, chemistry and biology. Finally, the multimedia learning path aims to give students and teachers methodological and practical hints to independently conduct and analyse their own teaching experiments on such systems.

**Hydrophobic, hydrophilic, amphiphilic: in brief**

As regards the interaction with water, material surfaces show a wide spectrum of behaviours, ranging from those that are wetted by water easily and completely, to those that are not wetted by water at all. On the former surfaces, water spreads and flattens out forming a film, while on the latter, water collects into almost spherical droplets to minimize the contact with them. This variety of behaviour is due to a physicochemical property of the material surface that we can define as the “affinity of the surface towards water”. The easiest method to make such a property a measurable physical quantity relies on the concept of “contact angle”, defined in Figure 1.

![Figure 1.](image)

*Figure 1.* For a liquid drop setting on a solid surface, the contact angle is defined as the angle where the drop’s liquid/vapour interface meets the solid surface. Conventionally this angle is measured through the liquid.
Depending on the value of contact angle, surfaces are broadly classified as shown in Figure 2. In this perspective, the two terms “hydrophilic” (from the Greek “water-loving”) and “hydrophobic” (“water-hating”) are complementary aspects of a single property, i.e. the affinity of the surface towards water.

![Figure 2. Classification of surfaces with respect to the contact angle](image)

The whole spectrum of hydrophobicity/hydrophilicity can be encountered in everyday life surfaces. Figure 3 shows some examples: a microscope glass slide (labelled “normal glass” in the Figure) is markedly hydrophilic (contact angle around 20°); a 5 Euro-cents coin exhibits a borderline behaviour (about 90° contact angle); a “smoked glass” (i.e., a glass slide on which a film of soot was deposited by holding it over a burning candle) is super-hydrophobic, featuring a contact angle close to 160° (water drops in Figure 3 are blue since methylene blue dye has been added to improve drops visibility).

![Figure 3. Examples of (coloured) water drops on surfaces exhibiting different affinity towards water.](image)

So far, we spoke about hydrophobicity/hydrophilicity as a property exhibited by a macroscopic surface when interacting with water. It is important to underline that a quite similar variety of behaviour (as regards the affinity for water) is shown, on a completely different scale, by single molecules. Polar molecules (as, for example, NaCl, i.e. the common kitchen salt) have a great affinity for water, while non-polar molecules (typically water insoluble hydrocarbon chains, as
for example the fatty acids composing the olive oil) have a much more reduced affinity for water. In other words, kitchen salt is hydrophilic, while olive oil is hydrophobic. Something more interesting happens when considering molecules exhibiting both characteristics, i.e. molecules having a localized hydrophilic portion and another portion that is hydrophobic. Such molecules are said to be amphiphilic (a term coming from Greek, essentially meaning “loving both”). Amphiphilic molecules in water solution give rise to autoaggregation phenomena (see, for example, figures and description in Sacristan 2014) which have an extremely relevant biological importance, including possible mechanisms for the beginning of life (SCQ 2004, and references therein). Autoggregation of amphiphilic molecule is an “emergent property” (Huttermann and Terzidis, 2010) whose “driving force” is constituted by the tendency of the hydrophobic portion of molecules to be shielded against water.

Experiments based on super-hydrophobic toys

Physical properties recalled in the last section can be beautifully illustrated and explained in an educational context by using some well-known toys based on the super-hydrophobic effect. The most significant of such toys is Magic Sand (Magic Sand, 2014). It consists of normal sand grains coated with a superhydrophobic compound. In this way, when put in water, grains self-aggregates in order to minimize surface area exposed to the polar solvent. Conversely, when the sand is removed from water, it is completely dry. This characteristic gives rise to a truly amazing behaviour able to elicit learners’ curiosity, which is a prerequisite for the discovery-based learning.

![Figure 4. Polystyrene chunks (3x1.5x0.5 cm) for the self-assembly experiment.](image)

Another useful toy in the aim of illustrating the particular behaviour of water when interacting with super-hydrophobic surface is the “Aqua Drop” (Shakerin 2011). It is a sort of “water pinball” in which the ball is constituted by a droplet freely sliding/rolling on a super-hydrophobic surface. Video analysis of water drops impinging on the Aqua Drop surface allows students to acquire confidence with the “elastic” behaviour of water drops. Consequently, such an activity (which we will briefly mention in the following) may be usefully included in any learning paths aimed to introduce experimentally the phenomenon of surface tension.
Playing whit self-assembling

The first educational experiment we propose (based on Magic Sand) aims at illustrating the phenomenon of hydrophobicity-driven self-assembly, on a macroscopic scale directly accessible to the human eye. To this end, some polystyrene chunks (Figure 4) were coated either with normal sand (NS, strongly hydrophilic) or with Magic sand (MS, strongly hydrophobic). Two such chunks were put in water, letting them to freely float. Then, students gently push the chunks one against the other (by using, for example, a clean drinking straw) observing what happens. The experiment is repeated by using all three possible couple of coated chunks (NS-NS, MS-MS, NS-MS) and the observations are compared and discussed. The experimental outcome is a bit surprising (especially if one is unfamiliar with the Magic Sand behaviour): MS-MS chunks exhibit an evident attraction, NS-NS chunks manifest a repulsive interaction, while the MS-NS couple doesn’t show any evident interaction (neither attractive nor repulsive).

Figure 5. Pictorial representation of the collective interaction of water molecules (blue/red dots) whit polystyrene chunks coated with normal sand (NS, left) and magic sand (MS, right). Water molecules are graphically modelled as two hydrogen atoms (red dots) rigidly linked to an oxygen (blue dot). The H-O-H angle in figure is only indicative, since accordingly with usual pedagogical models (Laing, 1987; Yalkowsky, 1993) it can range between 90° and 105° depending on the model.

Figure 5 gives the conceptual key to interpret the experimental outcomes. When two NS-coated chunks come close each other, water molecules are not completely expelled from the gap between them, because the highly hydrophilic boundaries of the gap have a great affinity towards water. In other words, water molecules are “pulled” in the opening between the hydrophylic bodies, “pushing” them away (left side of Figure 5). On the other hand, when two MS-coated chunks are approaching one another, the expulsion of water molecules from the gap very easily happens, being energetically favourable since it leads to the minimization of the super-hydrophobic surface exposed to water (right side of Figure 5). This collective “expulsion” of water molecules macroscopically results in an “attraction” between chunks.

The experimental exploration of self-aggregation phenomena can be extended at wish, for example building “amphiphilic” rods and qualitatively observing the mean configuration when a number of them is allowed to float on water (one can simply build “amphiphilic” rods by MS-coating one end tip of some wooden toothpick, since the wood they are made of is usually very hydrophilic). Gently moving rods, with some patience, occasionally one can observe the
formation of radial structures in which the super-hydrophobic tips of the rods meet together, minimizing the exposition to water.

**Elasticity of water**

Water is (slightly) viscous, but probably any student (and teacher) agree on the fact that it is by no means elastic! This is certainly true when considering almost exclusively the *volume properties* of water; while the situation can be very different when the *surface properties* come more and more into play, i.e. when the surface/volume ratio is relevant, for example, when considering small drops. Therefore, educational experiments with droplets can in principle offer a useful and rich context to illustrate the effects of surface tension of water in a visually impressive way. This is especially true when the elastic behaviour of droplets can be dynamically explored by means of high speed video analysis (Bonanno et al. 2013).

The main obstacle against such a kind of experiments is constituted by the material support employed to (statically or dynamically) handle the drops, which usually spread out (or stick) to some extent on the vast majority of common surfaces. This problem can be overcome by using super-hydrophobic surfaces to support drops. We obtained our own home-made super-hydrophobic support by coating a microscope glass slide with a finely ground MS powder. Figure 6 shows the experimental setup we used, allowing us to precisely control the horizontality of the super-hydrophobic support for drops. This is a critical issue, since drops, on such a support, are extremely mobile and rolls away very easily if the support is not perfectly horizontal.

![Experimental setup for experiments with water drops](image)

**Figure 6.** Experimental setup for experiments with water drops

Various kind of experiments can be done with the simple apparatus in Figure 6. We give in the following some significant, but not exhaustive, example.
Figure 7 shows a qualitative comparison between the contact angles formed (on the same surface) by a pure water drop and a drop of soapy water (in order to improve the visibility of water it has been added with a small amount of fluorescein, which doesn’t significantly change its surface tension). The effect of soap in reducing the water’s surface tension is very evident from the marked reduction of the contact angle. Such an experiment can be done quantitative by measuring the contact angle (by means of a free image software, such as GIMP) when the soap concentration is varied.

Figure 7. Effect of soap on the water’s surface tension visualized through the contact angle variation.

Another significant class of experiments can be performed to investigate the dynamic (elastic) behaviour of water droplets, for example when bouncing on a super-hydrophobic surface. Figure 8 shows a frame sequence of an high-speed video taken by using a commercial-grade camera capable of shooting up to 1200 frames per second (Nikon 1 V2)\(^1\). The sequence (time interval between frames = 2.5 ms) corresponds to the partially elastic impact of a water drop on a MS-coated glass slide. The video analysis of drop impact can be used both for illustrative purposes and for quantitative measurements, for example by using the software Tracker (Tracker 2014).

Figure 8. Frame sequence of a fluoresceine-coloured water drop bouncing on a MS-coated surface (the time interval between frames is around 2 ms).

\(^1\) Such a kind of device is affordable for a school lab and can be termed "economic" in its kind, since it costs a few hundred Euros, in comparison with the tens of thousands of a professional high speed camera.
Dynamic experiments aimed to determine the degree of elasticity of a drop impacting on a surface can also be usefully done by using as super-hydrophobic surface that obtained by an Aqua Drop toy.

Conclusions

In this work we suggest a series of experimental educational activities, based on super-hydrophobic toys (and on cheap components easily obtainable by these toys), allowing high school students to get in touch with intriguing phenomena concerning water properties, which have a great interdisciplinary relevance (especially at the crossway among physics, biology and chemistry). The experiments we proposed can be carried out with simple teaching equipment and are well suited to undergraduate students. In particular they:

- Provide a rich context for inexpensive and impressive experiments on water properties arising from surface tension;
- Allow building original demonstrations/experiments helping to highlight hydrophobicity as the “emerging” property that constitutes the “driving force” of very important cross-disciplinary phenomena such as auto-aggregation of macromolecules.
- Can be extended to the dynamical (surface tension-driven) behavior of water, by means of cheap (but advanced) imaging devices, so highlighting peculiar phenomena on a timescale too short for the human perception.

The described experiments have been proposed to high school students in the context of an Orientation Program, held at the Campus of the University of Calabria during the spring 2014. The ludic and visually oriented character of the proposed activities has aroused considerable interest from the students, who have spontaneously built conceptual links between a numbers of topics they learned at school in the context of different disciplines (chemistry, biology, and physics) without seizing – at that time - the mutual connections.

Finally, suggested experiments (which are suitable for high school students) can also be “downgraded” at various levels, including a very simple and illustrative level suitable for primary school pupils.

References


Tracker (2014). *Video Analysis and Modeling Tool for Physics*. Freely available at the URL: [https://www.cabrillo.edu/~dbrown/tracker/](https://www.cabrillo.edu/~dbrown/tracker/)


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