Learning physics in a water park

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Abstract

Entertaining and educational experiments that can be conducted in a water park, illustrating physics concepts, principles and fundamental laws, are described. These experiments are suitable for students ranging from senior secondary school to junior university level. Newton's laws of motion, Bernoulli's equation, based on the conservation of energy, buoyancy, linear and non-linear wave propagation, turbulence, thermodynamics, optics and cosmology are among the topics that can be discussed. Commonly available devices like smartphones, digital cameras, laptop computers and tablets, can be used conveniently to enable accurate calculation and a greater degree of engagement on the part of students.

Introduction

An apparent contradiction between physical theories and earlier or alternative conceptions held by students poses a major challenge to science educators [1]. A partial vision of the world and a lack of understanding of the scientific method, among other factors, often prevent students from grasping the implications of physical models and the coherence between apparently opposing predictions. Because of this, concepts studied in the science class appear to have no connection with real life. Even those students who learn to complete their assignments satisfactorily may not have assimilated basic underlying concepts. This dissociation between students' preconceived ideas and formal education can result in a lack of interest and motivation, and ultimately causes scientific knowledge to be rapidly discarded as irrelevant.

One possible strategy to address this conflict is to analyse everyday problems through the lens of physics. The problems should engage students in making predictions, testing their conceptions and comparing them with experimental results arrived at through active participation. Visits to amusement or theme parks are carried out systematically in some countries [2–5]. As early as the 1970s, Roeder [2] analysed the working principles of some attractions, such as the Ferris (giant) wheel, dodgem (bumper) cars and merry-go-rounds (carousels), illustrating concepts like acceleration, centripetal force, and kinetic and potential energy, among others. Non-classroom activities, further defined and perfected, have been institutionalized and systematized in some countries.

The book [3] and the website [6] provide comprehensive and detailed guidance to teachers wishing to plan outings to amusement parks with primary and secondary students. The author analyses useful mechanics problems, such as the optimum design of a roller coaster and rule-of-thumb methods for measuring acceleration in the reference frame of the different attractions, and provides practical procedures for indirectly calculating heights or distances. The book also includes fill-in questionnaires, data sheets and

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report cards, and addresses practical questions like safety and the responsibility of the institutions involved. More recently, classroom-support activities specifically for use in amusement parks have been devised [4, 5].

Smartphone usage has expanded dramatically in recent years worldwide. This revolution has also impacted upon undergraduate laboratories, where different experiences are facilitated by the use of the sensors these devices usually include. Recently, several articles have proposed [7–9] the use of smartphones in physics experiments. The application of these devices is not limited to the classroom; actually, most of the mentioned outdoor activities also benefit from the popularization of these technologies.

It is worth noting that most of the activities proposed are aimed at amusement parks with mechanical attractions, and, with few exceptions, do not involve games in water. Thus, it appeared appealing to devise activities to be carried out in water parks with the aid of new technologies, especially smartphones, digital cameras and tablets.

We organized a series of ‘Physics Workshops in the Water Park’, held at the hot spring facilities existing in the north of Uruguay, which were attended by secondary education teachers from the region. Using digital cameras or smartphones, tripods and laptops or tablets, as well as a collection of ordinary objects like balls, twine and small buoys or floaters, experiments were carried out in groups of around four participants. In this paper, some of these experiments are described, their results are analysed and practical recommendations and conclusions are outlined.

Experiments

Newton on the water slide

Newton’s second law was illustrated by a volunteer sliding down a water chute. The Acuamanía water park [10] has two giant water slides, as shown in figure 1. Both chutes are curved on the vertical plane, but as their curvatures are different, a greater maximum speed is attained on one of them, namely, that shaped like the brachistochrone curve or curve of fastest descent. Starting at a height of 18 m (equivalent to a six-storey building), both chutes have a permanent flow of water to reduce friction between the volunteer and the chute surface. In the lower section of the chutes a larger countercurrent of water ensures relatively smooth braking.

A video recording was taken of a volunteer sliding down the water chute. A position to one side of the chutes was chosen so as to enable the widest possible angle of view, and a digital camera was mounted on a tripod, placing the sensor as parallel as possible to the plane of the chutes. A suitable focal distance was selected and an object of known length (in this case a sunshade pole) was used as a reference scale. Even though the reference was not in the same focal plane as the water slide, its apparent size was corrected using similar triangles, allowing the use of its height as a reference. Throughout each recording, special care was exercised to keep the camera firmly fixed and aligned, the reference scale clearly visible and the focal distance unaltered. The number of frames per second and the resolution (pixels) of the camera were set at full range.

Based on the recorded trajectory, the volunteer’s movement was analysed with LoggerPro software [11], although Tracker could also have been used [12]. Knowing the scale of magnitude, it was possible to derive the volunteer’s velocity and acceleration along a set of points. Figure 1 (left) shows a typical snapshot of the volunteer’s descent. The dots (right) show the volunteer’s position at different times, i.e., as detected in different frames. The time interval between dots varied according to the maximum number of frames per second (or sampling rate) available on each camera. Figure 2 shows a plot of the horizontal and vertical components of position, while figure 3 shows the kinetic energy, potential energy and total energy/mass ratio, as a function of time.

As shown in figure 3, the total energy versus time plot clearly displays the energy loss due to friction along the trajectory. The rate of decay of total energy was sufficiently slow to not have interfered significantly with the thrilling effect of the attraction, which was in direct relation to the high speeds attained (ca. 50 km h^{-1}, while the maximum possible velocity in the absence of friction would have been ca. 68 km h^{-1}). In this experiment there were two sources of friction, that between the volunteer and the chute surface, and air resistance. The former was reduced by the lubricating effect of the water flow, and can be modelled as a force determined by a dynamic friction coefficient multiplied by the magnitude

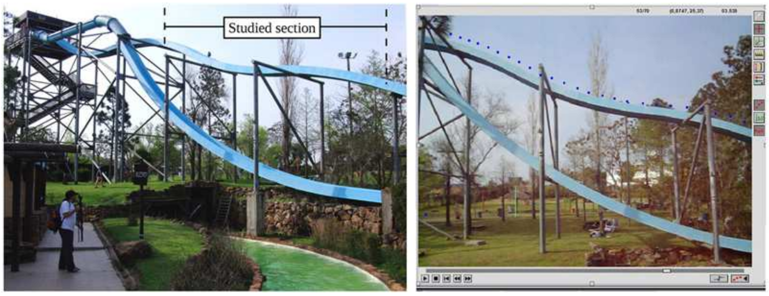

Figure 1. Overview of the Acuamanía park water slides (left) and screen shot of the LoggerPro software showing the position of the participant at different times (right). The section of the water slide analysed by the LoggerPro is schematically indicated in the left panel. The green vertical line in the background of the right panel, under the chute, was used as a reference scale, in this case the height of a sunshade pole.

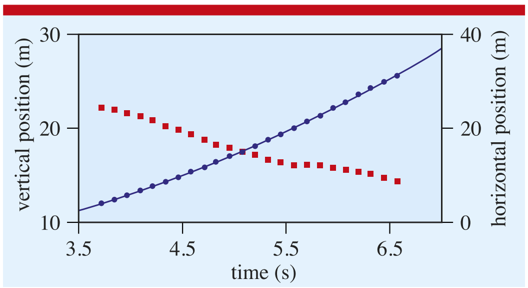

Figure 2. Vertical (red squares) and horizontal (blue circles) components of position as a function of time, together with a fit to a quadratic function of horizontal position as a function of time (approximating the behaviour of a body moving at a constant acceleration).

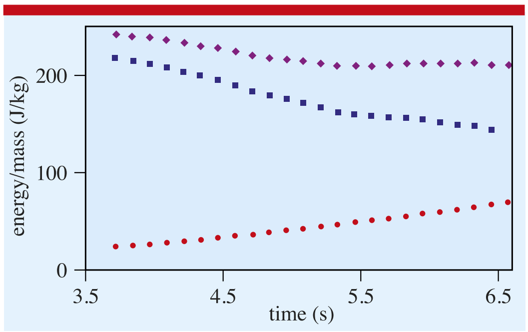

Figure 3. Kinetic energy (red circles), potential energy (blue squares) and total energy (purple diamonds) against time, for the same time interval as in figure 2.

of the normal force exerted by the volunteer onto the chute surface. The latter, due to the effect of turbulence, is proportional to the velocity squared and, presumably, depends on the posture of the volunteer. Although the data available did not suffice to enable a differentiation between these factors, the quadratic function fit, shown in figure 2, suggests a greater degree of friction between the volunteer and the chute surface than between the volunteer and the surrounding air, under the experimental conditions of this study.

Analysis of this experiment provides an excellent opportunity to compare the motion of objects on different water slides, in terms of total time of descent and maximum velocity. The design of a water slide that minimizes the time of descent can also be discussed. The solution to this problem was discovered by J Bernoulli in 1696 and is represented by the brachistochrone curve. Bernoulli's mathematical methods are more complex than those used in secondary schools, but some interesting behaviour of this curve can be discussed [13, 14].

Dynamics of a ball subjected to buoyancy

A classical problem found in many general physics textbooks is that of a ping-pong ball released underwater at a given depth below the surface. The aim is to calculate the height attained by the ball above the surface. This problem is usually tackled by assuming negligible viscous friction, and using the conservation of energy or Archimedes' law to calculate the force exerted on the ball. Either method easily leads to an equation enabling the calculation of the maximum height attained by the ball [14].

An underwater camera (or ordinary camera in waterproof casing) was positioned near the water

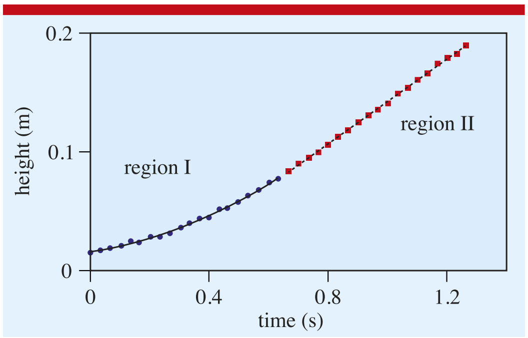

Figure 4. Vertical trajectory of a ping-pong ball released under water. The ball was initially subject to acceleration (region I, blue squares) and eventually reached a final velocity (region II, red circles). Theoretical quadratic and linear functions were fitted to region I (continuous curve) and region II (dotted curve), respectively. The final velocity under water (end of region II) was 0.17 m s^{-1}.

surface so as to be able to record the velocity of a small ball beneath and above the water surface. A scale of length was placed across the water–air interface; in this case a ruler was conveniently located near the ball. Figure 4 shows the trajectory obtained with LoggerPro.

Unlike the oversimplified view, the experiment showed that the ball did not follow a one-dimensional trajectory, but, especially during the initial moments, fluctuated horizontally due to parasitic motion in the water. Once the ball had reached a given vertical velocity, its movement stabilized and the degree of horizontal wobbling decreased.

The analysis of vertical movement shows two distinct stages, as depicted in figure 4. At first, the ball's motion was subject to an acceleration that approximated the theoretical value, but after a relatively short time, the ball attained a constant final velocity, characteristic of movement in a viscous medium. Based on this final velocity, a friction coefficient and the dimensionless Reynolds number were calculated for the system. The value obtained was $Re \approx 800$.

Finally, we found, as expected, that the height attained was considerably lower than predicted for an ideal fluid, since the effect of viscosity was non-negligible. Specifically, the empirical heights were two- to four-fold lower that the theoretical values for a frictionless system.

Figure 5. Wave-profile measuring device made of a set of equally spaced floats joined by fishing line. Here, the device was placed near the edge of the pool to keep the floats in line. Still photographs enabled the identification of wave profiles and wavelengths, while video recording was used to determine periods.

Wave propagation

Water is an excellent medium for the propagation of waves of different kinds, such as sound waves or surface waves. Surface waves, which can be observed in any relatively motionless swimming pool or pond, can be generated by either gravitational force or surface tension phenomena (capillary action) [14].

Surface waves in a pool provide an opportunity to review the concepts of frequency, wavelength, amplitude and propagation velocity, and to discuss methods of measuring these parameters. Video and photography were used, as in the above experiments, to enable these measurements, see for example figure 5. In the experiment shown there, to minimize the effects of the perturbations inherent to a recreational pool, wave characteristics were measured near the edge of the pool.

The phenomenon known as Stokes drift describes the displacement of a small object, such as a piece of cork floating on a water surface, when a wave or waves act on it. This is purely non-linear behaviour, as approximate, linear equations predict this displacement to be zero. With a little imagination, a game or small competition can be devised to qualitatively illustrate this phenomenon. In further experiments, the dispersion relation that connects wave properties like frequency and wavenumber can be quantified and compared for waves in deep and shallow water.

The quest for the hydraulic jump

The hydraulic jump is a ubiquitous phenomenon that can be easily observed in a range of natural

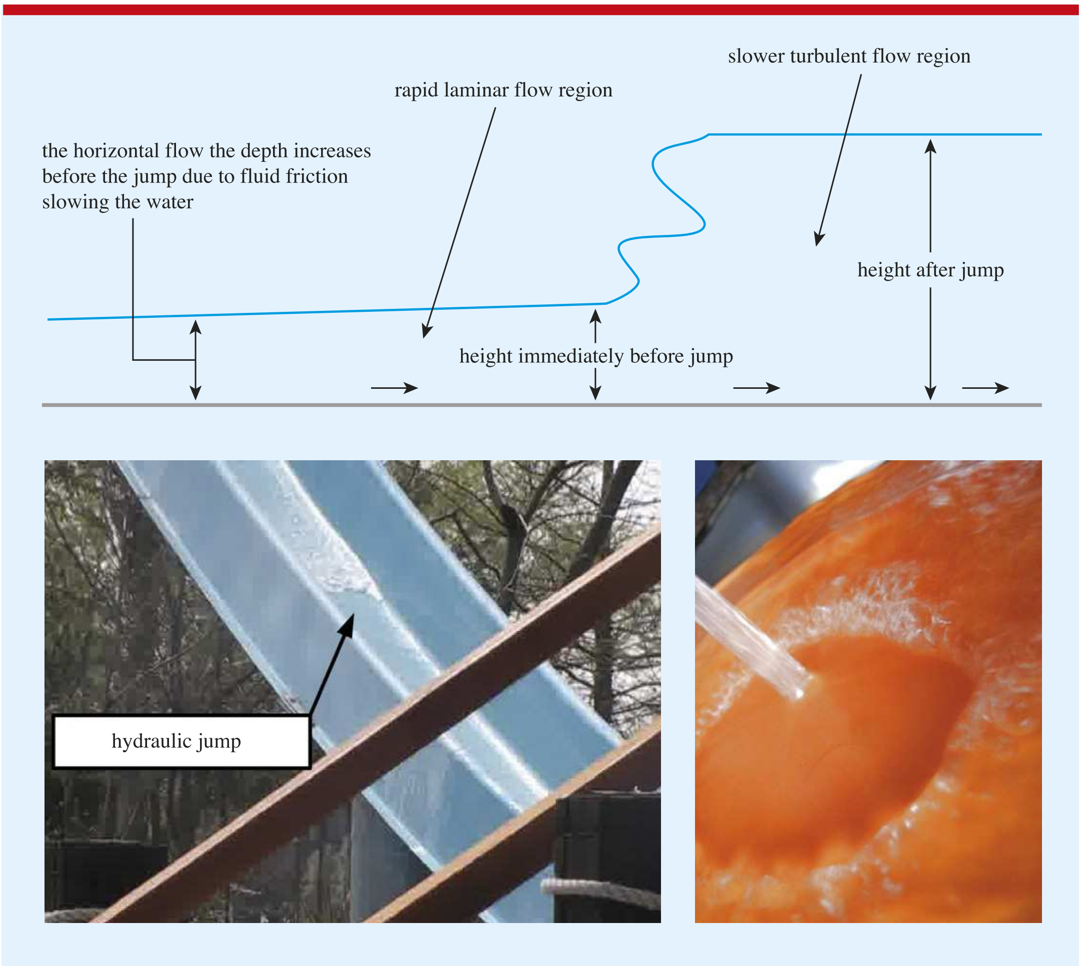

Figure 6. The top panel schematically explains the generation of a hydraulic jump due to a faster downstream velocity current encountering a slower upstream current. The bottom panels show two photographs of hydraulic jumps; one of them formed a water slide (left) in the aquatic park and the other a homemade hydraulic jump (right).

or man-made settings, from large open channels (rivers, canals, waterfalls) to domestic kitchen sinks [15]. When a fluid is discharged at a high velocity into a river or basin, a sudden elevation of the fluid level leads to a significant decrease in flow velocity downstream of the point of elevation. The hydraulic jump is seldom noted by the ordinary observer, yet is essential to a number of applications. By way of example, dams are designed to create a hydraulic jump with the aim of preventing excessive flow velocity that could seriously erode the dam structure.

Water games available in water parks often produce hydraulic jumps. These hydraulic jumps may be moving or static, and undulating or oscillating, among other characteristics. One factor determining the flow characteristics is the dimensionless Froude number. A quantitative study of hydraulic jumps depends on the availability of a method to determine the flow velocity or the ratio of heights upstream and downstream of the hydraulic jump. An expression relating the loss of kinetic energy and the Froude number can be derived, and interesting aspects can be discussed [15]. Qualitative studies provide an approximation to this phenomenon. Figure 6 shows an example of a hydraulic jump in the park.

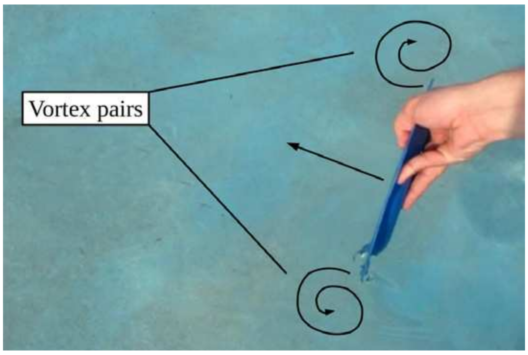

Figure 7. Workshop participant creating vortex pairs. The direction of movement to create the perturbation and the resultant vortex pairs are depicted.

Creating vortex pairs

Vortices or swirls are relatively stable structures commonly formed in fluid systems. They are characterized by approximately circular trajectories of particles within the fluid. Swirls can be readily observed in autumn when the wind stirs up fallen leaves. On a larger scale, tornadoes are simply large vortices moving with their axis perpendicular to the Earth's surface. Vortices can also be observed in open waters, cigarette smoke, washbasins and toilets.

The dynamics of vortices were studied in the 19th century by, among others, Lord Kelvin and H von Helmholtz, with a series of results proved with extraordinary mathematical elegance [10]. The equation determining vorticity lines is similar to that of magnetic induction. Therefore, vortex lines within a fluid must either form closed loops or terminate at the surface.

Vortices can readily be created by moving a flat object, like a plate or board, in a direction tangential to a fluid's surface, as shown in figure 7. This creates a U-shaped vortex line with its ends at the surface. In this qualitative experiment, vortex pairs were created, and the vortex line joining the two vortices was photographed from below the surface, using the small air bubbles that form spontaneously as tracers.

Falaco solitons or the relationship between fluids and cosmology

A surprising connection between cosmology and fluid physics arose a few years ago, when R M Kiehn visited the Brazilian physicist J Falaco in Rio de Janeiro, and observed that rotation on the surface of a swimming pool created a sort of discontinuity which acted as a lens, generating well-defined shadows on the bottom of the pool. By analogy with optical solitons (structures found in electromagnetic fields), and due to a misprint in the paper that reported it, the phenomenon was called the Falaco soliton [16]. To observe Falaco solitons, we created vortex pairs which produced two circular shadows on the bottom of the pool, as shown in figure 8.

Other experiments

Another experiment focused on the study of refraction at the air–water interface using Snell's law. The refraction index in water can be determined from the apparent length of a submerged body. From a certain distance below the water surface, total internal reflection at the water–air interface can also be observed.

The tipping bucket (figure 9) is a practical example involving the concepts of centre of gravity, torque and water flow. A water tank revolves around an asymmetrical horizontal axis. When the bucket is empty, the centre of gravity is below the rotation axis and the system is in stable equilibrium. As the bucket is filled, the centre of gravity rises. When the centre of gravity is above the axis, the bucket becomes unstable and the water in it is discharged onto unaware passers-by. The conditions leading to stability can be discussed, and measurements can be made based on bucket size and the time interval between discharges.

A ball stably positioned on top of a jet of water (figure 10) is a classical demonstration of Bernoulli's principle. The principle establishes that the sum of kinetic and pressure terms is constant, so that an increase in velocity implies a reduction in pressure. On the side of the ball where the water velocity is greater, the pressure is lower, and the net force is such that the system is kept stable.

Recommendations and conclusions

The following should be considered before your water park outing.

- Prepare students for the water park outing in order to communicate the goals and strategies to be used. The preparation stage

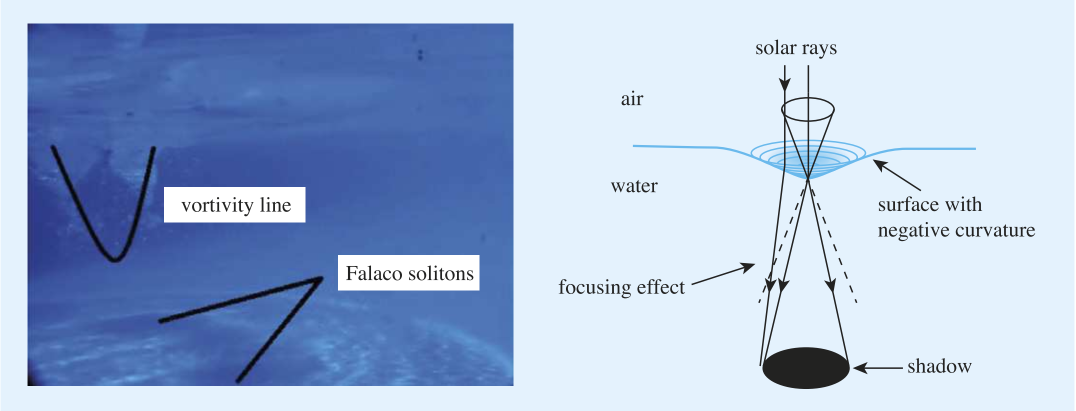

Figure 8. Underwater photograph (left) and diagram (right) of Falaco solitons.

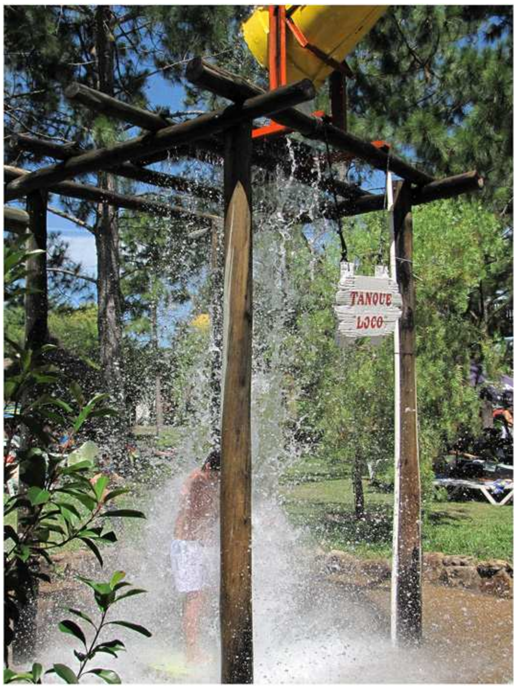

Figure 9. Tipping bucket being discharged onto an unaware passer-by.

should preferably take place in the classroom rather than the park, so that the participants' excitement does not discourage fruitful discussion. It may be worth making the students fill in a questionnaire on some of the concepts discussed in order to ensure that they make the most of the workshop.

Figure 10. Demonstration of Bernoulli's principle: the ball balances on the jet of water. A lower pressure on the side of the ball where water passes at a higher velocity is responsible for keeping the ball in equilibrium.

- Plan the experiments carefully and include protocols and data sheets. This planning does not preclude the use of open questions or challenges requiring more ingenuity.
- Secure all necessary permits to take students on a visit to the park and comply with all safety regulations. Inquire with the park authorities about these matters and, as far as possible, choose days and times when the park is not overcrowded.
- Carefully record data on the location, alignment and appropriate scales of reference for all measurements. Failure to attend to these aspects is highly likely to lead to inconclusive results.

- Processing the data and discussing the results are integral parts of the experiments, and students should be encouraged to participate fully in these aspects, as the various concepts involved add to the usefulness of the experiments.

These recommendations contribute to a water park outing being a useful academic experience, but also one that is fun and motivating. The experiments show that physics and science in general help us to gain a better understanding of commonplace phenomena. In many developed countries, physics teaching activities are carried out in amusement parks, but, to the best of our knowledge, these have always been dry mechanical parks. A visit to a water park, as described, adds originality and exhilaration to the physics experience.

Acknowledgments

We thank the Faculty of Sciences of Universidad de la Republica and the Association of Physics Teachers of Uruguay (APFU).

Received 22 October 2013, in final form 27 November 2013, accepted for publication 2 December 2013
doi:10.1088/0031-9120/49/2/187

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