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Bruno Andreotti, Wladimir Toutain, Camille Noûs, Sofia El Rhandour-Essmaili, Guillaume Pérignon-Hubert and Adrian Daerr

The ping-pong ball water cannon

Tribute to an exemplary man: Yves Couder

Teaching, arts

The ping-pong ball water cannon

Bruno Andreotti[*, a]**, Wladimir Toutain**[b]**, Camille Noûs**[c]**, Sofia El Rhandour-Essmaili**[b]**, Guillaume Pérignon-Hubert**[b] **and Adrian Daerr**[b]

[a] Laboratoire de Physique de l'ENS, UMR 8550 Ecole Normale Supérieure – CNRS – Université de Paris – Sorbonne Université, 24 rue Lhomond, 75005 Paris, France

[b] Matière et Systèmes Complexes, UMR 7057 Université de Paris – CNRS, 10 rue Alice Domon et Léonie Duquet, 75013 Paris, France

[c] Laboratoire Cogitamus, France
URL: https://www.cogitamus.fr/

E-mails: bruno.andreotti@phys.ens.fr (B. Andreotti),
wladimir.toutain@univ-paris-diderot.fr (W. Toutain), camille.nous@cogitamus.fr
(C. Noûs), sofia.lrhandour@etu.univ-paris-diderot.fr (S. El Rhandour-Essmaili),
guillaume.perignon@etu.univ-paris-diderot.fr (G. Pérignon-Hubert),
adrian.daerr@univ-paris-diderot.fr (A. Daerr)

Abstract. The course "Phy Ex" was created by Yves Couder in the Paris VII university to teach experimental physics through projects. In this article, we present this teaching method through a particular project that took place in the autumn semester 2019: the ping-pong ball water cannon. In this experiment, a glass containing water and a floating table tennis ball is dropped from some height to the ground. Following the impact, the ball is ejected vertically upwards at speeds that can be several times the impact speed. We report the student team's initial dimensional and order-of-magnitude analysis, and describe the successive experimental set-ups that showed (1) that free flight is essential for the phenomenon to occur, (2) that the order of magnitude of the ball ejection momentum is correctly predicted by a momentum balance based on integrating the pressure impulse during impact and (3) that making the ball surface more wettable, or stirring the liquid, drastically increases the momentum transfer. The proposed explanation, confirmed by direct high-speed video observations, is that the immersion depth of the ball increases during free fall due to capillary forces or vortex depression—in the absence of buoyancy—and that the enormous excess pressure on the bottom of the ball during impact drives the ball up towards its buoyancy equilibrium. The transfered momentum is sufficient to expel the ball at high velocity, very similar to the formation of liquid jets in collapsing cavities in liquids.

Résumé. Yves Couder a créé un enseignement de physique expérimentale par projets, « Phy Ex », à l'université de Paris VII. Cet article présente la méthode d'enseignement à travers le projet d'un binôme d'étudiants au premier semestre 2019/2020 : le canon à eau propulsant une balle de ping-pong. Le projet consistait à identifier les mécanismes physiques en jeu dans l'expérience suivante : on fait tomber verticalement un verre en plastique contenant de l'eau avec une balle de ping-pong à sa surface. Lorsque le verre percute le sol, la balle de ping-pong est éjectée vers le haut à une vitesse pouvant largement dépasser la vitesse de chute. Nous résumons l'analyse dimensionnelle et d'ordre de grandeur faite par le binôme d'étudiants en amont des expériences. Puis nous décrivons les montages successifs qui montrent (1) que la phase de chute libre précédant l'impact est essentielle dans ce phénomène, (2) que l'ordre de grandeur de la vitesse d'éjection

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* Corresponding author.

est correctement prédit par un bilan de quantité de mouvement basé sur l'intégration du pic de pression résultant de l'impact, et (3) que rendre la balle plus mouillante, ou que mettre l'eau en rotation avant la chute, résulte en une augmentation importante de la quantité de mouvement transmise à la balle. L'image physique ayant émergé au cours de ce projet, et qui s'appuie également sur des images vidéo prises à l'aide d'une caméra rapide, est que la profondeur d'immersion de la balle augmente pendant la brève période de chute libre par l'action des forces capillaires ou par la dépression au cœur d'un vortex en présence de rotation — la poussée d'Archimède habituellement dominante étant nulle pendant la chute — et que la pression considérable sur la partie immergée de la balle pendant la décélération au sol repousse la balle vers son équilibre de flottaison. La quantité de mouvement transmise dans ce processus est alors tellement importante que la balle est expulsée vers le haut à grande vitesse, de la même manière que l'effondrement d'une cavité à la surface d'un liquide conduit à la formation d'un jet rapide au centre.

1. On the "Phy Ex" course at Université Paris VII

1.1. *On the importance of teaching experimental projects in Physics*

Although people, in most industrialised societies, still trust science far more than they (statistically) trust governments or enterprises, in some areas like climate change, evolution or vaccination, the level of public suspicion is high. The most obvious threat to a public debate based on facts and scientific arguments, the "post-truth", results from the "destruction (. . .) of the effective, public social norms and behaviours that the common search for truth presupposes" [1]. However, beyond the gradual disappearance of a public space of thought and confrontation based on shared objective standards for truth, the scientific world faces another danger. Great confusion in the public debate results from the belief that the Truth will naturally emerge from the free competition of opinions and ideas, in an open marketplace of ideas—called the *Catallaxy* by Hayek [2]. It is taken for granted that the collective information processing in a society is spontaneously efficacious in producing knowledge—one must assume more than any other human collective activity—regardless of the participants' training, education, expertise or even ability to reason. Some of the advocates of Open Science and "Science 2.0", amongst which think tanks and fake institutes like the Ronin Institute, Center for Open Science, openscienceASAP, UK Open Data Institute, PCORI or the Laura and John Arnold Foundation, to cite just a few, promote the substitution of internet platforms, inspired from social media, for old style scientific procedures, based on the Humboldtian model. The discredit of science used as a political strategy (by some actors in the fossil fuel industry, for instance, in the face of climate change) should alarm scientists on the more subtle calls for deregulation of scientific methods, claiming that spontaneous order will magically solve the nuisances of contemporary science, including the occasional corruption of private scientific journals and the crisis of replicability.

It has always been part of scientific education to disentangle belief and knowledge, to identify the proper contours of the scientific and political spheres and to discuss the grey zone in between: expertise and techniques. The threats to scientific thought now require academics to pay particular attention to the place given in university training to the scientific method and its specific rules of probation and truthfulness. Experimenting with original teaching methods to do this is all the more urgent since, taking advantage of the prevailing credulity, more and more pressure

groups are trying to claim the "scientific" nature of their opinions, developed outside any scientific method. The scientific method is based on the establishment and publication of objectifiable facts (in physics, experimental measurements and mathematical theories) published alongside a discourse of proof and an extensive review of the scientific literature on the subject.

The scientific method needs to be taught as early as possible, yet much of it can only be learned through guided practice. How can undergraduate students learn the scientific method when they do not have a sufficient theoretical background to tackle open problems on the forefront of science? Experience shows that pretending to "investigate" a problem whose solution is perfectly known is tantamount to making science a dead language. Actually, most of the french elite is formed in dedicated professional schools, known since Napoleonic times as "Grandes Écoles", where students never encounter a problem which does not present a clean, well known, analytical solution. In the third year of the bachelor's degree at the physics department of Paris VII university, the attempt at a more fruitful approach consists in letting students conduct experimental research in teams of two over the course of one semester, on a subject chosen from a range of largely open-ended scientific problems in macroscopic physics.

This presupposes suitable problems, and means. Students are thus led to work on a scientific question by themselves, to design and implement an experiment, to develop a model, to read primary scientific sources, to practice peer review (*disputatio*), to write down a draft including scientific evidence and reasoning. This guided approach to research has been pioneered by Yves Couder: the next section tells of the genesis, the initial rationale and the evolution of this course over the past decades. In the second part of this article, we will report on one of the experiments performed by a group of students in the academic year 2019–2020.

1.2. *A short history of experimental physics projects (Phy Ex) at Univ. Paris VII*

Yves Couder has created this experimental physics course (here after referred to as *Phy Ex*) in an entirely different context, at the creation of the Université Paris VII, born from the division of Université de Paris. Université Paris VII, which had also gone by the name of Université Paris Diderot in the past years, has recently merged with Université Paris 5 to become Université de Paris, closing a historic cycle. *Phy Ex* was inspired by the novel pedagogical approach developed in the *Centre universitaire expérimental de Vincennes* after 1968. Yves Couder had met Michel Juffé during the 1968 movement at the *Commission Nationale Interdisciplinaire* (CNID, rue d'Assas, Paris). From May to June '68, under the presidency of Marc Hatzfeld, student in political science, this group—which included personalities such as Michel Alliot, Pierre Bourdieu, Henri Cartan, Jacques de Chalendar, Hélène Cixous, Jacques Monod and Laurent Schwartz—produced a programmatic document to change University, entitled "Proposition pour de nouvelles structures universitaires". In 1972, at the *Département de Sciences de l'éducation*, in Vincennes, an innovative method (BETIS) was experimented by Guy Berger, Ruth Kohn, Yves Couder, Michel Juffé and Antoine Savoie: between 30 and 40 undergraduate students, in groups of 5 or 6, where asked to produce an interdisciplinary work on educational methods, based on book reading, discussion and research. The BETIS research project would be awarded from 0 to 10 credits—out of the 30 required to obtain the *Licence* (Batchelor) grade in three years—depending on the amount of work. This method favouring autonomy turned out to be so time demanding that the students could hardly follow other courses. It was one full university year out of three devoted to research and *disputatio*. The role of the five teachers (a spinozist philosopher, a physicist, a critical sociologist from the institutional analysis school, an epistemologist practising the participant observation, and a pedagogue) was to guide, to discuss, to improve the quality of reasoning. Forming groups with students of all three *Licence* years, having therefore different degree of maturity in their disciplines, proved most effective. The project oriented teaching method became official in 1976

and remained active for decades. When Michel Juffé left Vincennes in autumn 1977, Yves Couder stopped teaching there and started *Phy Ex* at Paris VII university. The paper archives of all the experimental projects since the creation of the course are conserved to date in the experimental room.

The original motivation for *Phy Ex* was directly related to the emancipation movement of the 1970's. The idea of a co-production of knowledge by students immediately after attending University was a reaction to both the conservative old style of Sorbonne bigwigs and to the post-war development of a standardised mass university. It aimed at breaking or at least re-examining the existing hierarchy between teachers and students. Simultaneously, an experimental physics course would promote practical knowledge against theoretical knowledge and thus in principle add value to the popular do-it-yourself culture (DIY, *bricolage*), against a cultural capital backdrop of mathematics accused of reproducing inequalities by social inheritance. Yves Couder himself, in his research, has defended the possibility of pure experiments not initially motivated by any theory, starting from minute table-top experiments. He had two simple principles to let surprises emerge from an experimental set-up: turn the button to the maximum, and ask yourself and others "what happens if". For instance, Yves Couder's famous bouncing drop experiment [3,4] started in *Phy Ex* as a Faraday instability experiment, using a sabre saw as shaking device. How could he resist encouraging the students to push the sabre saw vibration to the maximum, rather than to obediently reproduce curves provided in the scientific article they were starting from.

Since the late seventies, social changes have profoundly modified the perception of *Phy Ex*. Experimental projects in physics are now taught in many universities. Projects are no longer associated with innovative emancipatory teaching methods, but with mainstream management control techniques. The current goal of *Phy Ex* has conceptually changed a lot, although the teaching itself may be close to its original form. The students, for the first time, are confronted with the scientific method, and with knowledge less well established and polished than what they are taught in regular courses. They discover the existence of academic journals, of formal peer review of papers. They see the social practices around science: for instance, in *Phy Ex*, preliminary results are frequently discussed; it is only progressively that the scientific matter is settled and that knowledge coming from an experiment becomes trustworthy. They have to identify key control parameters, to perform measurements, to understand how an experiment is designed and built to solve a question. As soon as they have experimental data, they are confronted to ethics and intellectual virtues—starting with: am I allowed to remove a bad data point? A permanent expectation since the pioneering times of *Phy Ex* is to create the conditions of a particular involvement of students in their experiments, an appropriation of knowledge. The success of a project is judged primarily by the hedonic reward provided by a resistant experiment that suddenly starts working after some effort. As manual skill is decisive for this, *Phy Ex* reveals to dozens of students each year their ability to devise and develop practical tools to understand a physical phenomenon. They learn that nature can be made to reveal some of its inner workings through some ingenious set-up, rather than through theoretical calculus, and that an experiment is but a dialog where one has to learn to ask the right questions and make sense of the answers. Hence the pleasure students ordinarily report experiencing in the last few weeks of the semester.

1.3. *The contemporary organisation of Phy Ex*

Experimental projects in physics at Paris 7 university take 8 h a week (2 times 4 h) over the course of a semester (12 weeks). Each group is composed of 30 to 36 students, who work in pairs on 15 to 18 projects. A well equiped machine shop with one permanent lathe-mill operator is assigned to *Phy Ex* to help setting up the experiments. A second technician is responsible for the material (especially fragile or expensive parts) and for the supervision of computers. Three or

four experienced academics are needed to supervise the projects. Initially, around 25 projects are proposed by the teachers, based on open problems or on a physics paper. An essential rule is to check that there is at least one quantity to measure and one control parameter, in order to ensure that an experimental curve, at least, can be drawn. Open questions that are too qualitative, or that involve fields rather than scalar quantities are rejected. There is a collective check of prior feasibility. As subjects in acoustics, hydrodynamics, capillarity, optics, electrostatics, elasticity, granular material, *etc*, are easier to design, attention is paid to avoiding many subjects in the same field, and to finding subjects involving quantum mechanics, solid state physics, astrophysics, and so on.

During the first hour, each subject in turn is described in two minutes and one video-projected slide in front of all students. They are then invited to sign up for up to three subjects, with a priority on one of them. During one hour, we help resolving cases where several groups would like to work on the same problem. It is important to avoid initial frustration as much as possible. Then, the students devote the first 5 time slots (20 h) to the theoretical analysis of their subject. They are asked to formalise a question in scientific terms, sometimes starting from a problem posed in every day terms. Most often, they have to read (for the first time) a scientific paper, see the typical structure and the bibliography. Most of the time is then devoted to reading chapters of books to learn elementary physics that they need for the subject. In the specific case presented below, the students had no background in either hydrodynamics or capillarity: they only knew rigid body mechanics and hydrostatics. Very often, the students are encouraged to perform the dimensional analysis of their problem, which is usually far too complicated to be solved theoretically. They need to think about the orders of magnitude involved in the experiment and the way they will measure central quantities. At the sixth sequence, all the groups present their theoretical work and provide a short written report. They then work on their experiment for the next 18 periods of 4 h. At the end, they are expected to obtain reliable experimental curves and to be able to discuss them. In some cases, the comparison with the theory can be pushed further. The students finally write a second report and prepare an oral presentation of the whole project in front of all other students and teachers.

In the rest of the article, we will report the project performed by Sofia El Rhandour-Essmaili and Guillaume Pérignon-Hubert, with the technical help of Wladimir Toutain, in autumn 2020.

2. Problem and theoretical developments

2.1. *The water cannon problem*

The project discussed here as an example was proposed as problem number 1 in the International Physicists' Tournament (IPT) 2020 under the title *Cumulative cannon*. The subject description pointed to a Youtube video [5] where "Mr. Hacker" puts a table tennis ball in a transparent plastic glass partly filled with water, that he has previously set into rotation, and lets the glass fall to the floor. Just after the impact with the ground, the table tennis ball is ejected upwards at high velocity. The IPT problem consisted in two questions. *How high may a ping-pong ball jump using the setup on the video? What is the maximal fraction of the total kinetic energy that can be transferred to the ball?* [6]

French undergraduate students in the third year of university do not have a background in hydrodynamics nor in capillarity. Most of the first twenty hours of theoretical investigation were therefore devoted to learn in autonomy the basic concepts in this field. With the help of the supervising team, the project team produced conservation arguments based on energy, as suggested by the IPT problem formulation, and on momentum transfer. We summarise below their theoretical elaboration, rephrasing them in a more rigorous scientific language. It must not

be understood as a final answer to the problem, but as an intermediate stage aiming to prepare the experiment and to identify the relevant control parameters.

2.2. *The energetic upper bound*

A plastic cup of mass m_c is filled by a mass $M - m_c$ of liquid. A table tennis ball of mass $m \ll M$ is deposited at the surface, in the centre of the cup. The cup is released from a height ζ above a flat solid ground whose mass is much larger than M. It reaches the ground with a velocity $U \simeq \sqrt{2g\zeta}$. After the impact, the table tennis ball is ejected with a velocity v. The aim of the project, once rephrased in scientific terms, is to determine the dependence of v on the control parameters of the experiment: the release height ζ, the amount of water in the cup, the size of the cup, the initial rotation ω of the liquid, the surface tensions involving the liquid and the ball.

The kinetic energy of the ejected table tennis ball $(1/2)mv^2$ is limited by the total initial gravitational energy $(M + m)g\zeta$, so the ball's velocity has the following upper bound:

$$v < \sqrt{\frac{M}{m}}U, \quad m \ll M. \tag{1}$$

Any change in wetted area of the ball during this process can be neglected in the energy budget: the capillary energy difference between a dry and a wet ball, $4\pi R^2 \gamma \cos\theta < 4\pi R^2 \gamma \simeq 3 \times 10^4$ J, where γ is the liquid–air surface tension and θ a typical contact angle of the liquid on the ball (see Figure 7), is orders of magnitude below the kinetic energy, of around 2 J (the inverse ratio is the Weber number We $= \rho_w U^2 R/\gamma \simeq 10^4 \gg 1$). Finally, the large Reynolds number Re $= RU/\nu \simeq 10^5$ implies that inertia dominates over viscous dissipation.

Capillary forces alone cannot be responsible for the ball ejection itself. A rough order of magnitude shows that the work they can perform on the ball could accelerate it to at most $\sqrt{\gamma R^2/m} \simeq 0.2$ m·s^{-1}. Although some plants and mushrooms are known to use capillary forces to eject spores [7–9], a capillary "snap" mechanism due to sudden meniscus shape change during impact can be ruled out here. This reflects in the high Weber number estimated above.

2.3. *Scaling law based on momentum conservation during the shock*

Imagine the situation where a glass partly filled with water, without the table tennis ball, hits the ground flat. Assume the free surface of the water is horizontal. The impact sees a pressure shock wave propagating through the water from the bottom upward, progressively stopping the water motion. At the shock front each water layer effectively collides with the cylinder of water below which is already at rest. By invariance in the horizontal plane, if menisci and free surface perturbations can be neglected, neither wave nor central jet is excited: water goes to rest, the free surface remaining flat [10].

The table tennis ball displaces water, but in terms of momentum it can be replaced by an equal mass of water. If the table tennis ball were at its equilibrium buoyancy position at the moment of impact, this substitution would precisely take us back to the case of a flat water surface (see next section), so we would not expect the ball to rebound any more than the substituted water.[1] However pictures just before impact reveal that the ball position differs from static equilibrium, in which case the following argument shows that ejection occurs.

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[1]This neglects the balls elasticity which can store some potential energy during impact, causing the ball to rebound almost as on solid ground, at least for weak immersion depth from which the ball can extract with only moderate loss of momentum.

Consider a point inside the liquid at depth h. The pressure increases from atmospheric pressure by about $\rho U c$ when it is reached by the stopping front, whose unknown velocity[2] is noted c. This excess pressure is maintained until the stopping front has reached the free surface and a relaxation front has propagated backwards, and its integral over time is $\rho U h$, corresponding to the momentum surface density above the considered point. Integrated across the immersed surface of the table tennis ball and the shock duration, this pressure injects an upwards momentum $m_w U$ into the ball, where m_w is the mass of water displaced by the ball, that may overcompensate the downward momentum mU of the ball before impact. The net momentum transfer is therefore expected to eject the ball at a speed

$$v = \frac{m_w - m}{m} U.$$

(2)

2.4. *Equilibrium position of a table tennis ball with and without gravity*

At first sight, the previous formula seems to imply that no ball ejection is to be expected. Indeed, static balance between Archimedes buoyancy force and gravity states that $m_w = m$ for a ball floating on a static bath (Figure 3a). Neglecting surface tension, the immersed volume under gravity is related to the depth H by:

$$\frac{m}{\rho} = \pi H^2 \left(R - \frac{H}{3} \right)$$

(3)

where R is the ball radius and ρ the density. However, here, the ball during the free flight does not feel gravity. Its equilibrium position and therefore m_w is controlled by surface tensions. The interface must obey Young's law selecting the contact angle both on the ball and on the plastic glass. With no hydrostatic pressure gradient during free fall the interface connecting the two circular contact lines on the centred ping-pong ball and on the glass is a constant mean curvature surface, or Delaunay surface [11]. The Laplace pressure associated with this constant curvature balances the capillary forces on the glass and on the ping-pong ball. When the ball is in equilibrium, the resultant of capillary forces and Laplace pressure acting on it must vanish. A zero Laplace pressure configuration arises in the simplest case of a contact angle equal to 90° on the glass. The interface is simply flat and horizontal (Figure 3b), and joins the ball horizontally [12–14]. Young's law selects the ball immersion depth. Then, the volume displaced corresponds to $H = R(1 + \cos\theta)$ leading to:

$$m_w = \rho R^3 \left(1 - \frac{\cos\theta}{3} \right) \cos^2\theta.$$

(4)

The calculation of the displaced mass m_w from the general unduloid or nodoid interface, as a function of the contact angle on the glass, remains outside the scope of this paper.

3. Experimental results

3.1. *Experimental set-up and preliminary observations*

The first goal of the project has been to perform controlled experiments. In order to test the theoretical ideas, a first set-up was designed to strike a static glass from below. A large metallic block, used as the mass of a meter scale pendulum attached to a spring, formed a "hammer" that would hit the plastic glass, containing a table tennis ball floating on water, through the

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[2]In a hard-walled glass on a hard floor the front is expected to be relatively localised, and its speed close to the bulk sound speed. For more compliant vessels the stopping front should be broader and the pressure increase slower.
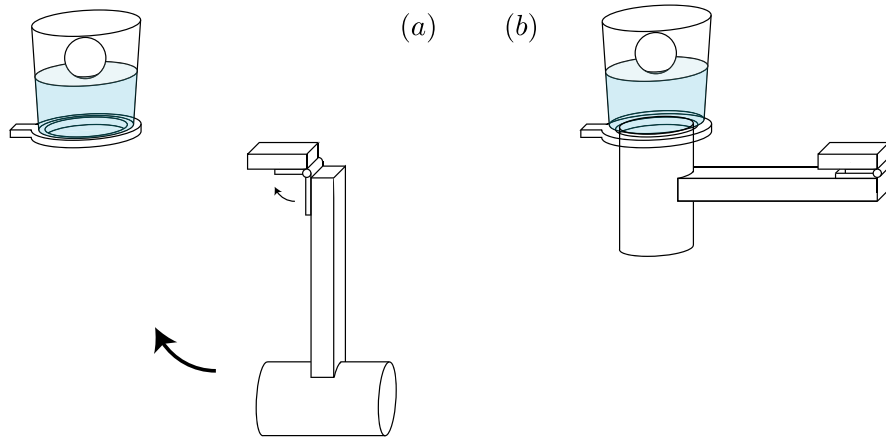
Figure 1. Schematic of the first experimental set-up, using a pendulum as a hammer to hit the bottom of the glass.

central hole of an annular support (Figure 1). The geometry was adjusted to get a planar collision between the hammer and the glass bottom. Except for the case where the water was stirred to make it rotate, or for the case of a ball in an empty glass, without water, the table tennis ball was never ejected from the glass. This is exactly what is expected from Equation (2) for $m_w = m$ (for why rotation changes the outcome radically see Section 3.4). In conclusion, the free flight is essential to the cannon effect, which implies that the conditions under which the glass is released at null velocity must be controlled with precision.

In the final set-up, a spring-loaded trapdoor supports the plastic glass (Figure 2). An electric lock is used to trigger the release of the trapdoor, which is hollowed out beneath the glass to avoid aerodynamic suction and disturbances as much as possible. The spring is chosen such that the trapdoor moves out of the way faster than the glass falls. A visco-elastic shock absorber made of a polymeric foam prevents a rebound of the trapdoor once it reaches a vertical orientation. The trapdoor is carefully levelled, to within 0.1° of the horizontal, so that the glass is upright when released. Within this precision, thanks to the elasticity of the plastic, the impact takes place over the whole surface of the glass bottom.

The glass impact is imaged with a 1632 × 1200 fast video camera borrowed from a nearby laboratory. The resolution is 190 µm per pixel in the focal plane and the imaging frequency is 1000 Hz. The impact velocity U and the ball ejection velocity v are automatically measured from the slope of a space time diagram (strip-videograph) of a line passing though the centre of the ball.

Figure 4 shows a sequence of images in a typical experiment. The motion of the table tennis ball reverses direction less than a millisecond after the impact. The ejected ball is always accompanied by a columnar liquid jet. We checked that there is no such central jet in the absence of the ball.

3.2. *Dependence of the ejection velocity on the release height*

We first consider the dependence of ejection velocity v as a function of the impact velocity U. Figure 5(a) compares the relation between U and the release height ζ to the conservative theory, neglecting the drag force exerted by air. Its overall agreement is excellent and one can judge the quality of the velocity measurement.
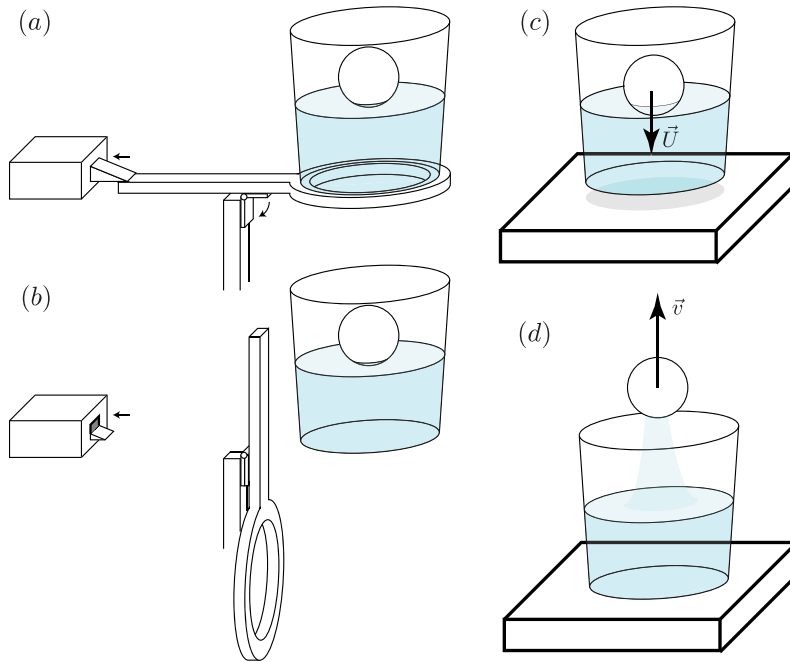
Figure 2. Schematic of the experimental set-up. (a) The glass with water and table tennis ball rests on a trapdoor mounted on a spring-loaded hinge. (b) When the lock's bolt retracts, the trapdoor is released and pivots, moving away from under the glass at more than gravitational acceleration due to the spring. The glass starts its free fall. (c) Glass, water and ball impact the flat ground at a velocity $\vec{U}$. (d) Shortly after the impact, the ball is ejected upwards at velocity $\vec{v}$.
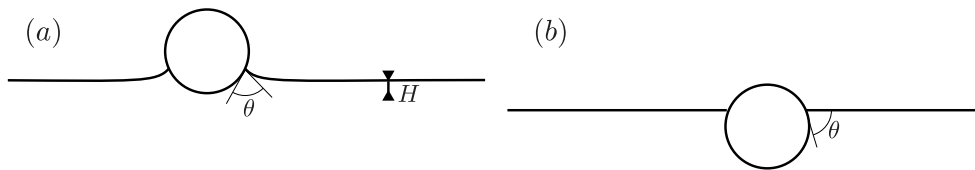

Figure 3. Schematic showing the equilibrium position of the ping-pong ball (a) under gravity and (b) during the free flight.

We performed two series of experiments using the same type of plastic glass and the very same table tennis ball. In the first series the fluid does not rotate, while in the second the water is stirred manually beforehand. We tried to reproduce the same initial condition when depositing the table tennis ball at the surface of the water (wetting meniscus height, centring in the glass). In many cases, the glass broke at the impact, in which case the velocity is much smaller than that reported in Figure 5(b). Those cases were discarded. The dispersion of the data presented in this figure mostly result from the contact angle hysteresis and on the exact impact conditions. Despite dispersion, one can conclude that the ejection velocity is reasonably linear in impact velocity, both with and without rotation.
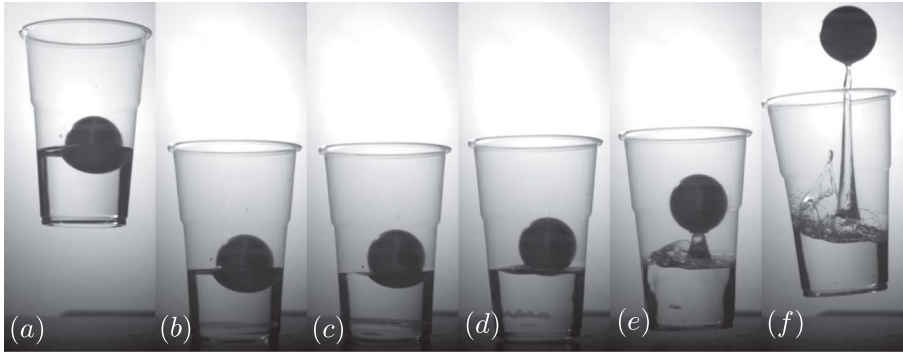
Figure 4. Series of pictures extracted from a fast movie. Images taken at $t = 0$ ms, 16 ms, 17 ms, 18 ms, 21 ms and 33 ms. The diameter of the table tennis ball is 40 mm.
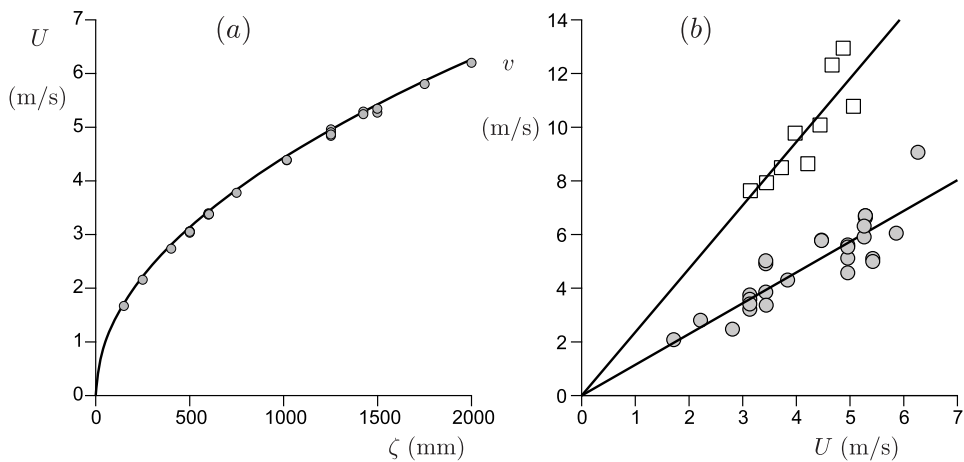

Figure 5. (a) Dependence of the impact velocity U on height ζ. The solid line corresponds to $\sqrt{2g\zeta}$. (b) Ejection velocity v as a function of impact velocity U, varying the release height ζ. Circles: without rotation. Squares: with a constant rotation.

3.3. *Dependence of the ejection velocity on the ball mass*

We have changed the ball mass by injecting some liquid inside through a small hole by means of a hypodermic needle. Figure 6(a) shows the immersion depth of the ball as a function of the ball mass m, as compared to the theory neglecting surface tension. The agreement is, as expected, very good. Figure 6(b) shows the ratio of the ejection velocity to the impact velocity as a function of the ball mass m. The data obey a very simple relationship: the momentum transferred to the ball, mv is roughly constant. Note that this is not entirely consistent with the prediction of (2).

3.4. *Dependence of the ejection velocity on surface tension and rotation*

Two independent factors can greatly increase the ejection velocity. Stirring the water into rotation—a trick used in the introductory video to centre the table tennis ball—has the effect of creating a radial pressure gradient that will drag the ball into the liquid during free fall. Likewise, increasing the wettability of the ball's surface will cause surface tension to pull the ball under during free fall. In both cases the net result is an increase in displaced volume, and a strongly
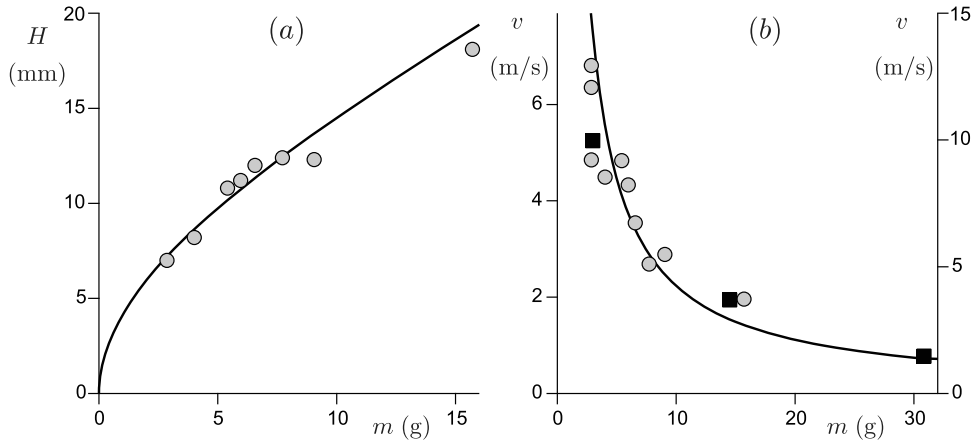
Figure 6. (a) Depth H as a function of the ball mass m in the static case. The solid line is the theoretical prediction, when capillarity is neglected: $m = \pi \rho_w H^2 (R - H/3)$. (b) Ejection velocity v as a function of the ball mass m, with (black squares, right axis, release height $\zeta = 1$ m) and without (circles, left axis, release height $\zeta = 1.42$ m) rotation.

increased ratio of ejection velocity to impact velocity. To change wettability we have found two routes to be equally effective, either adding surfactant to the water, or using a mixture of water and ethanol to vary the liquid surface tension and therefore the liquid contact angle θ continuously (Figure 7(c)).

Ethanol wets the table tennis ball plastic more than water. As a consequence, the contact angle θ is lower. We have measured the immersion depth of the ball in the static case, under gravity (Figure 7(a)). When going from pure water to pure ethanol, H remains almost constant. Indeed, gravity is the dominant force determining the equilibrium position of the ball, and the change of the liquid density is small. On the opposite, the immersion depth just before impact strongly increases with the volume fraction ϕ of ethanol. This directly shows that the equilibrium of the ball changes during the free flight: capillarity, which is negligible for the equilibrium position under gravity becomes dominant in the micro-gravity conditions of free fall. The lower the contact angle, the deeper the ball gets immersed, leading to a stronger momentum transfer during the collision.

Figure 7(b) shows the ejection velocity v as a function of ϕ for the same impact velocity $U \simeq 5$ m·s^{-1}. With 70% ethanol, the ejection velocity is three times higher than with water. Two series of measurements performed on two different dates, with distinct types of plastic glasses, present a systematic difference. This may either be due to different wetting properties of the ball used, or point to an influence of either geometric or material properties of the plastic glasses. Plastic dissipation at impact may change the deceleration kinetics. We found for instance that test experiments using paper cups, whose hollow bottom deforms permanently at impact, produced much lower restitution coefficients. The black square corresponds to a run performed with a surfactant—commercial dish-washing liquid—which causes water to wet the plastic ball. The ejection velocity is observed to be higher than with ethanol, as expected, and reaches 50% of the upper bound from (1). We have also added two runs performed in water with a strong rotation, which also exhibit high ejection velocities (angular frequency of the ball during free fall $\omega \simeq 1.4$ rad·s^{-1}).

It may come as a surprise that the ball depth can change significantly during the free fall phase, which lasts only about 0.5 s. Indeed, the suction force on the ball is weak: in the rotation case the
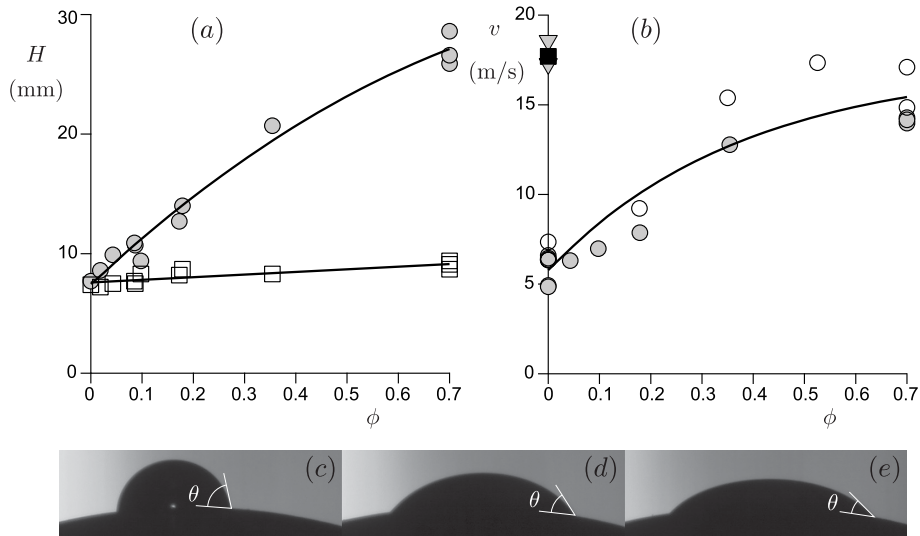
Figure 7. Dependence on surface tension determined using a mixture of water and ethanol. (a) table tennis ball depth H as a function of the ethanol fraction ϕ. Circles: just before impact (free fall height $\zeta = 1.42$ m); squares: at rest. (b) Circles: Ejection velocity as a function of the ethanol fraction ϕ, release height $\zeta = 1.42$ m. The grey and white symbols correspond to two types of plastic glass. Square: water with surfactant, $\zeta = 1.06$ m. Triangles: water with a strong rotation, $\zeta = 1.41$ m. The solid lines in (a) and (b) are phenomenological parabolic fits. (c) Drop of liquid on the table tennis ball: from left to right, water, $\phi = 35\%$ ethanol and $\phi = 70\%$ ethanol.

pressure below the ball is roughly 1 Pa below atmospheric pressure, causing a downward force of merely 1 mN. This force is small, but as the otherwise dominant buoyancy forces are suspended during free fall, it can accelerate the ball downwards and move it up to 3 cm neglecting added mass effects. This is in accordance with observations, which show the ball almost completely submerged for strong rotation rates. Capillary forces acting on the perimeter of the ball are in the same milli-Newton range.

4. Conclusion

4.1. *A physical picture of the phenomenon*

The most striking observation on the video recordings is the change in immersion depth of the ball compared to the static buoyancy equilibrium position, which we attributed to the effect of either capillary forces or vortex depression (in the case of rotating liquid) acting during free fall. During impact the pressure inside the liquid in excess of atmospheric pressure suddenly increases from zero to large values (for rigid glasses on hard floors up to $\rho U c$ where c is the speed of sound in the liquid). As a result the ball is pushed up very strongly, and accelerates upwards to velocities in excess of the impact velocity.

The physical picture of the dynamics during impact is not unique and depends on the relative magnitude of several time scales that are involved. One is the time it takes for the impact shock to travel through the liquid, from the bottom to the free surface. In a rigid glass this would be the height of the liquid free surface above the glass bottom divided by the bulk speed of sound in the liquid: around 50 µs. In a compliant vessel the elasticity of the walls reduce the effective

speed of the shock front [15]. A second time scale is the impact duration. On a hard substrate this is equal to the previous time, but on a soft substrate (picture a rigid glass falling on a soft foam layer) it may be governed by the total mass of the glass and the elasticity of the substrate. Last, but not least, the impact duration has to be compared to a third time scale, the time for the table tennis ball to accelerate out of the liquid. For short impacts in this scale the momentum transfer will be maximal, while for very long impacts the ball leaves the liquid early with only part of the momentum transfered.

It turns out that except for the very last case mentioned above, the prediction of (2) is the same even outside the hard glass hard bottom limit described when deriving it in Section 2.3. It is instructive to describe the momentum transfer mechanism in other regimes. Consider the case where the impact duration is much longer than the time required for a bulk compression wave to propagate through the liquid from the bottom to the free surface: as all water molecules then share the same velocity and decelerate at the same rate, the pressure becomes a linear function of depth just as in the hydrostatic case. Its gradient is much larger however, because the deceleration rate is larger than gravitational acceleration g by a factor given by the ratio of free fall duration (500 ms) to impact duration ($\approx$1 ms). During the brief impact period the glass-water-ball system can thus be considered as subject to a high effective gravity field, and it is clear that the ball will tend to relax very quickly to its buoyancy equilibrium position. Arriving at this position, having acquired momentum, it continues upward.

A precise calculation of the ejection velocity and the energy transfer coefficient is undoubtedly a very complex hydrodynamic problem. The students were not expected to arrive at a quantitative restitution model. Their experiments do however confirm the expected proportionality between v and U, and provide the correct order of magnitude. It also predicts the dependence on wetting. The prediction of the restitution coefficient $(m_w - m)/m$ could not be tested quantitatively, due to the difficulty to determine m_w experimentally. This remains one of the major issues to tackle in the future.

To answer the International Physicists' Tournament question on the maximum kinetic energy transfer, one would have to better understand the simultaneous creation of a liquid jet which carries part of the momentum.

4.2. *Worthington jet vs dynamic entrainment by the ball*

Imagine the ball would magically disappear at the very instant the glass impacts the floor. The void left by the ball would collapse and create a jet exactly in the same way a meniscus on the side-walls of a tube collapses and creates a jet upon deceleration [10, 16]. This collapse dynamics was also studied under standard gravitational acceleration in cavities created by the impact of a solid body [17] or in cavities left at the rupture of surface bubbles [18], and the explanation of the basic jet formation mechanism dates back to Worthington and Cole [19, 20]. The radial inward motion induced by the collapse causes a strong dynamical pressure to build up at the centre, by which the liquid is expelled along the axis. The presence of the table tennis ball changes the boundary condition at the cavity's free surface by adding a dynamic pressure (the ball is injecting its momentum as it decelerates as well). In fact, taking the table tennis ball out and filling the cavity partly by this ball's mass in liquid should lead to the same momentum balance. With a ball at its equilibrium buoyancy depth ($m_w = m$) this amounts to completely filling the cavity, and producing no jet (an elastic ball still allows for rebound and jet). However when the ball moves into the liquid we have an effective cavity and the jet velocity is expected to scale as $(m_w - m)U/m$ just like the ball velocity according to (2). In practice the two velocities appear to be approximately equal. If the jet were pushing the ball we would expect to see a splash on the bottom of the ball, which is rarely seen (and when it is, the mass involved is minute).

On the opposite, we could consider that the liquid jet is entrained by the ball, slowing it down. When a solid object is withdrawn from a bath of liquid in partial wetting, the contact line can remain steady in the frame of reference of the lab if the solid velocity is sufficiently small [21]. Above a critical value of the capillary number $\eta v/\gamma$, a dynamical wetting transition occurs [22–26]: as capillary forces can no longer compete with the viscous stress that develops inside the flow, liquid is entrained dynamically [27]. The velocity difference between the contact line and the solid surface is selected by the critical capillary number, and is proportional to γ/η. This may explain the conical shape of the water column below the ball, similar to that observed in the cat lapping problem [28].

If this interpretation is correct, the resistive force exerted by the liquid on the ball would remain relatively small, scaling on γR. Indeed, at the scale of the ball, everything goes as if the effective macroscopic contact angle was vanishing. The overall viscous force exerted on the ball is then simply governed by the unbalanced Young force. This does not preclude the existence of an added mass to the moving sphere during the impact itself, scaling on $\rho_w R^3$.

Both the Worthington jet and the dynamic entrainment explanations shall contain a part of the correct picture: on the one hand, the pressure gradient inside the fluid should accelerate both the ball and the liquid below; on the other hand, the flow structure close to the contact line should resemble that observed at the critical point for dynamical entrainment.

4.3. *"Phy Ex" and research in macroscopic physics*

In conclusion, we have exemplified here one particular physics project performed in the *Phy Ex* initially created by Yves Couder. Indicative of the fruitful proximity of this teaching to full-fledged research is that occasionally, a successful experiment leads to a publication of the group of students and their supervisors in a scientific journal [29]. More famously some research projects started in *Phy Ex* have lead to discoveries that spawned a whole research branch over the following years. One example is a problem involving Quincke rollers, proposed by Denis Bartolo when he was teaching *Phy Ex* as faculty member of Université Paris 7, which became the starting point of his subsequent work on the collective behaviour of large collections of these Quincke rollers [30, 31]. A second example is Yves Couder's proposal of a problem on the Faraday instability, cited above, that led to the fortuitous discovery of walking droplets, which have since been largely studied in laboratories around the world [3, 4, 32, 33].

Acknowledgements

Supplementary data

Supporting information (video) for this article is available on the journal's website under https://doi.org/10.5802/crmeca.46 or from the author.

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