Projets de Physique Expérimentale
Learning the Scientific Method by doing

UMR 7057 Matière et Systèmes Complexes

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Yves Couder and the course "*Projets de Physique Experimentale*"

Teaching experimental physics through projects

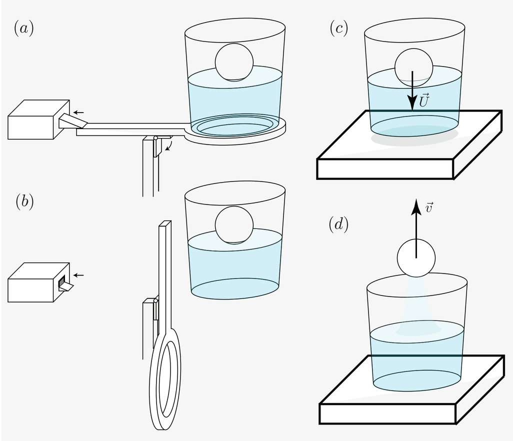
- Principles
  - Students confronted with the scientific method,
  - …and with knowledge less established than presented in courses.
  - Learn to identify key control parameters
  - Design an experiment, perform measurements, make sens of answers
  - Discover:
    - Academic journals, peer review
    - Social practices of research: discussing preliminary results, iterative improvement of trustworthiness of findings
    - Ethics: may I remove a bad data point ?
  - Goal & expectation: involvement of the students, hedonic experience on making progress
  - Understand precedence of observations over theory
- Current format
  - 2 x 4 h / week over 12 weeks
  - 15 to 18 projects (students in pairs)
  - Well equipped machine shop (lathe, mill, drill, laser-cutter, 3d printer …) with one permanent operator
  - 3–4 experienced academics, second technician (managing instruments, computers, tools, …)
  - Budget for new instruments and consumables
- Organisation
  - 25 suggestions presented by teachers (open problems or paper); rule: at least one control parameter and one quantity to measure
  - Students sign up for preferred project, conflicts are resolved
  - First 20 h: Theoretical analysis and preliminary experiments:
    - Formalise project aim in scientific terms
    - Read papers and/or learn required physics from books (e.g. examples below: hydrodynamics and capillarity)
    - Dimensional analysis, orders of magnitude
    - Write up and present work of first phase
  - Next 18 times 4 obtain reliable experimental curves, discuss, compare to theory/model as possible.
  - Complete report and present whole project in front of students & teachers.

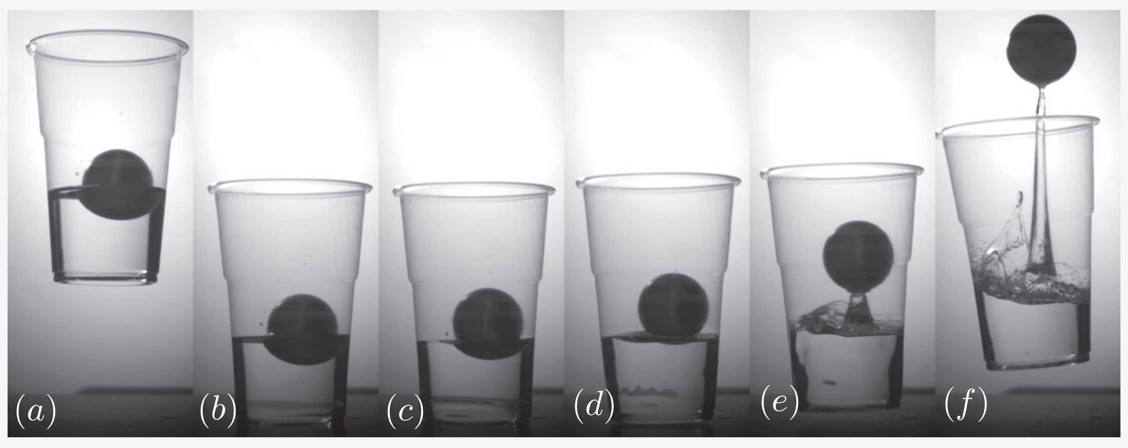
Genesis.

- Created in 1977 by Yves Couder
- Had previously experimented with innovative teaching methods in Vincennes (with Guy Berger, Michel Jaffé, Ruth Kohn, and Antoine Savoie):
  - mixing first to third year students,
  - tutoring by a physicist, a philosopher, an epistemologist, a sociologist, a pedagogue
- Original idea radical: co-production of knowledge by teachers and students
- Has since conceptually evolved, but expectations and organisation conserved

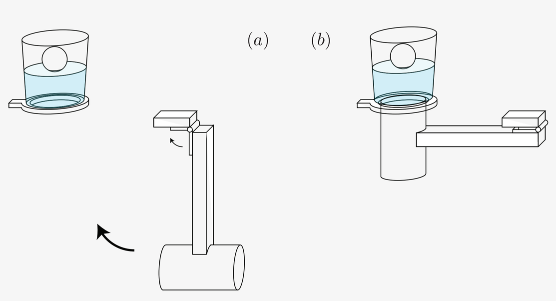
Example project 1: the ping pong ball water cannon

Comptes Rendus. Mécanique 348.6–7 (2020): 423–437.



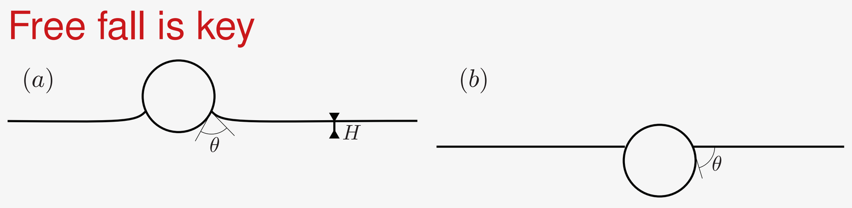


(Left, a–d) Experimental set-up. (Right, a–f) Series of pictures at $t = 0$ ms, 16 ms, 17 ms, 18 ms, 21 ms and 33 ms. Table tennis ball diameter is 40 mm.



Control experiment using a pendulum as hammer ▸ no ejection.

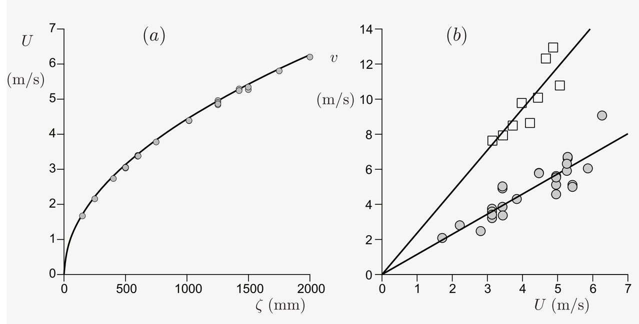
Free fall is key



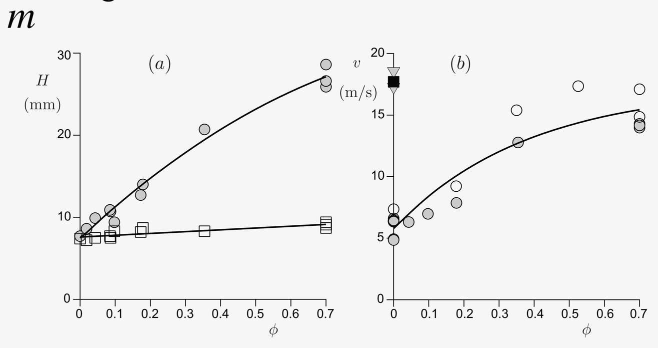
Equilibrium position of ping-pong ball (a) under gravity, (b) during free fall.

Excess pressure during impact integrated over duration $\rho U h$ (momentum surface density), integrated across ball cross section ▸ upwards momentum transfer into ball: $m_w U$, where m_w is mass of water displaced by ball.
Subtracting downward momentum mU before impact ▸ Expected ball ejection speed

$$v = \frac{m_w - m}{m} U \qquad (1)$$



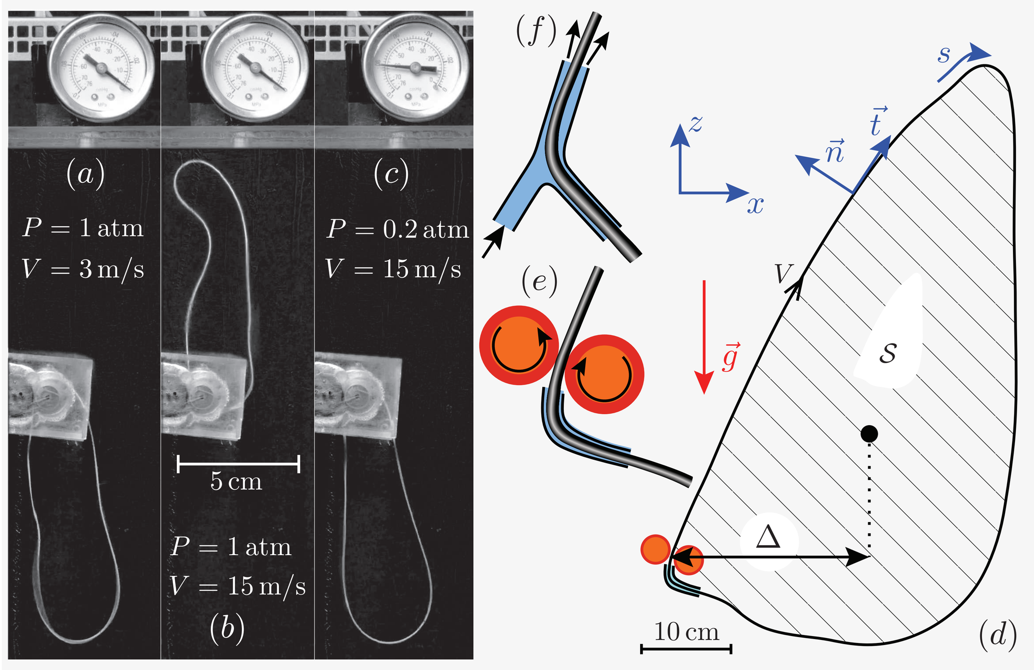
(a) Impact velocity U function of height ζ (line: $\sqrt{2g\zeta}$). (b) Ejection velocity v function of impact velocity U, varying the release height ζ. Circles: without rotation. Squares: constant rotation.



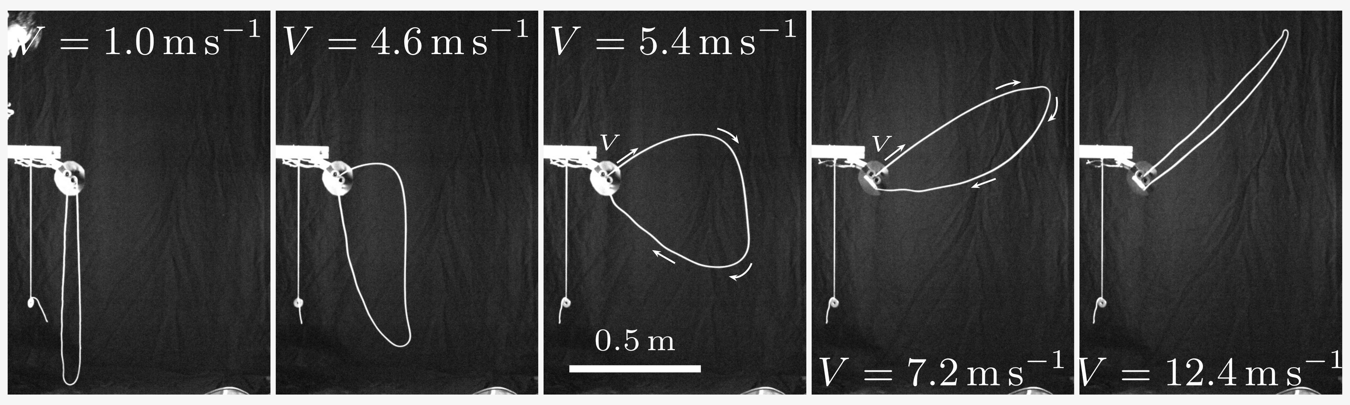
(a) Ball depth H function of ethanol fraction ϕ. Circles: just before impact; squares: at rest. (b) Circles: Ejection velocity function of ethanol fraction ϕ. (c) Drop spreading on ball, $\phi = 0$ (water), $\phi = 35\,\%$, $\phi = 70\,\%$.

Example project 2: Self-supporting loops through air drag

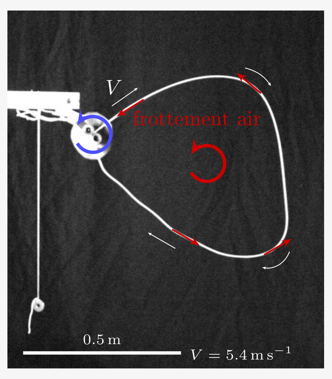
J. Fluid Mech. (2019), vol. 877, R2, doi:10.1017/jfm.2019.631



String loop entrained at speed V by two counter-rotating wheels (e) or air blown along a small segment (f) exhibits a transition from (a) a gravity dominated regime at low velocity towards (b) a self-supporting loop regime. (c) Reducing the pressure from atmospheric pressure to 20 kPa while keeping the high velocity reverts the string back to its lowered configuration.

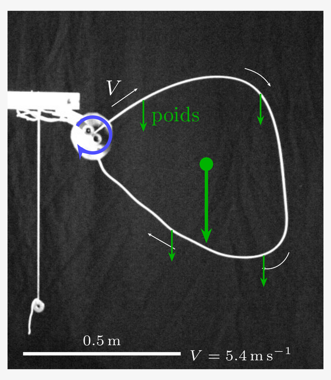


Air drag
(increases with speed V)

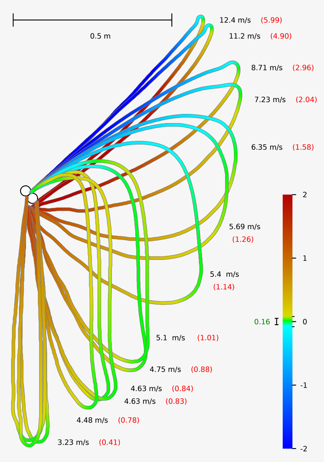


Centre of mass:
Zero net force, non-zero moment

Weight



Centre of mass:
Zero moment, non-zero net force



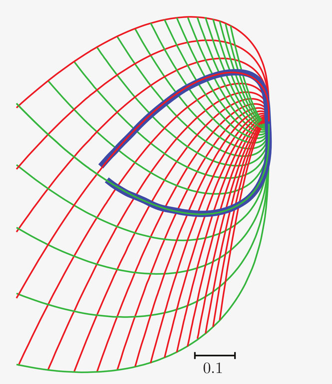
- Opposite torques at the propelling system.

Minimal model

- assume inextensible, flexible string
- inertia + string tension + gravity + longitudinal drag

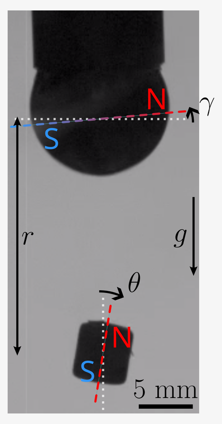
$\rho_s A_s$	mass per unit length,
$A_s = \pi R^2$	string cross-section,
ρ_f	air density
α	turbulent drag coefficient

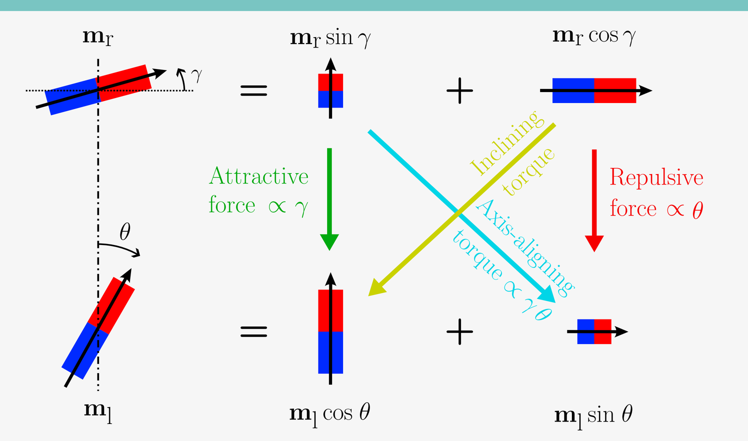
$$\rho_s A_s \frac{d\vec{v}}{dt} = \frac{\partial (T\vec{t})}{\partial s} + \rho_s A_s \vec{g} - \alpha \rho_f R |\vec{v}| \vec{v}$$

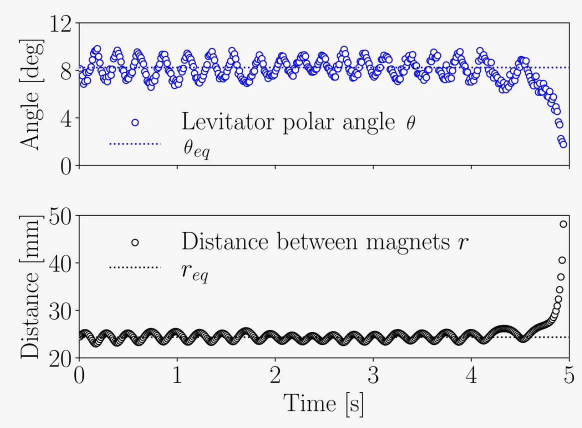


Formal resemblance with hydrodynamics, where "pressure = - tension".

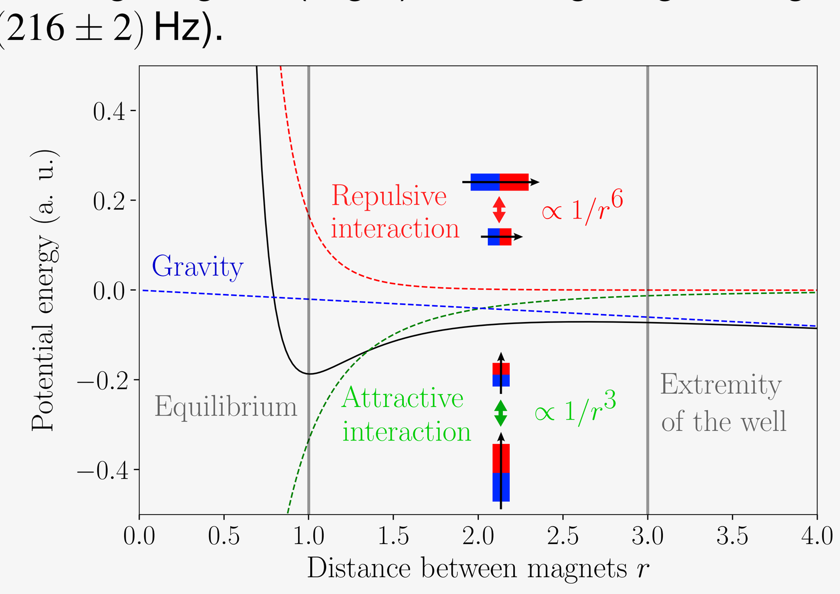
Example project 3: Magnetic levitation in the field of a rotating dipole



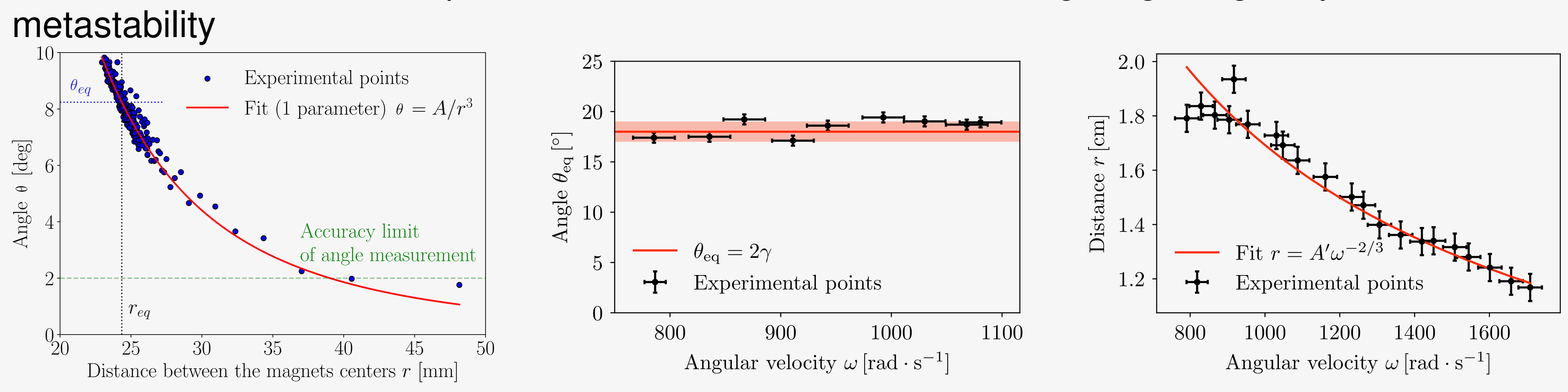




(Left) Snapshot of experiment. (Middle) Magnetic interactions (forces and torques) between the rotor magnet and the levitating magnet. (Right) Levitating magnet angle and distance, function of time (rotor freq. $f = (216 \pm 2)$ Hz).



Potential energy (arbitrary units), function of the distance between magnets r, is sum of an attractive term $\propto -1/r^3$ and a repulsive term $\propto \theta/r^3$. Since $\theta \propto 1/r^3$, the repulsive interaction potential energy is as $1/r^6$. The equilibrium position is at the minimum of the energy well, where small oscillations can take place. For a levitator below the rotating magnet, gravity leads to metastability



Model predictions. (left) Levitating magnet inclination angle, function of the distance between the two magnets ($f = (216 \pm 2)$ Hz), with predicted power law A/r^3 (red solid line, A adjusted). The equilibrium values for the distance r_{eq} and the inclination θ_{eq} are indicated in dotted lines. (middle) Tilt θ_{eq} of levitating magnet at equilibrium for different rotor angular velocities, compared to twice the rotor angle $\gamma = (9.0 \pm 0.5)°$. (right) Equilibrium distance r between the two magnets, function of rotation speed ω, with an adjustment of $r = A'\omega^{-2/3}$ via A'.