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# The granular Brownian ratchet: carrying out a historical thought experiment.

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We present an experimental realisation at macroscopic scale of the storied Brownian ratchet, which is an illustration of the Maxwell's demon. In our mechanism, the rotation of a centimetre-scale 1D Brownian object in a granular gas is detected by an electromechanical converter (dynamo), generating a voltage proportional to its angular velocity. The current generated by this random rotation is rectified by an electronic device (*demon*), such that only positive current passes. Eventually, work is produced. The advantage of such a macroscopic setup is to allow measurement of all the observables per time unit: useful power (work), heat taken from the bath, and finally the efficiency of the equivalent heat engine. The feedback allowing the conversion from heat into work, expresses as a bias on the Brownian motion.

## I. INTRODUCTION

The phenomenological theory of thermodynamics was founded in the XIX<sup>th</sup> century on primal principles, inspired by experience. Beyond the plainness of their statements, they reveal a profound significance [1]. The 2<sup>nd</sup> law, among many other consequences, implies that heat spontaneously flows from high to low temperature bodies. James K. Maxwell was one of the first to sense the statistical nature of these axioms [2]. More precisely, he had the intuition that they should be taken into account only for the averaged observables. We now know that state variables are fluctuating quantities, but it was not the case then. Indeed, the conception of matter as composed of atoms and molecules in random thermal motion was not yet accepted in Maxwell's time. Such considerations were revolutionary and among the very first openings to statistical physics!

To illustrate his point, Maxwell proposed an experiment that would, if performed, contradict the 2<sup>nd</sup> principle, i.e., a paradox. The principle is as follows. If an imaginary *being* is able to take information on the state of a system (measurement), it can act on this system. For instance, it can sort particles or extract work from heat, at no cost of energy. This being has been later called *Maxwell's demon*. Different versions of this simplistic thought experiment fueled rich and profound discussions for over 150 years. The most famous are the Szilard engine [3], the Brillouin's rectifier [4], and the ratchet and pawl [5]. The detailed operation of these devices cannot be discussed here, we refer to the detailed review from H. S. Leff and A. F. Rex [6].

The paradox of Maxwell's demon has been first resolved by Smoluchowski, arguing that no sorting is possible if the demon itself is not at a temperature lower than that of the gas [7]. In other words, the Maxwell's demon is actually a heat engine, the cold bath being not apparent at first sight (detailed in Feynman [5]). Looking closer, the Maxwell's demon is operating a conversion from in-

formation into heat (entropy transferred to a cold bath). The detailed process was first clarified by Brillouin [4], and Landauer [8], paving the way to the very active field of information thermodynamics [9–11].

Experiments were technically unrealisable in Maxwell's time. They could only be performed in the last decade, thanks to a colloidal Brownian rotor under feedback controlled rotating electric field [12], or a colloid bead oscillating randomly in the simple or double-well potential of optical tweezers [13]. These pioneering experiments made it possible to investigate quantitatively the functioning of Maxwell's demons. We present a novel experimental construction of the celebrated 'ratchet and pawl' [5]. This is a mechanical realization of a Maxwell's demon, illustrating the arguments of Smoluchowski. In [5], the random torque caused by the collisions with a molecular gas sets a rotor into a 1D Brownian motion. Consider a rectifying mechanical device, like a ratchet and pawl, fixed on its shaft, allowing the rotation in one direction only. In this case, work can be extracted, seemingly from a single heat reservoir, which constitutes a perpetual motion of the 2<sup>nd</sup> kind. This is the Maxwell's demon paradox.

We present here our first measurements in such system, of time-dependent observables such as heat and work per time unit. The originality of our setup is twofold. First, it is macroscopic (centimetre scale). The role of the molecular heat bath is played by a granular gas. Being dissipative, external power has to be supplied to sustain a Non-Equilibrium Steady State. It is a *thermostat*, in the sense that it sets an effective temperature [22],  $kT \simeq 1.36 \cdot 10^{-7} \text{ J}$  [16]. Second, it makes use of an electromechanical conversion: the movement of the rotor is converted into an electrical voltage. Using an electronic rectifying device as the demon avoids at once all difficulties linked to mechanical plays and friction.

## II. EXPERIMENT

A centimetre-size rotor is embedded in a granular gas playing the role of heat bath (about 340 stainless steel beads of 3 mm diameter and 0.1 mg mass). Such a macroscopic gas is dissipative, i.e., some power is

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supplied to balance dissipation on the average, and achieve a steady-state. The beads are contained in a 5 cm cylindrical vessel, accelerated vertically at a few g (gravitational acceleration) by an electromagnetic shaker (B&K 4809), at a frequency of 40 Hz (see Fig. 1):

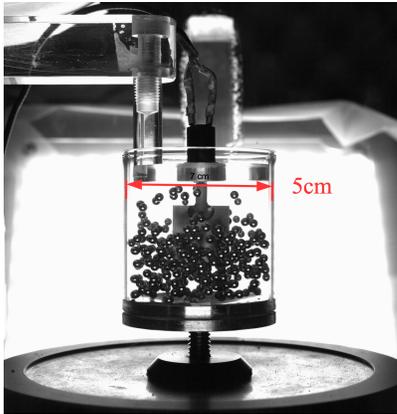


FIG. 1. Photograph of the experimental system. The beads are vibrated vertically in a vessel by an electromagnetic shaker. A blade is immersed in the grains, fastened on the shaft of a small DC-motor. (Exposure time: 300  $\mu$ s.)

A rotating  $20 \times 20 \times 0.4$  mm stainless steel blade, immersed in the granular gas, is secured on the shaft of a DC micro-motor (Maxon RE10 118391), set vertically on the axis of symmetry of the 5 cm diameter cell. The micro-motor is simply used as an electro-mechanical converter (dynamo). The voltage at its terminals is the image of the angular velocity:  $e(t) = \alpha \dot{\theta}(t)$ , thanks to Faraday induction. The prefactor  $\alpha \simeq 0.0095$  V/(rad/s) is characteristic of the device.

The granular gas colliding the blade causes its random rotation, realizing a macroscopic 1D Brownian motion. If the electrical circuit is closed on a load, the fluctuating voltage at the terminals of the motor gives rise to a current  $i(t)$ . This current is modulated by an electrical Maxwell's demon, composed of a voltage comparator and a switch. Whatever the voltage fluctuations, only one direction of current is allowed: the demon is an electrical rectifier, analog to the usual ratchet and pawl. To avoid spurious transients, we chose a high-speed voltage comparator, with compensated thermal drift (ref.: MAX987). It triggers a static switch IC, able to commute within 200 ns (ref.: ADG734BRUZ).

The fluctuating AC voltage ultimately gives rise to a rectified current. This DC current can be used to produce work, like for instance charge a capacitor or a battery, or even lift a weight. For convenience, we used here an Ohmic resistor  $R = 200 \Omega$  as the load, without changing the principle of the measurement (pictured in Fig. 2):

We record voltages  $u_1$  and  $u_2$  thanks to a NI-PXI 4462 24 bits synchronous A/D converter. The induced voltage is  $e = u_1 + ri$ . The current  $i = \frac{1}{R}u_2$ , caused by  $e$ ,

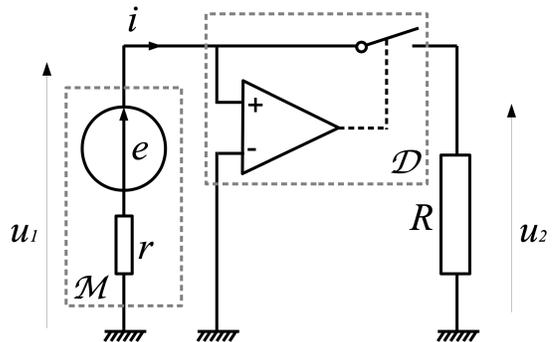


FIG. 2. Electrical circuit associated with the probe – The motor  $\mathcal{M}$  is represented in a dashed rectangle by an ideal voltage source  $e$  and its internal resistance  $r$ . The demon  $\mathcal{D}$  is composed of a comparator, at the terminals of the motor, triggering a switch that allows the current to pass or not in the load resistance  $R$ , depending on the polarity of  $u_1$ .

is flowing into the resistance  $R$  whenever the switch is closed. The resistance of this switch in the closed state is  $r' \simeq 2.5 \Omega$ , otherwise  $r' \simeq \infty$  in the open state (leak current  $\lesssim 100$  pA). This electronic demon behaves as a perfect diode (zero voltage threshold).

If  $u_1 > 0$ , a current flows:  $i = \frac{e}{R_t}$ , where the total resistance in the loop is  $R_t = R + r + r'$ . The internal resistance of the motor is  $r \simeq 120 \Omega$ . It is measured, like  $R$ , thanks to an ohmmeter. The current through the motor gives rise to a torque that opposes the rotation (Lenz's law). In other words, when the switch is closed, an Ohmic damping adds to the viscous damping of the gas. The ohmic load represents the weight lifted by the winch in the mechanical ratchet described in Feynman's lectures.

The voltage noise  $e(t)$ , represents the velocity of a rotor in the granular gas (hot bath). To detect properly the sign of the voltage, the thermal (Nyquist) noise of comparator itself must be much lower than  $e(t)$ . This is obviously the case at room temperature ( $k_B T \simeq 10^{-21}$  J). This is, in electrical words, the expression of the Feynman-Smoluchowski's explanation of Maxwell's paradox: work can be produced because the heat engine is coupled to, both a hot bath and a cold bath. The demon stays in the low temperature heat bath.

### III. THE DEMON'S CHOICE

Let us now compare the motion of the rotor with and without the demon. In the latter case, the rotor is subject to the random forcing of the gas, whereas the averaged collisions cause damping (gas viscosity). This equilibrium on average, is the essence of the fluctuation-dissipation theorem, taking into account the temperature of the gas [16]. On average, the angle of the rotor remains constant (blue trajectory in Fig. 3). When the demon is

at work, the symmetry between positive and negative rotation breaks, because ohmic dissipation in  $R$  occurs in one direction only. It results in a drift  $\langle \dot{\theta} \rangle$  (temporal average). One example is presented in Fig. 3:

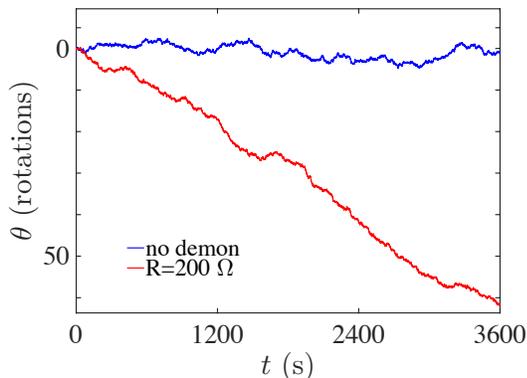


FIG. 3. 1h time samples of angular trajectories of the rotor, with the demon active (red), or inactive (blue).

Let us now consider the variance  $\langle \delta_\tau \theta^2 \rangle - \langle \delta_\tau \theta \rangle^2$  of the angular time increments  $\delta_\tau \theta(t) = \theta(t + \tau) - \theta(t)$ , over a time  $\tau$ . It is the time coarse-grained mean square rotation. One clearly identifies in Fig. 4 a ballistic and a diffusive regime, where the variance is proportional to  $\tau^2$  or  $\tau$ , for time-lags respectively smaller or larger than a certain crossover time. We note that this time is approximately the correlation time of the angular velocity:  $\tau^* \simeq 18$  ms. Remarkably,  $\langle \delta_\tau \theta^2 \rangle - \langle \delta_\tau \theta \rangle^2$  has exactly the same time dependence whether the demon is active or not: red and blue lines are exactly superimposed in Fig. 4. It means that the rotor undergoes a similar diffusion process, if considered in a frame of reference rotating at speed  $\langle \dot{\theta} \rangle$ . Note that the average rotation with the demon is quite small, typically 5 rotation per hour, it is indeed a tiny perturbation onto the gas. Consistently, the rotor speed histograms are almost the same with or without demon (see Fig. 5). On the histograms, the negative fluctuations, when switch is open, are of course unaffected ( $\dot{\theta} < 0$ ). It could be different on the  $\dot{\theta} > 0$  side, where the demon causes a very slight depletion, due to the damping of the blade motion by the load. The effect on the histogram of velocity is so small it can barely be seen. The overall effect is a slight angular drift under the action of the demon, already mentioned with Fig. 3.

The smallness of the perturbation,  $\langle \dot{\theta} \rangle \simeq 0.016$  rps, can be understood in different ways. It confirms that the fluctuations of the rotor are strongly coupled with the dynamics of the beads, and the energy taken from the bath is small. The bath is a good thermostat, for a demon that makes a weak perturbation. The measurements of heat and work rates are discussed in the next section.

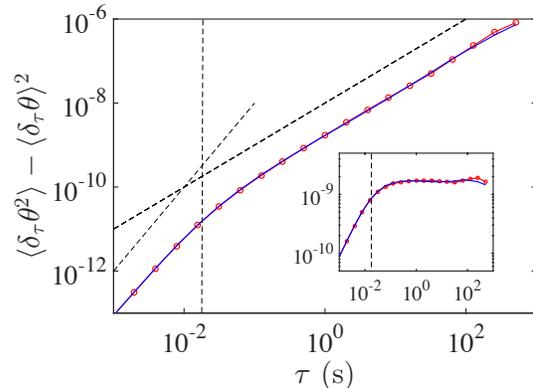


FIG. 4. Variance of the angular increments  $\delta_\tau \theta$  over the time-lag  $\tau$  with demon (red line with symbols) or without (blue line). As an eye guide, dotted lines of slopes 1 and 2 are drawn. The insert shows  $\frac{1}{\tau}(\langle \delta_\tau \theta^2 \rangle - \langle \delta_\tau \theta \rangle^2)$  against  $\tau$ . Vertical dashed lines figure the velocity correlation time,  $\tau^* \simeq 18$ ms.

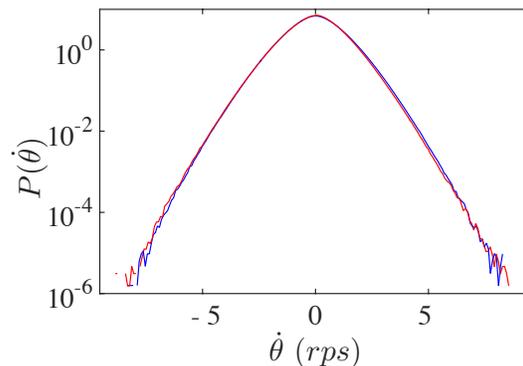


FIG. 5. Histograms of the rotor's speed. A very slight depletion can be seen on the right wing, when demon is active (red), in comparison to the case where demon is off (blue).

#### IV. HEAT, WORK, AND EFFICIENCY

The paradox of the Maxwell's demon, as explained in The Feynman Lectures, is to consider the ratchet and pawl system as a heat engine, working between a hot bath on the one hand (here the granular gas at temperature  $kT$ ), and a cold bath on the other hand (the surroundings). The electronic demon system stands at room temperature (comparator and switch), as well as the load  $R$  and the motor. This model thermal machine extracts heat from the hot bath and releases part of it into the cold one, producing some work in between. Now, let us see the energy balance of this steady state heat engine. Per time unit,  $\dot{w} = Ri^2$  represents the work produced thanks to the ratchet heat engine. On the other hand, the heat per time unit extracted from the hot bath is  $\dot{q} = ei$ . Both histograms show fat tails for positive power fluctuations (see Fig. 6).

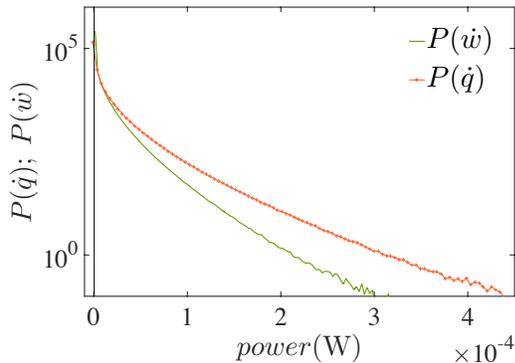


FIG. 6. Normalized histograms of the heat and work per time unit,  $\dot{q}$  (orange dotted line) and  $\dot{w}$  (green line). Averaged heat and work per time unit are  $\langle \dot{q} \rangle = \langle \dot{e}i \rangle \simeq 6.6 \mu\text{W}$  and  $\langle \dot{w} \rangle = R\langle i^2 \rangle \simeq 4.2 \mu\text{W}$ .

Two comments can be made:  $\dot{q}$  and  $\dot{w}$  are positive, and exhibit a zero most probable value, corresponding to the switch opened. These statistics deserve specific investigation, but that is beyond the scope of this article. Let us consider the averaged quantities. Per time unit, the heat taken from the granular gas is  $\langle \dot{q} \rangle \simeq 6.6 \mu\text{W}$ , and the work produced is  $\langle \dot{w} \rangle \simeq 4.2 \mu\text{W}$ . We note again that these values are very small if compared to the power used to keep the granular gas in a steady state,  $\sim 10 \text{ W}$ , called *house keeping heat* [17]. It is a reliable thermostat. The efficiency of the heat engine is  $\eta = \frac{\langle \dot{w} \rangle}{\langle \dot{q} \rangle} \simeq 64\%$ . An upper bound for the efficiency corresponds theoretically to a reversible exchange. It is the Carnot efficiency:  $\eta_C = 1 - \frac{kT_c}{kT_h}$ , where  $kT_c$  and  $kT_h$  are the temperatures of the cold and hot baths, respectively. The temperature of the gas is  $kT_h = 1.36 \pm 0.15 \cdot 10^{-7} \text{ J}$ , and the room temperature is  $kT_c = k_B T_{\text{room}} \simeq 10^{-21} \text{ J}$ . This leads to  $\eta_C \simeq 1 - 10^{-14} \simeq 1$ . As expected,  $\eta < \eta_C$ . The difference is mainly due to the losses. To be specific, it is mostly Joule dissipation:  $(r + r')\langle i^2 \rangle \simeq 2.3 \cdot 10^{-6} \text{ W}$ . One must mention another contribution, the heat released to the cold bath because of the entropy production in the erasure of the demon's information, as proposed by Brillouin [4]. It can be obtained from the digital switching signal of the demon,  $k_B T \log 2$  per bit of information erased. As it is, at room temperature, this contribution is extremely small, barely measurable ( $\sim 3 \cdot 10^{-18} \text{ W}$  on the average). The investigation of this digital signal is in progress.

## V. DISCUSSION

We designed and produced a macroscopic version of the sometimes-called 'Feynman-Smoluchowski ratchet', a thought experiment that allows to convert heat into work through the action of an information device, a Maxwell's demon. Our setup is operating in contact with a granular gas as heat bath. It makes use of, first, electromechanical conversion, and, second, an electronic device as demon, to replace the traditionally represented mechanical ratchet and pawl system.

Granular ratchets have been studied in the past, but, to our knowledge, no measurements were performed on their thermodynamic properties [18]. Our system is profitable in that no friction exists in the demon's part. The only relevant damping effects are the finite impedance of the motor, and in the open and closed states of the switch, easy to take into account. The dissipation in the gas itself is evidently irrelevant. Indeed, as it is merely a source of noise, the dynamics of the rotor is not affected by the dissipation in the beads' collisions. Only the effective temperature matters.

We deliberately chose Smoluchowski and Feynman's take on Maxwell's demon paradox. In that regard, it is a heat engine running between a hot heat bath (granular gas) and a cold one (room). We measured time series of the heat extracted from the hot reservoir, and the work performed on a load (here represented by  $R$ ).

Thanks to this macroscopic approach we can measure precisely various fluctuating observables, such as heat and work per time unit:  $\dot{q}(t)$  and  $\dot{w}(t)$ . We can therefore access the stochastic efficiency, defined as the ratio of the instantaneous work produced over heat consumed at the same time:  $\eta(t) = \frac{\dot{w}(t)}{\dot{q}(t)}$ . Such quantity, fluctuating in small scale systems, has attracted increasing interest in recent years [19]. One must note an experimental contribution on colloidal cyclic heat engines [20].

More interesting, our Brownian ratchet gives a direct access to the measurement of the entropy of information. It is a convenient experimental test rig, allowing to measure any fluctuating observable in a reliable way.

Besides, from a more practical viewpoint, macroscopic Brownian ratchets typify the very principle of *energy harvesting*, ie., extracting useful work from fluctuations [21].

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