Information and Thermodynamics in quantum hybrid systems

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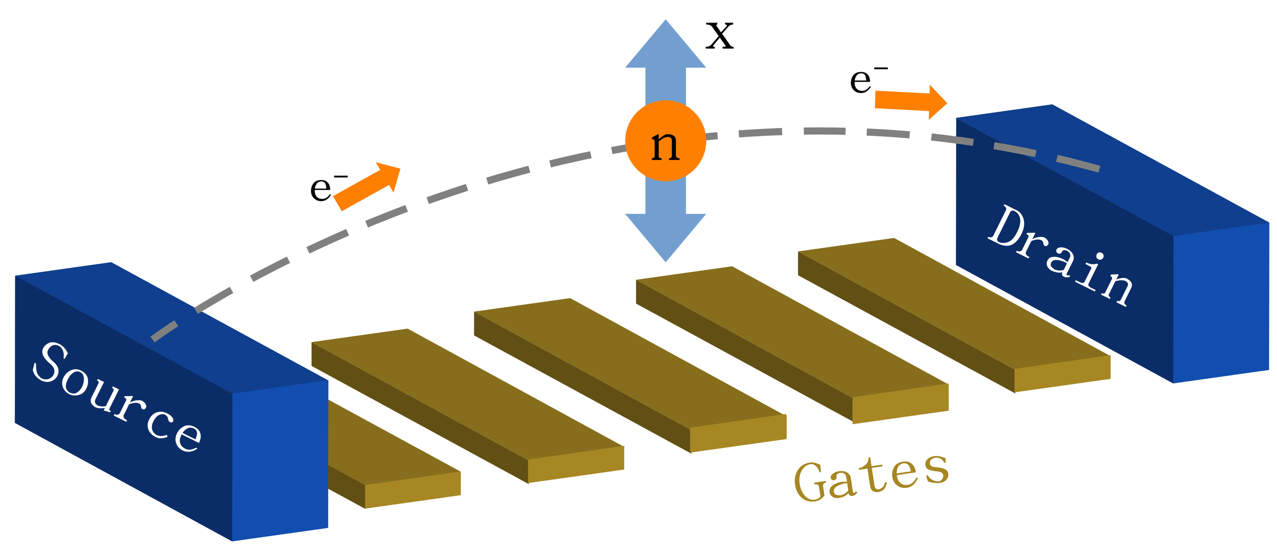
At the nanometric scale, the laws of Thermodynamics have been a challenge since Maxwell's time. Since he proposed the Demon paradox, there has been an intuition of the importance of Information Theory in these laws, but we still need to improve our control of experiments at the nanoscale. Hybrid systems combine quantum and classical degrees of freedom in such a way that we can directly observe both energy flows between the two and dissipation phenomena. This makes them excellent experimental platforms for thermodynamic analysis. In this work we use the information flow formalism to evaluate entropy generation on a realistic devices and propose a particular experimental implementation.

Hybrid Device

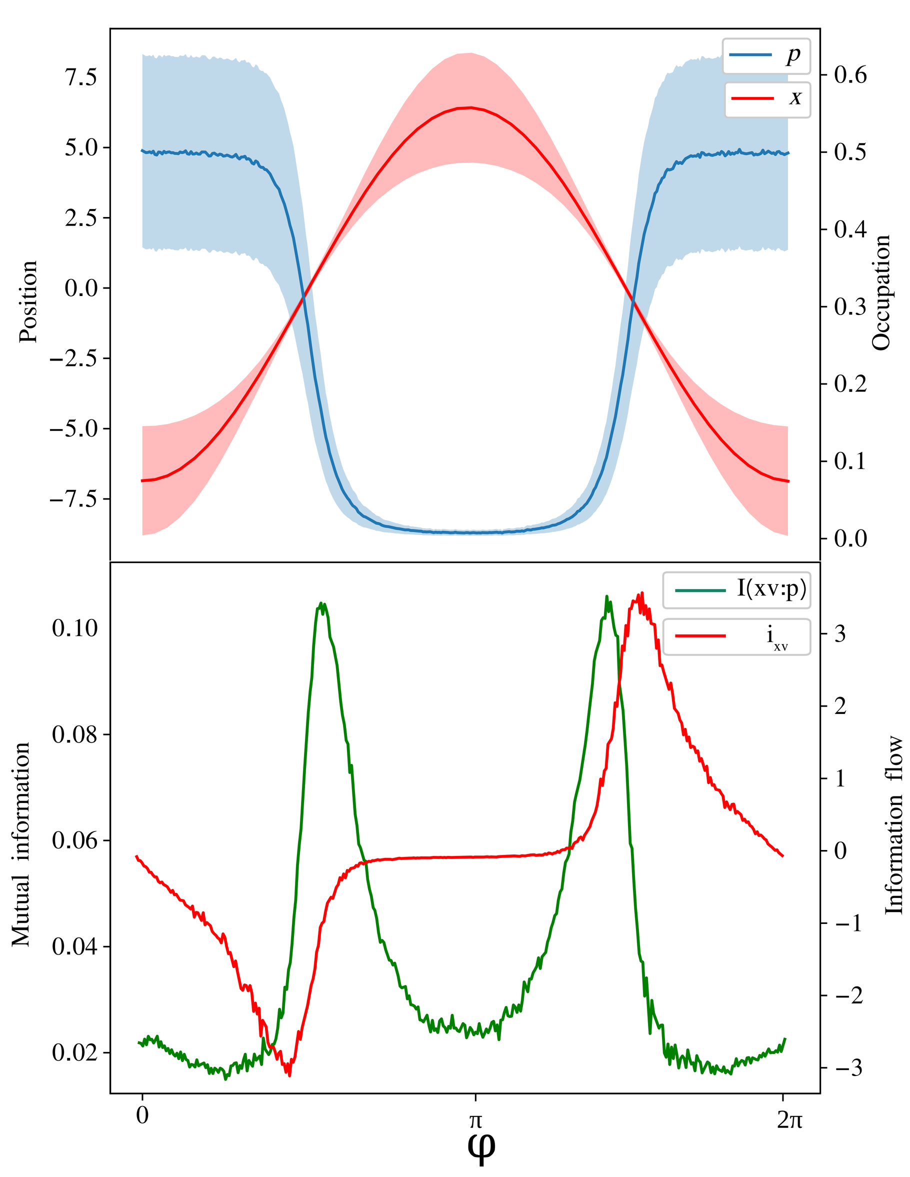


Our model is based on a widely used experimental set-up [1].

1.- The device is configured by a **carbon nanotube** arranged over a series of voltage gates.
2.- We establish a **current of electrons** flowing along the nanotube from Source to Drain. The gate voltages control the electron flow along the nanotube.
3.- We can describe the system through the *amplitude of the nanotube oscillations* (x), and the *number of electrons within carbon nanotube* (n) in Coulomb Blockade. Both quantities are related through capacitive coupling. Their evolution can be written in terms of a stochastic dynamical system of the form

$$\ddot{x} = -kx - \gamma\dot{x} - g_0 n + \xi,$$
$$\dot{n} = \Gamma_{\rm in}(x)(1-n) - \Gamma_{\rm out}(x)n$$

Landauer's erasure



Landauer's erasure takes place when a *bit of information* is rewritten to the state 0, independently of the initial state. It is therefore an irreversible operation.

In our device, we replicate this opperation using the oscillator movement to damp the electron current. The electron number acts as an information bit which is forced to be erased.

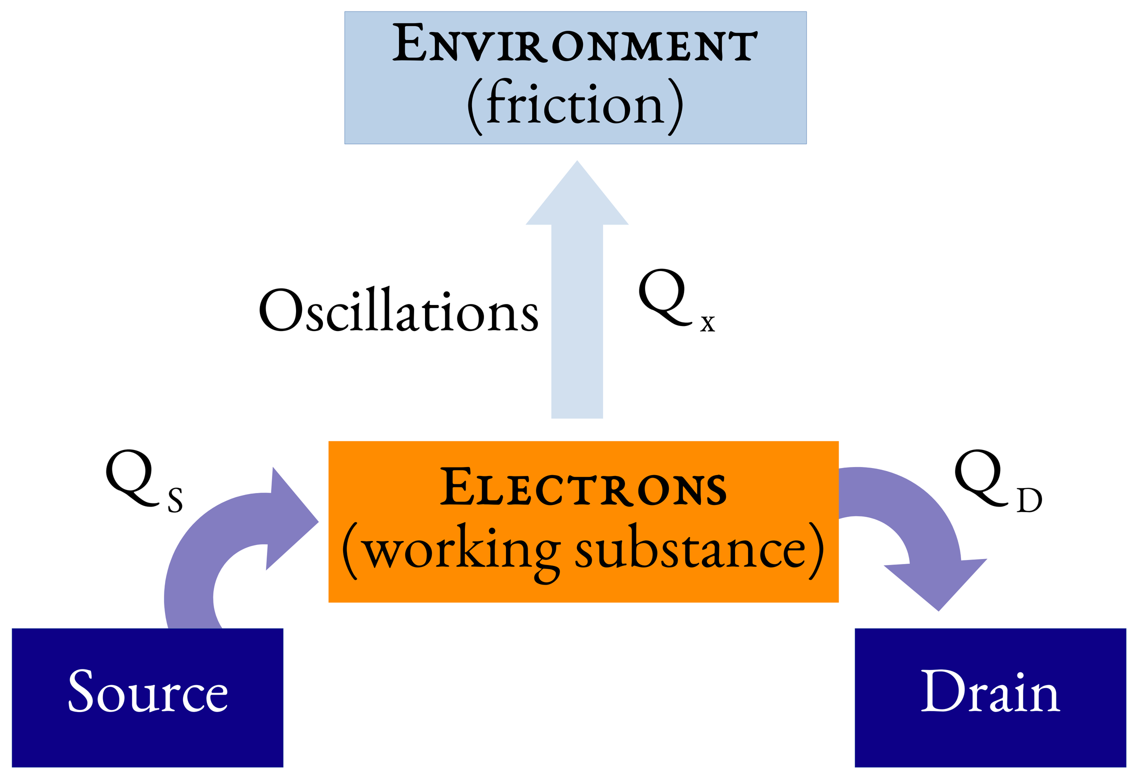
Information thermodynamics establish a minimal value of entropy generation given by

$$-\log 2 - \delta i_p - \beta(\delta Q_L + \delta Q_R) \geq 0.$$

As we prove in the Figure, a part of the irreversibility of the process comes from the correlations between the oscillator and the current.

Figure: (up) oscillator position and instantaneous electron number as a function of the oscillation phase. (Down) Mutual information and information flow along the process.

Thermodynamics of Information flows



The system entropy is [2]

$$S = S_x + S_n - I(x:n)$$

Last term corresponds to the **mutual information**. The system follows the *local* second law

$$d_t S_x - \beta_x Q_x - i_x \geq 0$$
$$d_t S_n - \beta_S Q_S - \beta_D Q_D - i_n \geq 0$$
$$d_t I(x:n) = i_n + i_x$$

Landauer's principle states that an irreversible computational operation cannot be performed without thermal emission in the computer. Our goal is to use this formalism to evaluate the thermodynamic losses in the most elementary irreversible operation: the Landauer's erasure.

1.- The thermodynamics of hybrid systems admits an interesting interpretation in terms of information. While the ordinary laws of Thermodynamics are still useful globally, the bipartition of entropy allows us to better understand the processes occurring in each of the parts, which may be relevant in nanoscience applications.

From a fundamental point of view, these advances bring us closer to foundational ideas of Thermodynamics, such as Maxwell's Demon or Szillard's Engine.

2.- The role of information can be directly analysed from an experimental point of view, by examining the efficiency of different phenomena (erasure, ergotropy, self-oscillations...). This analysis is generating feedback between experiments and theory with useful technological approaches.

[1]Wen, Y., Ares, N., Schupp, F. J., Pei, T., Briggs, G. A. D., & Laird, E. A. (2020). A coherent nanomechanical oscillator driven by single-electron tunnelling. Nature physics, 16(1), 75-82.
[2] Wächtler, C. W., Strasberg, P., Klapp, S. H., Schaller, G., & Jarzynski, C. (2019). Stochastic thermodynamics of self-oscillations: the electron shuttle. New Journal of Physics, 21(7), 073009.
[3] Horowitz, J. M., & Esposito, M. (2014). Thermodynamics with continuous information flow. Physical Review X, 4(3), 031015.

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