Noise in Physical Systems Laboratory

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Improving energy efficiency in ICT? Limit is the sky

Research recently published on Nature Communications shows that traditional logic gates, used in present computers, could be operated without minimum energy dissipation.

Reducing energy consumption in Information and Communication Technology (ICT) devices has nowadays become a strategic task to further improve performances and diffusion of such technology. Both the future of supercomputing and the dawn of the Internet-of-Things scenario are at risk if the power consumption problem is not solved: too much electric energy is required by ICT devices. On the other hand: aren't we tired enough of continuously recharging the battery of mobile phones?

To complicate things, the continuous improvement in the efficiency (number of operation per Watt) of computing devices over the years has finally brought the technology close to what was supposed to be a fundamental limit of physics: the so-called Landauer's limit.

An experiment at NiPS Lab, in Perugia (Italy) shows that a traditional logic gate could, in principle, be operated below the Landauer's limit and thus the supposed minimum energy expenditure for operating traditional logic gates, does not exist. A good news for those interested in further improving energy efficiency in ICT.

The results of this experiment made by the scientists of NiPS Laboratory, led by Prof. Luca Gammaitoni, at the University of Perugia, published on Nature Communications on 28th June 2016, will be presented in the next few weeks at two international conferences: the *ICT-Energy Science conference* in Aalborg (DK) on Aug. 17th by Miquel Lopez-Suarez and the *ICAND 2016 conference* in Denver (CO) on Aug. 29 by L. Gammaitoni.

Landauer's limit

In 1961 **Ralph Landauer,** at that time at IBM, published a work where for the first time "information", usually considered a purely mathematical quantity, assumed a role in physics (IBM JOURNAL OF RESEARCH AND DEVELOPMENT, VOL. 5, NO. 3, 1961). Specifically, the work of Landauer was aimed at identifying the minimum energy required to do computation, using standard thermodynamics. Landauer wrote:

We shall call a device logically irreversible if the output of a device does not uniquely define the inputs. We believe that devices exhibiting logical irreversibility are essential to computing. Logical irreversibility, we believe, in turn implies physical irreversibility, and the latter is accompanied by dissipative effects.

In fact most of the standard logic operations in ordinary computers show "logical irreversibility". This is the case, for example, of the popular "OR" gate where we have two bits at the input and one bit at the output. In this way the sole knowledge of the value of the output is not enough to infer the actual values of the inputs (from this the idea of "irreversibility").

Soon after Landauer's paper other scientists worked to deepen and extend Landauer's principle to more general aspects of information processing. The most important result in this effort is attributed to **Charles Henry Bennett**, at IBM he himself. In 1973 he published a work entitled "Logical reversibility of computation"

(IBM Journal of Research and Development, vol. 17, no. 6, pp. 525-532, 1973) where he proposed to introduce a model of computing, i.e. new devices, where there was no information decrease between the input and output of any logic operation.

The motivation that led Bennet to introduce logical reversible operations was to overcome the minimum energy expenditure introduced earlier by Landauer. Bennet wrote:

Landauer has posed the question of whether logical irreversibility is an unavoidable feature of useful computers, arguing that it is, and has demonstrated the physical and philosophical importance of this question by showing that whenever a physical computer throws away information about its previous state it must generate a corresponding amount of entropy. Therefore, a computer must dissipate at least $k_B T \ln \mathbf{2}$ of energy (about $\mathbf{3} \times \mathbf{10}^{-21}$ Joule at room temperature) for each bit of information it erases or otherwise throws away.

Most notably this limit was generally attributed to all the logical irreversible devices and among them the traditional logic gates, like “OR”, “AND” and “NAND”. Landauer and Bennet works did not go unnoticed and a significant amount of scientific literature was produced to oppose or to support the existence of such minimum limit. It is not exaggerated to state that for more than 40 years the topic has been considered **highly controversial**.

Finally, this year an experiment at NiPS Lab, in Perugia (Italy) showed that **irreversible logic gates** can be operated below the Landauer’s limit and the supposed minimum energy expenditure for operating traditional logic gates does not exist.

The experiment

The experiment measured the amount of energy dissipated during the operation of a traditional “OR” logic gate, made with micromechanical cantilever acted by electrostatic forces, and showed that the logic operation can be performed with an energy toll as small as 5% of the expected limit of $k_B T \ln 2$. The conclusion of the Nature Communication article is that there is no fundamental limit and reversible logic is not required to operate computers with zero energy expenditure.

The difficulty of the experiment relies on the extraordinary sensitivity required to show that the Landauer limit could be overcome: better than 10^{-21} Joule, where 1 Joule is the energy that it takes to rise an apple for one meter above ground. This is a very small amount of energy in any regards.

The importance of the experiment is in the demonstration that there is no limit to how much we can lower energy consumption during computation. This will change our understanding of the energy dissipation processes and push forward the research.

It is expected this result will impact future developments at least in the following aspects:

- It will push the research towards “zero-power” computing: the search for new information processing devices that consume less and less energy. This is of strategic importance for the future of the entire ICT sector that has to deal with the problem of excess heat production during computation.
- It will call for a deep revision of the “reversible computing” field. In fact one of the main motivations for its own existence (the presence of a lower energy bound) disappears.

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http://www.nature.com/ncomms/2016/160628/ncomms12068/full/ncomms12068.html