Computing study refutes famous claim that 'information is physical'

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A quote often attributed to Einstein reads: "Everybody knows that some things are simply impossible until somebody who doesn't know that makes them possible."

In 1961, Ralph Landauer at IBM published a work suggesting that information, usually considered a purely mathematical quantity, played a role in physics (*IBM Journal Of Research And Development*, Vol. 5, no. 3, 1961). Specifically, Landauer aimed at identifying the minimum energy required to do computation using standard thermodynamics. Landauer initially focused on a specific operation, today know as "Landauer reset," which consists of putting into a given logic state (e.g. "0" state) a binary switch that can be in each of the two possible logic states "0" or "1." Such an operation is sometimes interpreted as "information erasure," because it reduces the amount of information that can be associated with the binary switch. Before the operation, two possible states exist; after, there is only one possible state.

According to thermodynamics, such a reduction in the number of available states for a physical device requires a minimum energy expenditure, easily computable using previous work done by Boltzmann.

In the same paper, Landauer generalized this result associated with the reset operation to the cases in which there was a decrease of information between the input and the output of a computing system. This is the case of the so-called logically irreversible devices. 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 "OR" gate, in which there are 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 this principle to more general aspects of information processing. The most important result in this effort is attributed to Charles Henry Bennett, also at IBM. In 1973, he published a work titled "Logical reversibility of computation" (IBM Journal of Research and Development, vol. 17, no. 6, pp. 525-532, 1973), in which he proposed a model of computing with 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 kBT ln2 of energy (about 3×10^{-21} Joule at room temperature) for each bit of information

it erases or otherwise throws away."

This limit was generally attributed to all the logical irreversible devices, and among them, the traditional logic gates like "OR", "AND" and "NAND." The work of Landauer and Bennet inspired a significant amount of scientific literature opposing or supporting the existence of such a minimum limit. It's no exaggeration to state that for more than 40 years, the topic has been considered highly controversial.

Now, an experiment has settled this controversy. It clearly shows that there is no such minimum energy limit and that a logically irreversible gate can be operated with an arbitrarily small energy expenditure. Simply put, it is not true that logical reversibility implies physical irreversibility, as Landauer wrote.

The results of this experiment by the scientists of NiPS Laboratory at the University of Perugia are published today in *Nature Communications*. They measured the amount of energy dissipated during the operation of an "OR" gate (that is clearly a logically irreversible gate) and showed that the logic operation can be performed with an energy toll as small as 5 percent of the expected limit of kBT ln2. The conclusion of the *Nature Communications* article is that there is no fundamental limit and reversible logic is not required to operate computers with zero energy expenditure.

Why did it take so long to discover this? Partly because the experiment had to achieve exceptional sensitivity in order to show that the Landauer limit could be beaten: more than 10 to 21 Joule, where 1 Joule is the energy that it takes to raise an apple one meter above the ground. This is a very small amount of energy.

What are the implications of this discovery? The "OR" logic gate used by the scientists is realized with a micro-electromechanical cantilever,

acted on by electrostatic forces. Although it cannot be considered a promising new technology for substituting the energetically expensive transistors in today's computers, 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 research forward.

This result is likely to 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 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.

Though Landauer famously said "information is physical," it turns out that information is not so physical after all.

More information: M. López-Suárez et al. Sub-kBT micro-electromechanical irreversible logic gate, *Nature Communications* (2016). DOI: 10.1038/ncomms12068

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