The realization of a new type of information demon that profits from gambling strategies

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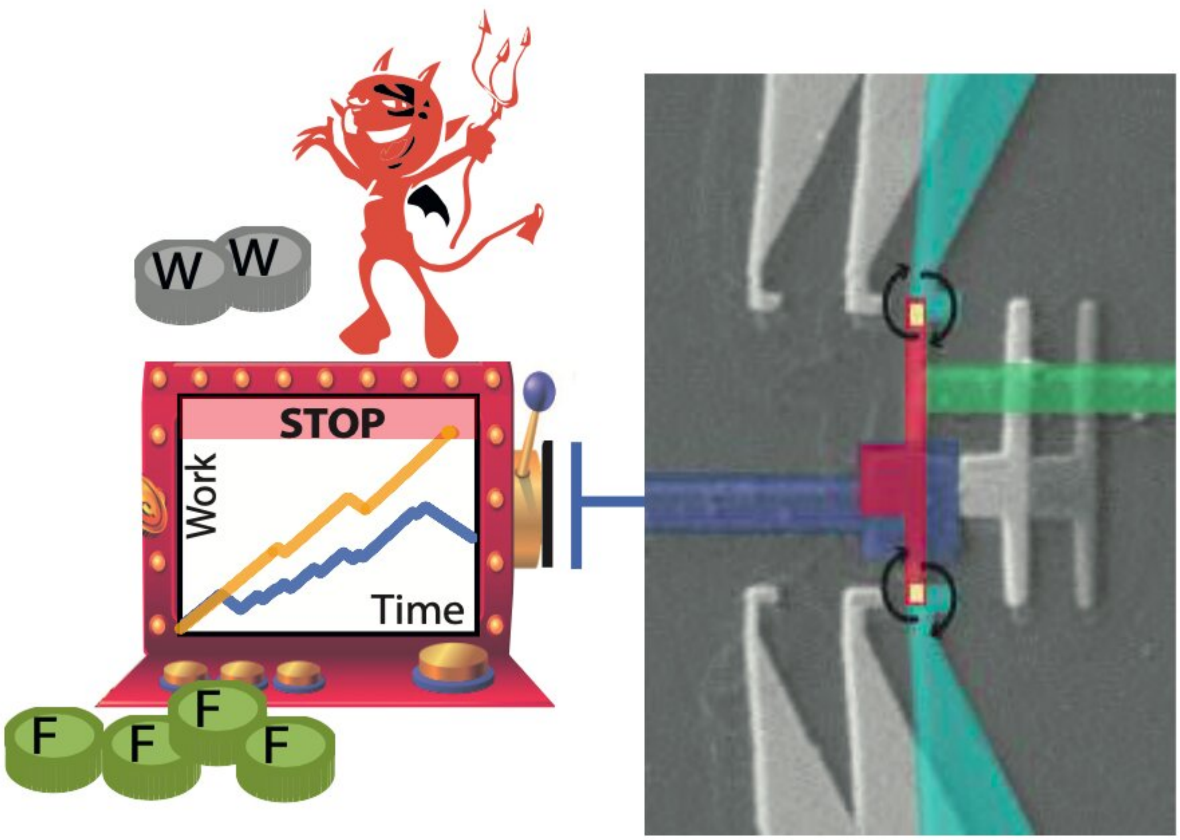

Credit: Manzano et al.

Researchers at the International Centre for Theoretical Physics (ICTP) in Italy and the PICO group at Aalto University in Finland have introduced the idea of an information demon that follows a customary gambling strategy to stop non-equilibrium processes at stochastic times. The new demons they realized, which differ from the renowned Maxwell's demon, were presented in a paper published in *Physical Review Letters*.

"Our research was driven by curiosity," Gonzalo Manzano, one of the researchers who carried out the study, told Phys.org. "We asked ourselves about the implications of processes whose fluctuations fulfill (or break) some strong properties of stochastic processes on the link between thermodynamics and information."

The recent study by Gonzalo Manzano, Edgar Roldan and their colleagues is based on previous works investigating the link between information and thermodynamics at the stochastic level. It also draws inspiration from recent research that explored the properties of a unique family of stochastic processes known as martingales in the context of thermodynamics.

Martingales are paradigmatic examples of stochastic processes that have been used in a variety of fields, including finance and mathematics. Manzano, Roldan and their colleagues applied knowledge of martingales to the study of thermodynamics with the aim of unveiling new universal thermodynamic laws.

"Our paper concerns the following questions: What happens when one gambles with the information acquired about the response of a small system during a nonequilibrium thermodynamic process?" Edgar Roldan, another researcher involved in the study, told Phys.org. "This can be formulated as a 'stopping' condition in which the gambler quits (e.g., quits playing roulette when its revenues have exceeded or fallen below a given amount)."

The main objective of the study carried out by Manzano, Roldan and their colleagues was to investigate the extent to which the laws of thermodynamics apply when using gambling-inspired protocols. To achieve this, they further developed the martingale theory of thermodynamics, a theoretical construct that they introduced a few years ago.

In their new study, the researchers introduced the idea of "gambling demons." A gambling demon is essentially a new version of the so-called Maxwell's demon, an idea and thought experiment introduced by physicist James Clerk Maxwell in 1867. In this thought experiment, Maxwell showed that by using information about the microscopic dynamics of a system, it may be possible to subvert the second law of thermodynamics, which states that heat will always move from hot to cold until it is spread evenly through a system. The apparent paradox has been an active area of research for many decades and was settled by considering the physical nature of the information produced by the demon, which would require work to be erased, according to Landauer's principle (first proposed in 1961).

"In Maxwell's original version, a small intelligent being (i.e., the demon) is able to defy the second law of thermodynamics by observing and manipulating a thermodynamic system at the microscopic level," Manzano said. "Even if the paradox is only apparent, Maxwell's demon is still of great interest today, because it allows extracting work at the price of producing entropy in the form of information. In the new version, we push the demon to its limits by taking away some of his powers."

In their paper, Manzano, Roldan and their colleagues considered the possibility that their theorized gambling demon can still observe the microscopic dynamics of a system but cannot manipulate it at will. Rather than manipulating the system, the demon can only decide to stop the thermodynamic process at any time it considers right.

"One may think that this less powerful demon cannot defy the second law, as in Maxwell's original setup, since one may naively expect that the demon would not be able to make good use of the information about the microscopic dynamics of the system," Manzano said. "However, we have seen that this is not the case, but the demon needs (i) a good strategy to meaningfully decide when to stop, and (ii) the dynamics of the system under consideration need to be non-stationary (or more technically, it needs to break time-reversal symmetry) and therefore, some investment of work is needed."

Manzano, Roldan and their colleagues explored the idea of gambling demons using techniques employed to study stochastic and quantum thermodynamics. More specifically, they derived a universal fluctuation theorem that relates the behavior of relevant thermodynamic quantities when stopping strategies are applied. This allowed them to explore the limits of these stopping strategies. Subsequently, the researchers verified their predictions in a series of experiments.

"The experimental configuration of our collaborators at the Pekola lab consisted of a small copper island maintained at a very low temperature (0.67 Kelvin) where electrons from two aluminum leads can jump," Manzano said. "In addition, a time-dependent voltage is applied to the metallic island, performing work into the system, and ensuring that the system is not stationary."

At particularly low temperatures, single electrons that enter a metallic island can be counted individually. By counting electrons one by one, the researchers were able to gather valuable information about a system. Using this information, they were then able to compute the relevant thermodynamic quantities and test stopping strategies.

"While we don't stop the system dynamics on the fly, the data obtained allow us to analyze the effect of different gambling strategies corroborating our theoretical predictions," Manzano said. "We also find that in this setup, a 'winning' strategy consists in stopping the dynamics if too much work is being invested. Applying it, we found that work can be extracted from information, overcoming the traditional second-law limits."

The researchers draw an analogy between the demon they introduced and casino games. According to Roldan, "one could think of a gambler playing the roulette and expecting profit based on his/her good chance of winning. If this individual played every day until the casino closed, he/she should expect that to lose money. However, the gambler could also devise a strategy that would allow him/her to make a net profit, for instance, by only playing until his/her revenue exceeds a pre-defined threshold value." Nevertheless, such strategies might only work if the probabilities of the numbers in the roulette change during the day.

"Consider a small system immersed in a thermal bath which is driven for a fixed total time following a deterministic nonequilibrium protocol," Roldan said. "If the protocol is always allowed to be completed, the work done on the system averaged over many realizations of the process is larger or equal than its free energy change, as follows from the second law of thermodynamics. What happens, however, when the process is stopped at a random time following a given criterion (e.g., a gambling strategy)?"

The idea can be linked to the concept of information demons. In the context of thermodynamics, for instance, Maxwell's demon leads to apparent violations of the second law by opening and closing a gate separating two containers at random times.

"Maxwell's demon uses two properties to seemingly violate the limits of the second law," Roldan explained. "First, it acts at stochastic times when a specific event takes place, a hot/cold particle gets close to the gate. Second, it applies feedback control, opening the gate it changes the dynamics of the process."

The gambling demons proposed by Manzano, Roldan and their colleagues are essentially devices that allow for apparent violations of the second law of thermodynamics using only the first component of Maxwell's original demon proposal. This first component is the execution of a task at a stochastic time. The resolution of the paradox follows nevertheless the same lines as it does in the original version.

"The key idea here is the use of a very particular set of strategies inspired in gambling that lead to stopping of the dynamics following a prescribed criterion," Roldan said. "Because the system upon which the demon acts is small and affected by fluctuations, the time at which the demon stops the dynamics is different in each cycle. This is crucial for work extraction, as we show in our work."

In their paper, Manzano, Roldan and their colleagues show that the gambling demon they realized can be used to extract work from a thermodynamic system beyond its free energy change. Using martingale theory, they calculated the average work extraction that these demons can achieve and tested their predictions in an experiment.

In this experiment, the researchers analyzed time series data collected using a single-electron transistor. They then applied gambling strategies based on measurements of the work done to the transistor. In other words, when the work exceeded a specific threshold, the demon stopped the system's dynamics; otherwise, it continued its evolution for a larger (fixed) amount of time.

"Our work implies that information-to-work conversion can be realized in systems where a precise control of the dynamics is not available," Manzano said. "This greatly extends the scope of Maxwell's original scenario and clarifies the minimal ingredients needed to link information and thermodynamics."

The idea of gambling demons and the universal nonequilibrium relations described in the paper could be applied to a number of areas of study. In the specific context to which they applied it, the demon could stop a system's dynamics following a strategy. However, the relations they described could also be applied to systems in which dynamics naturally stop when a specific condition is met, such as biological systems.

"The key insight of our study is that contrarily to beliefs up until now, it is not necessary to apply feedback to extract work beyond the free energy change," Roldan said. "This can be done applying suitable gambling strategies and we show how much work one can extract from them. Notably, our findings suggest that the amount of work one can extract through gambling is bounded by a measure of the time asymmetry of the physical process, so highly irreversible (far from equilibrium) dynamics can lead to large values of work extraction, much like arbitrage opportunities in the stock market."

In the future, the new gambling-based approach proposed by Manzano, Roldan and their colleagues could be used to improve the efficiency of microscopic heat engines and motors. In their next studies, the researchers plan to analyze the results they collected from a quantum physics standpoint. Their work could pave the way towards the development of gambling-based strategies for research and technology development that outperform more conventional methods.

"We believe our study is a first step in the development of new possibilities for efficient energy harvesting protocols at the nanoscale, which may use our fundamental knowledge on how to profit from fluctuations using clever information processing strategies," Roldan said.

More information: Thermodynamics of gambling demons. *Physical Review Letter*(2021). [DOI: 10.1103/PhysRevLett.126.080603](https://doi.org/10.1103/PhysRevLett.126.080603)