Physicists pin down the pay off between speed and entropy

August 25 2020, by Anna Demming

Understanding the relation between the rates of processes and the entropy produced can give insights into some of the stochastic processes that sustain life. Credit: pxfuel

"You have to work harder to get the job done faster," explains Gianmaria Falasco, a researcher at the University of Luxembourg as he sums up the results of his latest work with Massimiliano Esposito. This will come as no surprise to anyone with any experience of racing around trying to meet appointments and deadlines, but by defining specific parameters for the relation between work expended in terms of dissipation and the rate at which a system changes state, Falasco and Esposito provide a valuable tool for those developing ways of manipulating non-equilibrium systems, be that the behavior of living cells or an electronic circuit. Additionally, the "dissipation-time uncertainty relation" they developed to define this behavior is tantalizingly suggestive of other uncertainty relations in quantum physics.

Life is a non-equilibrium process, ceaselessly maintaining an organism against decomposition and disintegration into its environment. Take a mouse or any other creature to equilibrium, and all you have is a pile of goo. A lot of the cellular processes that sustain life can be described as chemical reactions that are essentially probabilistic and prone to thermal fluctuations; nonetheless, they enable molecular motors fuelled by adenosine triphosphate (ATP), various cell signaling pathways and many of the other biological processes that keep us ticking over. As device sizes continue to shrink, thermal fluctuations become increasingly prominent in the dynamics of their mechanical components, as well, not to mention the electronic circuits that drive them. For understanding these and a wealth of other non-equilibrium systems, there is great value in a clean mathematical definition that pins down the pay-off between dissipation and the rates at which these processes proceed.

These latest results from the University of Luxembourg researchers follow on from developments over the past 20 years in what Esposito describes as a "real boom" in the field of statistical physics, and nonequilibrium statistical physics, in particular. Over the 1990s and 2000s, a series of theorems emerged that placed parameters around the probabilistic nature of the second law of thermodynamics, which states that the entropy of an isolated system should "tend" to increase until it reaches equilibrium. These fluctuation theorems found that the exponential of entropy production equals the ratio of the probability of fluctuations moving in the direction of increasing entropy versus the probability of fluctuations going against the grain in this respect. "In a sense, we are still discovering all the consequences of these fluctuation relations and of this field that is called stochastic thermodynamics," says Esposito.

A shift in perspective

A seminal development in this flurry of activity was the "thermodynamic uncertainty relation," defined in 2015 by researchers at the Universität Stuttgart in Germany. They showed that the precision of a system's final state increased with the amount of energy needed to shift it. (These theorems generally refer to small systems where thermal dynamics cause significant fluctuations). Meanwhile, in quantum physics, another seminal development had placed a speed limit on how fast you could achieve the kinds of manipulations of quantum states that are used for quantum computation. "Our work was born in the effort of joining these two research lines," says Falasco.

As they applied themselves to this work, Falasco and Esposito noticed that most studies considered how a system can change its state, but real physical systems performing tasks of interest are more likely to change the state of their surroundings instead by moving (or changing) energy or matter from one place (or form) to another. Take a radiator, essentially a pipe of hot water connecting the boiler to a cold room—the radiator doesn't change its state, but it does heat the room. "We arrived at our result turning this idea into math," says Falasco.

Once Falasco and Esposito had defined their systems in this way and applied the probability ratio defined in the fluctuation theorems, they were able to define a disarmingly simple relationship describing the pay-off between the time taken to reach a different state and the energy dissipated (or entropy produced): The product of the average time and the energy dissipated can never be less than the value of one of the universal constants of nature, the Boltzmann constant.

See this relation written out, and it bears a fascinating resemblance to Heisenberg's uncertainty relations for the precision by which a quantum system's energy and time or momentum and position can be predicted from initial conditions—the product of these quantities can never be less than half of Planck's constant. "So the analogy is very striking and intriguing," says Esposito. Gaining a better understanding of what significance if any the similarity bears will be the focus of future work in this field.

More information: Gianmaria Falasco and Massimiliano Esposito, The dissipation-time uncertainty relation, *Physics Review Letter* (2020). journals.aps.org/prl/accepted/ … d47de1eebb1b192da9e5