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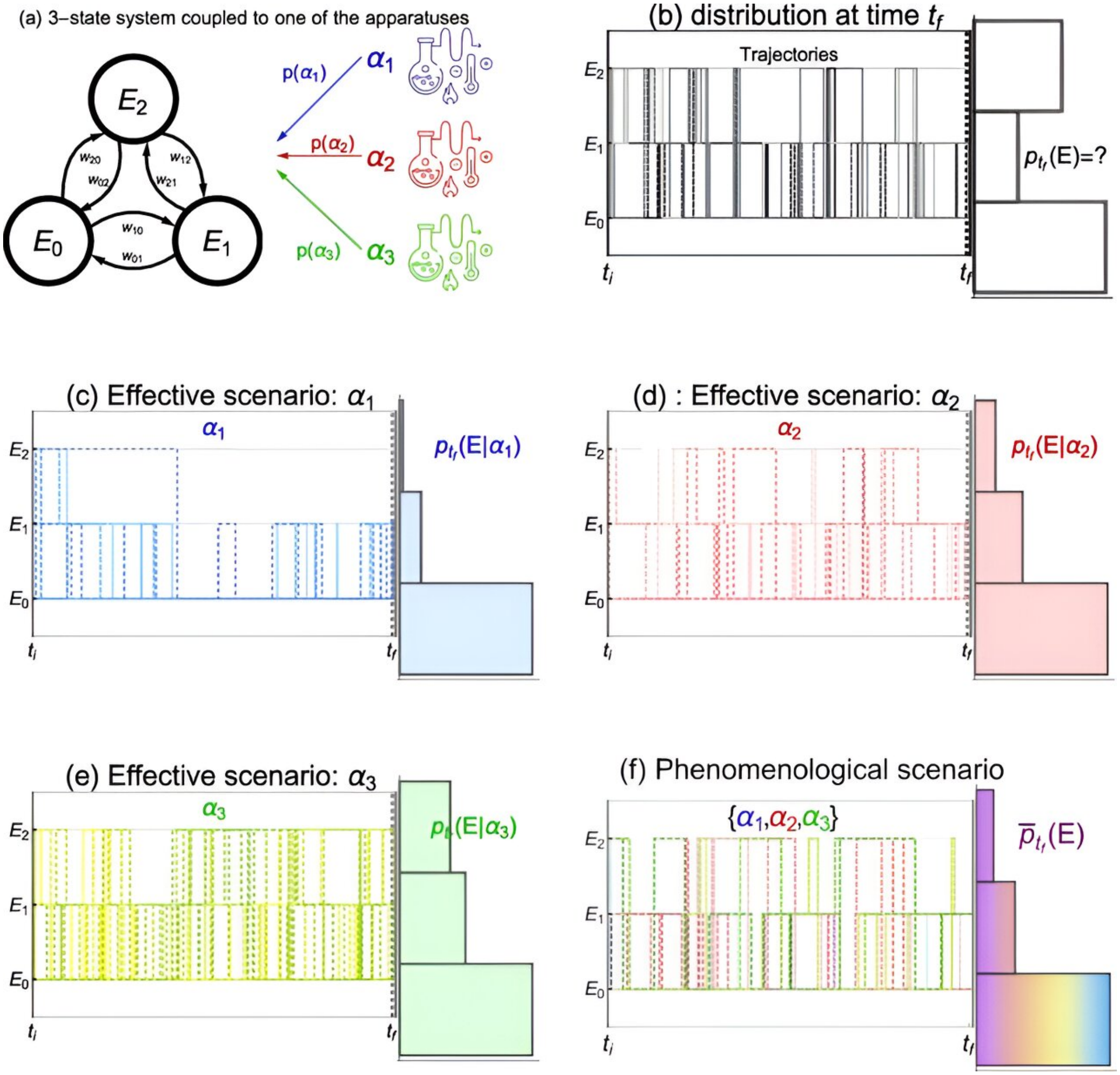
Physicists identify overlooked uncertainty in real-world experiments

January 15 2024



Comparison of the two uncertain apparatus scenarios considered in this paper.

Credit: *Physical Review Research* (2024). DOI: 10.1103/PhysRevResearch.6.013021

The equations that describe physical systems often assume that measurable features of the system—temperature or chemical potential, for example—can be known exactly. But the real world is messier than that, and uncertainty is unavoidable. Temperatures fluctuate, instruments malfunction, the environment interferes, and systems evolve over time.

The rules of statistical physics address the uncertainty about the state of a system that arises when that system interacts with its environment. But they've long missed another kind, say SFI Professor David Wolpert and Jan Korbel, a postdoctoral researcher at the Complexity Science Hub in Vienna, Austria.

In a new paper published in *Physical Review Research*, the pair of physicists argue that uncertainty in the thermodynamic parameters themselves—built into equations that govern the energetic behavior of the system—may also influence the outcome of an experiment.

"At present, almost nothing is known about the thermodynamic consequences of this type of uncertainty despite its unavoidability," says Wolpert. In the new paper, he and Korbel consider ways to modify the equations of stochastic thermodynamics to accommodate it.

When Korbel and Wolpert met at a 2019 workshop on information and thermodynamics, they began talking about this second kind of uncertainty in the context of non-equilibrium systems.

"We wondered, what happens if you don't know the thermodynamic parameters governing your system exactly?" recalls Korbel. "And then we started playing around." The equations that describe thermodynamic systems often include precisely defined terms for things like temperature and chemical potentials. "But as an experimenter or an observer you don't necessarily know these values" to very large precision, says Korbel.

Even more vexing, they realized that it's impossible to measure parameters like temperature, pressure, or volume precisely, both because of the limitations of measurement and the fact that these quantities change quickly. They recognized that uncertainty about those parameters not only influences information about the original state of the system, but also how it evolves.

It's almost paradoxical, Korbel says. "In thermodynamics, you're assuming uncertainty about your state so you describe it in a probabilistic way. And if you have quantum thermodynamics, you do this with quantum uncertainty," he says. "But on the other hand, you're assuming that all the parameters are known with exact precision."

Korbel says the new work has implications for a range of natural and engineered systems. If a cell needs to sense the temperature to carry out some chemical reaction, for example, then it will be limited in its precision. The uncertainty in the temperature measurement could mean that the cell does more work—and uses more energy. "The cell has to pay this extra cost for not knowing the system," he says.

Optical tweezers offer another example. These are high-energy laser beams configured to create a kind of trap for charged particles. Physicists use the term "stiffness" to describe the particle's tendency to resist being moved by the trap. To determine the optimal configuration for the lasers they measure the stiffness as precisely as possible. They typically do this by taking repeated measurements, assuming that the uncertainty arises from the measurement itself.

But Korbel and Wolpert offer another possibility—that the uncertainty arises from the fact that the stiffness itself may be changing as the system evolves. If that's the case, then repeated identical measurements won't capture it, and finding the optimal configuration will remain elusive. "If you keep doing the same protocol, then the particle doesn't end up in the same point, you may have to do a little push," which means extra work that's not described by the conventional equations.

This uncertainty could play out at all scales, Korbel says. What's often interpreted as uncertainty in measurement may be uncertainty in the parameters in disguise. Maybe an experiment was done near a window where the sun was shining, and then repeated when it was cloudy. Or perhaps the air conditioner kicked on between multiple trials. In many situations, he says, "it's relevant to look at this other type of uncertainty."

More information: Jan Korbel et al, Nonequilibrium thermodynamics of uncertain stochastic processes, *Physical Review Research* (2024). DOI: 10.1103/PhysRevResearch.6.013021

Provided by Santa Fe Institute

Citation: Physicists identify overlooked uncertainty in real-world experiments (2024, January 15) retrieved 27 April 2024 from https://phys.org/news/2024-01-physicists-overlooked-uncertainty-real-world.html