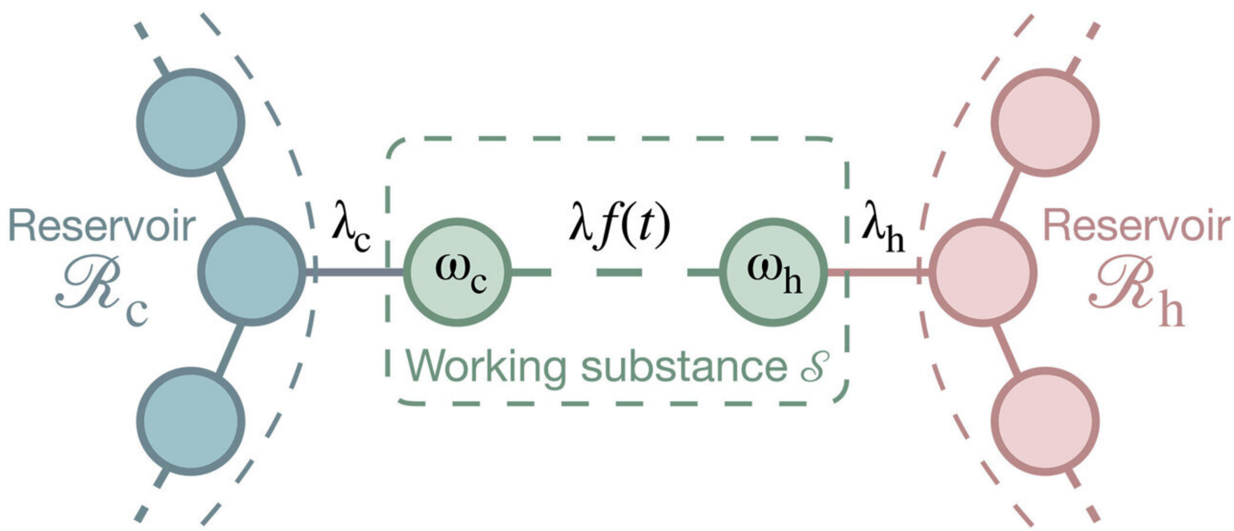
Quantum mechanics trumps the second law of thermodynamics at the atomic scale

October 16 2025, by Lena Jauernig



Two-oscillator quantum engine. Credit: *Science Advances* (2025). DOI: 10.1126/sciadv.adw8462

Two physicists at the University of Stuttgart have proven that the Carnot principle, a central law of thermodynamics, does not apply to objects on the atomic scale whose physical properties are linked (so-called correlated objects). This discovery could, for example, advance the development of tiny, energy-efficient quantum motors. The derivation has been published in the journal *Science Advances*.

Internal combustion engines and steam turbines are thermal engines:

They convert thermal energy into mechanical motion—or, in other words, heat into motion. In recent years, quantum mechanical experiments have succeeded in reducing the size of heat engines to the microscopic range.

"Tiny motors, no larger than a single atom, could become a reality in the future," says Professor Eric Lutz from the Institute for Theoretical Physics I at the University of Stuttgart. "It is now also evident that these engines can achieve a higher maximum efficiency than larger heat engines."

Professor Lutz and Dr. Milton Aguilar, a postdoctoral researcher at the Institute for Theoretical Physics I, explain the reasons behind this in their paper. In this interview, the two scientists summarize their discovery.

What exactly did you discover?

Almost exactly 200 years ago, French physicist Sadi Carnot determined the maximum efficiency of heat engines. The Carnot principle, the second law of thermodynamics, was developed for large, macroscopic objects. This applies to steam turbines, for example. However, we have now been able to prove that the Carnot principle must be extended to describe objects on the atomic scale—for example, strongly correlated molecular motors.

Why is that?

Carnot demonstrated that the temperature difference has a decisive influence: the greater the difference between hot and cold, the higher the maximum possible efficiency of a heat engine. However, the Carnot principle neglects the influence of so-called quantum correlations. These are special bonds that form between particles on a very small scale.

For the first time, we have derived generalized laws of thermodynamics that fully account for these correlations. Our results show that thermal machines operating at the atomic scale can convert not only heat but also correlations into work. As a result, they can produce more work—and the efficiency of a quantum engine can surpass the traditional Carnot limit.

What prospects does your basic research open up?

Our work deepens our knowledge of the world at the atomic level. The better we understand the physical laws that apply in these dimensions, the sooner we will be able to use them to develop technologies for tomorrow—such as tiny, highly efficient quantum motors that can precisely perform tasks at the nanoscale. Perhaps one day such motors will power medical nanobots or control machines that process materials at the atomic level? The potential is enormously diverse.

More information: Milton Aguilar et al, Correlated quantum machines beyond the standard second law, *Science Advances* (2025). DOI: 10.1126/sciadv.adw8462

Provided by University of Stuttgart

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