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Efficiency asymmetry: Scientists report fundamental asymmetry between heating and cooling

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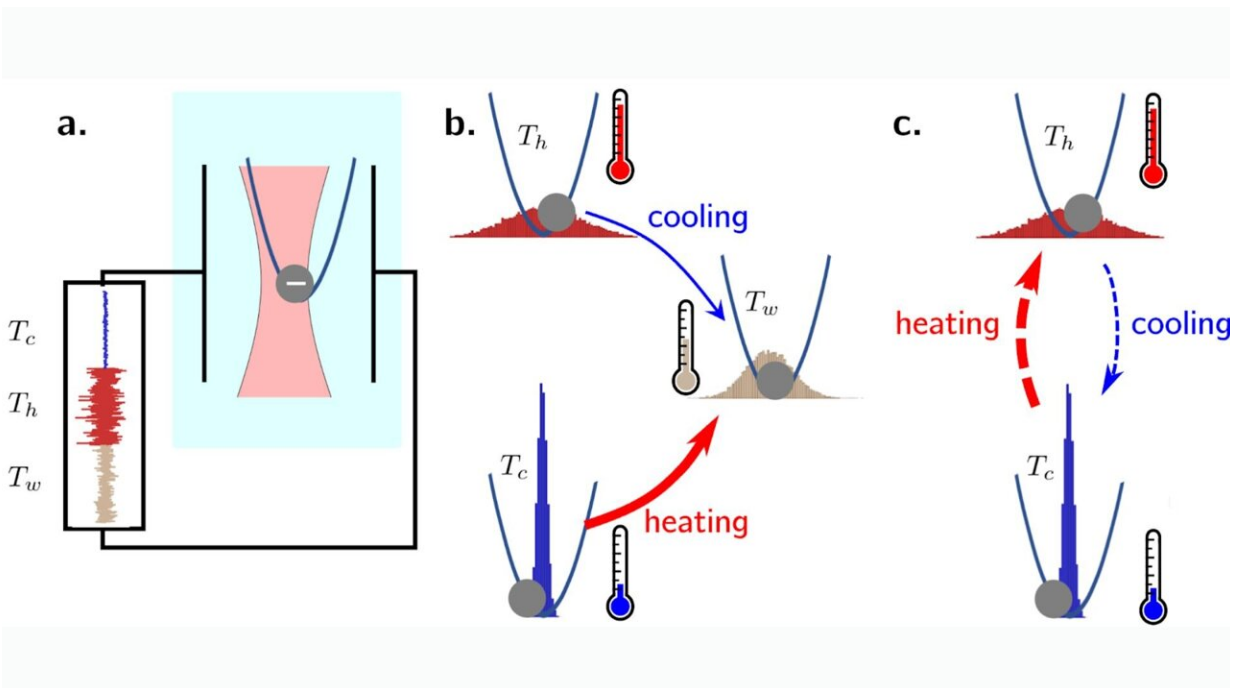

(a) Experimental Setup: A charged microparticle is trapped using a laser beam in a parabolic trap. Temperature control is achieved through a noisy electrical signal simulating a thermal bath. (b) Evolution Kinematics: The evolution kinematics are analyzed between two initial states—one hotter and one colder than the intermediate target state, equidistant from both. Results show that heating is faster than cooling in this scenario. (c) Temperature Asymmetry: The initially observed asymmetry holds when focusing on two temperatures, comparing the processes of cooling and heating between them. Credit: Prof. Raúl A. Rica Alarcón/Dr. Aljaz Godec

A new study led by scientists from Spain and Germany has found a fundamental asymmetry showing that heating is consistently faster than cooling, challenging conventional expectations and introducing the concept of "thermal kinematics" to explain this phenomenon. The findings are published in *Nature Physics*.

Traditionally, heating and cooling, fundamental processes in thermodynamics, have been perceived as symmetric, following similar pathways.

On a microscopic level, heating involves injecting energy into individual particles, intensifying their motion. On the other hand, cooling entails the release of energy, dampening their motion. However, one question has always remained: Why is heating more efficient than cooling?

To answer this questions, researchers led by Associate Prof. Raúl A. Rica Alarcón from the Universidad de Granada in Spain and Dr. Aljaz Godec from the Max Planck Institute for Multidisciplinary Sciences in Germany have introduced a new framework: thermal kinematics.

Speaking of their motivation behind exploring such a fundamental topic, Prof. Alarcón told Phys.org, "Since childhood, I've been intrigued by why heating is more efficient than cooling. And have questions like: 'Why don't we have a device like a microwave oven for fast cooling?'"

Dr. Godec added, "Thermal relaxation phenomena have always been a big research topic in the group (these are hard problems in non-equilibrium physics). However, specific questions about the heating and cooling asymmetry were initially provoked by mathematical intuition. We did not expect the answer to be so striking."

Processes at microscopic scales

At the microscopic level, heating and cooling are processes involving the exchange and redistribution of energy among individual particles within a system.

In the context of the recent research, the focus is on understanding the dynamics of microscopic systems undergoing thermal relaxation—how these systems evolve when subjected to temperature changes.

In heating, energy is injected into each particle of a system, leading to an intensification of the particles' motion. This causes them to move more vigorously. The higher the temperature, the more intense the Brownian (or random) motion of these particles due to increased collisions with surrounding water molecules.

On the other hand, cooling at the microscopic level involves the release of energy from individual particles, resulting in a dampening of their motion. This process corresponds to the system losing energy, leading to a decrease in the intensity of particle movement.

"Our work is devoted to the analysis of the evolution of a microscopic system after it is driven far from equilibrium. We consider the thermalization of a microscopic system, i.e., how a system at a given temperature evolves to the temperature of a thermal bath it is put in contact with," explained Dr. Godec.

Prof. Alarcón. further explained, "A clear example would be taking an object from a boiling-water bath (at 100 degrees Celsius) and immersing it in a mixture of water and ice (at 0 degrees Celsius)."

"We compare how fast the system equilibrates with the reverse protocol when the object is initially in the cold bath and heated in boiling water.

We observe that, at the microscale, heating is faster than cooling, and we explain this theoretically by developing a new framework we call thermal kinematics."

Optical tweezers and thermal kinematics

The researchers employed a sophisticated experimental setup to observe and quantify the dynamics of microscopic systems undergoing thermal relaxation. At the heart of their experimentation were optical tweezers—a powerful technique using laser light to capture single microparticles made of silica or plastic.

"These tiny objects move in an apparently random fashion due to the collisions with water molecules, executing the so-called Brownian motion while they are confined to a small region by tweezers. The higher the temperature of the water, the more intense the Brownian motion will be due to more frequent and intense collisions with water molecules," explained Prof. Alarcón.

To induce thermal changes, the researchers subjected the confined microparticles to varying temperatures. They carefully controlled the temperature of the surrounding environment using a noisy electrical signal, simulating a thermal bath.

"Our experimental device allows us to track the motion of the particle with exquisite precision, giving access to these previously unexplored dynamics," said Dr. Godec.

By manipulating the temperature and observing the resulting movements, the team gathered crucial data to understand the intricacies of heating and cooling at the microscale level.

The development of the theoretical framework (thermal kinematics) played a pivotal role in explaining the observed phenomena. This framework combined principles from stochastic thermodynamics—a generalization of classical thermodynamics to individual stochastic trajectories—with information geometry.

"Defining distance and speed in the space of probability distributions, we conducted mathematical proofs using methods from analysis to show that the effect is general," explained Dr. Godec.

Thermal kinematics provided a quantitative means to elucidate the observed asymmetry between heating and cooling processes. This allowed the researchers not only to validate theoretical predictions but also to explore the dynamics between any two temperatures, revealing a consistent pattern of heating being faster than cooling.

Asymmetry and Brownian heat engines

Prof. Alarcón and Dr. Godec discovered an unexpected asymmetry in the heating and cooling processes. Initially aiming to experimentally verify a proposed theory by their colleagues at the Max Planck Institute, the researchers found that the asymmetry extended beyond specific temperature ranges, holding true for heating and cooling between any two temperatures.

The implications of this asymmetry extend to Brownian heat engines—microscopic machines designed to generate useful work from temperature differences.

"Understanding how a system thermalizes with different thermal baths can optimize the power generation process. The equilibration time becomes a key parameter for precisely designing the device's operational protocols," explained Prof. Alarcón.

While no immediate practical applications exist, the researchers envision enhanced efficiency in micromotors, microscale cargo transport, and materials that can self-assemble or self-repair.

The broader implications suggest contributions to the development of new general theories for the dynamics of Brownian systems driven far from equilibrium.

"We expect that the effect is not limited to thermal perturbations, quenches in composition, etc., and will likely display analogous asymmetries. At this point, it is too early to make statements about these situations, but we are certainly already thinking about it," added Dr. Godec.

Prof. Alarcón concluded, saying, "We aim to broaden our findings to various protocols and systems, conducting experiments involving small groups of interacting particles and systems with broken time-reversal symmetry. Advancing theoretical understanding and mathematical control of non-self-adjoint stochastic systems is crucial for this direction. Our ongoing strategy involves concurrent development of experiments and theories."

More information: M. Ibáñez et al, Heating and cooling are fundamentally asymmetric and evolve along distinct pathways, *Nature Physics* (2024). DOI: 10.1038/s41567-023-02269-z