



A single-atom heat engine

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The power of an engine scales with the number of particles that make up its working fluid, a generalization that has proven true down to a single atom.

By converting thermal energy into mechanical work, heat engines are used almost universally to generate motion. The working substance in which the heat-to-work conversion takes place is typically a gas or liquid consisting of some 10^{24} atoms. During his 1959 lecture, “There’s Plenty of Room at the Bottom,” presented at an American Physical Society meeting at Caltech, Richard Feynman envisioned motors operating at the atomic level. The realization of such devices, however, had to wait for the advent of nanotechnology for the experimental techniques required to control matter at tiny length scales.

Thermodynamics of small systems

The laws of thermodynamics were originally formulated for macroscopic systems. The typical example, found in most textbooks, dates back to the Industrial Revolution: a gas trapped in a cylinder attached to a moving piston. Work is performed on the gas when the piston is pressed in, whereas work is produced by the gas when it pushes the piston back out. In cases in which both processes take place at the same temperature, the two work values are equal in magnitude—but not in sign—and their sum vanishes.

Net positive work can be obtained when expansion is carried out at a higher temperature than compression. Work production thus necessitates distinct heating and cooling phases and the coupling of the system to two heat reservoirs. Heat engines work by cyclically repeating those expansion and compression steps.

Colloidal particles, enzymes, and molecular machines are common in nature. And because of the particles’ minuscule size, their thermal fluctuations are comparable to their mean energies and cannot be safely neglected, as is often done in the macroworld. As a result, key thermodynamic quantities, such as heat, work, energy, and entropy, are intrinsically random variables. In the past two decades, the framework of thermodynamics has been successfully extended to describe microscopic objects and to include the effects of fluctuations. (See the article by Carlos Bustamante, Jan Liphardt, and Felix Ritort, *PHYSICS TODAY*, July 2005, page 43.)

Those random variables can be defined along single stochastic trajectories that are experimentally measured by tracking the position of a microparticle. In stochastic thermodynamics, as the formalism is now called, work refers to the energy change induced by the variation of an external parameter, such as the position of the piston in a gas-filled cylinder. Heat is the energy

exchanged with the surrounding medium, whose temperature sets that of the small system.

Tiny motor

Four years ago, my colleagues and I wanted to build a heat engine that uses a single atom as the working fluid. To achieve that vision, we held a calcium ion in an electromagnetic Paul trap having an unusual conical shape; the trap is named after Wolfgang Paul, whose invention of the device earned him a share of the Nobel Prize in Physics in 1989. Reservoir-engineering techniques allowed us to couple the ion to hot and cold baths by moving it back and forth in the trap.

To make a cold reservoir, we used standard laser-cooling techniques on the $^{40}\text{Ca}^+$ ion, which loses heat to the photons. To make a hot reservoir, we shook the ion with an electric field, whose noise increases the ion’s kinetic energy. We then modulated the ion’s temperature by passing it back and forth between the reservoirs. Because of energy fluctuations, the ion exists in a thermal distribution whose width is proportional to its temperature.

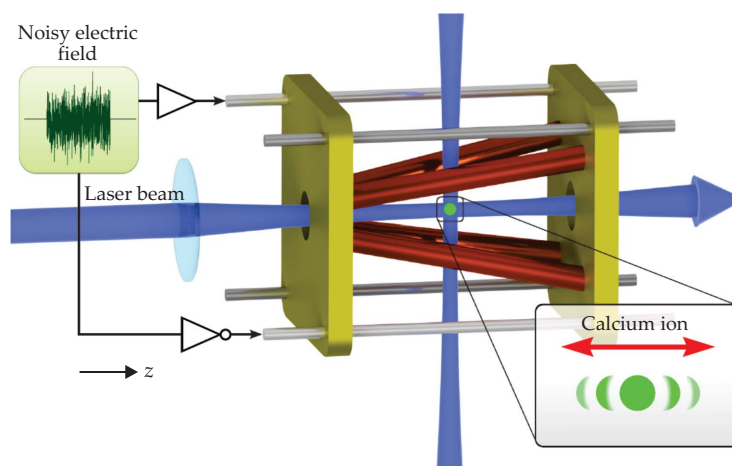


FIGURE 1. A SINGLE TRAPPED ION (green) is confined in a conical ion trap with four RF electrodes (red) having a tapered geometry. The ion is alternately cooled (blue) and heated by noisy electric fields applied to outer electrodes (gray). The engine cycle is implemented in the radial directions, and the work produced after each cycle is stored in the axial (z) direction. The position of the ion, whose oscillatory motion acts like a flywheel, is imaged on a CCD camera. (Adapted from J. Roßnagel et al., *Science* **352**, 325, 2016.)

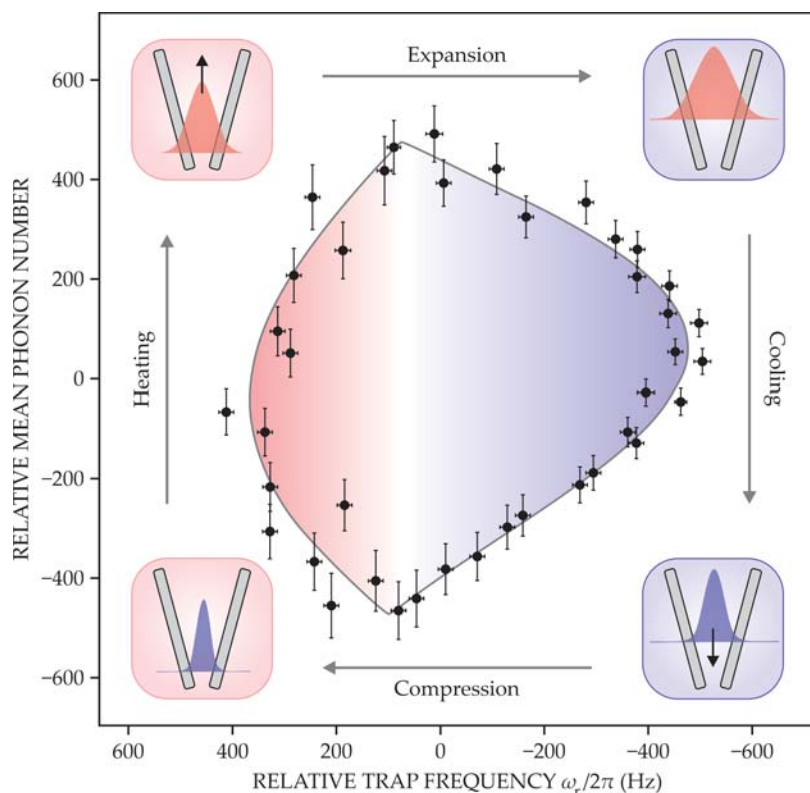


FIGURE 2. THIS THERMODYNAMIC CYCLE of the engine shows the mean occupation, or phonon, number of a $^{40}\text{Ca}^+$ ion as a function of the (radial) trap frequency ω_r of the harmonic trapping potential. The area inside the curve is proportional to the work produced during each cycle. The insets illustrate the four steps of the engine: compression, expansion, heating, and cooling. Blue corresponds to cooling and red to heating. (Adapted from J. Roßnagel et al., *Science* **352**, 325, 2016.)

The engine's cycle starts with the atom located in the narrow region of the conical trap, shown in figure 1. During the heating phase—once electrical noise has been switched on—the width of the thermal distribution increases and pushes the atom to the wide region of the trap. At that point cooling begins: The noise is switched off, the thermal distribution shrinks, and the atom moves back to its original position, where the cycle starts anew.

My colleagues and I determined the ion's temperature stroboscopically using a fast thermometry method that works from the observation of thermally induced broadening of levels in the Ca ion's fluorescence spectrum. The level broadening showed that the temperature varied between 6 mK and 51 mK, and a high-resolution camera captured the atom's position and displacement through 11 nm. That displacement corresponds to changes of the force inside the trapping potential of 2×10^{-22} N.

Knowing the trap's geometry, we inferred the ion's oscillation frequency as 450 kHz. The work generated by the ion, which acts much like a flywheel in a mechanical engine, drives the harmonic motion along the axial (z) direction. After each cycle, the ion's oscillation amplitude increases slightly, during which the ion stores the generated energy.

Power and efficiency

Figure 2 captures the engine's performance as it passes through the four steps of the cycle. As in a familiar pressure–volume diagram, the work produced during each cycle is given by the enclosed area. When divided by the cycle time, given by the inverse oscillation frequency, the enclosed area yields the motor's power, 3×10^{-22} W. The corresponding power-to-particle ratio is about 1.5 kW/kg, a value comparable to that of a typical car engine. The comparison reveals that the power scales with the number of particles of the working medium.

We calculated the absorbed heat from the corresponding temperature-entropy diagram. The efficiency, defined by the ratio of produced work to absorbed heat, is roughly 0.3%. That

modest value indicates that the trap parameters were not optimal. (The average efficiency of a modern gasoline car engine is about 15–20%.) The performance of the engine could be improved by, for example, increasing the angle of the conical trap, which would lead to a higher radial frequency. For comparison, the first piston engine built by Thomas Newcomen around 1710 had an efficiency of about 0.5%.

To judge by our proof of concept, heat engines can be reduced in size to the ultimate single-particle limit. They also offer insight into different energy-conversion mechanisms at the nanoscale. Developed over 3 billion years, micro-

scopic molecular motors in nature extract mechanical work out of thermal fluctuations from a single heat bath as the motors are driven away from equilibrium by chemical energy. Such motors are often referred to as Brownian ratchets (see the article by Dean Astumian and Peter Hänggi, *PHYSICS TODAY*, November 2002, page 33). In contrast, macroscopic heat engines, developed by engineers in the past 300 years, produce useful work out of heat while being coupled to two heat baths. The realization of a single-atom engine shows that the same mechanism is at work down to the subnanoscale level.

The high level of control achieved in our experiments opens the possibility of pushing heat engines into novel regimes not accessible to common molecular motors. When the reservoirs are cooled to a few nanokelvin, quantum effects such as coherent superposition of states are expected to appear. Interestingly, researchers predict that quantum coherence is a physical resource—a so-called quantum fuel—that may be exploited to increase the efficiency of a quantum heat engine beyond what is possible in classical physics.

By using ground-state cooling techniques already developed in conventional ion traps, one could operate the single-atom heat engine in the quantum domain to verify that tantalizing prediction.

Additional resources

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- D. Leibfried et al., "Quantum dynamics of single trapped ions," *Rev. Mod. Phys.* **75**, 281 (2003).
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- M. O. Scully et al., "Extracting work from a single heat bath via vanishing quantum coherence," *Science* **299**, 862 (2003). **PT**