It's a negative on negative absolute temperatures

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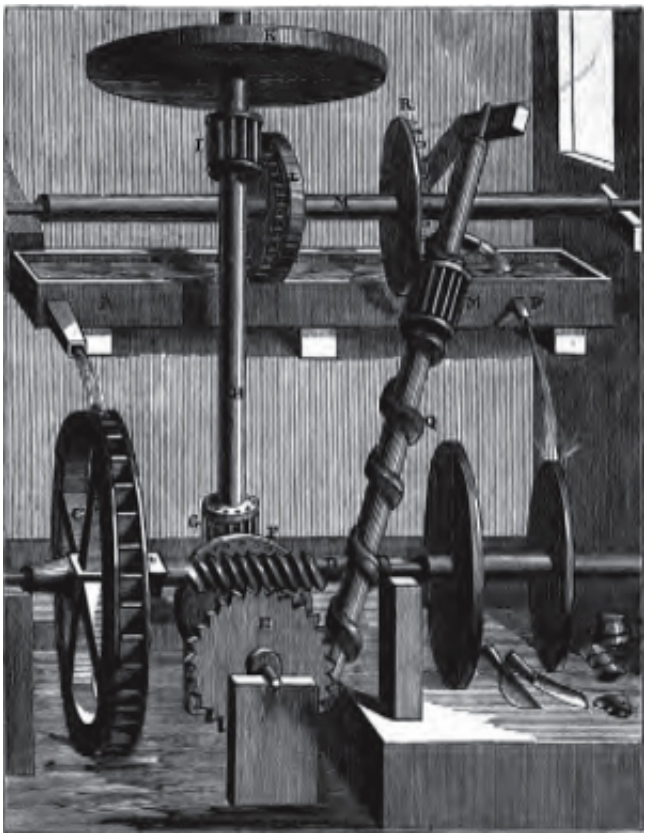

A 1660 wood engraving of Robert Fludd's 1618 "water screw" perpetual motion machine, widely credited as the first recorded attempt to describe such a device for useful work. Credit: George A. Bockler

The concept of a perpetual motion machine is an enticing one: Imagine a machine that runs continuously without requiring any external energy—a

feat that could make refueling vehicles a thing of the past.

While a perpetual motion machine inspires appealing possibilities, most scientists agree that such a machine is impossible, as the very concept—doing work without any energy input—defies the laws of thermodynamics. Nevertheless, some researchers have forged ahead with efforts to create systems resembling perpetual motion at microscopic scales, including spin systems and ultracold quantum gas, which have suggested that perpetual motion machines may be more than pie-in-the-sky notions.

But now, mathematicians at MIT and the Max Planck Institute for Astrophysics have challenged these ideas with equations showing that such systems, while innovative, do not illustrate the dynamics of perpetual motion. The main claim of such experiments is that they are able to produce systems with negative absolute temperatures, or temperatures below 0 degrees Kelvin. If true, such systems could be used to build machines that produce more work than the heat energy put into them—a key characteristic of perpetual motion.

In a paper published this month in the journal *Nature Physics*, the researchers analyzed past claims of negative absolute temperature and found that in all cases, scientists were interpreting experiments based on a flawed—though universally accepted—definition of entropy, or heat. This definition, called the Boltzmann entropy, appears in modern physics textbooks, and is widely used to calculate the absolute temperature of a wide range of physical systems.

But as the MIT team found, the definition only works when atomic or molecular energy states exhibit a normal distribution, where higher energy levels are less frequently populated than lower ones. In more exotic systems, such as certain quantum gases, the definition breaks down. Accounting for this error, the team performed mathematical

consistency checks using an earlier definition of entropy, and found that such systems actually exhibited positive absolute temperatures—a result suggesting that previous studies were using the wrong definition, or essentially an inaccurate theoretical "thermometer," to measure the absolute temperature of exotic systems.

"It's sad in a sense, because you want something to be spectacular, and you want to find something new," says Jörn Dunkel, an assistant professor of mathematics at MIT. "But it's good, in a way, because the implications of negative absolute temperatures would have shaken up the foundations of physics."

The case for going below absolute zero

We typically think of temperature as measured in degrees Celsius or Fahrenheit, which can reach subzero temperatures. In contrast, absolute temperature, measured along the Kelvin scale, represents the motion of molecules within a system. At absolute zero, molecules stop moving, and the system cannot get any colder.

Interestingly, the concept of negative absolute temperature doesn't imply that a system is colder than absolute zero, but in fact, much, much hotter. Systems above absolute zero typically exhibit a normal energy distribution in which there are more atoms or molecules in lower than higher energy states.

Under very special conditions, it is possible to flip-flop, or invert, such energy distributions. A well-known example is the laser, which relies on the fact that the majority of its electrons occupy high-energy states. Applying Boltzmann's definition of entropy in these situations yields a negative temperature. If one inserts such negative temperatures into an equation for the efficiency of a heat engine, known as Carnot's formula, then one can obtain efficiency values larger than 1—predicting, in

effect, perpetual motion.

Rewriting the textbooks

To check whether past claims of negative absolute temperatures were indeed correct, Dunkel and Stefan Hilbert, a postdoc at the Max Planck Institute, methodically examined the equations used in earlier studies to calculate absolute temperature. They found that, while the Boltzmann definition of entropy works well in calculating positive absolute temperature, it quickly falls apart when used to find the temperature of systems with an inverted distribution of molecules.

Going further back in the literature of thermodynamics, the researchers reviewed another definition of entropy described by physicist J. Willard Gibbs in the early 20th century. As it turns out, the absolute temperatures derived using both the Gibbs and Boltzmann definitions for entropy are nearly identical for classical systems with a normal molecular distribution. But for more exotic systems with an inverted distribution, results from the two equations diverge greatly.

Dunkel and Hilbert performed mathematical checks and found that, using the Gibbs equation, they calculated positive absolute temperatures in inverted systems that scientists had thought were negative. The group's new calculations are consistent with the laws of thermodynamics and agree with standard measurement conventions for pressure and other thermodynamic variables, showing that while a system may exhibit an inverted distribution of atomic or molecular energies, this abnormal spread doesn't necessarily signal negative absolute temperatures.

Dunkel suggests that going forward, any researchers seeking to accurately measure the absolute temperature of exotic systems such as quantum gases should use Gibbs' formula over Boltzmann's.

"There are only a small number of textbooks that teach [Gibbs'] formula," Dunkel says. "They don't discuss negative temperatures, because at the time, it wasn't really relevant. But then [the formula] got lost at some point, and now all the modern textbooks publish the other formula. To correct that will be difficult."

Peter Hanggi, a professor of physics at the University of Augsburg, says the paper's findings will help scientists make much more accurate interpretations of rare, exotic systems.

"There were a lot of things being claimed and repeated in the general literature over 50 years, and this group has done an excellent job in sorting out the incorrect from the correct," says Hanggi, who was not involved in the research. "The main significance is to point out to everybody, 'Hey, wait a minute, if you calculate temperature, what does it mean for thermodynamics and for the experiment?' One cannot be too quick in their calculations."

As for creating a perpetual motion machine, Dunkel says the possibility is slim at best, and will require very careful calculations to verify.

"If you create a new class of systems, that's a huge experimental feat," Dunkel says. "But if you go on and interpret the things you measure on these systems, you need to be really careful. If you make just a small mistake in your assumptions, it can amplify hugely."

More information: Consistent thermostatistics forbids negative absolute temperatures, *Nature Physics* (2013) DOI: 10.1038/nphys2815

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