Clocks that tell time more accurately use more energy, new research reveals

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Clocks pervade our lives, from the cellular clocks inside our bodies to the atomic clocks that underlie satellite navigation.

These atomic clocks can measure time accurately to within one second in billions of years. But there could be a price to pay for this accuracy, in the form of energy.

Our new experiment found clocks that measure time more accurately consume more energy than their less accurate counterparts. This suggests nature imposes a fundamental energy cost for keeping time, and it may mean there's a limit to how accurate we can make clocks.

The branch of science that studies the energy required for different physical processes is called thermodynamics. Its laws are inescapable, and all our machines are constrained by them, including power stations, computers and engines.

A key principle of thermodynamics is that energy always eventually flows from hot objects to cold ones. If we reverse the flow in one place, such as a refrigerator, we must pay for it elsewhere, such as in a power station.

A consequence of this is that everything in the universe will ultimately reach the same temperature. At this point life, which relies on energy flow, will become impossible. This grim scenario—which lies in the far distant future, if the universe lasts that long—is known as heat death.

The one-way evolution driven by the laws of thermodynamics, often called the arrow of time, profoundly constrains what technology can and can't do. For example, there's a maximum useful energy that can be extracted by burning a given amount of fuel at a given temperature. No engine will ever be more efficient than this. Thermodynamics also imposes a price for rewriting information, and constrains the efficiency of any possible computer memory.

Studying time

There may be other thermodynamic machines constrained in this way. Some intriguing hints suggest that clocks are a third example.

Simulations of clocks inside bacteria and the latest "quantum" clocks show that, even though their innards are completely different, both of them must be supplied with energy to create the same flow from hot to cold. This is the cost they must pay to keep time, and the thermodynamic theory of clocks predicts that it must increase when the accuracy of the clock improves.

Credit: AI-generated image (disclaimer)

To find out whether such a constraint applies to real clocks, we and our colleagues, including Ph.D. candidate Anna Pearson, built a particularly simple clock based on a pendulum clock, in which the flow of energy could be measured and controlled.

Our "pendulum"—perhaps more accurately described as a drum—was a suspended membrane, just 50 nanometres (billionths of a meter) thick, which vibrated at a set frequency. Each vibration corresponded to one tick of the clock. We could increase the strength of these vibrations by supplying energy to the membrane in a controlled way. Determining the accuracy of the clock became a matter of measuring how regularly the ticks occurred, which we did using an electrical circuit.

Just like any other engine, the clock had to release part of the energy supplied to it as heat. In our design, this heat contributed to the signal from the electrical circuit. We could measure both the accuracy of the clock and the price in terms of heat released.

The thermodynamic theory of clocks made two predictions about our experiment. First, the more energy we supplied, the more accurately the clock should run. Second, the amount of heat released by the clock should increase in proportion to its accuracy.

Both these predictions came true. What's more, the ratio between the accuracy and the heat released was close to the value the theory predicts, once the electrical noise in the experiment was taken into account.

The cost of measuring time

Our results show there is indeed a price for measuring time accurately, at least for this simple clock. Interestingly, our theory predicts quite accurately the energy consumption of more complex clocks in everyday life. For example, it says that a wristwatch should consume at least one microwatt (millionth of a watt) of power—which is indeed slightly less than the actual consumption.

So do humans' efforts to measure time inescapably accelerate the universe's journey towards heat death? We don't need to worry, for two reasons.

First, some clocks, particularly the most accurate atomic clocks, are much more efficient than our theory predicts. This shows the thermodynamic constraint we have found does not apply in the same way to all clocks, meaning we still lack an all-encompassing understanding of timekeeping.

More importantly, the energy dissipated by clocks is minuscule on a universal scale. The heat death of the universe may eventually happen—but the cause will lie not in ourselves, but in the stars.

More information: A. N. Pearson et al, Measuring the Thermodynamic Cost of Timekeeping, *Physical Review X* (2021). DOI: 10.1103/PhysRevX.11.021029

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