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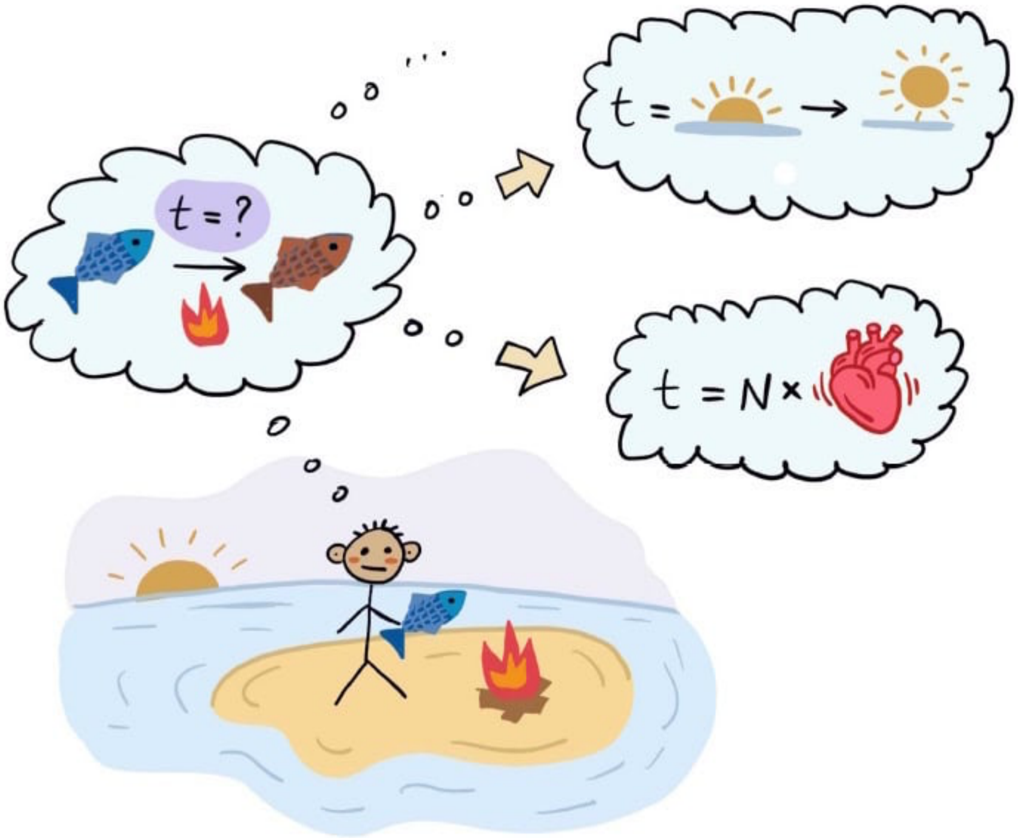
QUANTUM RESEARCH UPDATE

# Cracking the limits of clocks: a new uncertainty relation for time itself

09 Jan 2026 Jessica Tucker



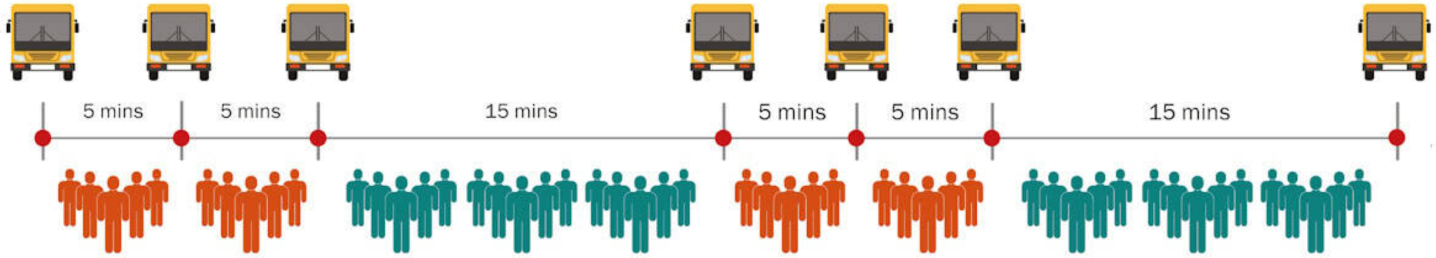
**Estimating time** Tasks such as successful cooking require an accurate and precise time estimator to be constructed from an observer's record of events. (Courtesy: CC BY 4.0/Nuriya Nurgalieva/*Phys. Rev. X* 10.1103/rpls-mp8z/)

What if a chemical reaction, ocean waves or even your heartbeat could all be used as clocks? That's the starting point of a new study by

Kacper Prech, Gabriel Landi and collaborators, who uncovered a fundamental, universal limit to how precisely time can be measured in noisy, fluctuating systems. Their discovery – the clock uncertainty relation (CUR) – doesn't just refine existing theory, it reframes timekeeping as an information problem embedded in the dynamics of physical processes, from nanoscale biology to engineered devices.

The foundation of this work contains a simple but powerful reframing: anything that "clicks" regularly is a clock. In the research paper's opening analogy, a castaway tries to cook a fish without a wristwatch. They could count bird calls, ocean waves, or heartbeats – each a potential timekeeper with different cadence and regularity. But questions remain: given real-world fluctuations, what's the best way to estimate time, and what are the inescapable limits?

The authors answer both. They show for a huge class of systems – those described by classical, Markovian jump processes (systems where the future depends only on the present state, not the past history – a standard model across statistical physics and biophysics) – there is a tight achievable bound on timekeeping precision. The bound is controlled not by how often the system jumps on average (the traditional "dynamical activity"), but by a subtler quantity: the mean residual time, or the average time you'd wait for the next event if you start observing at a random moment. That distinction matters.



**The inspection paradox** The graphic illustrates the mean residual time used in the CUR and how it connects to the so-called inspection paradox – a counterintuitive bias where randomly arriving observers are more likely to land in longer gaps between events. Buses arrive in clusters (gaps of 5 min) separated by long intervals (15 min), so while the average time between buses might seem moderate, a randomly arriving passenger (represented by the coloured figures) is statistically more likely to land in one of the long 15-min gaps than in a short 5-min one. The mean residual time is the average time a passenger waits for their bus if they arrive at the bus stop at a random time. Counterintuitively, this can be much longer than the average time between buses. The visual also demonstrates why the mean residual time captures more information than the simple average interval, since it accounts for the uneven distribution of gaps that biases your real waiting experience. (Courtesy: IOP Publishing)

The study introduces CUR, a universal, tight bound on timekeeping precision that – unlike earlier bounds – can be saturated and the researchers identify the exact observables that achieve this limit. Surprisingly, the optimal strategy for estimating time from a noisy process is remarkably simple: sum the expected waiting times of each observed state along the trajectory, rather than relying on complex fitting methods. The work also reveals that the true limiting factor for precision isn't the traditional dynamical activity, but rather the inverse of the mean residual time. This makes the CUR provably tighter than the earlier kinetic uncertainty relation, especially in systems far from equilibrium.

The team also connects precision to two practical clock metrics: resolution (how often a clock ticks) and accuracy (how many ticks before it drifts by one tick.) In other words, achieving steadier ticks comes at the cost of accepting fewer of them per unit of time.

This framework offers practical tools across several domains. It can serve as a diagnostic for detecting hidden states in complex biological or chemical systems: if measured event statistics violate the CUR, that signals the presence of hidden transitions or memory effects. For nanoscale and molecular clocks – like biomolecular oscillators (cellular circuits that produce rhythmic chemical signals) and molecular motors (protein machines that walk along cellular tracks) – the CUR sets fundamental performance limits and guides the design of optimal estimators. Finally, while this work focuses on classical systems, it establishes a benchmark for quantum clocks, pointing toward potential quantum advantages and opening new questions about what trade-offs emerge in the quantum regime.

Landi, an associate professor of theoretical quantum physics at the University of Rochester, emphasizes the conceptual shift: that clocks aren't just pendulums and quartz crystals. "Anything is a clock," he notes. The team's framework "gives the recipe for constructing the best possible clock from whatever fluctuations you have," and tells you "what the best noise-to-signal ratio" can be. In everyday terms, the Sun is accurate but low-resolution for cooking; ocean waves are higher resolution but noisier. The CUR puts that intuition on firm mathematical ground.

Looking forward, the group is exploring quantum generalizations and leveraging CUR-violations to infer hidden structure in biological data. A tantalizing foundational question lingers: can robust biological timekeeping emerge from many bad, noisy clocks, synchronizing into a good one?

Ultimately, this research doesn't just sharpen a bound; it reframes timekeeping as a universal inference task grounded in the flow of events. Whether you're a cell sensing a chemical signal, a molecular motor stepping along a track or an engineer building a nanoscale device, the message is clear: to tell time well, count cleverly – and respect the gaps.

The research is detailed in *Physical Review X*.

**Jessica Tucker** is a PhD student contributor to *Physics World*. Jessica is studying quantum technology at Florida Agricultural and Mechanical University. **Find out more about our student contributor networks**

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