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Distinguishing between evidence and its explanations in the steering of atomic clocks

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HIGHLIGHTS

- Atomic clocks are steered in frequency toward an aiming point.
- The aiming point depends on a chosen wave function.
- No evidence alone can determine the wave function.
- The unknowability of the wave function has implications for spacetime curvature.
- Variability in spacetime curvature limits the bit rate of communications.

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ABSTRACT

Quantum theory reflects within itself a separation of evidence from explanations. This separation leads to a known proof that: (1) no wave function can be determined uniquely by evidence, and (2) any chosen wave function requires a guess reaching beyond logic to things unforeseeable. Chosen wave functions are encoded into computer-mediated feedback essential to atomic clocks, including clocks that step computers through their phases of computation and clocks in space vehicles that supply evidence of signal propagation explained by hypotheses of spacetimes with metric tensor fields.

The propagation of logical symbols from one computer to another requires a shared rhythm—like a bucket brigade. Here we show how hypothesized metric tensors, dependent on guesswork, take part in the logical synchronization by which clocks are steered in rate and position toward aiming points that satisfy phase constraints, thereby linking the physics of signal propagation with the sharing of logical symbols among computers.

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Recognizing the dependence of the phasing of symbol arrivals on guesses about signal propagation transports *logical synchronization* from the engineering of digital communications to a discipline essential to physics. Within this discipline we begin to explore questions invisible under any concept of time that fails to acknowledge unforeseeable events. In particular, variation of spacetime curvature is shown to limit the bit rate of logical communication.

1. Introduction

While outcomes are subject to quantum uncertainty, uncertainty is only the tip of an iceberg: how can one "know" that a wave function describes an experimental situation? The distinction within quantum theory between linear operators and probabilities implies a gap between any explanation and the evidence explained [1–4]:

Proposition 1. *To choose a wave function to explain experimental evidence requires reaching beyond logic based on that evidence, and evidence acquired after the choice is made can call for a revision of the chosen wave function.*

Because no wave function can be unconditionally known, not even probabilities of future evidence can be unconditionally foreseen. Here we show implications of the unknowability of wave functions for the second as a unit of measurement in the International System (SI), implications that carry over to both digital communications and to the use of a spacetime with a metric tensor to explain clock readings at the transmission and reception of logical symbols.

For reasons including quantum uncertainty, not even the best atomic clocks tick quite alike; they drift in frequency and position. Here we develop implications of the necessity of continually adjusting clocks in response to evidence of deviations from an aiming point, where the aiming point depends on provisional hypotheses—i.e., guesswork subject to revision as prompted by accumulated evidence. Although frequency instabilities approaching 10^{-18} shrink the leeway within which clock adjustments are made [5], adjustments within whatever leeway persists remain indispensable. Clocks that generate Universal Coordinated Time (UTC) are steered toward aiming points that depend on both a chosen wave function and an hypothesized metric tensor field of a curved spacetime. Like the chosen wave function, the hypothesis of a metric tensor, while constrained, cannot determined by measured data.

Examining how guesses enter the operations of atomic clocks, we noticed ubiquitous computational machinery, operating in a rhythmic cycle. Within this machinery, hypotheses are coded into computational processes that interact in a feedback loop that responds to evidence, leading to the generation of more evidence. The machinery updates records that determine an aiming point, and so involves the writing and reading of records. The writing must take place at a phase of a cycle distinct from a phase of reading, with a separation between the writing and the reading needed to avoid a logical short circuit.

To illustrate how physical clocks depend on computational machinery, Section 2 sketches the operation of an atomic clock in which computer-mediated feedback steers an active oscillator in frequency. First, off line, an hypothesis about how to steer the oscillator in response to evidence of scattering of the oscillator's radiation by one or more passive resonant atoms is developed. Then that hypothesis, though developed off line on the blackboard, so to speak, is encoded into a program in the computer memory that adjusts the oscillator on the workbench.

In Section 3 we picture an explanation used in the operation of a clock as a string of characters written on a tape divided into squares, one symbol per square. The tape is part of a Turing machine