The Physical Impossibility of Distributed Systems: A Systematic Deconstruction

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Episode 1: (What) Clock Coherence From Terrestrial Microdatacenters to Proxima Centauri

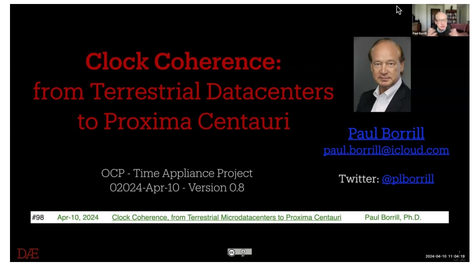

Figure 1: Episode 1: Clock Coherence from Terrestrial Microdatacenters to Interstellar Attoprobeswarms
Video Slides

Clock synchronization, as we know in this forum, is a hard problem. This talk is motivated by a project Robert G Kennedy III, who revealed a plan to send a swarm of nano-spacecraftt to Alpha Centauri and return pictures. [Asilomar Microcomputer Workshop, April 24-26, 2023]. Knowing techniques for distributed clock synchronization is apparently critical to the success of the project he asked us to describe the problems of clock synchronization and illuminate a potential solution based on his work in Distributed Systems in Terrestrial datacenters.

There is no now. You cannot synchronize clocks the way you think. Talk originally given at the 2023 Asilomar Microcomputer Workshop, presented live with Jonathan Gorard.

Motivation: (1) to get people thinking about the nature of time and causality, as far removed from the Earth (and TAI/GPS) as possible. (2) to stimulate "First Principles Thinking" for Distributed systems.

See The Last Theory Newsletter on What is the causal graph in Wolfram Physics

Episode 2: (Why) A Facade of Newtonianism in Networking

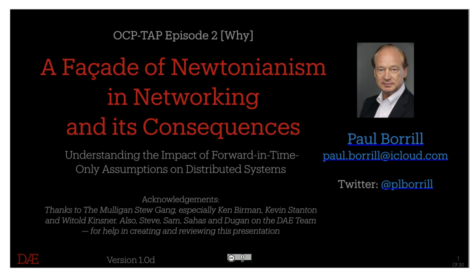

Figure 2: Episode 2: A Facade of Newtonianism in Networking and its Consequences
Video Slides

- Clocks can be disseminated, but require interaction to be synchronized
- Simultaneity planes don't exist (except in an empty frozen universe) Einstein proved this over 100 years ago Why do we still think we can synchronize clocks?
- Network Time Protocol (NTP) and Precision Time Protocol (PTP) are causal TREES — choose your root, and how you do failover
- Entanglement and indefinite causal order are the new relativity (Not restricted to low relative velocities or atomic scales)
- We cannot assume spacetime is irreversible and monotonic
- Irreversibility and monotonicity is in the Eye of the Observer

A hidden assumption of Newtonian time pervades all of computer science and networking. We make believe that an "inertial frame" allows us to ignore relativity, and that quantum effects are too small to matter. Nothing could be further from the truth. In this session we will explain why this matters: Inconsistent partial orders among different observers (e.g. logs in distributed databases), cause silently lost and corrupted data structures. We connect the dots between the hidden assumptions (smooth, monotonic irreversible), and the evidence/consequences seen in recent work on Partial Network Partitioning (PNP).

In Episode 1 (April 10) we showed [what] happens when we try to synchronize clocks. In this session (Episode 2 - Jun-05) we explore the

[Why] it matters, and the consequences. In Episode 3 (July 17 - "Race conditions and Exactly Once Semantics in Distributed Systems") we explore the [How] ways to address this indefinite causal order problem using Causal Networks based on PTM.

[EPISODE 2 - Hidden assumptions about causality lead to lost & corrupted data]. When we think about clocks as an incrementing number, we are committing the FITO fallacy – "Forward In-Time-Only" Thinking:

- Counterfactuals, i.e., "events that could have occurred but eventually did not, play a unique role in quantum mechanics in that they exert causal effects despite their non-occurrence"
- Clock Synchronization Error is indistinguishable from Latency
- Irreversibility (Monotonicity) is an illusion not guaranteed by physics, unless we build Ancilla to explicitly manipulate causality
- Irreversibility and "causal order" are IN THE EYE OF THE OBSERVER—not guaranteed to be consistent across different observers

Episode 3: Race Conditions and Exactly Once Semantics in Distributed Systems

Figure 3: Episode 3: Race Conditions and Exactly Once Semantics In Distributed Systems
Video Slides

How a Static PTP Hierarchy can be made Dynamic to support Causal Failover for Distributed System

In Episode 1 (What) and Episode 2 (Why) we showed how misunderstandings accumulate within a Newtonian framework of time, and how this leads to lost transactions and corrupted data. In this Episode we help the audience make the leap from Newtonian Time (what we know for certain that just ain't so) to Post-Newtonian Time (relativistic SR/GR, and Indefinite Causal Order (ICO). Now PTP is widely available, we propose experiments to falsify beliefs about the Newtonian Time. We will then show how to utilize the excellent engineering behind PTP and PTM, from a different perspective: using the clock hierarchy to build causal trees with reliable failover, to help address race conditions and achieve Exactly Once Semantics.

[EPISODE 3 — How a static PTP hierarchy can be made dynamic to support causal failover for distributed systems]. In Episode 1(What & Episode 2 (Why) we showed how misunderstandings accumulate within a Newtonian framework of time, and how this leads to lost transactions and corrupted data. In this Episode we help the audience make the leap from Newtonian Time (what we know for certain that just ain't so) to Post-Newtonian Time (relativistic SR/GR, and QM — Indefinite Causal Order (ICO).

- PTP is widely available in Datacenters, we propose experiments to falsify beliefs about Newtonian Time.
- All is not lost. The excellent engineering behind PTP and PTM, can still be used with a different perspective, by using the clock hierarchy to build Causal Trees and reliable failover, to help address race conditions and achieve Exactly Once Semantics

Episode 4: Timeout and Retry (TAR) in Distributed Systems

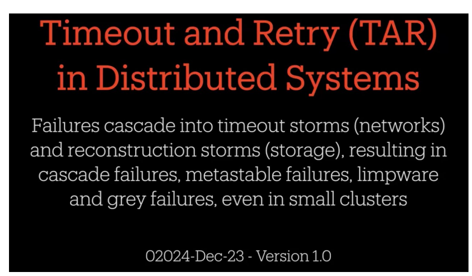

Figure 4: Episode 4: Timeout and Retry (TAR) in Distributed Systems
Video Slides

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[EPISODE 4 - Why we can't have nice things in Distributed Systems.]

- Instants are meaningless, only intervals (on the same computer/timeline) are relevant
- Photons don't carry timestamps, but timestamps are carried by photons
- The speed of light is the *pivot* around which time and space evolve
- Timeout and retry (TAR) on different timelines will silently corrupt data structures
- Shannon entropy is a logarithm. The logarithm of zero (no information) is minus infinity.
- Bayesian approaches require a prior belief, which can be unbounded (zero to infinity). Actually, it's much worse: can be $-\infty, -1, -0, +0, +1, +\infty$ We can't do Bayesian statistics under those conditions, mathematically, their results are undefined
- Shannon Entropy is uncertainty, and the same problem applies when you apply the set: $-\infty, -1, -0, +0, +1, +\infty$ to Information and Entropy $p \log(p)$
- Measurements *appear* instantaneous because there is no background of time on which to measure anything. Timestamps don't provide causal order.

Episode 5: Ethernet Spacetime

Figure 5: Episode 5: Ethernet Spacetime - Timestamps are an Illusion
Video Slides

Timestamps are an Illusion. They can't be fixed in software. The quest for a single, consistent timeline across distributed systems collides with the reality that physics itself does not provide a universal notion of time—and in many quantum scenarios, there isn't even a consistent causal order at all. Though timestamps will remain indispensable in engineering practice, we must recognize them as approximations rather than absolutes, and design our systems accordingly. Time synchronization is not merely a technical challenge—it's a conceptual one. Software Fixes Are Only Band-Aids, they can never be deterministic. In this presentation, we also announce the birth of Ethernet 2025.

THERE IS NO GLOBAL DRUM BEAT. In Episodes 1 through 4 we expressed doubts about the common belief system of a Newtonian view of the world in this community. We showed how to think about race conditions, and why Timeouts and Retries (TAR) are the root of all evil. Our conclusion is that Timestamps are an Illusion. They can't be fixed by software.

The quest for a single, consistent timeline across distributed systems collides with the reality that physics itself does not provide a universal notion of time—and in quantum mechanics (the machine code of our universe), there is no consistent causal order at all. We cannot, therefore, rely on this illusion of an irreversible drumbeat on an inaccessible "real line" to provide linear time order for events in our networked systems.

Although timestamps will remain indispensable in engineering practice, we must recognize them as approximations rather than absolutes, and design our systems accordingly.

Paul Borrill on Timestamps and the Reordering of Events

Leslie Lamport's original paper 1978 paper, *Time, Clocks, and the Ordering of Events in a Distributed System*, introduced important concepts such as logical clocks and the notion of "happened before", both of which are key ideas in understanding causality in distributed systems. Lamport's paper laid the groundwork that allows us to bypass the need for perfect synchronization in physical clocks, which is known to near impossible. However, due to a continuous misunderstanding of the nature of time in both physical and computer science, his work remains largely unfinished. In this talk, Paul highlights how traditional synchronizing methods such as PTP and NTP are fundamentally flawed because they assume a global notion of time through which perfect simultaneity can be achieved. To combat this problem, Paul introduces reversible computing, through which nodes in a system can undo events to recover from errors. Granting individual nodes with this ability reduces the need for a global fallback system and allows for nodes to have greater autonomy across their local neighborhoods.

Figure 6: Time Clocks and the Reordering of Events
Video Slides

Paul emphasizes that our conventional notions of time being linear, uniform, and discrete are misleading and make assumptions about the physical nature of our universe that simply don't exist. Rather, time should be thought about in the form of causal relationships that branch off from on another in a tree like structure. However, disagreements and discourse between physicists, mathematicians, and computer scientists limit progress in this regard. In order to solve problems of time and concurrency in distributed systems, increased collaboration is required.

Review: DÆDÆLUS OCP TAP Presentations, 2024-2025

Through a systematic five-part series presented to the Open Compute Project's Time Appliances Project, Paul Borrill has demonstrated that the foundational assumptions of distributed systems—particularly the ACID properties of database transactions—rest upon a *façade of Newtonianism* that is fundamentally incompatible with 20th Century physics. This analysis examines how modern understanding of relativity, quantum mechanics, and information theory renders impossible the very concepts upon which computer science has built its theoretical framework.

The Collapse of Simultaneity

The conventional wisdom in distributed systems assumes the existence of a global timeline—what Borrill calls the "global drum beat."[1] This assumption underlies every attempt to create consistent distributed state, from Google's Spanner to AWS's microsecond guarantees to the Time Appliances Project itself.

Yet Einstein demonstrated over a century ago that simultaneity is observer-dependent.[2] The fundamental premise of distributed systems—that we can establish a consistent global ordering of events—is *physically impossible*.

What we call "clock synchronization" is actually the construction of causal trees, not the establishment of universal time.[3] Every timing protocol creates a hierarchy of causality, not a plane of simultaneity.

The FITO Fallacy and Temporal Irreversibility

Modern distributed systems suffer from what Borrill terms the "FITO fallacy"—Forward In-Time-Only thinking.[4] This assumption of monotonic time progression underlies the Atomicity and Durability properties of ACID transactions.

However, irreversibility itself is observer-dependent.[5] What appears irreversible to one observer may not be to another, particularly when quantum mechanical effects are considered.

The assumption of monotonicity—that timestamps always increase—is an illusion not guaranteed by physics.[6] Without external mechanisms (ancilla) to enforce causal order, distributed systems cannot guarantee the temporal ordering upon which ACID properties depend.

[1] Borrill, P. "Ethernet Spacetime," TAP #121, Jan 1, 2025. "THERE IS NO GLOBAL DRUM BEAT. In Episodes 1 through 4 we expressed doubts about the common belief system of a Newtonian view of the world in this community."

[2] Borrill, P. "Clock Coherence: from Terrestrial Microdatacenters to Interstellar Attoprobeswarms," TAP #98, Apr 10, 2024. "Simultaneity planes don't exist (except in an empty frozen universe) Einstein proved this over 100 years ago Why do we still think we can synchronize clocks?"

[3] Ibid. "Network Time Protocol (NTP) and Precision Time Protocol (PTP) are causal TREES—choose your root, and how you do failover."

[4] Borrill, P. "A Facade of Newtonianism in Networking and its Consequences," TAP #102, Jun 5, 2024. "When we think about clocks as an incrementing number, we are committing the FITO fallacy—'Forward In-Time-Only' Thinking."

[5] Ibid. "Irreversibility and 'causal order' are IN THE EYE OF THE OBSERVER—not guaranteed to be consistent across different observers."

[6] Ibid. "Irreversibility (Monotonicity) is an illusion not guaranteed by physics, unless we build Ancilla to explicitly manipulate causality."

The Information-Theoretic Impossibility

The problems extend beyond relativity into fundamental information theory. Borrill demonstrates that the timeout and retry (TAR) mechanisms essential to distributed systems create mathematical impossibilities when applied across different timelines.[7]

The measurement problem is more fundamental than engineering approximations suggest: "instants are meaningless, only intervals (on the same computer/timeline) are relevant."[8] This directly contradicts the notion of atomic transactions, which require well-defined instants at which operations either occur or do not occur.

Moreover, the information propagation constraint creates an indistinguishability between clock synchronization error and network latency.[9] Since "photons don't carry timestamps, but timestamps are carried by photons," the very act of timestamp distribution introduces uncertainty that cannot be eliminated.[10]

[7] Borrill, P. "Timeout and Retry (TAR) in Distributed Systems," TAP #118, Dec 4, 2024. "Timeout and retry (TAR) on different timelines will silently corrupt data structures."

[8] Ibid. "Instants are meaningless, only intervals (on the same computer/timeline) are relevant."

[9] TAP #102. "Clock Synchronization Error is indistinguishable from Latency."

[10] TAP #118. "Photons don't carry timestamps, but timestamps are carried by photons."

Shannon Entropy and the Bayesian Breakdown

The mathematical foundations supporting distributed consensus suffer from fundamental problems in information theory. Shannon entropy, defined as $H = -\sum p_i \log p_i$, becomes undefined when probabilities approach zero.[11]

Bayesian approaches to distributed consensus require prior beliefs, but in distributed systems these priors can range over the *set*

$$[-\infty, -1, -0, +0, +1, +\infty]. \quad (1)$$

[12] Under these conditions, Bayesian inference becomes mathematically undefined, undermining probabilistic approaches to achieving consistency.

[11] TAP #118. "Shannon entropy is a logarithm. The logarithm of zero (no information) is minus infinity."

[12] Ibid. "Bayesian approaches require a prior belief, which can be unbounded (zero to infinity). Actually, it's much worse: can be [negative infinity, -1, -0, +0, +1, positive infinity]. We can't do Bayesian statistics under those conditions, mathematically, their results are undefined."

Quantum Mechanical Causal Indefiniteness

The final blow to distributed systems foundations comes from quantum mechanics. Modern physics recognizes indefinite causal order (ICO) as fundamental.[13] In quantum mechanics, "there is no consistent causal order at all."[14]

Perhaps most remarkably, quantum counterfactuals—"events that could have occurred but eventually did not"—can "exert causal effects despite their non-occurrence."[15] This suggests that distributed systems must account for the causal influence of operations that never actually execute.

[13] TAP #98. "Entanglement and indefinite causal order are the new relativity (Not restricted to low relative velocities or atomic scales)."

[14] TAP #121. "In quantum mechanics (the machine code of our universe), there is no consistent causal order at all."

[15] TAP #102. "Counterfactuals, i.e., 'events that could have occurred but eventually did not, play a unique role in quantum mechanics in that they exert causal effects despite their non-occurrence."

The Systematic Failure of ACID Properties

Borrill's analysis reveals how each ACID property fails under physical scrutiny:

Atomicity requires well-defined instants where operations occur or do not occur. But physics tells us that "measurements 'appear' instantaneous because there is no background of time on which to measure anything."[16] The atomic instant is a mathematical fiction.

[16] TAP #118. "Measurements 'appear' instantaneous because there is no background of time on which to measure anything. Timestamps don't help with causal order."

Consistency assumes a global state that can be maintained across distributed nodes. But consistency requires simultaneity, which "doesn't exist (except in an empty frozen universe)."[17] Global consistency is physically impossible.

[17] TAP #98. Simultaneity reference.

Isolation assumes operations can be segregated from one another temporally. But when "timeout and retry (TAR) on different timelines will silently corrupt data structures," true isolation becomes impossible across distributed timelines.[18]

[18] TAP #118. TAR corruption reference.

Durability assumes irreversible state changes. But "irreversibility is an illusion not guaranteed by physics" and is fundamentally "in the eye of the observer."[19] What appears durable to one observer may not be to another.

[19] TAP #102. Irreversibility references.

The Engineering Illusion

Borrill acknowledges that "timestamps will remain indispensable in engineering practice" but insists we must "recognize them as approximations rather than absolutes."[20]

[20] TAP #121. "Although timestamps will remain indispensable in engineering practice, we must recognize them as approximations rather than absolutes, and design our systems accordingly."

The Time Appliances Project, Google Spanner, and AWS microsecond guarantees represent sophisticated engineering attempts to create what amounts to a "simultaneity plane"—but this remains fundamentally an illusion. These systems work not because they solve the physical impossibilities, but because they create sufficiently convincing approximations within bounded error tolerances.

Implications for Distributed Systems Design

The recognition that distributed systems operate on physically impossible foundations suggests a fundamental reorientation is needed. Rather than attempting to create global consistency through temporal synchronization, systems should embrace causal ordering and accept the observer-dependent nature of temporal relationships.

Borrill's proposed solution involves using timing hierarchies to construct causal trees rather than attempting clock synchronization.[21] This represents a shift from fighting physics to working with it.

[21] TAP #105. "Using the clock hierarchy to build Causal Trees and reliable failover, to help address race conditions and achieve Exactly Once Semantics."

The quest for "exactly once semantics" and perfect consistency may be as futile as medieval attempts to build perpetual motion machines—not because the engineering is insufficient, but because the fundamental premises violate physical law.

Conclusion

Paul Borrill's systematic deconstruction reveals that computer science has been built upon a façade of Newtonianism that modern physics has thoroughly demolished. The ACID properties, the foundation of reliable distributed systems, assume a universe that does not exist—one with absolute time, universal simultaneity, and observer-independent causality.

This does not mean distributed systems cannot function, but it does mean we must abandon the illusion that we can engineer our way around fundamental physical constraints. Instead, we must design systems that acknowledge and work with the observer-dependent, probabilistic, and causally indefinite nature of reality itself.

The Time Appliances Project and similar efforts represent humanity's attempt to impose Newtonian order on a quantum mechanical universe. They succeed as engineering approximations but fail as fundamental solutions to the problems they purport to solve. Recognition of this distinction may be the first step toward building distributed systems that work with physics rather than against it.