Clock Coherence, from Terrestrial Microdatacenters to Interstellar Attoprobeswarms

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Clock Synchronization

- This clock talk is motivated by a project Robert G Kennedy III, who wants to send a swarm of nano-satellites to Alpha Centauri and return pictures. He will be revealing his approach and a project to actually do it at the Asilomar Microcomputer Workshop
- Knowing techniques for distributed clock synchronization is apparently critical to the success of the project. Clock synchronization is, as we know, a hard problem. Robert is seeking experts to transfer knowledge and assist.
- Physicists, Computer Scientists, Mathematicians, Neuroscientists, Philosophers and Practicing Engineers from the ItsAboutTime.club

With Paul Borrill

It's About Time!

A place to discuss our evolving knowledge of the nature of time and causality. For physicists, computer scientists, mathematicians, neuroscientists, philosophers, and practicing engineers.

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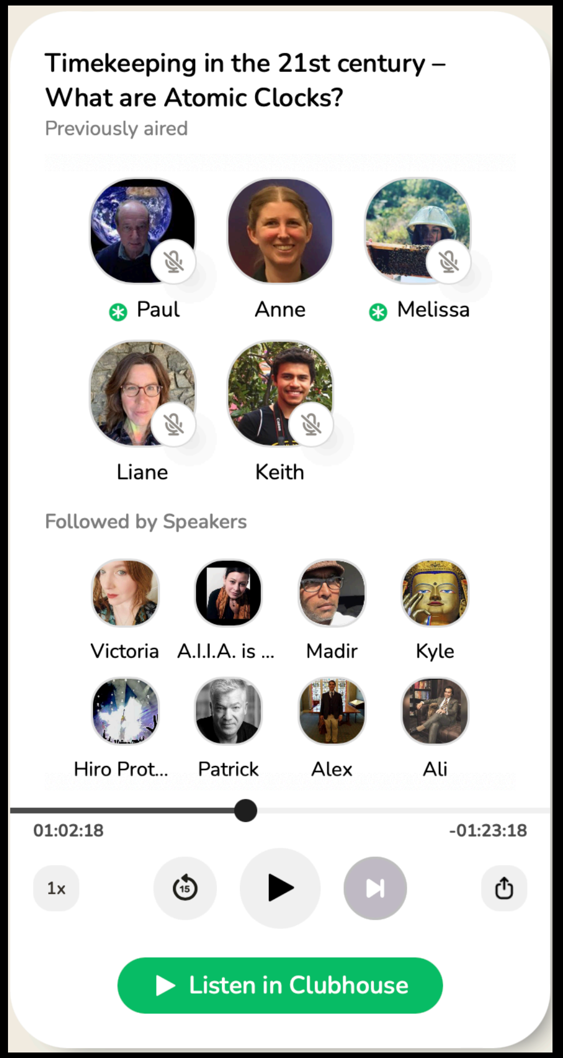
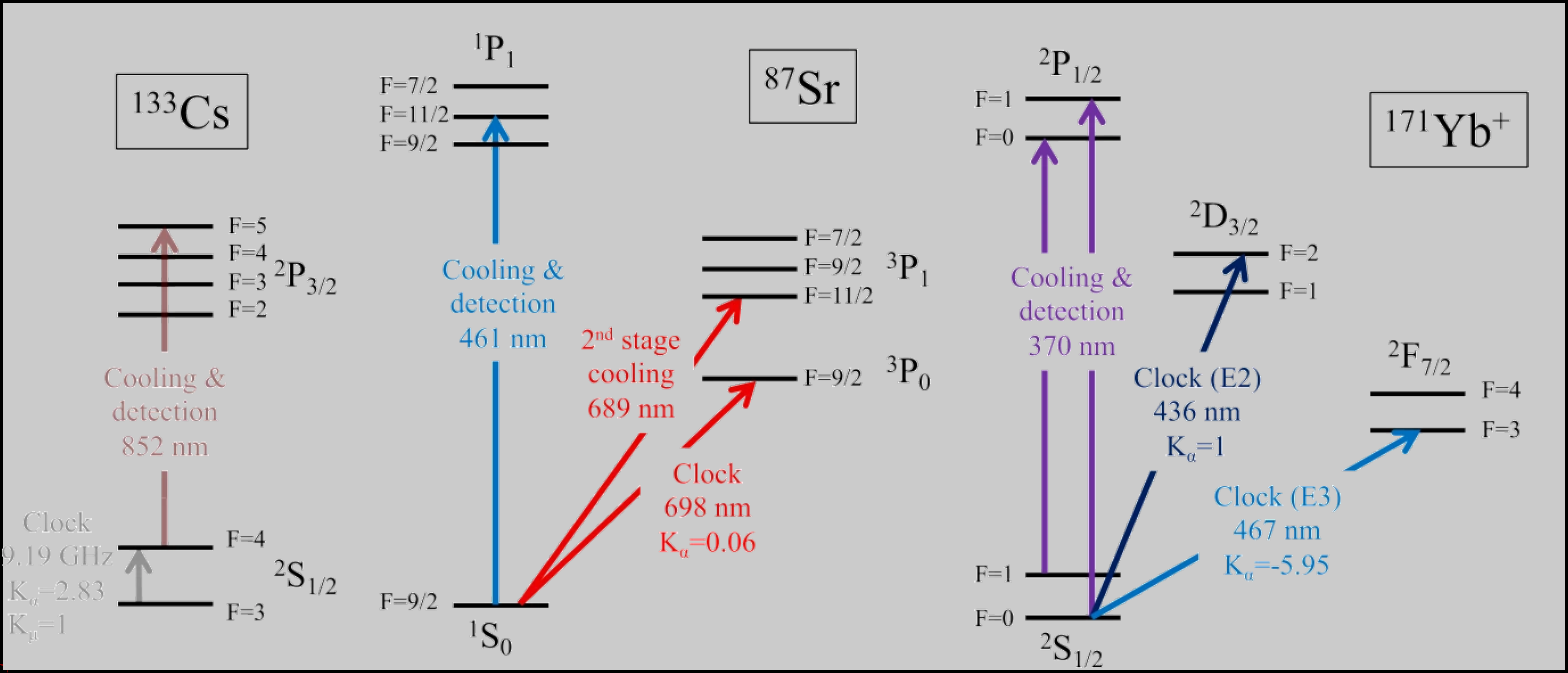
Atomic Clocks: Anne Curtis

- E Anne Curtis is an experimental physicist working in the Time & Frequency Department. She received her PhD from the University of Colorado for development of a calcium optical atomic clock at NIST, Boulder in the USA. After a 3-year Royal Society USA Fellowship at Imperial College London developing "atom chip" technologies for BECs and other integrated optics applications, she joined NPL to start a neutral atom optical clock programme.
- Anne presents invited talks and tutorial sessions at international conferences and for the general public in the areas of optical atomic clocks and molecular spectroscopy methods for trace gas detection. She works on single-ion systems for optical frequency metrology, tests of fundamental physics and redefinition of the SI second. She is developing a Photonic Technologies for Gas Sensing Metrology research programme, bringing together NPL expertise for applications in environmental monitoring and the clean energy and medical sectors, including ultra-sensitive real-time cavity-enhanced gas detection "NICE-OHMS" systems. Anne is also working to develop laser-stabilisation systems for space-based gas sensing, using gas-filled hollow-core fibre photonic technology.



Measuring the stability of fundamental constants with a network of clocks

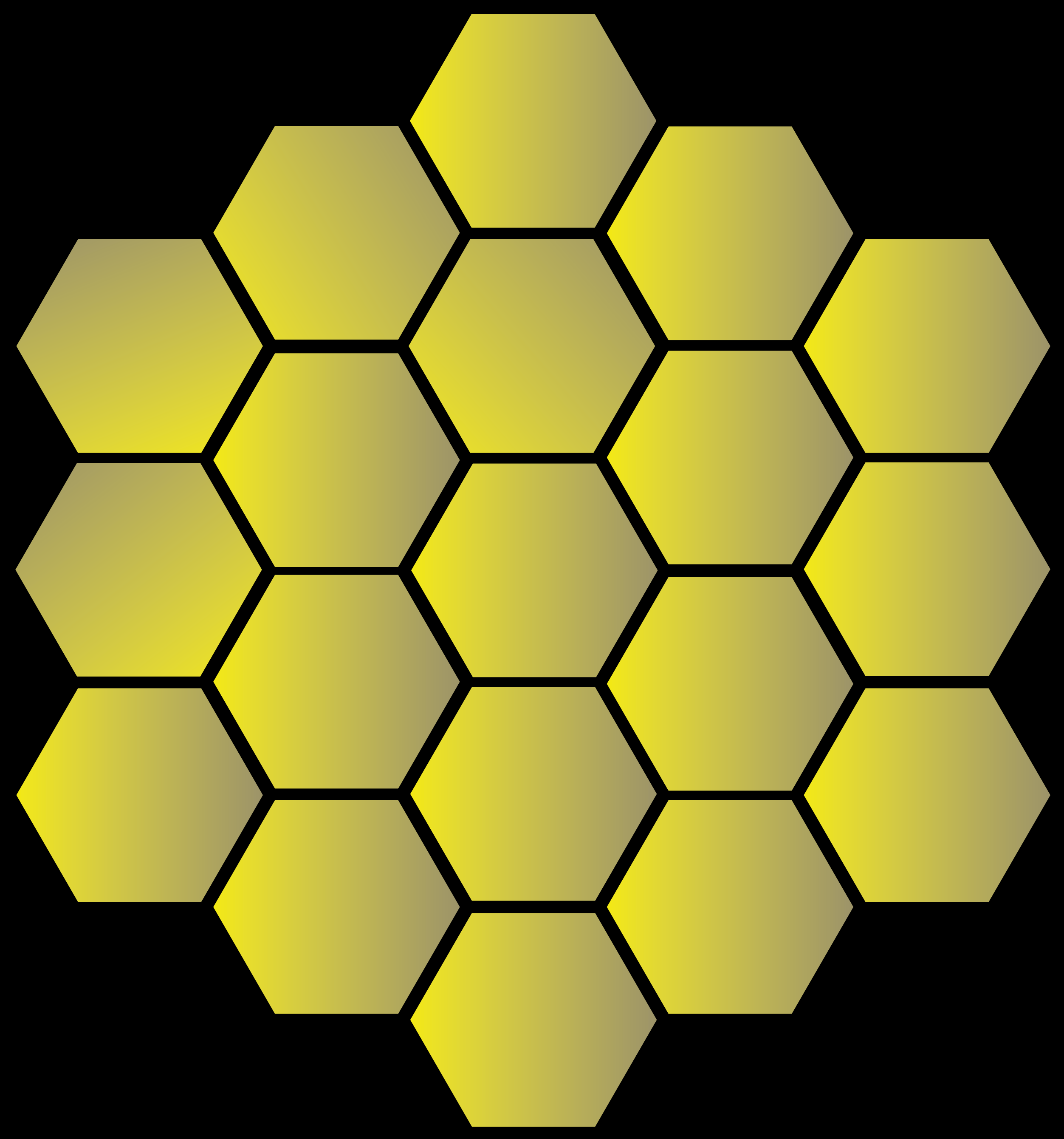
- [EPJ Quantum Technology]()



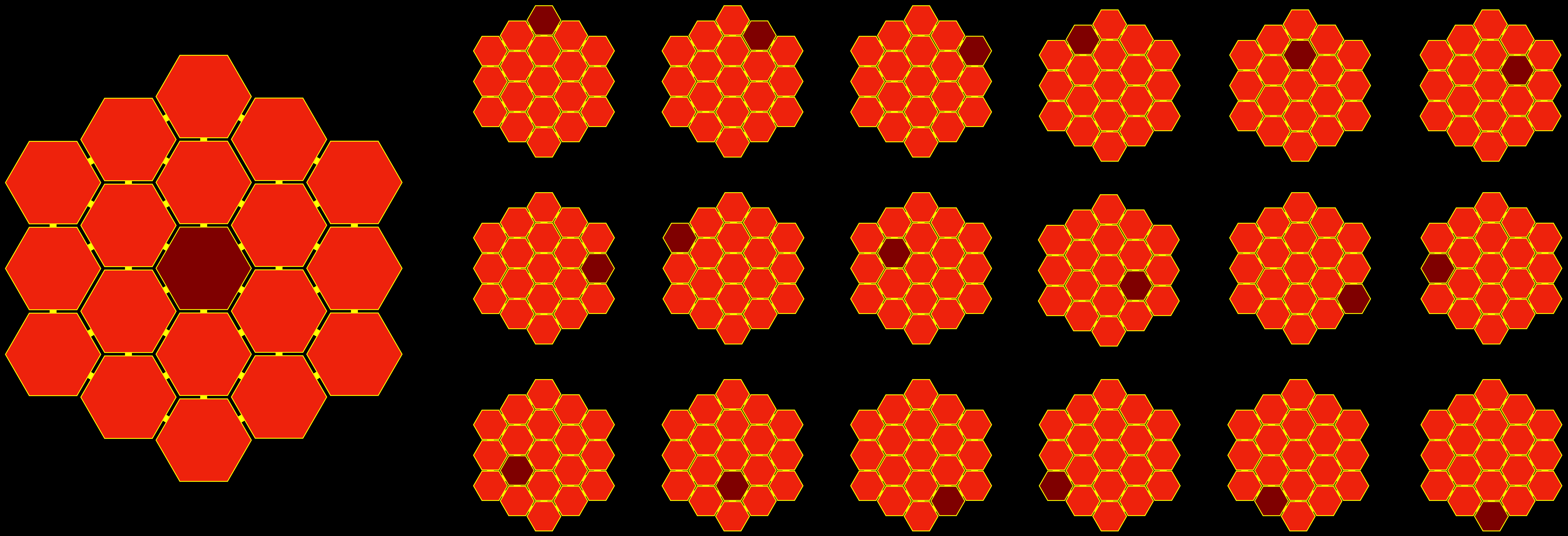
There is no Now

You cannot Synchronize Clocks the way you Think

Swarms in Formation



Swarms in formation



Complete Redundancy: Any Cell can become a controller if others fail

Questions

- If clocks can't be synchronized, then how do you "coordinate" the activity of a swarm of spacecraft 4.25 light years away?
- Can a Laser push get them up to 20% of the speed of light?
- How do we align the swarm to transmit Data back to Earth Coherently?
- How do we "repair" in flight, and in Proxima Centauri?
- Calculating the photon spectrum red shifted by 20% of c
- Calculating the subtended angle of transmitter and receiver arrays?
- What network architecture is needed?
  - Hint: it won't be Software Defined Networks (SDN is Not An Innovation)
  - Hint: What we need for microdatacenters here on Earth is exactly the same, and for the same reason: someone needs to invent Causal Networks: ItsAboutTime.club

Redefining Synchronization I

- Typically, when we speak of "synchronization" within distributed systems, we mean getting all nodes of a network to agree upon a single numerical value ("clock time")
- In principle, this can be done within an inertial frame, with a fixed network topology, and when all redshifts are calculable
- I.e. Alice sends Bob a packet containing her clock time; Bob receives it, sets his clock time to the same value, and uses the redshift of the incoming packet to calculate Alice's velocity and apply special relativistic corrections

Redefining Synchronization II

- But realistic frames are non-inertial, realistic redshifts are not always calculable, and realistic network topologies are not static!
- In (e.g.) a rotating reference frame, even within SR, the Einstein synchronization convention no longer makes sense. The synchronization relationship becomes non-transitive (i.e. if Alice synchronizes with Bob and Bob synchronizes with Charlie, they achieve a different synchronization than if Alice synchronizes with Charlie directly), and therefore path-dependent
- In full general relativity, and with dynamic network topology, the problem becomes even worse

Redefining Synchronization III

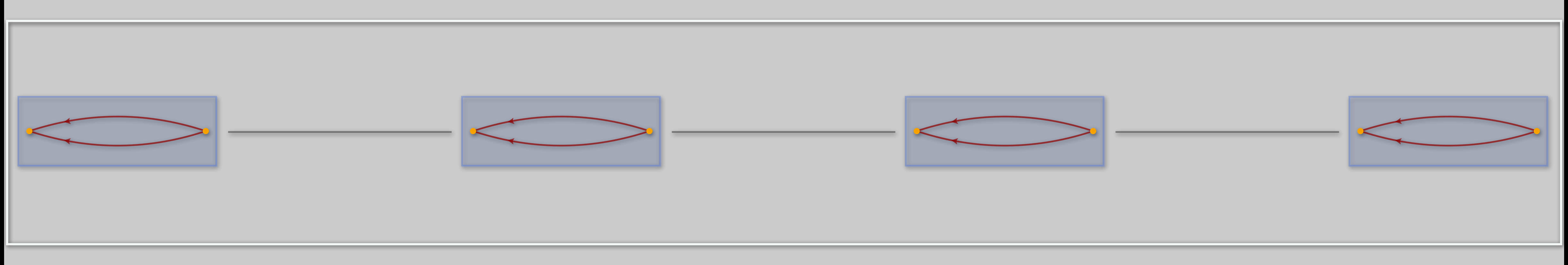
- But who cares about clock time? All we need to know is the *causal structure* (which events logically depend upon which other events).
- So let's simply just *redefine* synchronization to mean agreement of causal structure (as represented through a partial order/directed acyclic graph) across all nodes in the network
- The causal graphs perceived by different nodes may temporarily be non-isomorphic, but we can design communication algorithms that provably guarantee that they will eventually become isomorphic after a finite and bounded amount of communication (c.f. confluence, causal invariance, eventual consistency, etc.)

Redefining Synchronization IV

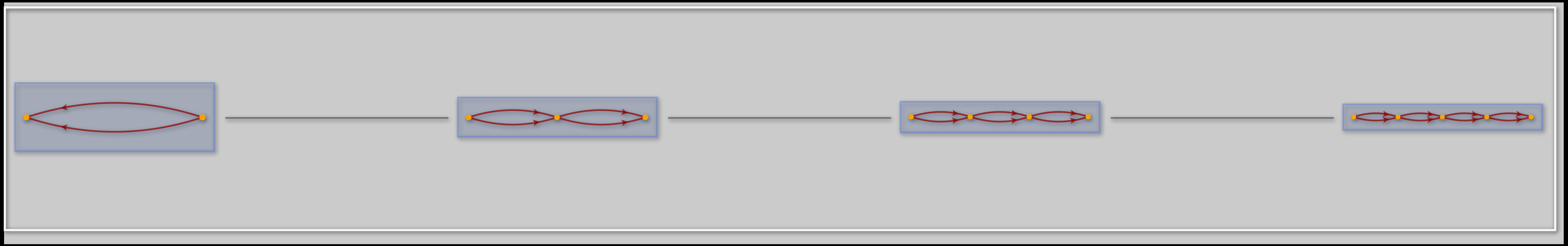
- This new notion of *causal* synchronisation, though strictly weaker than old-fashioned "clock synchronization", is all that is needed to guarantee correct ordering of packets, prevention of data loss, and all of the other desirable properties that one expects from a distributed protocol
- The algorithm that guarantees eventual consistency requires only fairly minimal modification of the Network Time Protocol (effectively replacing clock time with a DAG structure)
- And it works in full general relativity, with dynamic network topologies (as defined through graph rewriting), and with no assumptions regarding the underlying spacetime structure

A Proof-of-Concept Implementation I

- Here's a very basic (path-like) network topology, in which all nodes initially agree on the same (trivial) causal structure:

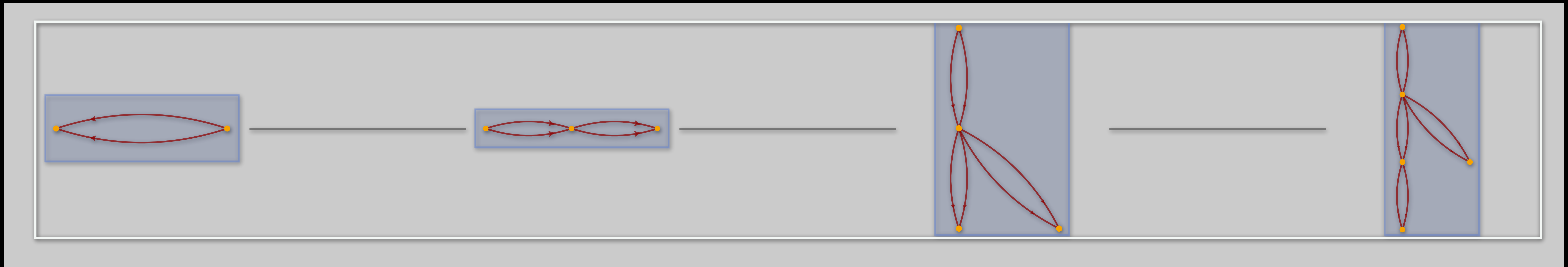


- After a packet is sent from left-to-right (and acknowledged by all intermediate nodes), the causal structures perceived by different nodes are now different:



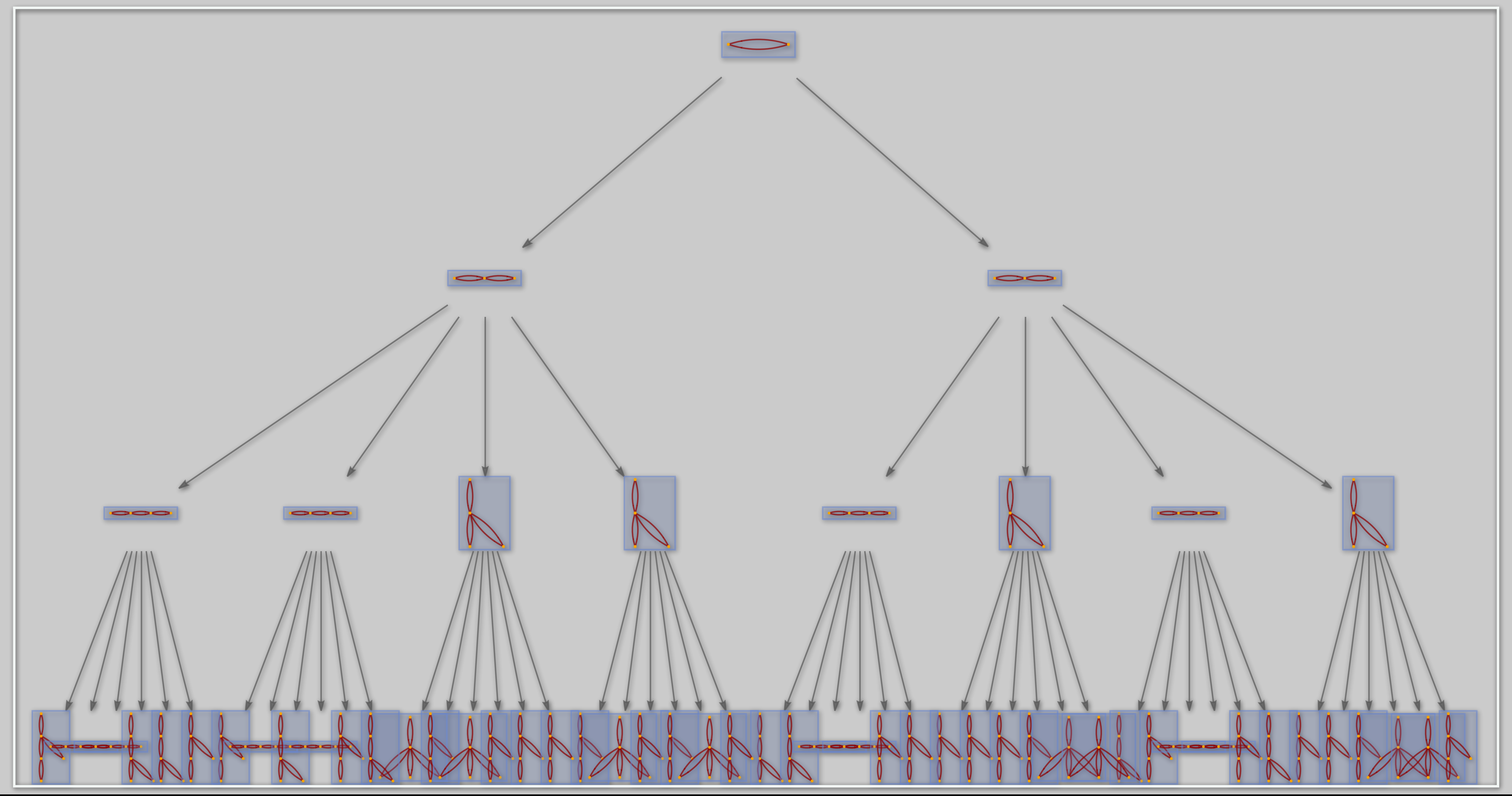
A Proof-of-Concept Implementation II

- Within an arbitrary spacetime geometry, and incorporating the effects of packet loss, etc., the perceived causal structures can become more-or-less arbitrarily different:



A Proof-of-Concept Implementation III

- The collection of all possible observable causal structures by different nodes in the network can be parameterized by means of a *multiway system*:



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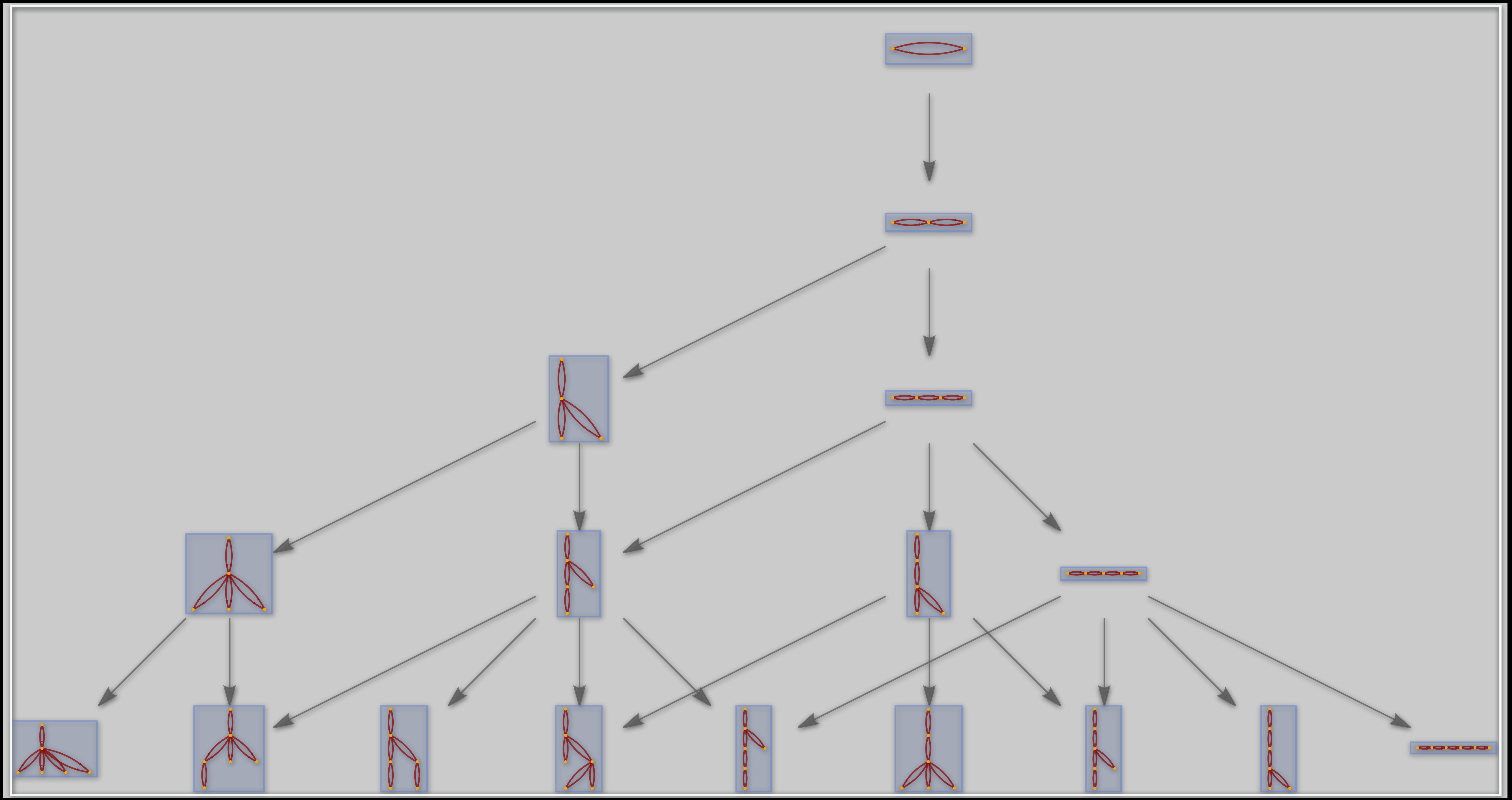
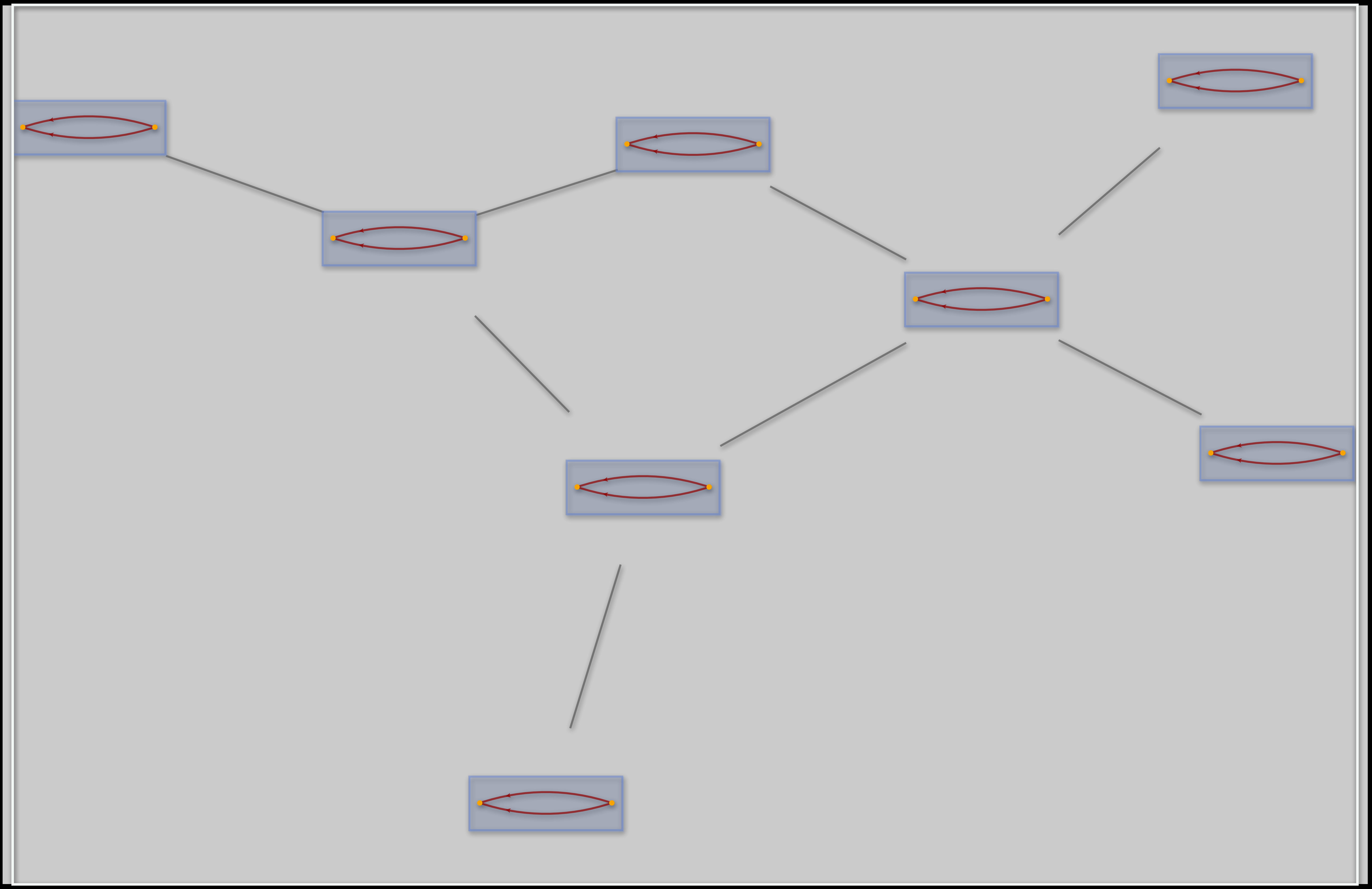
A Proof-of-Concept Implementation IV

- With finite and bounded communication, the algorithm guarantees that all multiway paths will eventually converge (i.e. causal invariance/ confluence/eventual consistency):



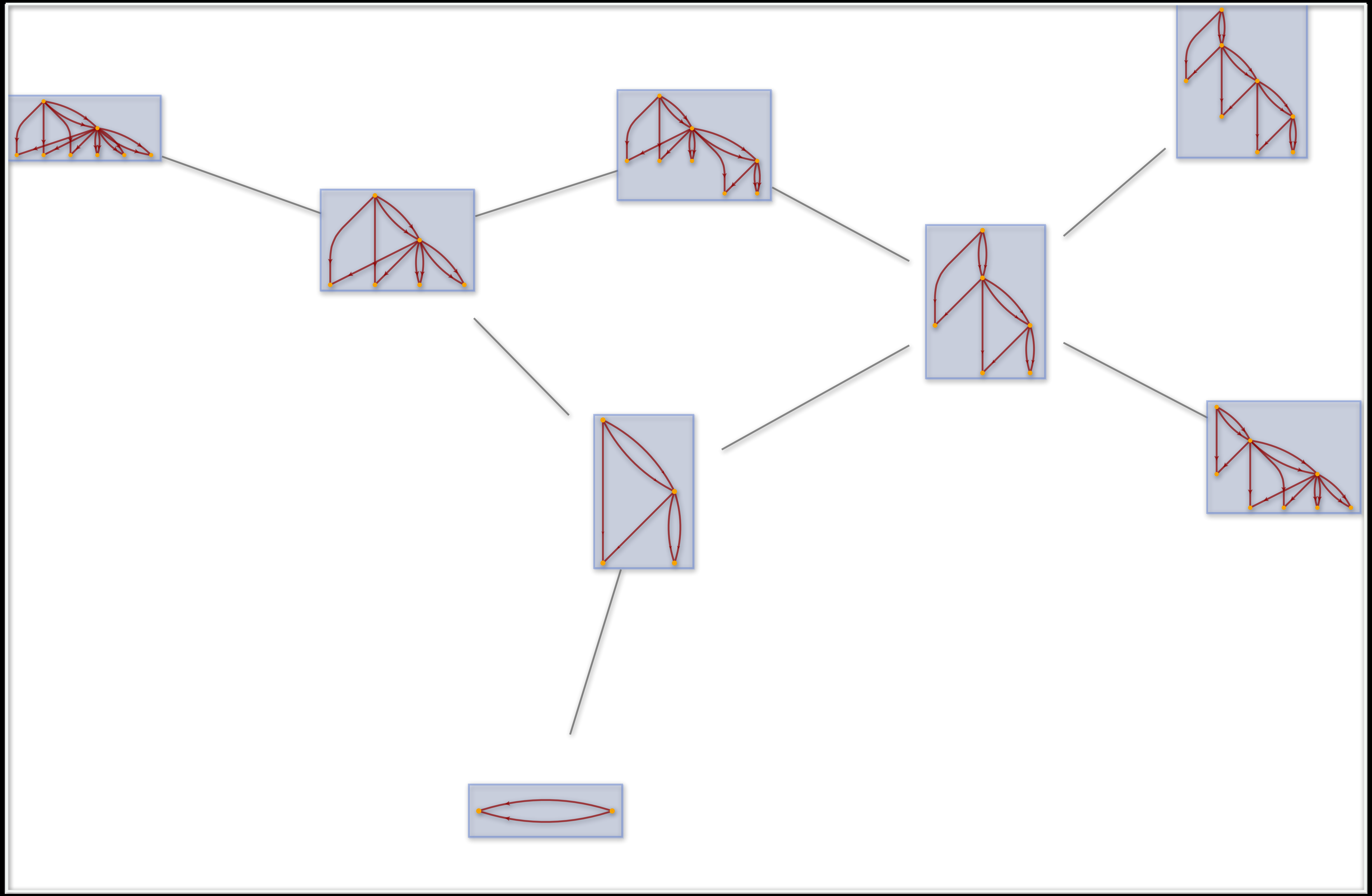
A More Sophisticated Example I

- An example of a network with a non-trivial (and dynamic) topology:



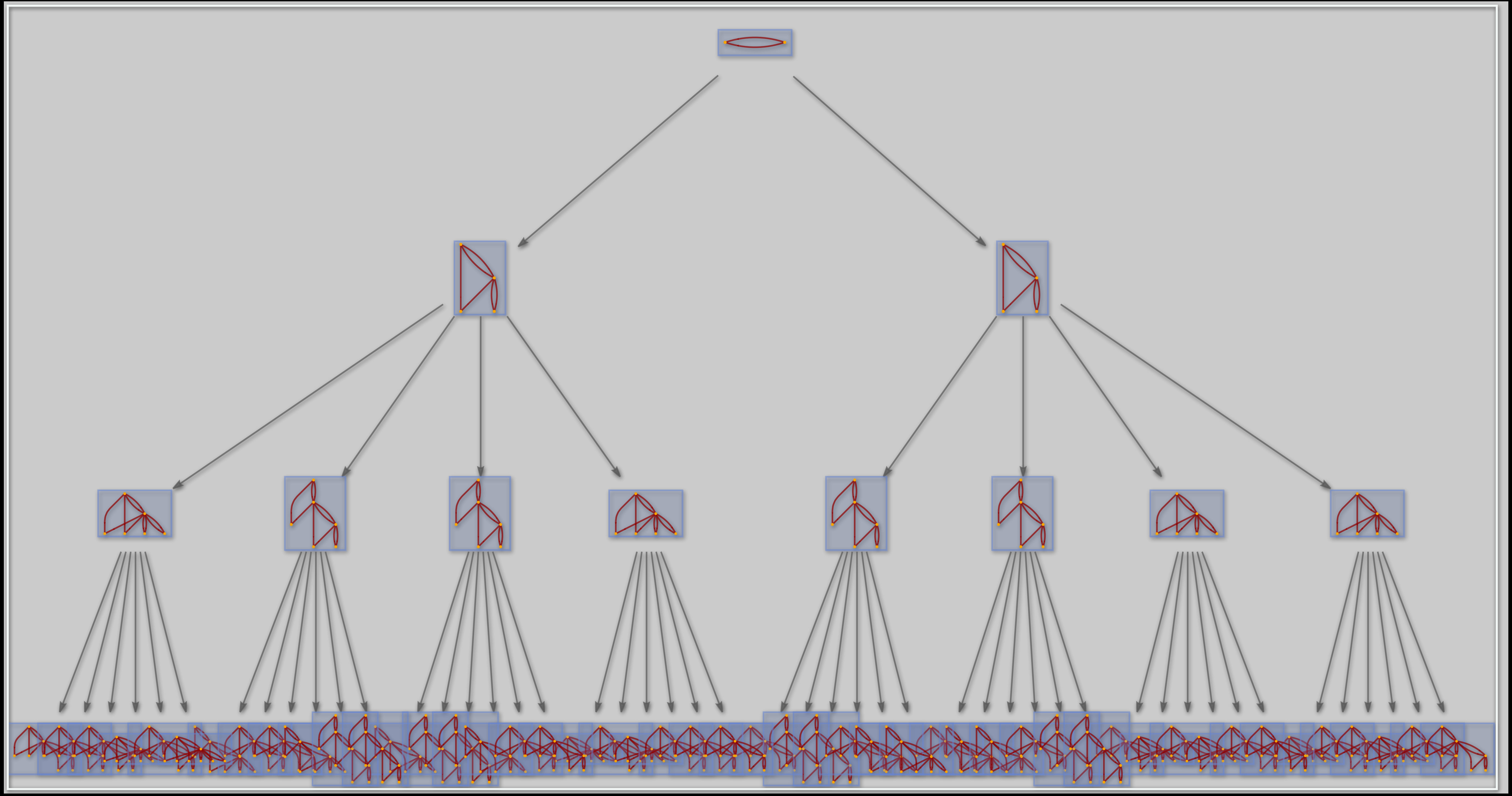
A More Sophisticated Example II

- After only a few rounds of packet exchange (within a non-trivial spacetime geometry), the perceived causal structures are now radically different:



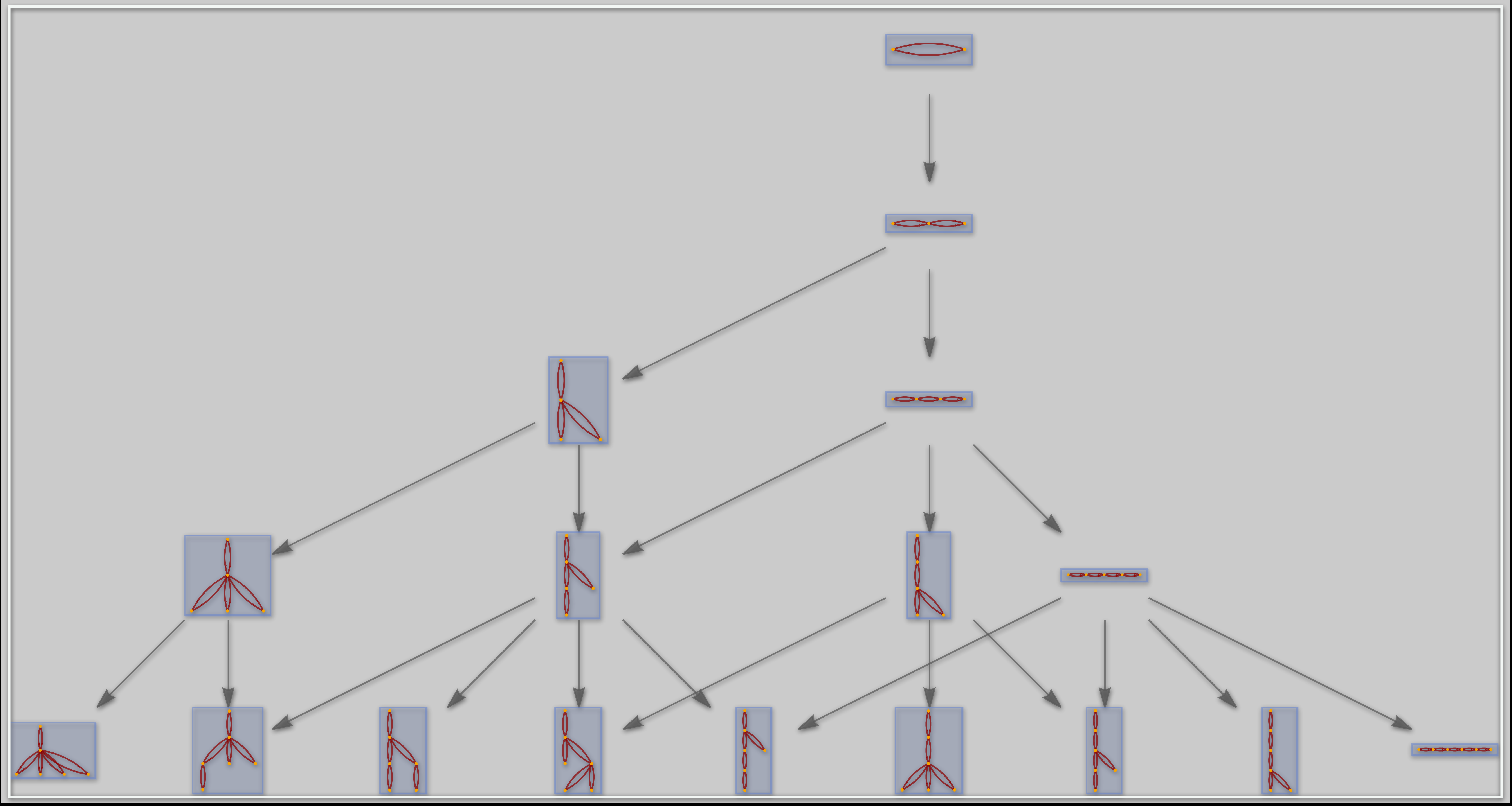
A More Sophisticated Example III

- The corresponding multiway evolution:



A More Sophisticated Example IV

- The algorithm still succeeds in achieving eventual consistency with a finite and bounded amount of communication:



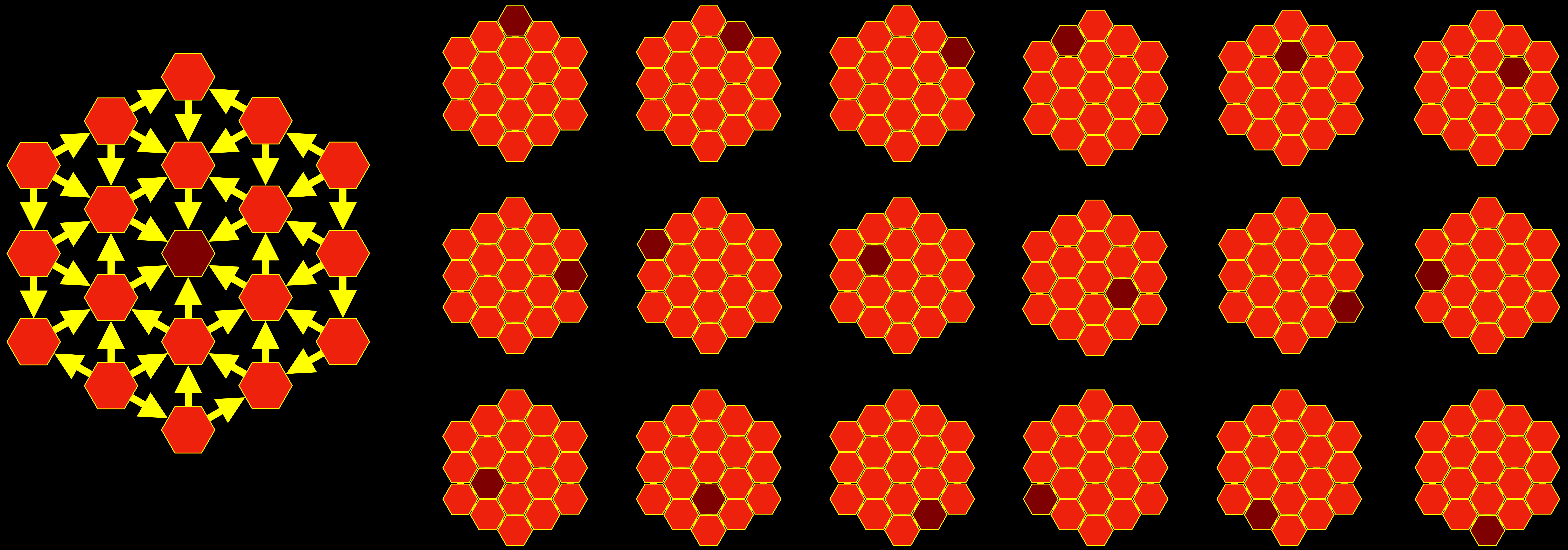
Time in Transactions

- All time is a Tree. High speed trading gets as close to the incoming clock source as possible, all the cables are equal length
- We cannot guarantee transactions without a protocol that conserves information.
- The conservation of information means there is a symmetry somewhere. We think that symmetry is time reversibility
- Exactly once semantics is impossible, unless we pair exactly once sending with exactly once receiving.
- Idempotency is notoriously tricky to get right [A16Z]

What do we need for the Journey?

- To get the power dissipation down for an interstellar journey, we need to use every trick in the book to manage energy
- The most important, is reversible computation, and reversible communication [Michael Frank]
- We need a distributed protocol (wireless packet encodings) that combine extreme robustness, sensitivity to doppler shifts and low power dissipation [Muriel Médard]
- When spacecraft are communicating with entangled links, they can get that for free. Only when they are communicating over long distances, does the Landauer Limit come into play [David Wolpert]

19 Rooted DAGs / Causal Trees



Complete Redundancy: Any Cell can become a controller if others fail

Compositional Causality Podcast

Jonathan Gorard	Compositional Causality
Short Description	Notions of causality invoked in quantum information theory, relatiivity, distributed systems, etc. seem incompatible, and fraught with philosophical difficulties. Can ideas from category theory help?
Long Description	The concept of causality gets invoked a lot in quantum information theory (e.g. quantum switches, indefinite causal orders), special/general relativity (e.g. conformal structure of spacetime), graph rewriting (e.g. unfoldings in algebraic graph rewriting, causal graphs in the Wolfram Physics Project), distributed systems (e.g. Petri nets, discrete event systems, concurrency models) and many other areas. It is far from obvious that these notions of causality are equivalent (because they aren't!), or even logically compatible. Even the very definition of causality in an abstract sense is philosophically problematic, depending, for instance, upon counterfactual notions of history which may not always exist. Indeed, the foundational problem of quantum gravity may be viewed as being a special case of the more general problem of relating a linear/"algebraic" notion of causality (e.g. from quantum mechanics) with a non-linear/"geometrical" one (e.g. from general relativity). In this talk, I'll explore how ideas from (higher) category theory and the Wolfram Physics Project may potentially be used to shed light on this fundamental problem, and will propose a new algebraic foundation for causality in general computational systems.

DÆDÆLUS?

- Platforms for secure, reliable, Distributed Computing on the edge
- The worlds most advanced way to reorder events in distributed systems
- Use Cases:
  - Distributed Microservices on the Edge
  - Digital Twin Infrastructures
  - Interface to Quantum Computers
  - Interstellar Attoprobeswarms
- DÆ = Distributed Atomic Ethernet

This slide was lost because of the failure of the iCloud synchronization algorithm.

It had to be retrieved from the exported version in powerpoint.

These kind of sync failures also occur in Dropbox, Gdrive, OneDrive .

References (Jonathan)

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  - J. Gorard, M. Namuduri, X. D. Arsiwalla (2020), https://arxiv.org/abs/2010.02752
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- Connections to Distributed Systems:
  - J. Gorard (2022), https://arxiv.org/abs/2301.04690
- Etc.

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  - Video: https://www.youtube.com/watch?v=IPTlTmH-YvQ
  - Slides: http://web.stanford.edu/class/ee380/Abstracts/161116-slides.pdf
  - Info: http://web.stanford.edu/class/ee380/Abstracts/161116.html
- Papers We Love 2016: “Lamport’s Unfinished Revolution” (July 2016)
  - Video: https://www.youtube.com/watch?feature=youtu.be&t=32m27s&v=CWF3QnfihL4
  - Slides: https://speakerdeck.com/pborrill/time-clocks-and-the-reordering-of-events-pwl-san-francisco-14-jul-2016
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- Stanford 2014: Time in Physics, and Implications for Computer Science
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  - Info: http://web.stanford.edu/class/ee380/Abstracts/091111.html
- A classical groupoid model for quantum networks
  - https://arxiv.org/abs/1707.00966

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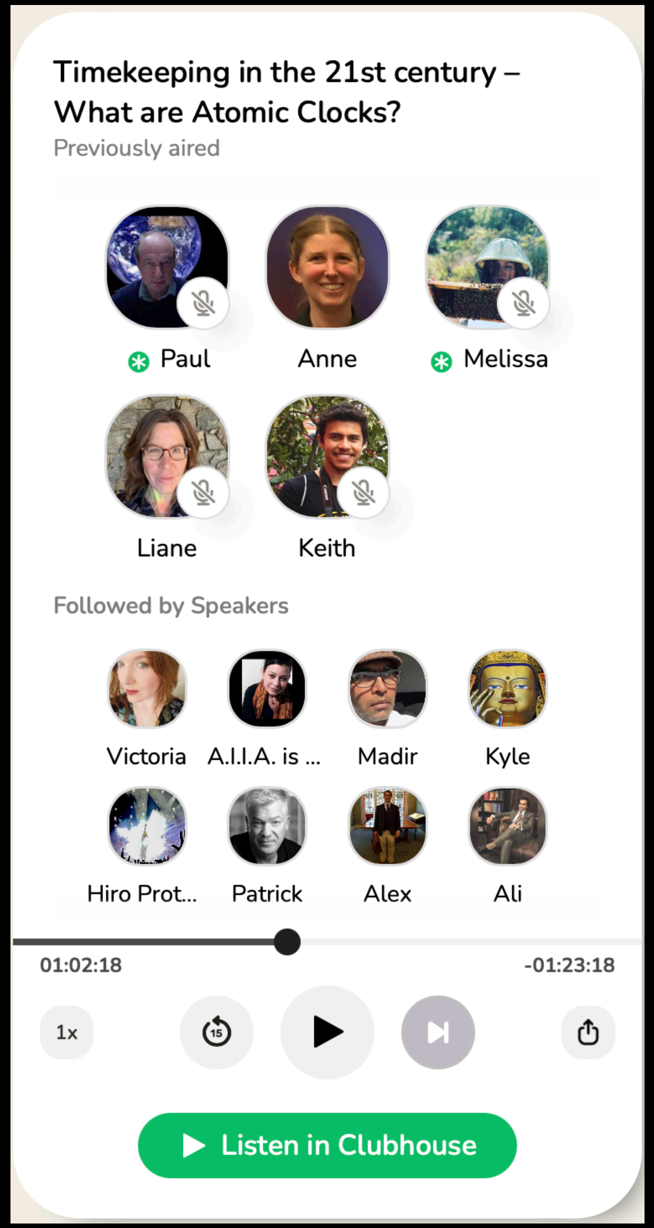
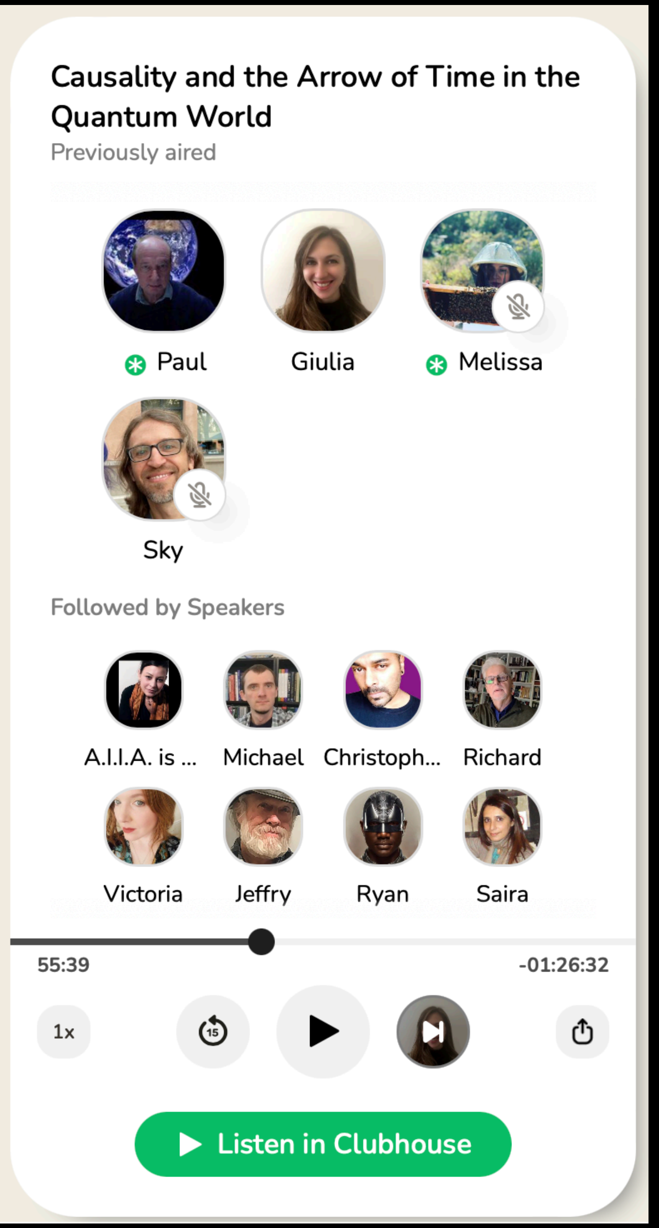
For physicists, computer scientists, neuroscientists, philosophers and practicing engineers.



Timekeeping in the 21st century – What are Atomic Clocks?

Anne Curtis



Causality and the Arrow of Time in the Quantum World

Giulia Rubino

Daedaelus:

We address fundamental problems in distributed systems using protocols, data structures & algorithms inspired by Quantum Information Theory and Multiway Systems

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