BFT Consensus

From Academic Paper to Mainnet

Alberto Sonnino

Alberto Sonnino

Research Scientist

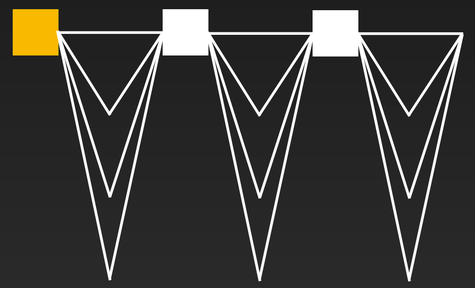
- PhD from UCL (George Danezis & Jens Groth)
- Co-founded Chainspace
- At Libra / Diem from day 1
- Now building the Sui blockchain

2019

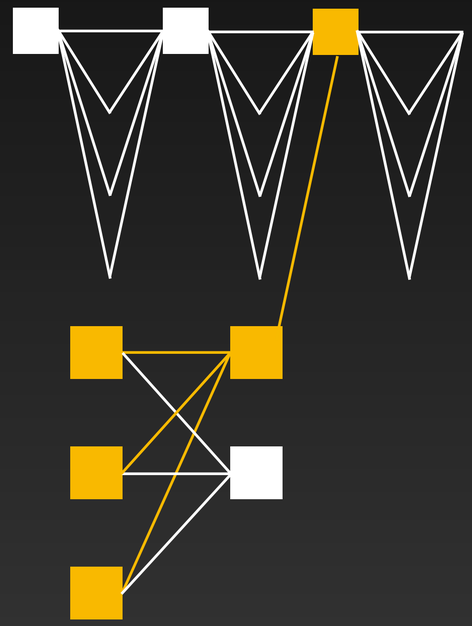
libra

2024

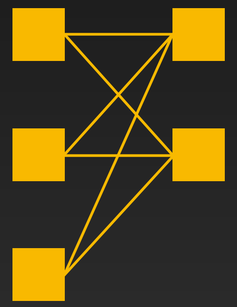
Sui



HotStuff



HotStuff + Mempool



Bullshark,

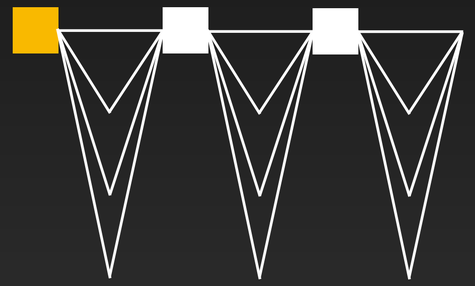
Mysticeti

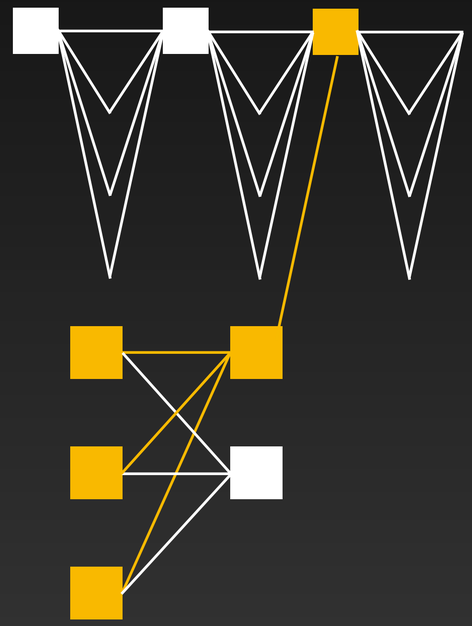
2019

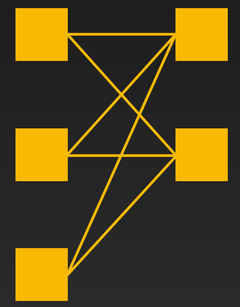
libra

2024

Sui







- Lessons learned
- Open research challenges

Research Gifts

(please keep it short)

Byzantine Fault Tolerance

Byzantine Fault Tolerance

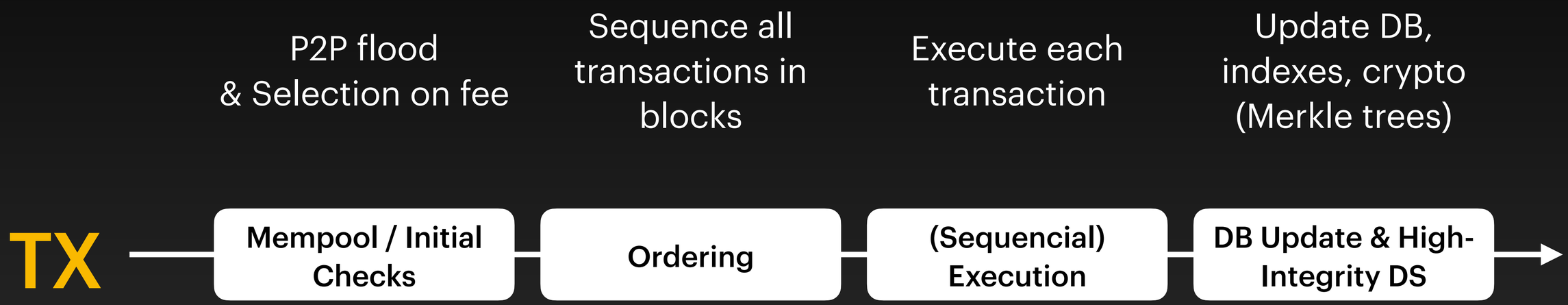
Partial Synchrony

Research Questions

1. Network model?

Lessons Learned

Typical Blockchain



Typical Blockchain

P2P flood & Selection on fee

Sequence all transactions in blocks

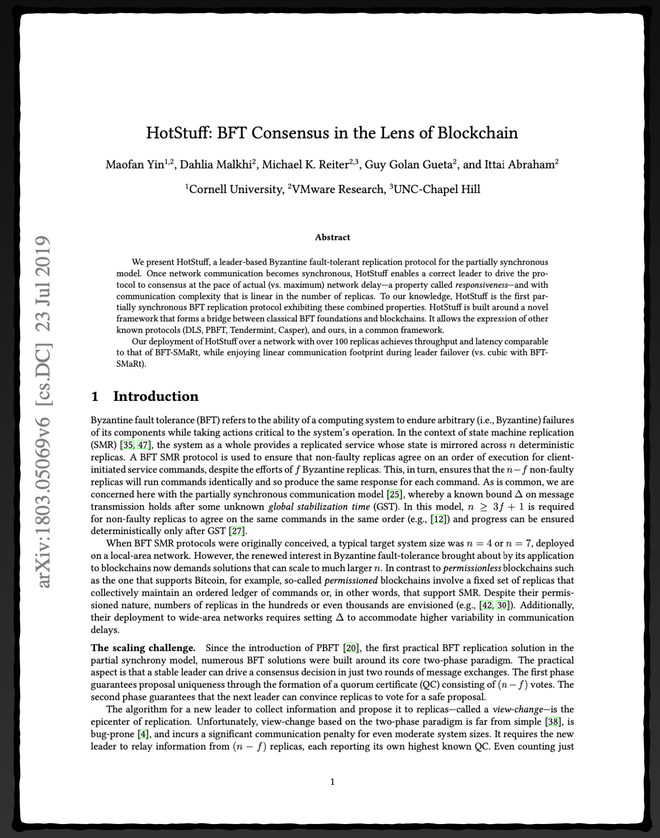
Mempool / Initial Checks

Ordering

Overlay flooding slow and with significant redundancy

Seconds latency, traditionally low throughput

Libra, 2019



HotStuff: BFT Consensus in the Lens of Blockchain

Maofan Yin[1,2], Dahlia Malkhi[2], Michael K. Reiter[2,3], Guy Golan Gueta[2], and Ittai Abraham[2]

[1]Cornell University, [2]VMware Research, [3]UNC-Chapel Hill

Abstract

We present HotStuff, a leader-based Byzantine fault-tolerant replication protocol for the partially synchronous model. Once network communication becomes synchronous, HotStuff enables a correct leader to drive the protocol to consensus at the pace of actual (vs. maximum) network delay—a property called *responsiveness*—and with communication complexity that is linear in the number of replicas. To our knowledge, HotStuff is the first partially synchronous BFT replication protocol exhibiting these combined properties. HotStuff is built around a novel framework that forms a bridge between classical BFT foundations and blockchains. It allows the expression of other known protocols (DLS, PBFT, Tendermint, Casper), and ours, in a common framework.

Our deployment of HotStuff over a network with over 100 replicas achieves throughput and latency comparable to that of BFT-SMaRt, while enjoying linear communication footprint during leader failover (vs. cubic with BFT-SMaRt).

1 Introduction

Byzantine fault tolerance (BFT) refers to the ability of a computing system to endure arbitrary (i.e., Byzantine) failures of its components while taking actions critical to the system's operation. In the context of state machine replication (SMR) [35, 47], the system as a whole provides a replicated service whose state is mirrored across n deterministic replicas. A BFT SMR protocol is used to ensure that non-faulty replicas agree on an order of execution for client-initiated service commands, despite the efforts of f Byzantine replicas. This, in turn, ensures that the $n-f$ non-faulty replicas will run commands identically and so produce the same response for each command. As is common, we are concerned here with the partially synchronous communication model [25], whereby a known bound Δ on message transmission holds after some unknown *global stabilization time* (GST). In this model, $n \geq 3f + 1$ is required for non-faulty replicas to agree on the same commands in the same order (e.g., [12]) and progress can be ensured deterministically only after GST [27].

When BFT SMR protocols were originally conceived, a typical target system size was $n = 4$ or $n = 7$, deployed on a local-area network. However, the renewed interest in Byzantine fault-tolerance brought about by its application to blockchains now demands solutions that can scale to much larger n. In contrast to *permissionless* blockchains such as the one that supports Bitcoin, for example, so-called *permissioned* blockchains involve a fixed set of replicas that collectively maintain an ordered ledger of commands or, in other words, that support SMR. Despite their permissioned nature, numbers of replicas in the hundreds or even thousands are envisioned (e.g., [42, 30]). Additionally, their deployment to wide-area networks requires setting Δ to accommodate higher variability in communication delays.

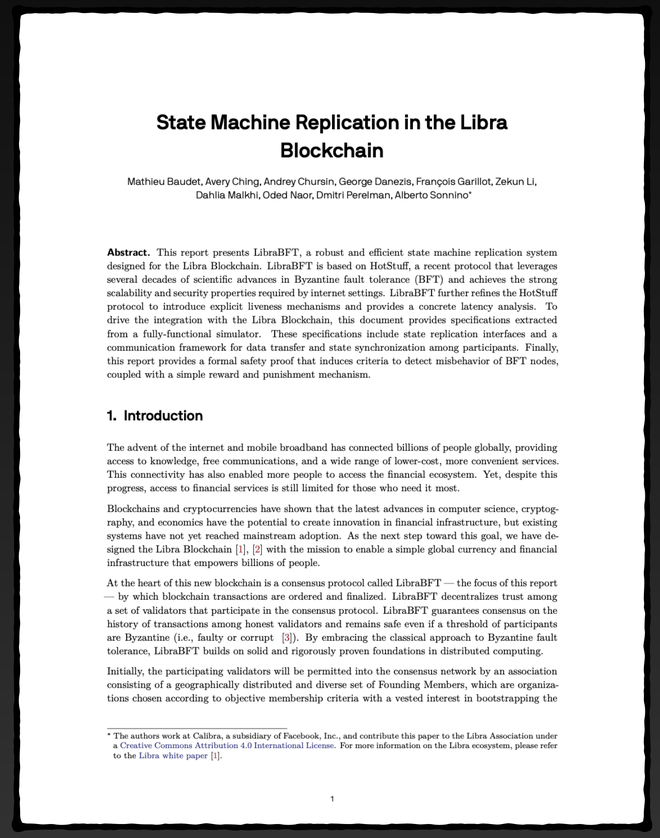
The scaling challenge. Since the introduction of PBFT [20], the first practical BFT replication solution in the partial synchrony model, numerous BFT solutions were built around its core two-phase paradigm. The practical aspect is that a stable leader can drive a consensus decision in just two rounds of message exchanges. The first phase guarantees proposal uniqueness through the formation of a quorum certificate (QC) consisting of $(n - f)$ votes. The second phase guarantees that the next leader can convince replicas to vote for a safe proposal.

The algorithm for a new leader to collect information and propose it to replicas—called a *view-change*—is the epicenter of replication. Unfortunately, view-change based on the two-phase paradigm is far from simple [38], is bug-prone [4], and incurs a significant communication penalty for even moderate system sizes. It requires the new leader to relay information from $(n - f)$ replicas, each reporting its own highest known QC. Even counting just

HotStuff

- Linear
- Clearly isolated components

The first 6 months...



State Machine Replication in the Libra Blockchain

Mathieu Baudet, Avery Ching, Andrey Chursin, George Danezis, François Garillot, Zekun Li, Dahlia Malkhi, Oded Naor, Dmitri Perelman, Alberto Sonnino*

Abstract. This report presents LibraBFT, a robust and efficient state machine replication system designed for the Libra Blockchain. LibraBFT is based on HotStuff, a recent protocol that leverages several decades of scientific advances in Byzantine fault tolerance (BFT) and achieves the strong scalability and security properties required by internet settings. LibraBFT further refines the HotStuff protocol to introduce explicit liveness mechanisms and provides a concrete latency analysis. To drive the integration with the Libra Blockchain, this document provides specifications extracted from a fully-functional simulator. These specifications include state replication interfaces and a communication framework for data transfer and state synchronization among participants. Finally, this report provides a formal safety proof that induces criteria to detect misbehavior of BFT nodes, coupled with a simple reward and punishment mechanism.

1. Introduction

The advent of the internet and mobile broadband has connected billions of people globally, providing access to knowledge, free communications, and a wide range of lower-cost, more convenient services. This connectivity has also enabled more people to access the financial ecosystem. Yet, despite this progress, access to financial services is still limited for those who need it most.

Blockchains and cryptocurrencies have shown that the latest advances in computer science, cryptography, and economics have the potential to create innovation in financial infrastructure, but existing systems have not yet reached mainstream adoption. As the next step toward this goal, we have designed the Libra Blockchain [1], [2] with the mission to enable a simple global currency and financial infrastructure that empowers billions of people.

At the heart of this new blockchain is a consensus protocol called LibraBFT — the focus of this report — by which blockchain transactions are ordered and finalized. LibraBFT decentralizes trust among a set of validators that participate in the consensus protocol. LibraBFT guarantees consensus on the history of transactions among honest validators and remains safe even if a threshold of participants are Byzantine (i.e., faulty or corrupt [3]). By embracing the classical approach to Byzantine fault tolerance, LibraBFT builds on solid and rigorously proven foundations in distributed computing.

Initially, the participating validators will be permitted into the consensus network by an association consisting of a geographically distributed and diverse set of Founding Members, which are organizations chosen according to objective membership criteria with a vested interest in bootstrapping the

* The authors work at Calibra, a subsidiary of Facebook, Inc., and contribute this paper to the Libra Association under a Creative Commons Attribution 4.0 International License. For more information on the Libra ecosystem, please refer to the Libra white paper [1].

SMR in the Libra Blockchain

- The LibraBFT/DiemBFT pacemaker
- Codesign the pacemaker with the rest

Research Questions

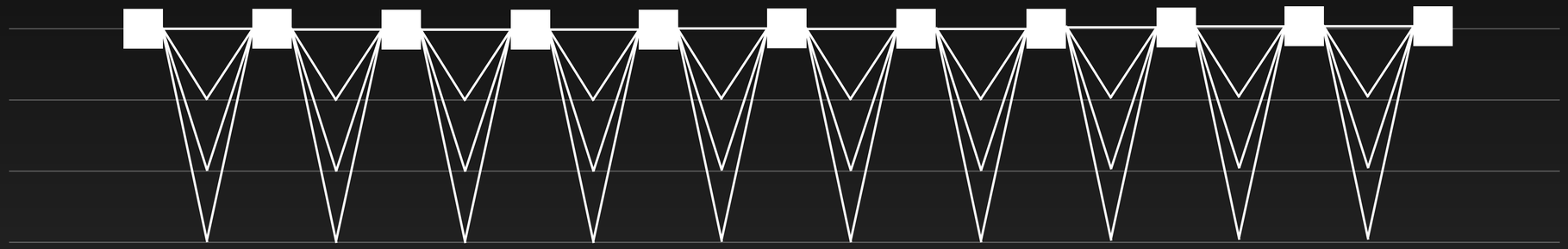
1. Network model?

Lessons Learned

1. Modularisation is a design strategy

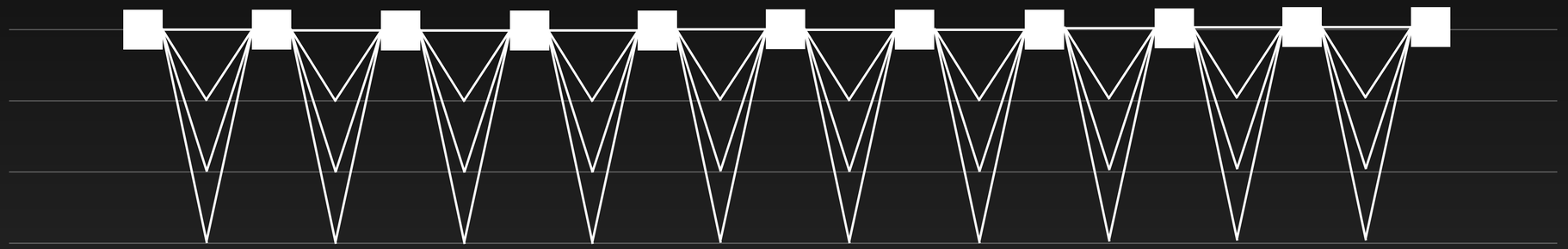
HotStuff

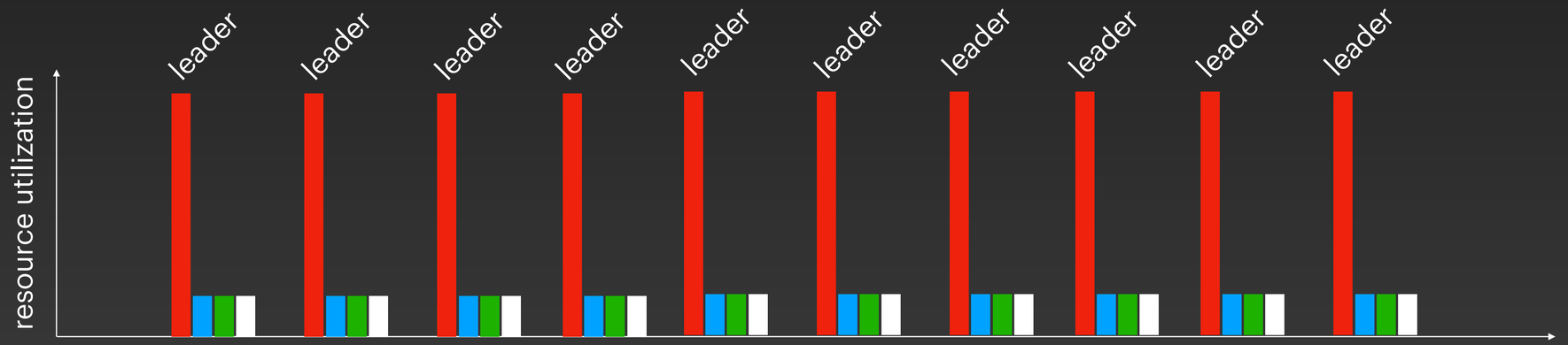
Typical leader-based protocols



HotStuff

Uneven resource utilisation





Research Questions

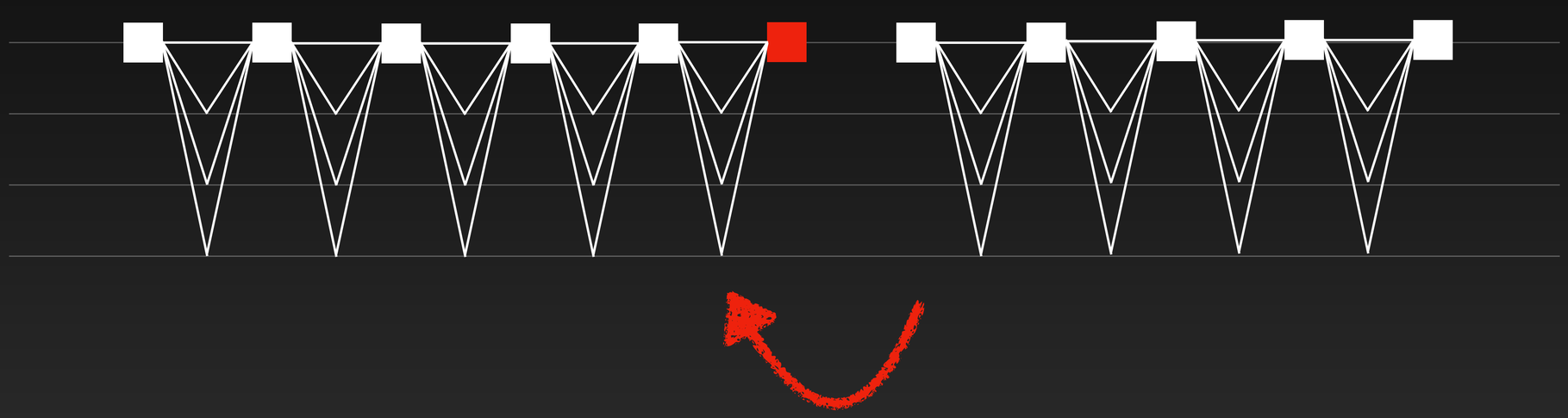
1. Network model?

Lessons Learned

1. Modularisation is a design strategy
2. Tasks-threads relationship

HotStuff

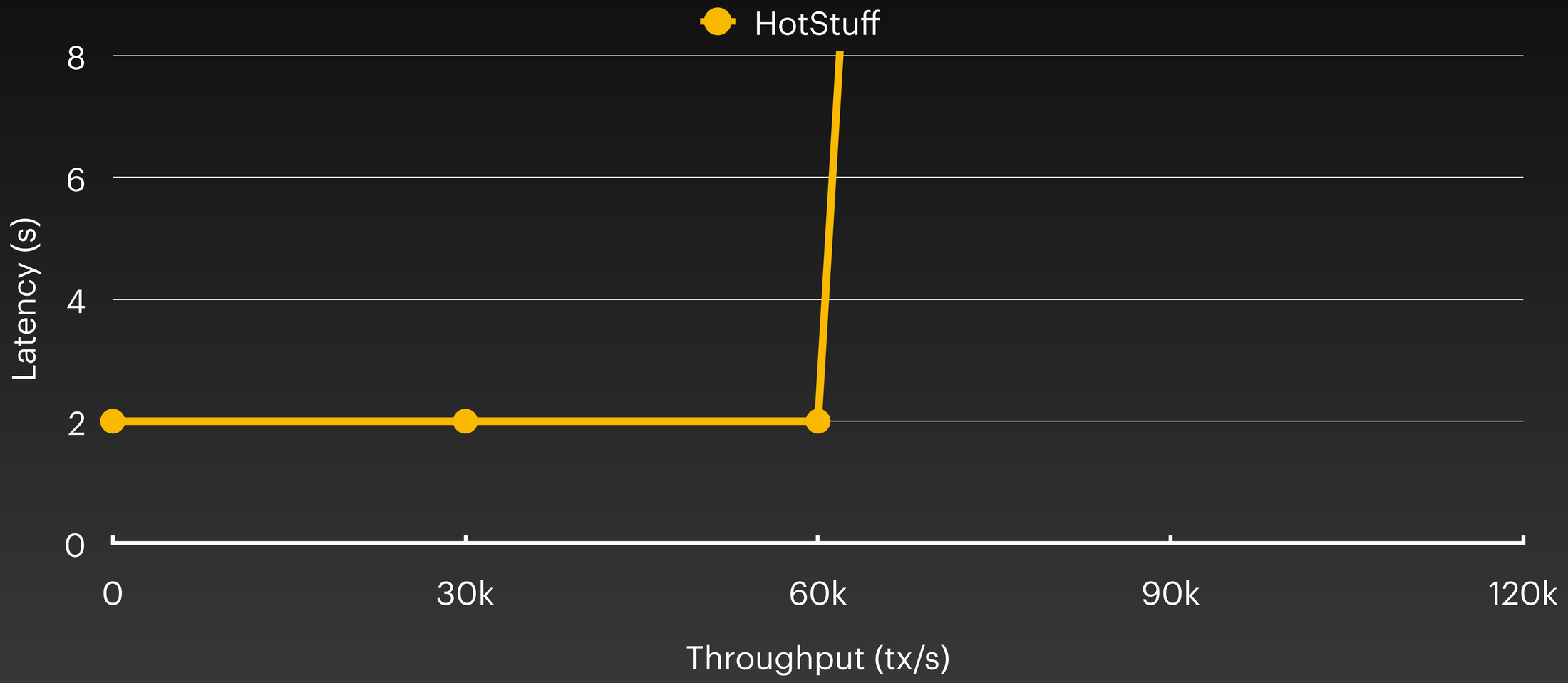
Fragility to faults and asynchrony



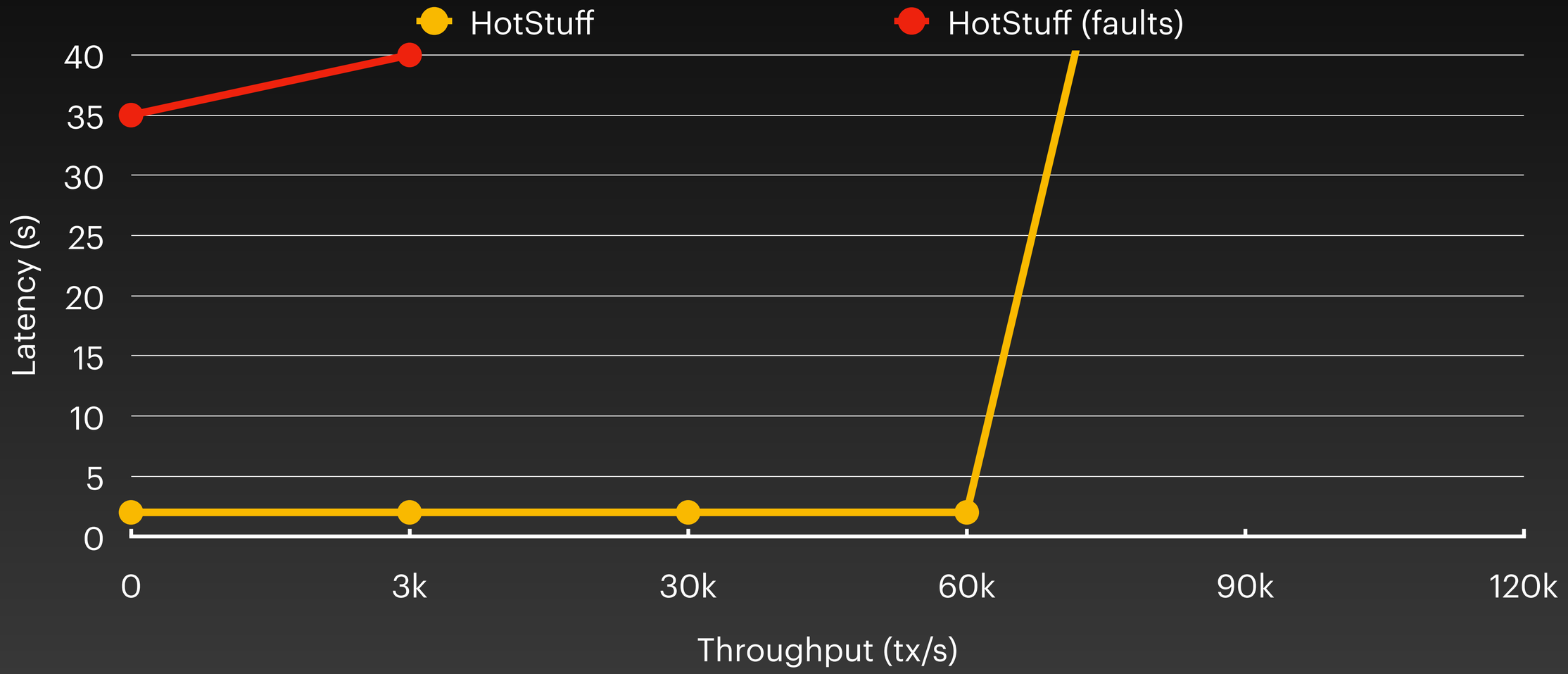
HotStuff

Fragility to faults and asynchrony

Performance



Performance



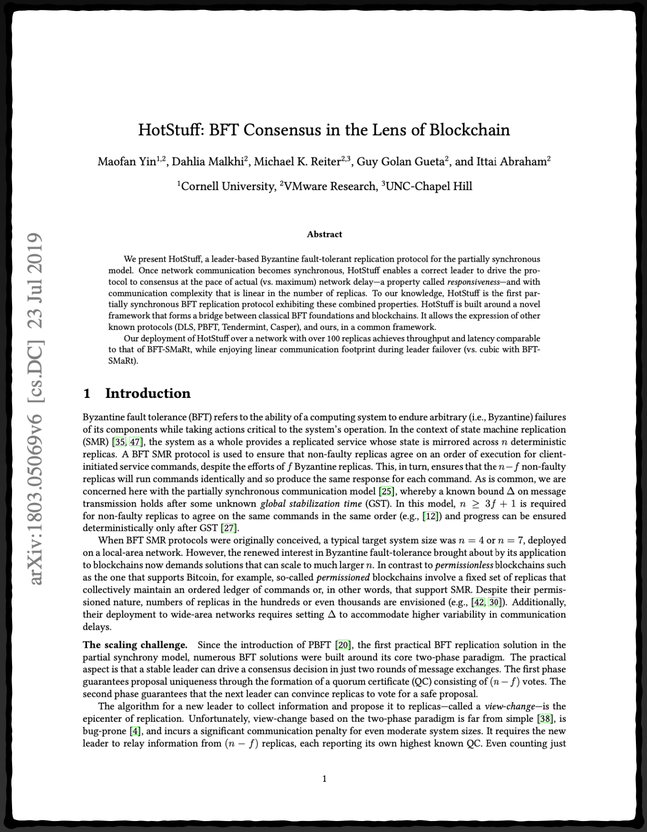
Research Questions

1. Network model?

Lessons Learned

1. Modularisation is a design strategy
2. Tasks-threads relationship
3. Benchmark early

Libra, 2019



arXiv:1803.05069v6 [cs.DC] 23 Jul 2019

HotStuff: BFT Consensus in the Lens of Blockchain

Maofan Yin[1,2], Dahlia Malkhi[2], Michael K. Reiter[2,3], Guy Golan Gueta[2], and Ittai Abraham[2]

[1]Cornell University, [2]VMware Research, [3]UNC-Chapel Hill

Abstract

We present HotStuff, a leader-based Byzantine fault-tolerant replication protocol for the partially synchronous model. Once network communication becomes synchronous, HotStuff enables a correct leader to drive the protocol to consensus at the pace of actual (vs. maximum) network delay—a property called *responsiveness*—and with communication complexity that is linear in the number of replicas. To our knowledge, HotStuff is the first partially synchronous BFT replication protocol exhibiting these combined properties. HotStuff is built around a novel framework that forms a bridge between classical BFT foundations and blockchains. It allows the expression of other known protocols (DLS, PBFT, Tendermint, Casper), and ours, in a common framework.

Our deployment of HotStuff over a network with over 100 replicas achieves throughput and latency comparable to that of BFT-SMaRt, while enjoying linear communication footprint during leader failover (vs. cubic with BFT-SMaRt).

1 Introduction

Byzantine fault tolerance (BFT) refers to the ability of a computing system to endure arbitrary (i.e., Byzantine) failures of its components while taking actions critical to the system's operation. In the context of state machine replication (SMR) [35, 47], the system as a whole provides a replicated service whose state is mirrored across n deterministic replicas. A BFT SMR protocol is used to ensure that non-faulty replicas agree on an order of execution for client-initiated service commands, despite the efforts of f Byzantine replicas. This, in turn, ensures that the $n-f$ non-faulty replicas will run commands identically and so produce the same response for each command. As is common, we are concerned here with the partially synchronous communication model [25], whereby a known bound Δ on message transmission holds after some unknown *global stabilization time* (GST). In this model, $n \geq 3f + 1$ is required for non-faulty replicas to agree on the same commands in the same order (e.g., [12]) and progress can be ensured deterministically only after GST [27].

When BFT SMR protocols were originally conceived, a typical target system size was $n = 4$ or $n = 7$, deployed on a local-area network. However, the renewed interest in Byzantine fault-tolerance brought about by its application to blockchains now demands solutions that can scale to much larger n. In contrast to *permissionless* blockchains such as the one that supports Bitcoin, for example, so-called *permissioned* blockchains involve a fixed set of replicas that collectively maintain an ordered ledger of commands or, in other words, that support SMR. Despite their permissioned nature, numbers of replicas in the hundreds or even thousands are envisioned (e.g., [42, 30]). Additionally, their deployment to wide-area networks requires setting Δ to accommodate higher variability in communication delays.

The scaling challenge. Since the introduction of PBFT [20], the first practical BFT replication solution in the partial synchrony model, numerous BFT solutions were built around its core two-phase paradigm. The practical aspect is that a stable leader can drive a consensus decision in just two rounds of message exchanges. The first phase guarantees proposal uniqueness through the formation of a quorum certificate (QC) consisting of $(n - f)$ votes. The second phase guarantees that the next leader can convince replicas to vote for a safe proposal.

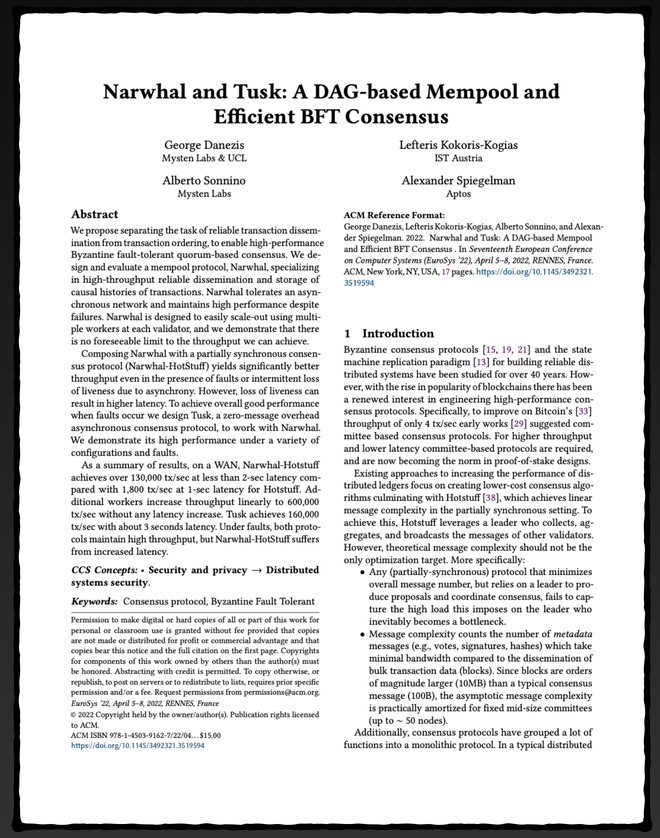
The algorithm for a new leader to collect information and propose it to replicas—called a *view-change*—is the epicenter of replication. Unfortunately, view-change based on the two-phase paradigm is far from simple [38], is bug-prone [4], and incurs a significant communication penalty for even moderate system sizes. It requires the new leader to relay information from $(n - f)$ replicas, each reporting its own highest known QC. Even counting just

HotStuff

- Linear
- Clearly isolated components

- Uneven resource utilisation
- Fragile to faults and asynchrony
- Unspecified components (pacemaker)

Libra, 2021



Narwhal and Tusk: A DAG-based Mempool and Efficient BFT Consensus

George Danezis
Mysten Labs & UCL

Lefteris Kokoris-Kogias
IST Austria

Alberto Sonnino
Mysten Labs

Alexander Spiegelman
Aptos

Abstract

We propose separating the task of reliable transaction dissemination from transaction ordering, to enable high-performance Byzantine fault-tolerant quorum-based consensus. We design and evaluate a mempool protocol, Narwhal, specializing in high-throughput reliable dissemination and storage of causal histories of transactions. Narwhal tolerates an asynchronous network and maintains high performance despite failures. Narwhal is designed to easily scale-out using multiple workers at each validator, and we demonstrate that there is no foreseeable limit to the throughput we can achieve.

Composing Narwhal with a partially synchronous consensus protocol (Narwhal-HotStuff) yields significantly better throughput even in the presence of faults or intermittent loss of liveness due to asynchrony. However, loss of liveness can result in higher latency. To achieve overall good performance when faults occur we design Tusk, a zero-message overhead asynchronous consensus protocol, to work with Narwhal. We demonstrate its high performance under a variety of configurations and faults.

As a summary of results, on a WAN, Narwhal-Hotstuff achieves over 130,000 tx/sec at less than 2-sec latency compared with 1,800 tx/sec at 1-sec latency for Hotstuff. Additional workers increase throughput linearly to 600,000 tx/sec without any latency increase. Tusk achieves 160,000 tx/sec with about 3 seconds latency. Under faults, both protocols maintain high throughput, but Narwhal-HotStuff suffers from increased latency.

CCS Concepts: • **Security and privacy → Distributed systems security**.

Keywords: Consensus protocol, Byzantine Fault Tolerant

EuroSys '22, April 5–8, 2022, RENNES, France

ACM ISBN 978-1-4503-9162-7/22/04…$15.00
https://doi.org/10.1145/3492321.3519594

ACM Reference Format:
George Danezis, Lefteris Kokoris-Kogias, Alberto Sonnino, and Alexander Spiegelman. 2022. Narwhal and Tusk: A DAG-based Mempool and Efficient BFT Consensus . In *Seventeenth European Conference on Computer Systems (EuroSys '22), April 5–8, 2022, RENNES, France.* ACM, New York, NY, USA, 17 pages. https://doi.org/10.1145/3492321.3519594

1 Introduction

Byzantine consensus protocols [15, 19, 21] and the state machine replication paradigm [13] for building reliable distributed systems have been studied for over 40 years. However, with the rise in popularity of blockchains there has been a renewed interest in engineering high-performance consensus protocols. Specifically, to improve on Bitcoin's [33] throughput of only 4 tx/sec early works [29] suggested committee based consensus protocols. For higher throughput and lower latency committee-based protocols are required, and are now becoming the norm in proof-of-stake designs.

Existing approaches to increasing the performance of distributed ledgers focus on creating lower-cost consensus algorithms culminating with Hotstuff [38], which achieves linear message complexity in the partially synchronous setting. To achieve this, Hotstuff leverages a leader who collects, aggregates, and broadcasts the messages of other validators. However, theoretical message complexity should not be the only optimization target. More specifically:

- Any (partially-synchronous) protocol that minimizes overall message number, but relies on a leader to produce proposals and coordinate consensus, fails to capture the high load this imposes on the leader who inevitably becomes a bottleneck.
- Message complexity counts the number of *metadata* messages (e.g., votes, signatures, hashes) which take minimal bandwidth compared to the dissemination of bulk transaction data (blocks). Since blocks are orders of magnitude larger (10MB) than a typical consensus message (100B), the asymptotic message complexity is practically amortized for fixed mid-size committees (up to ∼ 50 nodes).

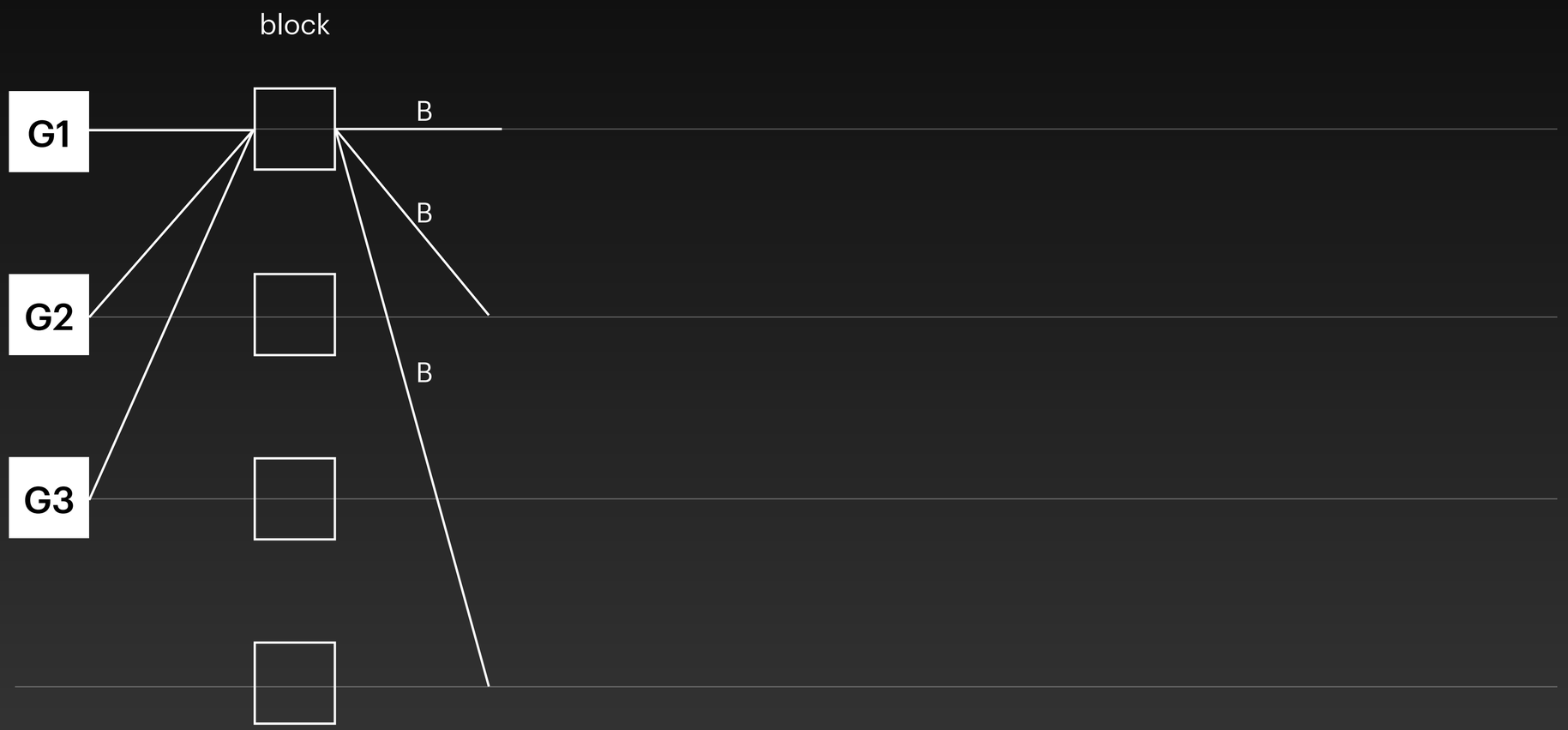
Additionally, consensus protocols have grouped a lot of functions into a monolithic protocol. In a typical distributed

Narwhal

- Quadratic but even resource utilisation
- Separation between consensus and data dissemination

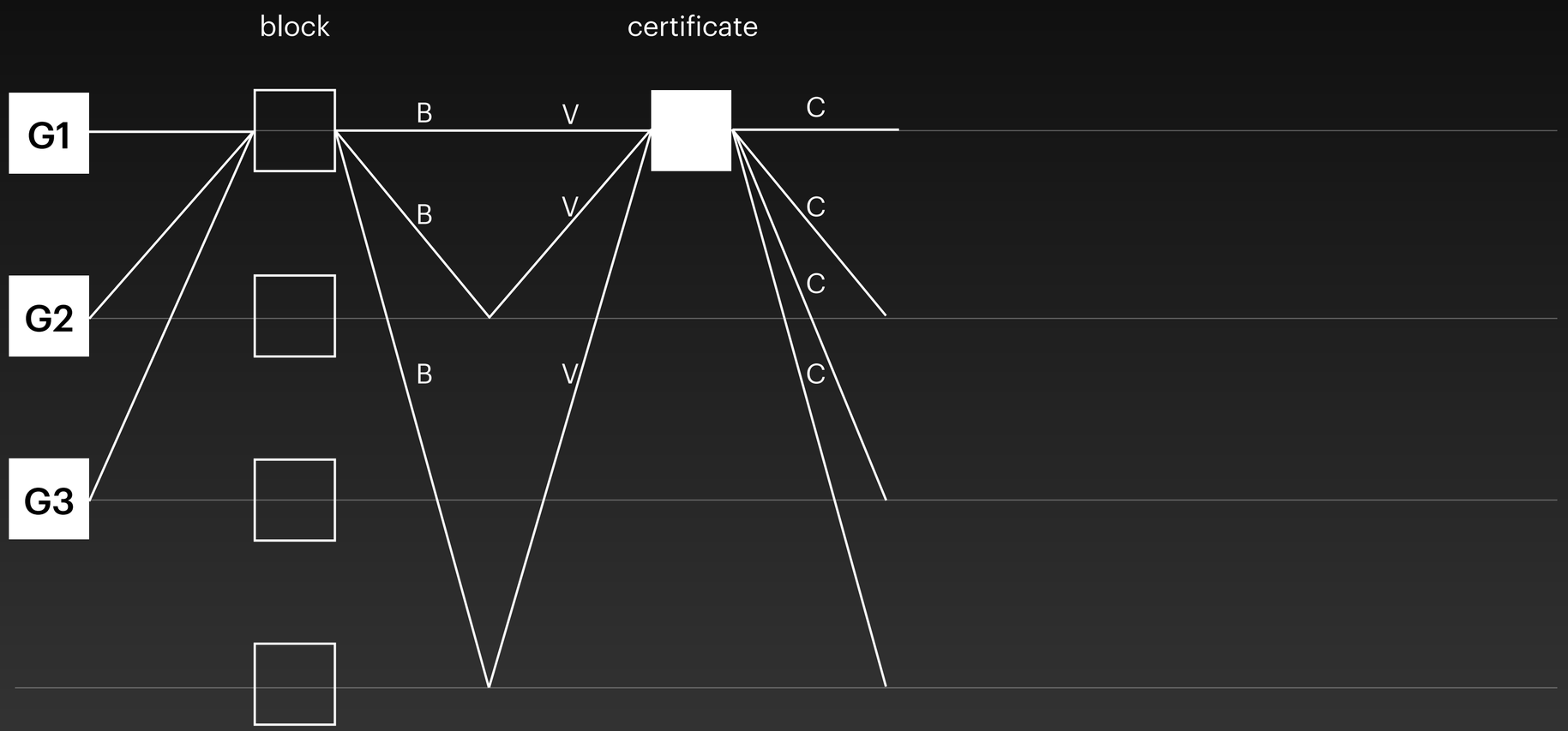
Narwhal

The primary machine

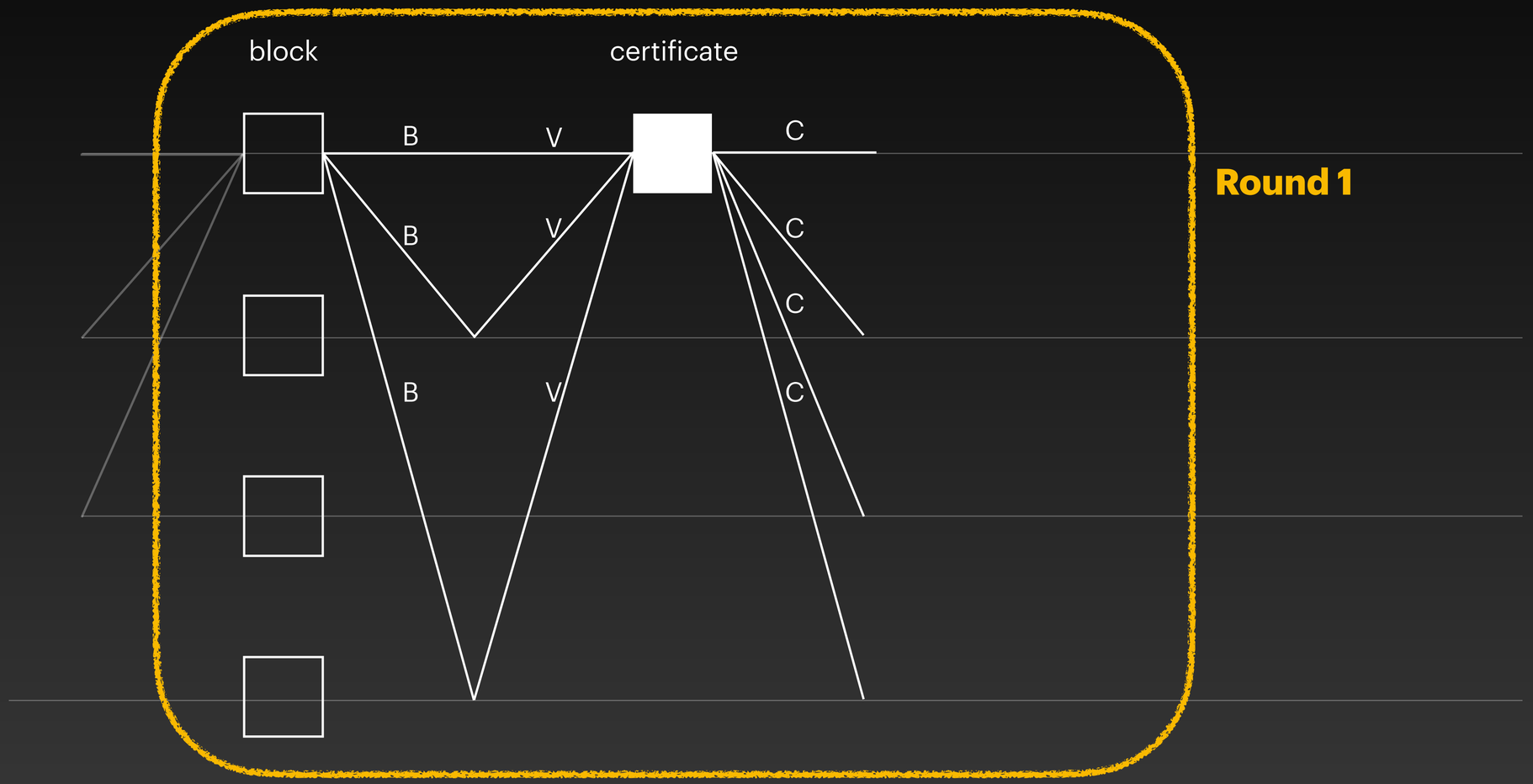


Narwhal

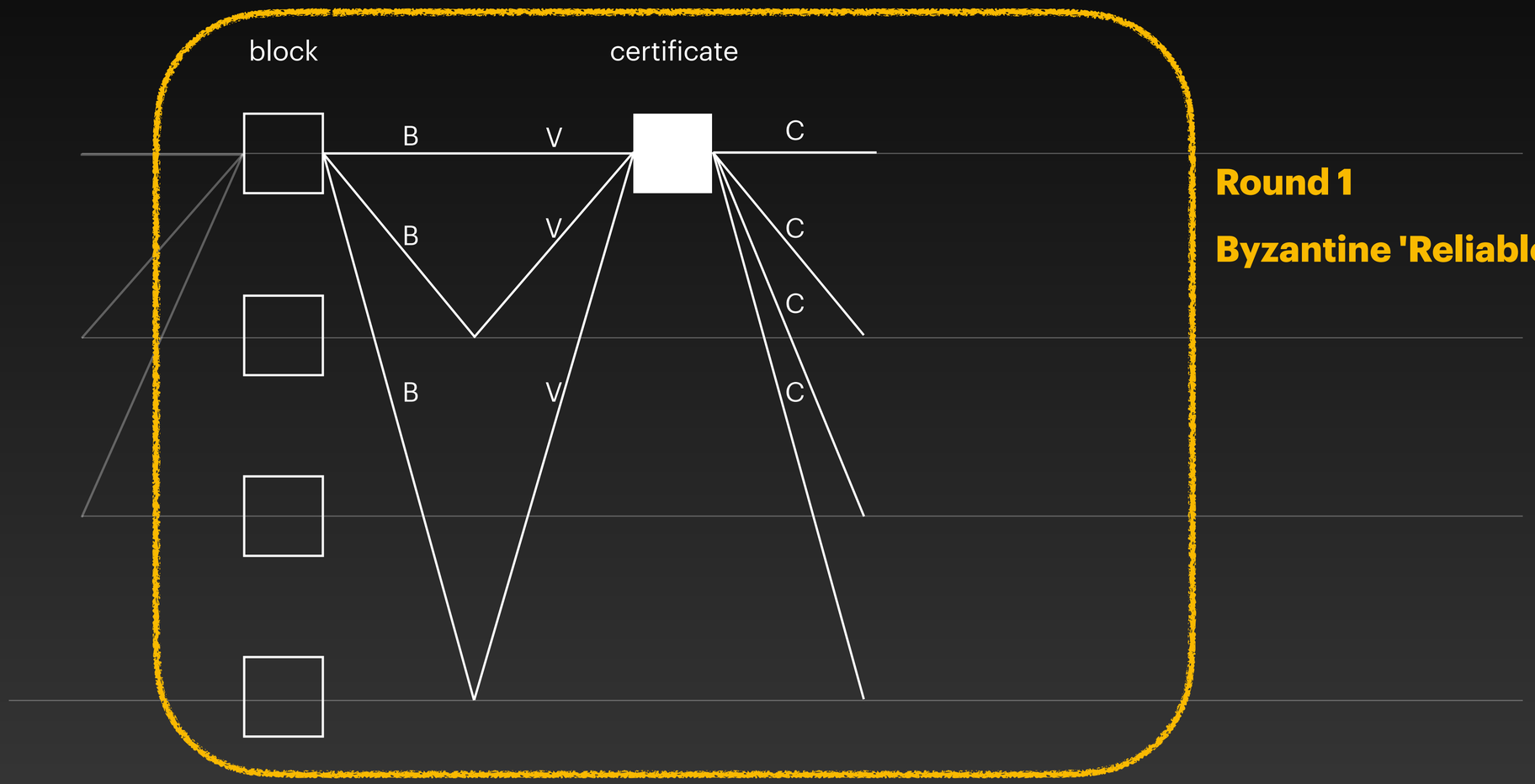
Narwhal



Narwhal



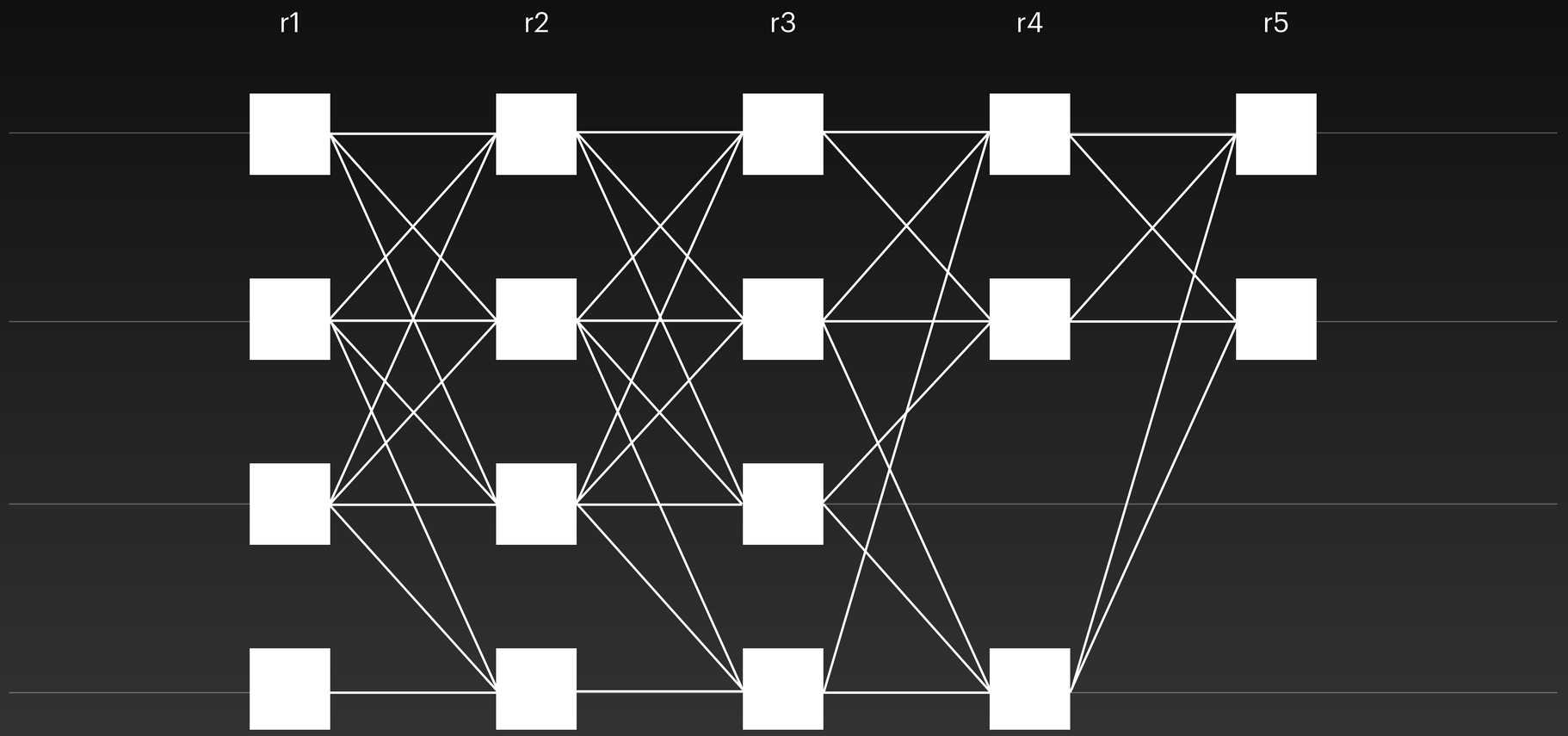
Narwhal



Round 1

Byzantine 'Reliable' Broadcast

Narwhal



Research Questions

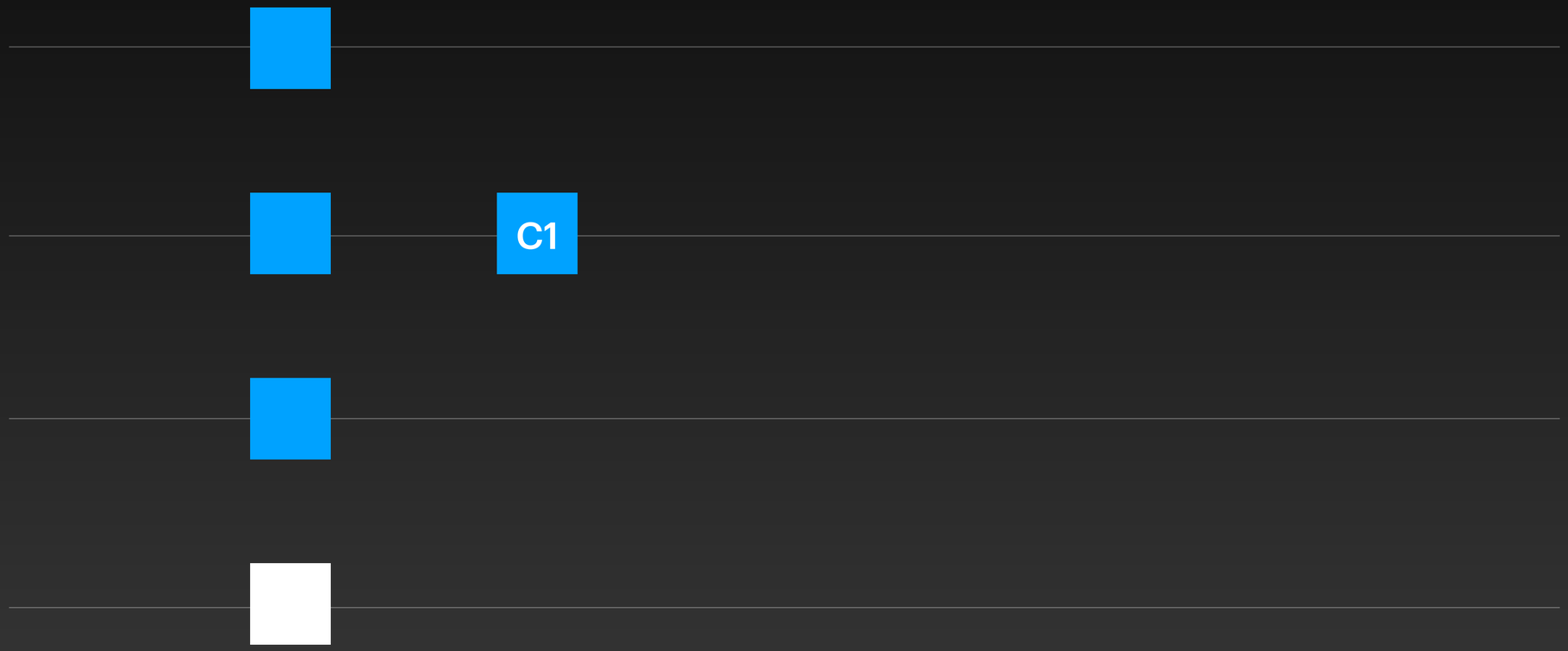
1. Network model?

Lessons Learned

1. Modularisation is a design strategy
2. Tasks-threads relationship
3. Benchmark early
4. Codesign with mem. and storage

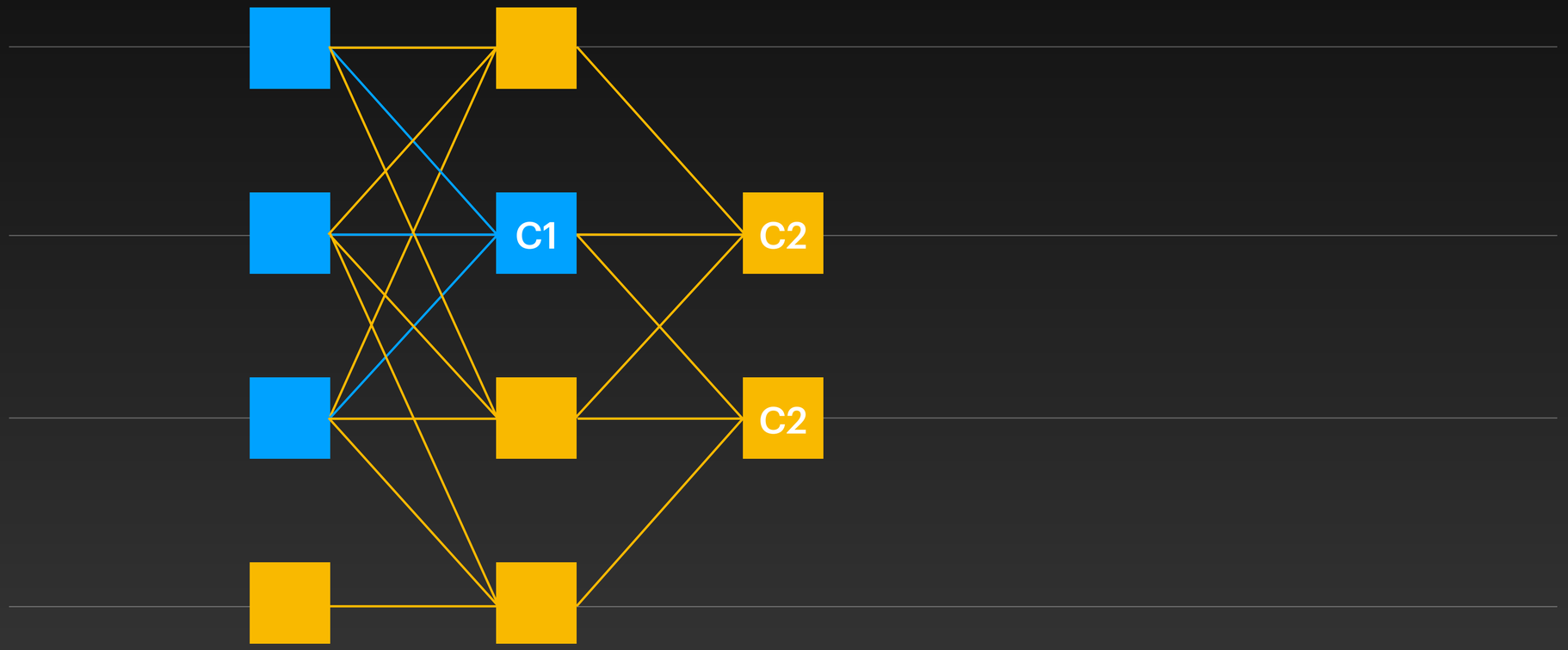
HotStuff on Narwhal

Enhanced commit rule



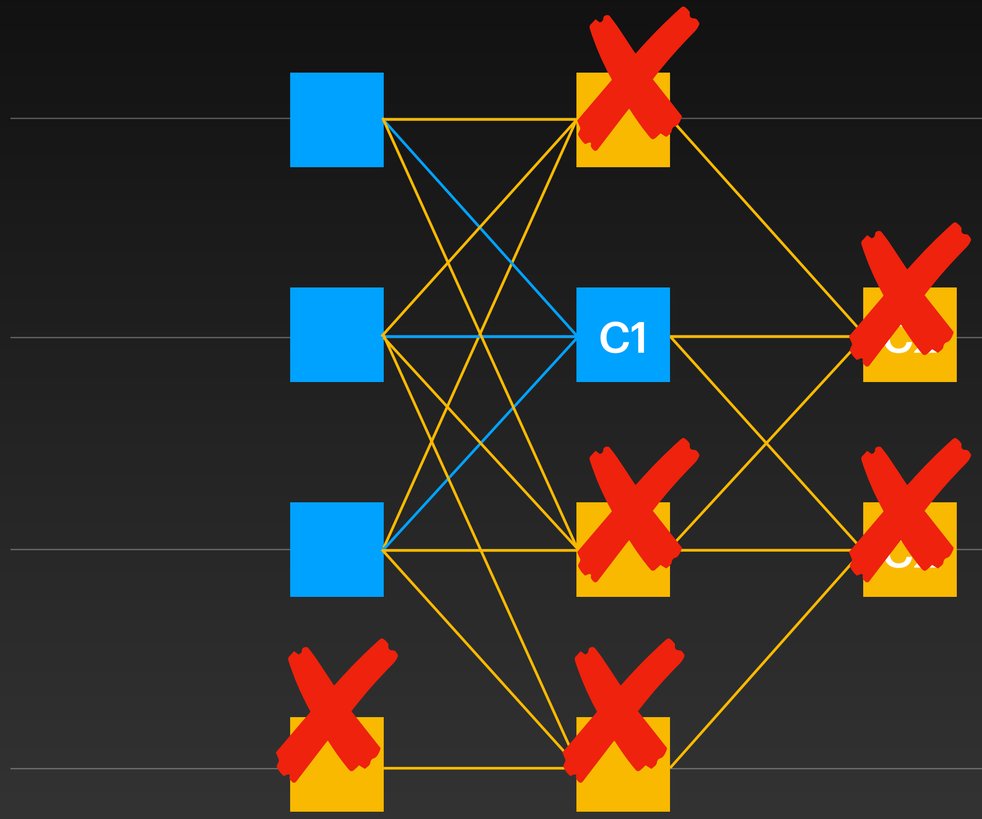
HotStuff on Narwhal

Enhanced commit rule



HotStuff on Narwhal

Enhanced commit rule

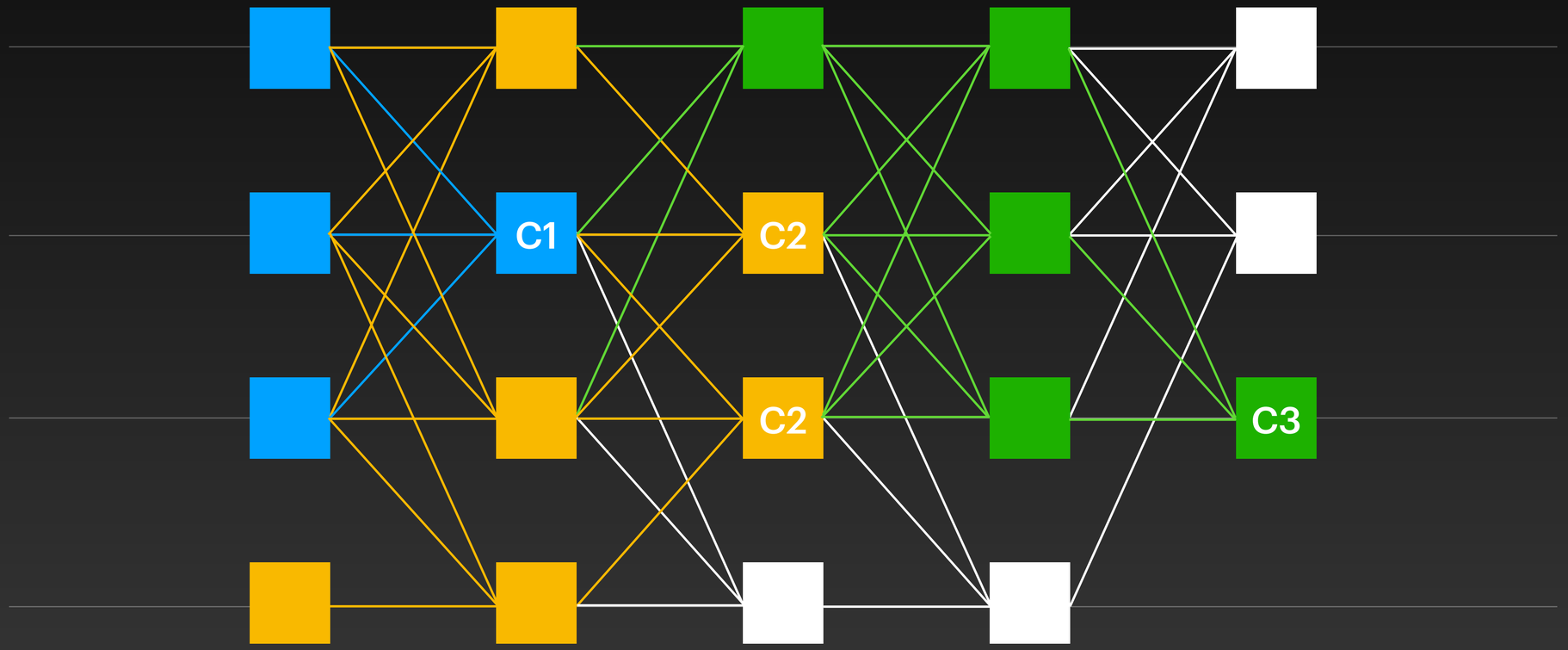


Faulty HotStuff Leader!

Blocks may still be ‘saved'

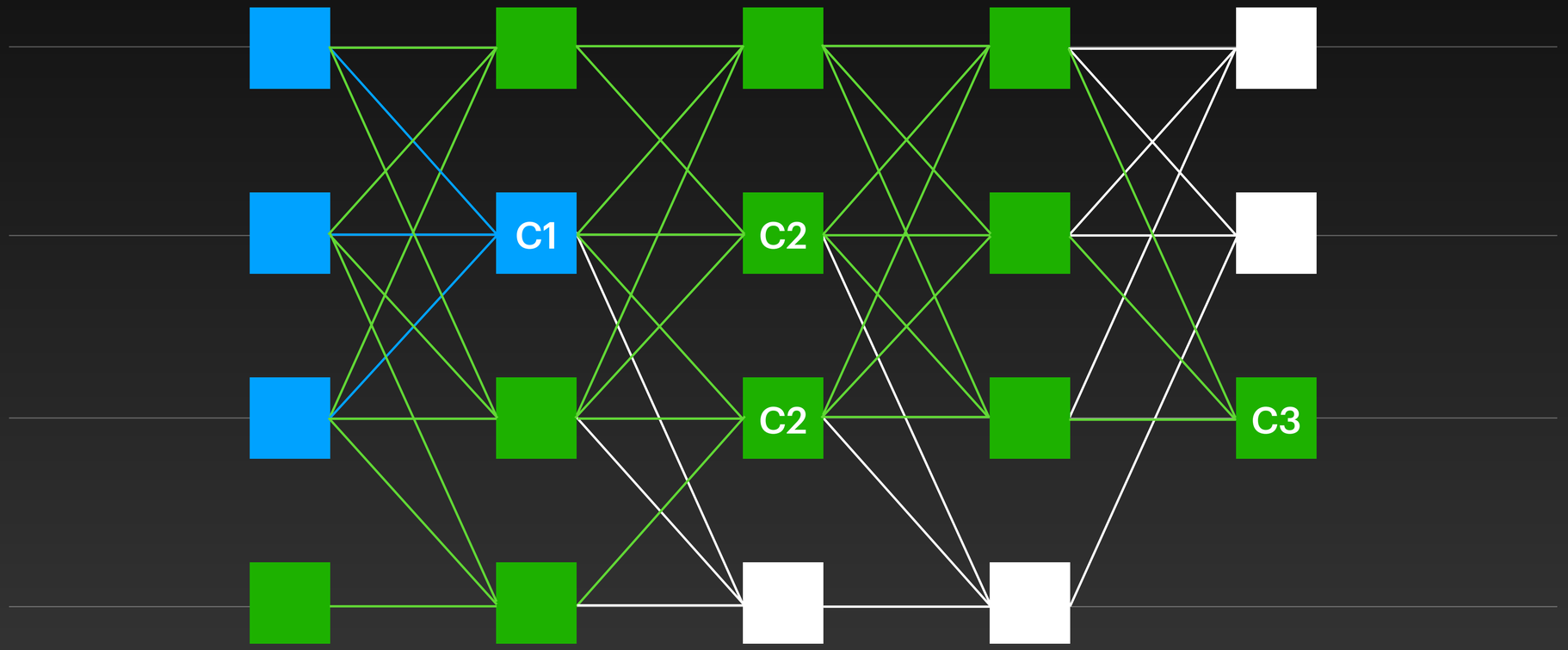
HotStuff on Narwhal

Enhanced commit rule

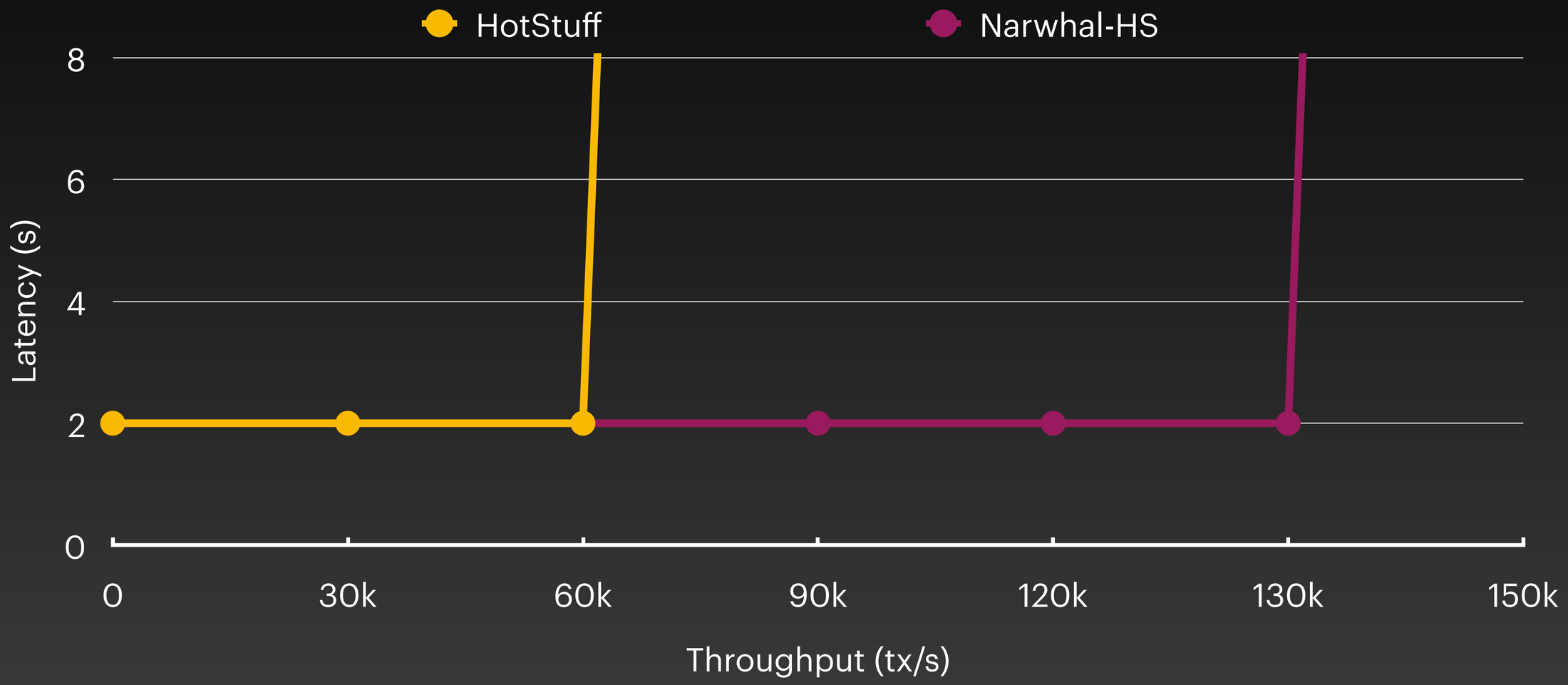


HotStuff on Narwhal

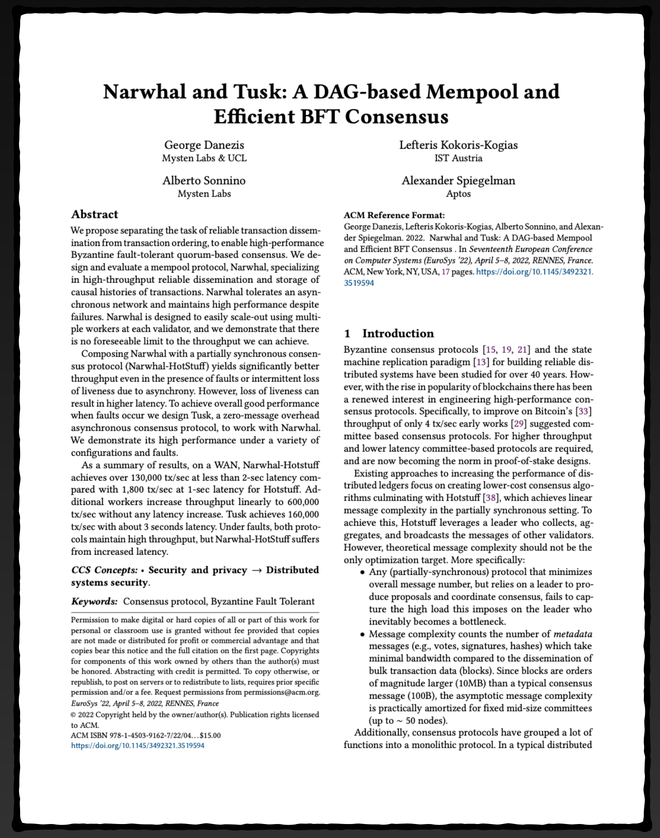
Enhanced commit rule



Performance



Libra, 2021



Narwhal and Tusk: A DAG-based Mempool and Efficient BFT Consensus

George Danezis
Mysten Labs & UCL

Lefteris Kokoris-Kogias
IST Austria

Alberto Sonnino
Mysten Labs

Alexander Spiegelman
Aptos

Abstract

We propose separating the task of reliable transaction dissemination from transaction ordering, to enable high-performance Byzantine fault-tolerant quorum-based consensus. We design and evaluate a mempool protocol, Narwhal, specializing in high-throughput reliable dissemination and storage of causal histories of transactions. Narwhal tolerates an asynchronous network and maintains high performance despite failures. Narwhal is designed to easily scale-out using multiple workers at each validator, and we demonstrate that there is no foreseeable limit to the throughput we can achieve.

Composing Narwhal with a partially synchronous consensus protocol (Narwhal-HotStuff) yields significantly better throughput even in the presence of faults or intermittent loss of liveness due to asynchrony. However, loss of liveness can result in higher latency. To achieve overall good performance when faults occur we design Tusk, a zero-message overhead asynchronous consensus protocol, to work with Narwhal. We demonstrate its high performance under a variety of configurations and faults.

As a summary of results, on a WAN, Narwhal-Hotstuff achieves over 130,000 tx/sec at less than 2-sec latency compared with 1,800 tx/sec at 1-sec latency for Hotstuff. Additional workers increase throughput linearly to 600,000 tx/sec without any latency increase. Tusk achieves 160,000 tx/sec with about 3 seconds latency. Under faults, both protocols maintain high throughput, but Narwhal-HotStuff suffers from increased latency.

CCS Concepts: • **Security and privacy → Distributed systems security**.

Keywords: Consensus protocol, Byzantine Fault Tolerant

EuroSys '22, April 5–8, 2022, RENNES, France

ACM ISBN 978-1-4503-9162-7/22/04…$15.00
https://doi.org/10.1145/3492321.3519594

ACM Reference Format:
George Danezis, Lefteris Kokoris-Kogias, Alberto Sonnino, and Alexander Spiegelman. 2022. Narwhal and Tusk: A DAG-based Mempool and Efficient BFT Consensus . In *Seventeenth European Conference on Computer Systems (EuroSys '22), April 5–8, 2022, RENNES, France.* ACM, New York, NY, USA, 17 pages. https://doi.org/10.1145/3492321.3519594

1 Introduction

Byzantine consensus protocols [15, 19, 21] and the state machine replication paradigm [13] for building reliable distributed systems have been studied for over 40 years. However, with the rise in popularity of blockchains there has been a renewed interest in engineering high-performance consensus protocols. Specifically, to improve on Bitcoin's [33] throughput of only 4 tx/sec early works [29] suggested committee based consensus protocols. For higher throughput and lower latency committee-based protocols are required, and are now becoming the norm in proof-of-stake designs.

Existing approaches to increasing the performance of distributed ledgers focus on creating lower-cost consensus algorithms culminating with Hotstuff [38], which achieves linear message complexity in the partially synchronous setting. To achieve this, Hotstuff leverages a leader who collects, aggregates, and broadcasts the messages of other validators. However, theoretical message complexity should not be the only optimization target. More specifically:

- Any (partially-synchronous) protocol that minimizes overall message number, but relies on a leader to produce proposals and coordinate consensus, fails to capture the high load this imposes on the leader who inevitably becomes a bottleneck.
- Message complexity counts the number of *metadata* messages (e.g., votes, signatures, hashes) which take minimal bandwidth compared to the dissemination of bulk transaction data (blocks). Since blocks are orders of magnitude larger (10MB) than a typical consensus message (100B), the asymptotic message complexity is practically amortized for fixed mid-size committees (up to ∼ 50 nodes).

Additionally, consensus protocols have grouped a lot of functions into a monolithic protocol. In a typical distributed

Narwhal

- Quadratic but even resource utilisation
- Separation between consensus and data dissemination
- High engineering complexity

Research Questions

1. Network model?
2. BFT testing?

Lessons Learned

1. Modularisation is a design strategy
2. Tasks-threads relationship
3. Benchmark early
4. Codesign with mem. and storage

DagRider

All You Need is DAG

Idit Keidar
Technion

Eleftherios Kokoris-Kogias
IST Austria and Novi Research

Oded Naor*
Technion

Alexander Spiegelman
Novi Research

ABSTRACT

We present *DAG-Rider*, the first asynchronous Byzantine Atomic Broadcast protocol that achieves optimal resilience, optimal amortized communication complexity, and optimal time complexity. *DAG-Rider* is post-quantum safe and ensures that all values proposed by correct processes eventually get delivered. We construct *DAG-Rider* in two layers: In the first layer, processes reliably broadcast their proposals and build a structured Directed Acyclic Graph (DAG) of the communication among them. In the second layer, processes locally observe their DAGs and totally order all proposals with no extra communication.

ACM Reference Format:
Idit Keidar, Eleftherios Kokoris-Kogias, Oded Naor, and Alexander Spiegelman. 2021. All You Need is DAG. In *Proceedings of the 2021 ACM Symposium on Principles of Distributed Computing (PODC '21), July 26–30, 2021, Virtual Event, Italy.* ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3465084.3467905

1 INTRODUCTION

The amplified need in scalable geo-replicated Byzantine fault-tolerant reliability systems has motivated an enormous amount of study on the Byzantine State Machine Replication (SMR) problem [17, 31]. Many variants of the problem were defined in recent years [28, 32, 43] to capture the needs of blockchain systems. To address the fairness issues that naturally arise in interorganizational deployments, we focus on the classic long-lived Byzantine Atomic Broadcast (BAB) problem [12, 19], which in addition to total order and progress also guarantees that all proposals by correct processes are eventually included.

Up until recently, asynchronous protocols for the Byzantine consensus problem [12, 16, 26] have been considered too costly or complicated to be used in practical SMR solutions. However, two recent single-shot Byzantine consensus papers, VABA [1] and later Dumbo [35], presented asynchronous solutions with (1) optimal resilience, (2) expected constant time complexity, and (3) optimal quadratic communication and optimal **amortized** linear communication complexity (for the latter). In this paper, we follow this recent line of work and present *DAG-Rider*, the first asynchronous BAB protocol with optimal resilience, optimal round complexity, and optimal amortized communication complexity. In addition, given a perfect shared coin abstraction, our protocol does not use signatures and does not rely on asymmetric cryptographic assumptions. Therefore, when using a deterministic threshold-based coin implementation with an information theoretical agreement guarantee [13, 34], the safety properties of our BAB protocol are post-quantum secure.

Overview. We construct *DAG-Rider* in two layers: a communication layer and a zero-overhead ordering layer. In the communication layer, processes reliably broadcast their proposals with some metadata that help them form a *Directed Acyclic Graph (DAG)* of the messages they deliver. That is, the DAG consists of rounds r, s.t. every process broadcasts at most one message in every round and every message has $O(n)$ references to messages in previous rounds, where n is the total number of processes. The ordering layer does not require any extra communication. Instead, processes observe their local DAGs and with the help of a little randomization (one coin flip per $O(n)$ decisions on values proposed by different processes) locally order all the delivered messages in their local DAGs.

A nice feature of DAG-Rider is that the propose operation is simply a single reliable broadcast. The agreement property of the reliable broadcast ensures that all correct processes eventually see the same DAG. Moreover, the validity property of the reliable broadcast guarantees that all broadcast messages by correct processes are eventually included in the DAG. As a result, in contrast to the VABA and Dumbo protocols that retroactively ignore half the protocol messages and commit one value out of $O(n)$ proposals, *DAG-Rider* does not waste any of the messages and all proposed values by correct processes are eventually ordered (i.e., there is no need to re-propose).

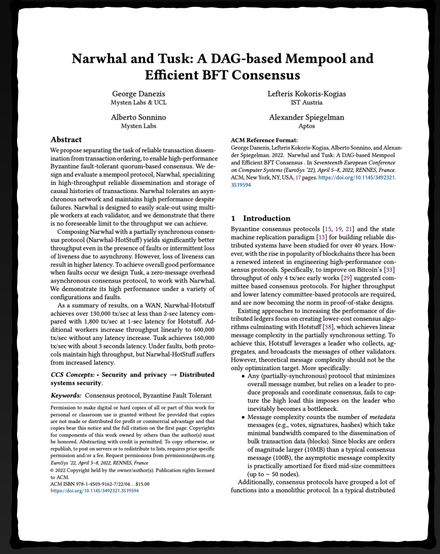
Complexity. We measure time complexity as the asynchronous time [16] required to commit $O(n)$ values proposed by different correct processes, and we measure communication complexity by the number of bits processes send to commit a single value. To compare DAG-Rider to the state-of-the-art asynchronous Byzantine agreement protocols, we consider SMR implementations that run an unbounded sequence of the VABA or Dumbo protocols to independently agree on every slot. To compare apples to apples in respect to our time complexity definition, we allow VABA and Dumbo based SMRs to run up to n slots concurrently. Note, however, that for execution processes must output the slot decisions in a sequential order (no gaps). Therefore, based on the proof in [6], the time complexity of VABA and Dumbo based SMRs is $O(\log(n))$. Table 1 compares DAG-Rider to VABA and Dumbo based SMRs.

Since our protocol uses a reliable broadcast abstraction as a basic building block, different instantiations yield different complexity. For example, if we use the classic Bracha broadcast [11] to propose a

*Oded Naor is grateful to the Technion Hiroshi Fujiwara Cyber Security Research Center and the Israel Cyber Bureau for providing a research grant. Part of Oded's work was done while at Novi Research.

ACM ISBN 978-1-4503-8548-0/21/07…$15.00
https://doi.org/10.1145/3465084.3467905

Tusk



Narwhal and Tusk: A DAG-based Mempool and Efficient BFT Consensus

George Danezis
Mysten Labs & UCL

Lefteris Kokoris-Kogias
IST Austria

Alberto Sonnino
Mysten Labs

Alexander Spiegelman
Aptos

Abstract

We propose separating the task of reliable transaction dissemination from transaction ordering, to enable high-performance Byzantine fault-tolerant quorum-based consensus. We design and evaluate a mempool protocol, Narwhal, specializing in high-throughput reliable dissemination and storage of causal histories of transactions. Narwhal tolerates an asynchronous network and maintains high performance despite failures. Narwhal is designed to easily scale-out using multiple workers at each validator, and we demonstrate that there is no foreseeable limit to the throughput we can achieve.

Composing Narwhal with a partially synchronous consensus protocol (Narwhal-HotStuff) yields significantly better throughput even in the presence of faults or intermittent loss of liveness due to asynchrony. However, loss of liveness can result in higher latency. To achieve overall good performance when faults occur we design Tusk, a zero-message overhead asynchronous consensus protocol, to work with Narwhal. We demonstrate its high performance under a variety of configurations and faults.

As a summary of results, on a WAN, Narwhal-Hotstuff achieves over 130,000 tx/sec at less than 2-sec latency compared with 1,800 tx/sec at 1-sec latency for Hotstuff. Additional workers increase throughput linearly to 600,000 tx/sec without any latency increase. Tusk achieves 160,000 tx/sec with about 3 seconds latency. Under faults, both protocols maintain high throughput, but Narwhal-HotStuff suffers from increased latency.

ACM Reference Format:
George Danezis, Lefteris Kokoris-Kogias, Alberto Sonnino, and Alexander Spiegelman. 2022. Narwhal and Tusk: A DAG-based Mempool and Efficient BFT Consensus. In *Seventeenth European Conference on Computer Systems (EuroSys '22), April 5–8, 2022, RENNES, France.* ACM, New York, NY, USA, 17 pages. https://doi.org/10.1145/3492321.3519594

1 Introduction

Byzantine consensus protocols [15, 19, 21] and the state machine replication paradigm [13] for building reliable distributed systems have been studied for over 40 years. However, with the rise in popularity of blockchains there has been a renewed interest in engineering high-performance consensus protocols. Specifically, to improve on Bitcoin's [33] throughput of only 4 tx/sec early works [29] suggested committee based consensus protocols. For higher throughput and lower latency committee-based protocols are required, and are now becoming the norm in proof-of-stake designs.

Existing approaches to increasing the performance of distributed ledgers focus on creating lower-cost consensus algorithms culminating with Hotstuff [38], which achieves linear message complexity in the partially synchronous setting. To achieve this, Hotstuff leverages a leader who collects, aggregates, and broadcasts the messages of other validators. However, theoretical message complexity should not be the only optimization target. More specifically:

- Any (partially-synchronous) protocol that minimizes overall message number, but relies on a leader to produce proposals and coordinate consensus, fails to capture the high load this imposes on the leader who inevitably becomes a bottleneck.
- Message complexity counts the number of *metadata* messages (e.g., votes, signatures, hashes) which take minimal bandwidth compared to the dissemination of bulk transaction data (blocks). Since blocks are orders of magnitude larger (10MB) than a typical consensus message (100B), the asymptotic message complexity is practically amortized for fixed mid-size committees (up to ~ 50 nodes).

Additionally, consensus protocols have grouped a lot of functions into a monolithic protocol. In a typical distributed

ACM ISBN 978-1-4503-9162-7/22/04…$15.00
https://doi.org/10.1145/3492321.3519594

Bullshark

Bullshark: DAG BFT Protocols Made Practical

Alexander Spiegelman
sasha8@aptoslabs.com
Aptos

Neil Giridharan
giridhn@berkeley.edu
UC Berkeley

Alberto Sonnino
alberto@mystenlabs.com
Mysten Labs

Lefteris Kokoris-Kogias
ekokoris@ist.ac.at
IST Austria

ABSTRACT

We present Bullshark, the first directed acyclic graph (DAG) based asynchronous Byzantine Atomic Broadcast protocol that is optimized for the common synchronous case. Like previous DAG-based BFT protocols [19, 25], Bullshark requires no extra communication to achieve consensus on top of building the DAG. That is, parties can totally order the vertices of the DAG by interpreting their local view of the DAG edges. Unlike other asynchronous DAG-based protocols, Bullshark provides a practical low latency fast-path that exploits synchronous periods and deprecates the need for notoriously complex view-change mechanisms. Bullshark achieves this while maintaining all the desired properties of its predecessor DAG-Rider [25]. Namely, it has optimal amortized communication complexity, it provides fairness and asynchronous liveness, and safety is guaranteed even under a quantum adversary.

In order to show the practicality and simplicity of our approach, we also introduce a standalone partially synchronous version of Bullshark which we evaluate against the state of the art. The implemented protocol is embarrassingly simple (200 LOC on top of an existing DAG-based mempool implementation [19]). It is highly efficient, achieving for example, 125,000 transaction per second with a 2 seconds latency for a deployment of 50 parties. In the same setting the state of the art pays a steep 50% latency increase as it optimizes for asynchrony.

ACM Reference Format:
Alexander Spiegelman, Neil Giridharan, Alberto Sonnino, and Lefteris Kokoris-Kogias. 2022. Bullshark: DAG BFT Protocols Made Practical. In *Proceedings of ACM Conference, Los Angeles, CA, USA, November 2022 (Conference'22).* 17 pages.
https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 INTRODUCTION

Ordering transactions is a distributed Byzantine environment via a consensus mechanism has become one of the most timely research areas in recent years due to the blooming Blockchain use-case. A recent line of work [8, 19, 21, 25, 33, 40] proposed an elegant way to separate between the distribution of transactions and the logic required to safely order them. The idea is simple. To propose transactions, parties send them in a way that forms a causal order among them. That is, messages contain blocks of transactions as well as references to previously received messages, which together form a *directed acyclic graph (DAG)*. Interestingly, the structure of the DAG encodes information that allow parties to totally order the DAG by locally interpreting their view of it without sending any extra messages. That is, once we build the DAG, implementing consensus on top of it requires *zero-overhead* of communication.

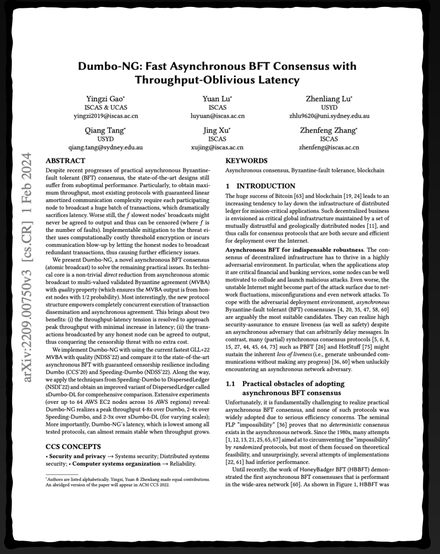
The pioneering work of Hashgraph [8] constructed an unstructured DAG, where each message refers to two previous ones, and used hashes of messages as local coin flips to totally order the DAG in asynchronous settings. Aleph [21] later introduced a structured round-based DAG and encoded a shared randomness in each round via a threshold signature scheme to achieve constant latency in expectation. The state of the art is DAG-Rider [25], which is built on previous ideas. Every round in its DAG has at most n vertices (one for each party), each of which contains a block of transactions as well as references (edges) to at least $2f + 1$ vertices in the previous round. Blocks are disseminated via reliable broadcast [11] to avoid equivocation and an honest party advances to the next round once it reliably delivers $2f + 1$ vertices in the current round. Note that building the DAG requires honest parties to broadcast vertices even if they have no transactions to propose. However, the edges of the DAG encodes the "voting" information that is sufficient to totally order all the DAG's vertices. So in this sense it is not different from other BFT protocols in which parties send explicit vote messages, which contain no transactions as well. Remarkably, by using the DAG to abstract away the communication layer, the entire edges interpretation logic of DAG-Rider to totally order the DAG spans over less than 30 lines of pseudocode.

DAG-Rider is an asynchronous Byzantine atomic broadcast (BAB), which achieves optimal amortized communication complexity $O(n)$ per transaction), post quantum safety, and some notion of fairness (called Validity) that guarantees that every transaction proposed by an honest party is eventually delivered (ordered). To achieve optimal amortized communication DAG-Rider combines batching techniques with an efficient asynchronous verifiable information dispersal protocol [14] for the reliable broadcast building block. The protocol is post quantum safe because it does not rely on primitives that a quantum computer can brake for the safety properties. That is, a quantum adversary can prevent the protocol progress, but it cannot violate safety guarantees.

However, although DAG-based protocols have a solid theoretical foundation, they have multiple gaps before being realistically deployable in practice. First, they all optimize for the worst case

ACM ISBN 978-x-xxxx-xxxx-x/YY/MM…$15.00
https://doi.org/10.1145/nnnnnnn.nnnnnnn

Dumbo-NG



Dumbo-NG: Fast Asynchronous BFT Consensus with Throughput-Oblivious Latency

Yingzi Gao*
ISCAS & UCAS
yingzi2019@iscas.ac.cn

Yuan Lu*
ISCAS
luyuan@iscas.ac.cn

Zhenliang Lu*
USYD
zhlu9620@uni.sydney.edu.au

Qiang Tang*
USYD
qiang.tang@sydney.edu.au

Jing Xu*
ISCAS
xujing@iscas.ac.cn

Zhenfeng Zhang*
ISCAS
zhenfeng@iscas.ac.cn

ABSTRACT

Despite recent progresses of practical asynchronous Byzantine-fault tolerant (BFT) consensus, the state-of-the-art designs still suffer from suboptimal performance. Particularly, to obtain maximum throughput, most existing protocols with guaranteed linear amortized communication complexity require each participating node to broadcast a huge batch of transactions, which dramatically sacrifices latency. Worse still, the f slowest nodes' broadcasts might never be agreed to output and thus can be censored (where f is the number of faults). Implementable mitigation to the threat either uses computationally costly threshold encryption or incurs communication blow-up by letting the honest nodes to broadcast redundant transactions, thus causing further efficiency issues.

We present Dumbo-NG, a novel asynchronous BFT consensus (atomic broadcast) to solve the remaining practical issues. Its technical core is a non-trivial *direct* reduction from asynchronous atomic broadcast to multi-valued validated Byzantine agreement (MVBA) with quality property (which ensures the MVBA output is from honest nodes with 1/2 probability). Most interestingly, the new protocol structure empowers completely concurrent execution of transaction dissemination and asynchronous agreement. This brings about two benefits: (i) the throughput-latency tension is resolved to approach peak throughput with minimal increase in latency; (ii) the transactions broadcasted by any honest node can be agreed to output, thus conquering the censorship threat with no extra cost.

We implement Dumbo-NG with using the current fastest GLL+22 MVBA with quality (NDSS'22) and compare it to the state-of-the-art asynchronous BFT with guaranteed censorship resilience including Dumbo (CCS'20) and Speeding-Dumbo (NDSS'22). Along the way, we apply the techniques from Speeding-Dumbo to DispersedLedger (NSDI'22) and obtain an improved variant of DispersedLedger called sDumbo-DL for comprehensive comparison. Extensive experiments (over up to 64 AWS EC2 nodes across 16 AWS regions) reveal Dumbo-NG realizes a peak throughput 4-8x over Dumbo, 2-4x over Speeding-Dumbo, and 2-3x over sDumbo-DL (for varying scales). More importantly, Dumbo-NG's latency, which is lowest among all tested protocols, can almost remain stable when throughput grows.

CCS CONCEPTS

• **Security and privacy** → Systems security; Distributed systems security; • **Computer systems organization** → Reliability.

KEYWORDS

Asynchronous consensus, Byzantine-fault tolerance, blockchain

1 INTRODUCTION

The huge success of Bitcoin [65] and Blockchain [19, 24] leads to an increasing tendency to lay down the infrastructure of distributed ledger for mission-critical applications. Such decentralized business is envisioned as critical global infrastructure maintained by a set of mutually distrustful and geologically distributed nodes [11], and thus calls for consensus protocols that are both secure and efficient for deployment over the Internet.

Asynchronous BFT *for* indispensable robustness. The consensus of decentralized infrastructure has to thrive in a highly adversarial environment. In particular, when the applications atop it are critical financial and banking services, some nodes can be well motivated to collude and launch malicious attacks. Even worse, the unstable Internet might become part of the attack surface due to network fluctuations, misconfigurations and even network attacks. To cope with the adversarial deployment environment, *asynchronous* Byzantine-fault tolerant (BFT) consensuses [4, 20, 35, 47, 58, 69] are arguably the most suitable candidates. They can realize high security-assurance to ensure liveness (as well as safety) despite an asynchronous adversary that can arbitrarily delay messages. In contrast, many (partial) synchronous consensus protocols [5, 6, 8, 15, 27, 44, 45, 64, 75] such as PBFT [26] and HotStuff [70] might sustain the inherent *loss of liveness* (i.e., generate unbounded communications without making any progress) [36, 40] when unluckily encountering an asynchronous network adversary.

1.1 Practical obstacles of adopting asynchronous BFT consensus

Unfortunately, it is fundamentally challenging to realize practical asynchronous BFT consensus, and none of such protocols was widely adopted due to serious efficiency concerns. The seminal FLP "impossibility" [36] proves that no *deterministic* consensus exists in the asynchronous network. Since the 1980s, many attempts [1, 12, 13, 21, 23, 65, 67] aimed at to circumventing the "impossibility" by *randomized* protocols, but most of them focused on theoretical feasibility, and unsurprisingly, several attempts of implementations [22, 61] had inferior performance.

Until recently, the work of HoneyBadger BFT (HBBFT) demonstrated the first asynchronous BFT consensuses that is performant in the wide-area network [46]. As shown in Figure 1, HBBFT was

*Authors are listed alphabetically. Yingzi, Yuan & Zhenliang made equal contributions. An abridged version of the paper will appear in ACM CCS 2022.

Core

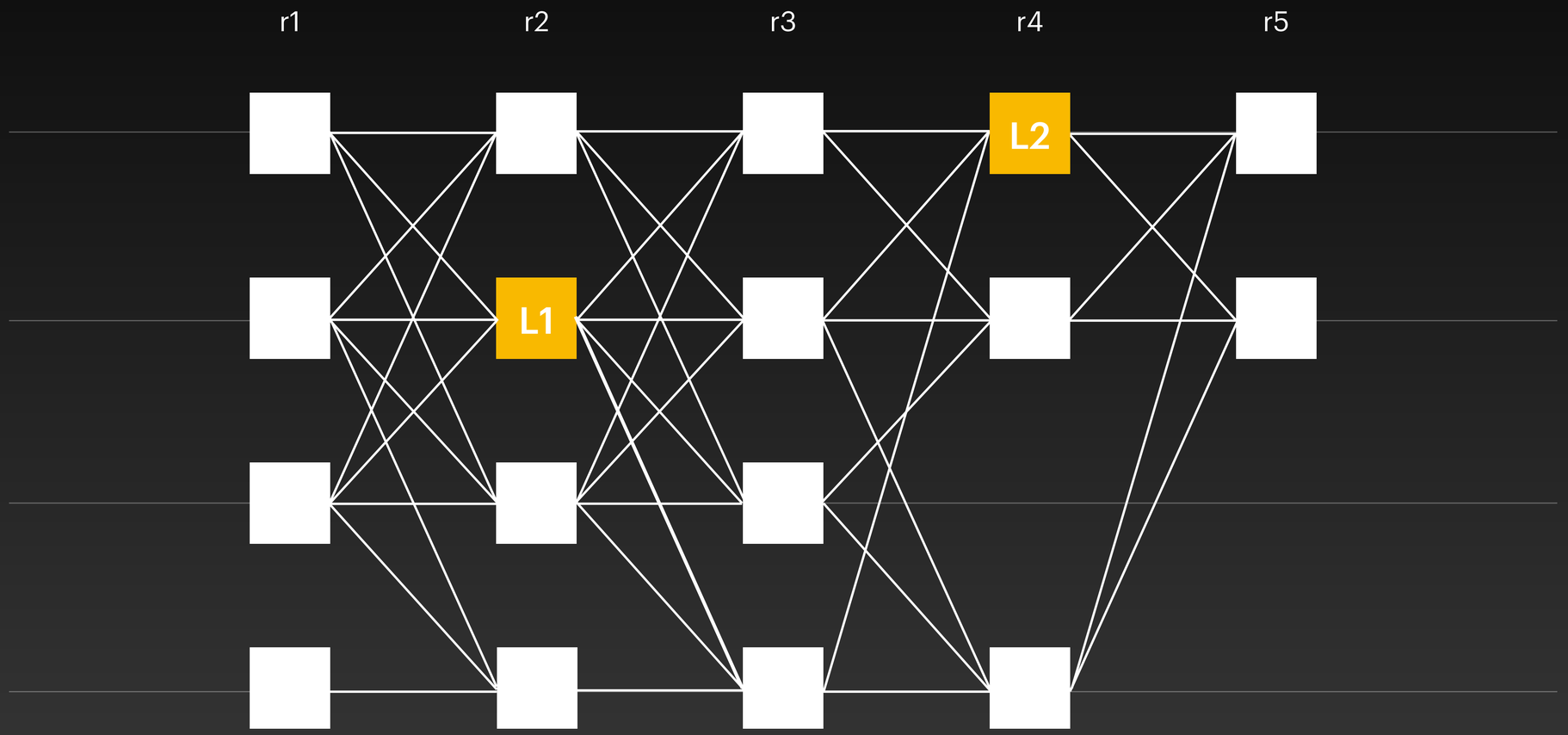
- Hard to make efficient
- 99% of the code

Consensus

- Error prone
- Isolated, easy to maintain

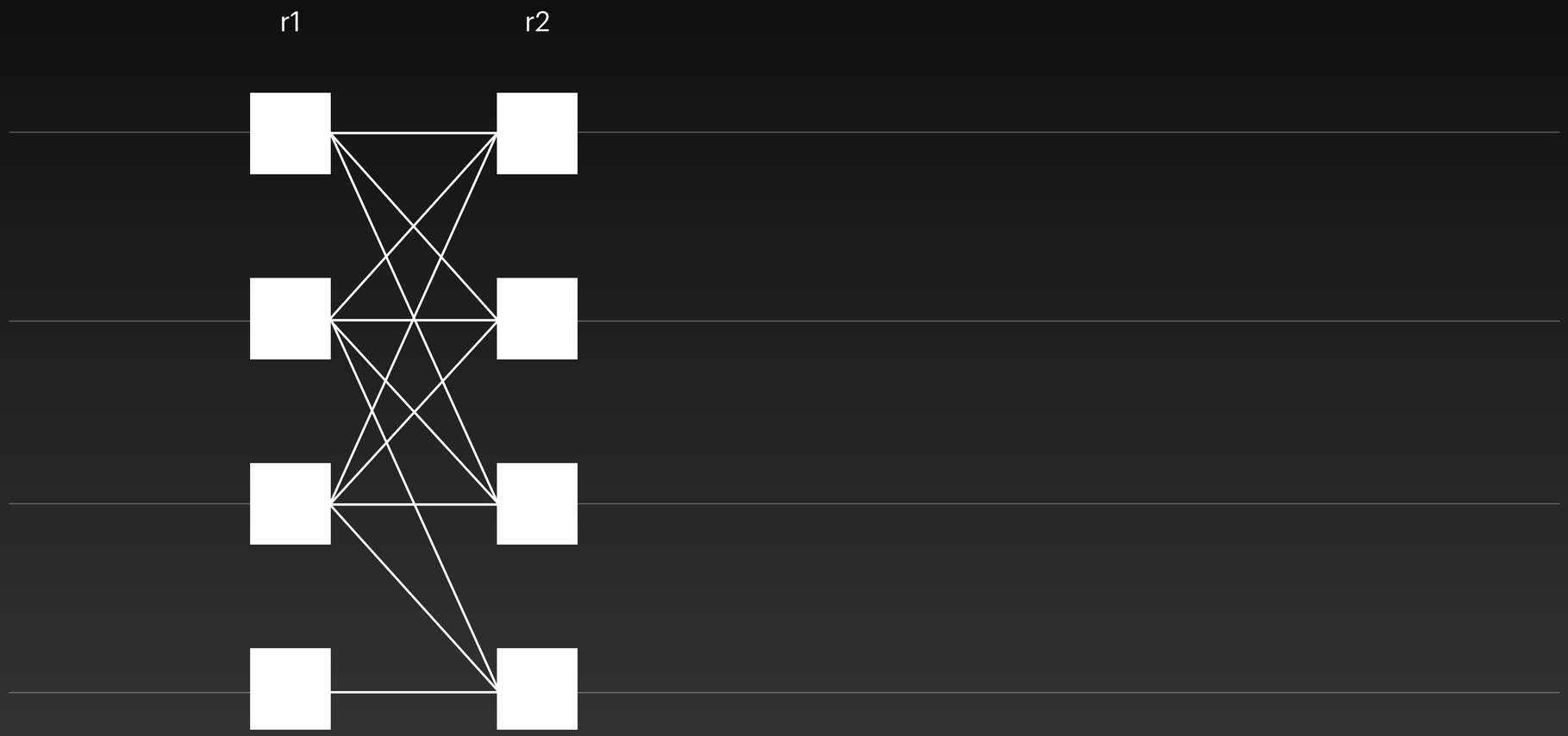
Modified Narwhal

Even rounds: wait for the leader (or to timeout)



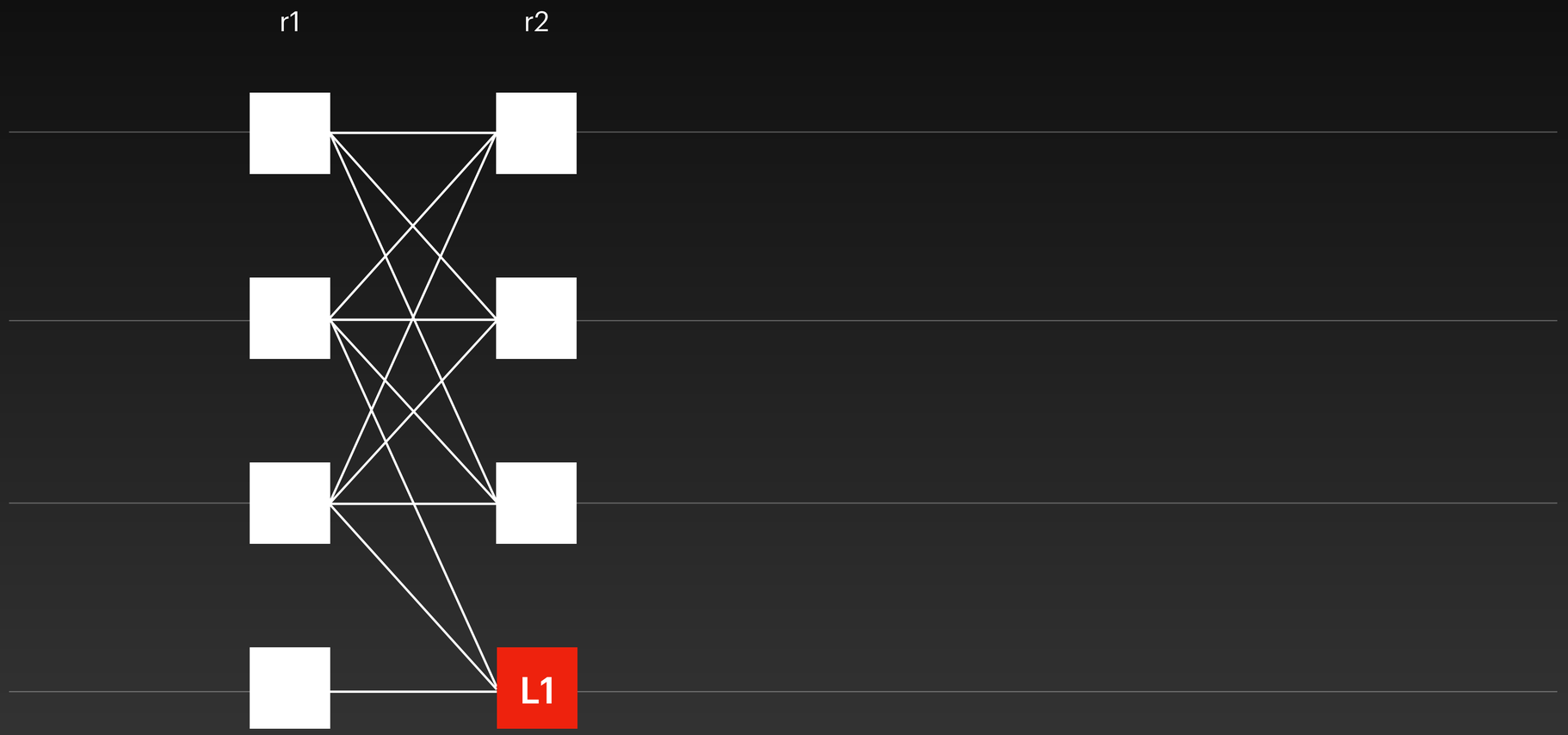
Bullshark

Just interpret the DAG



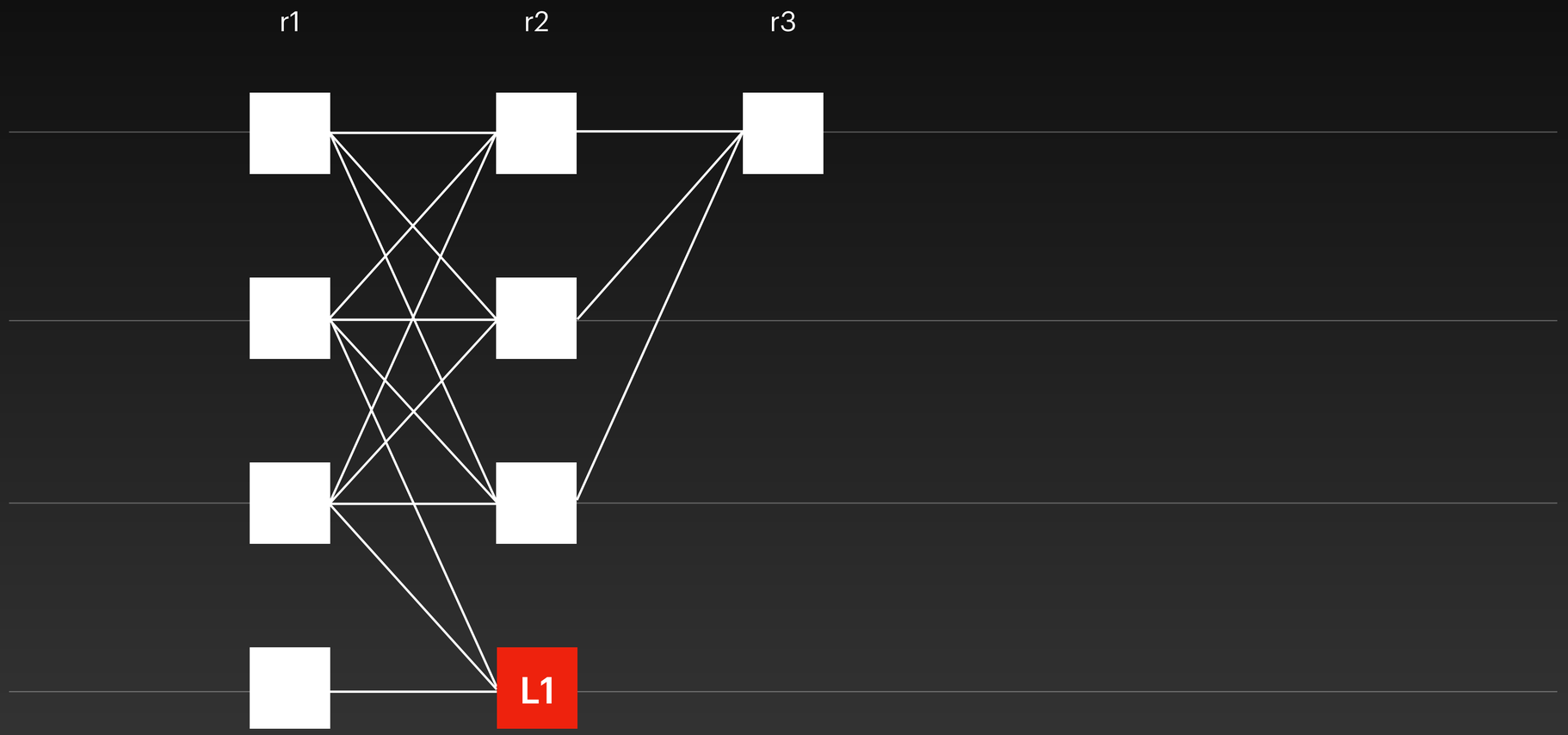
Bullshark

Deterministic leader every 2 rounds



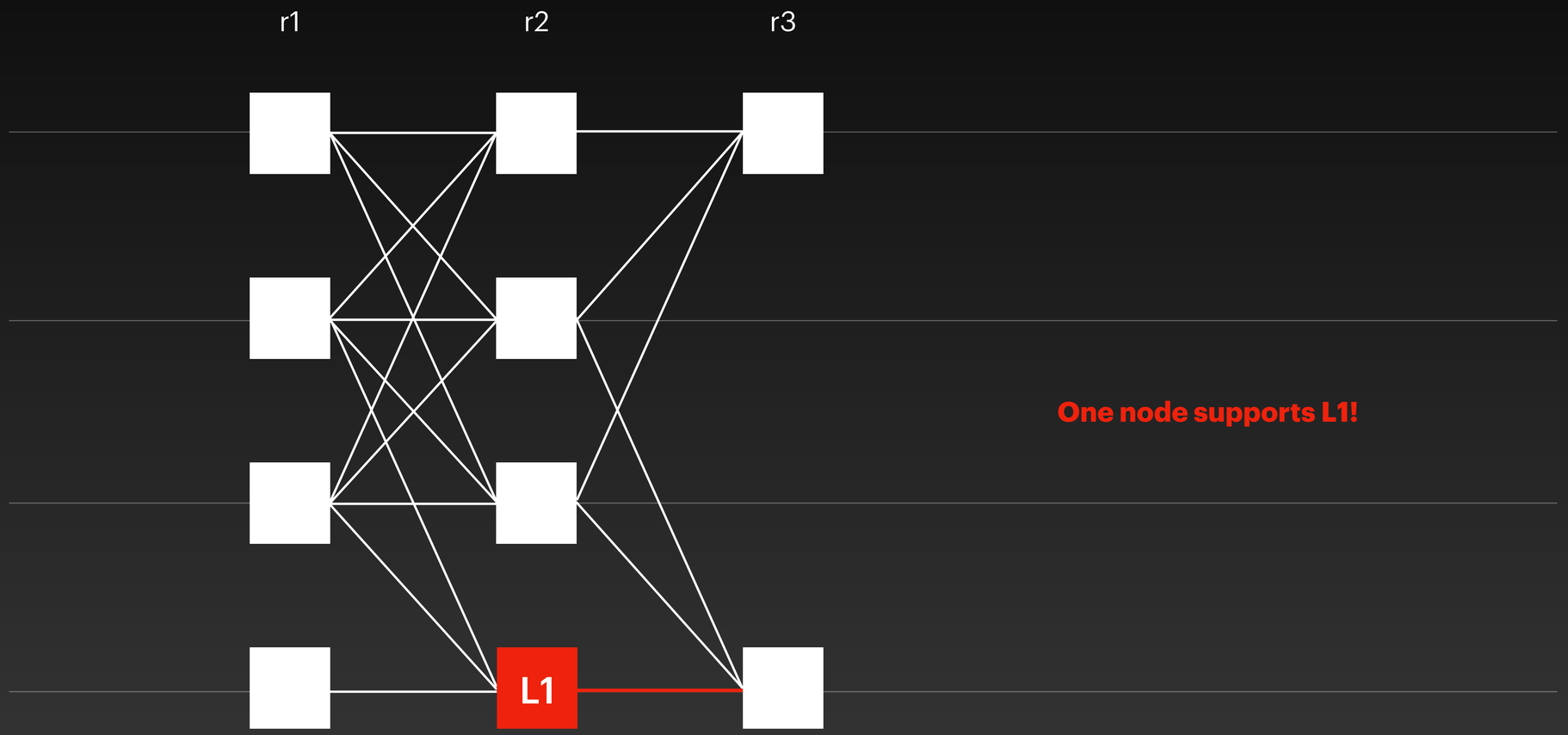
Bullshark

The leader needs f+1 links from round r3



Bullshark

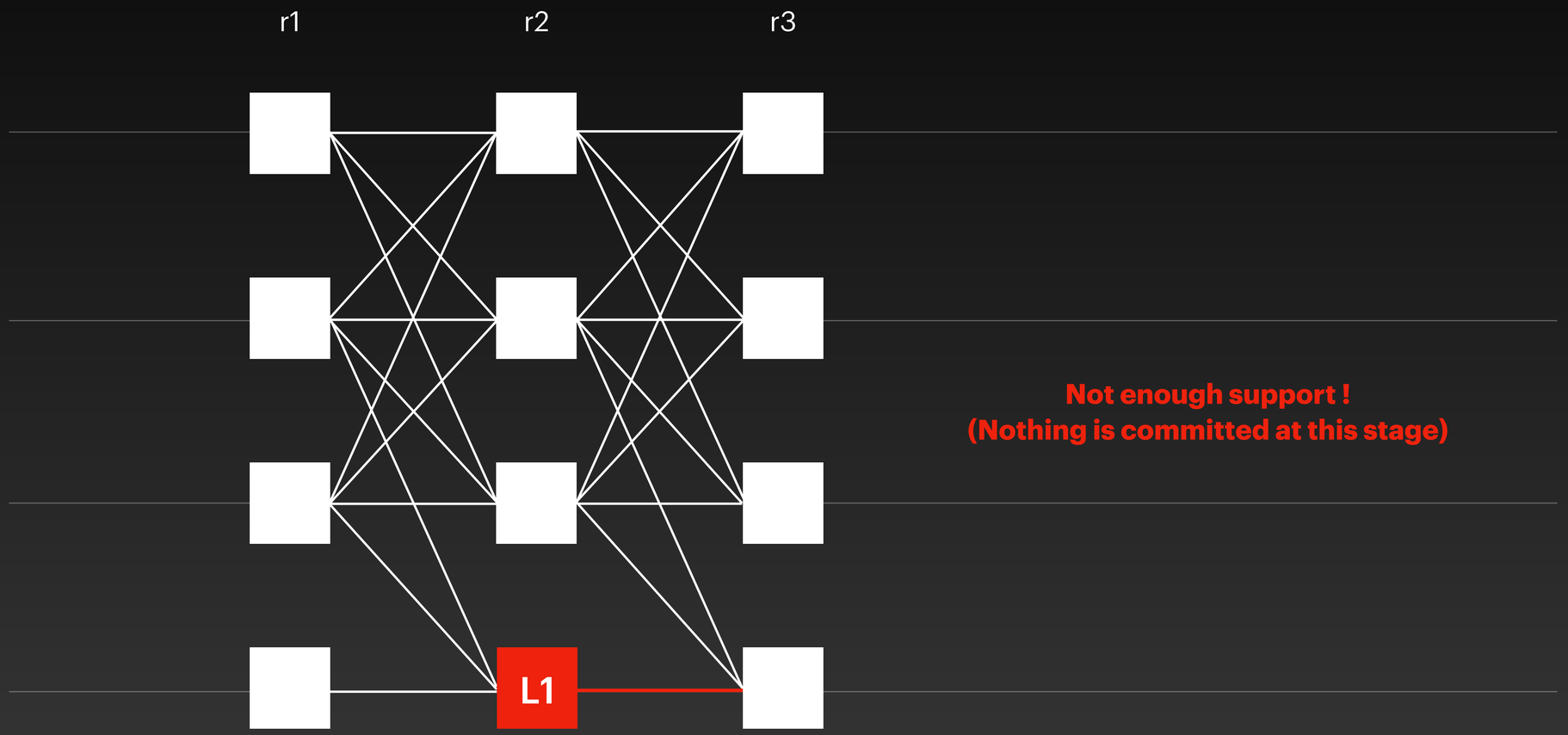
The leader needs f+1 links from round r3



One node supports L1!

Bullshark

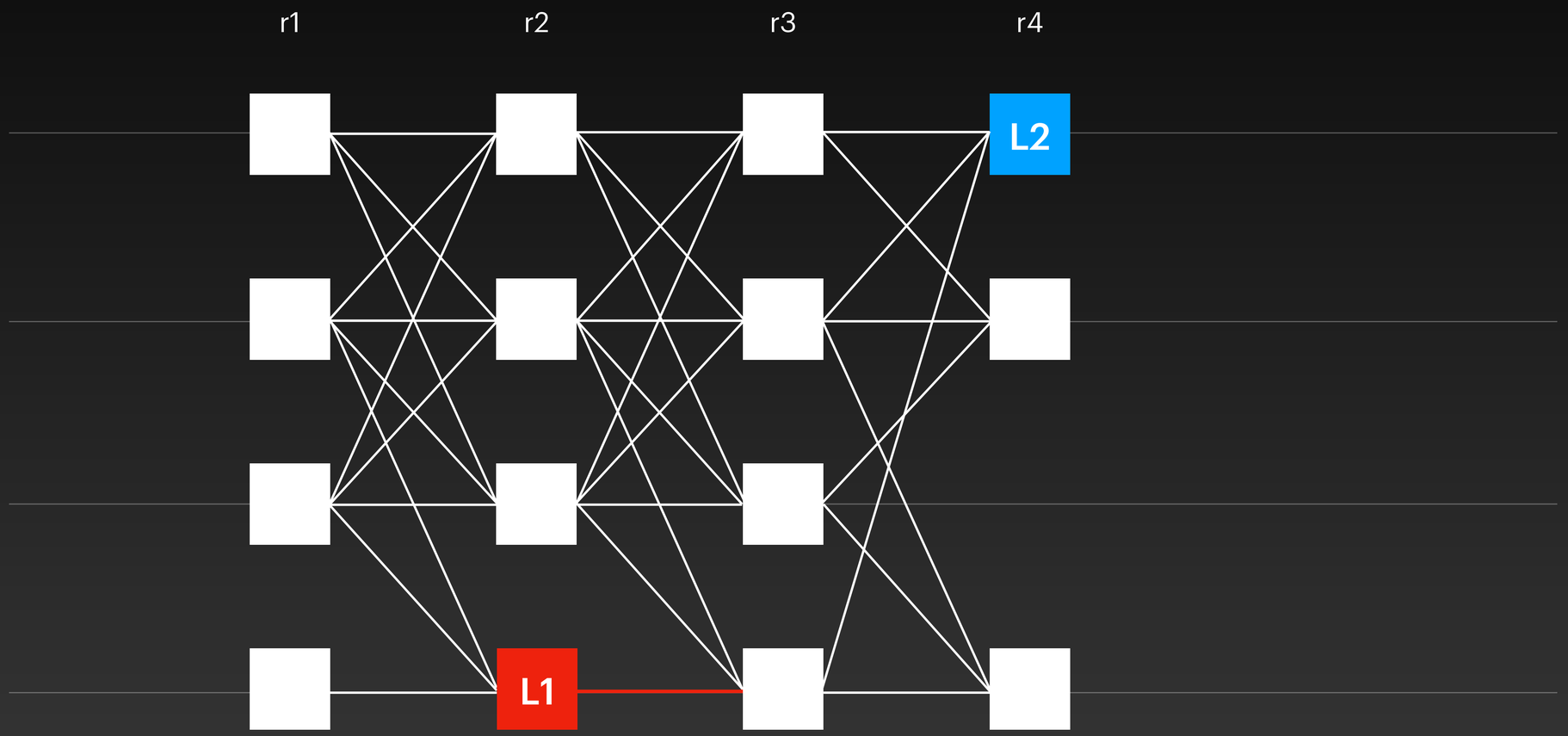
The leader needs f+1 links from round r3



Not enough support !
(Nothing is committed at this stage)

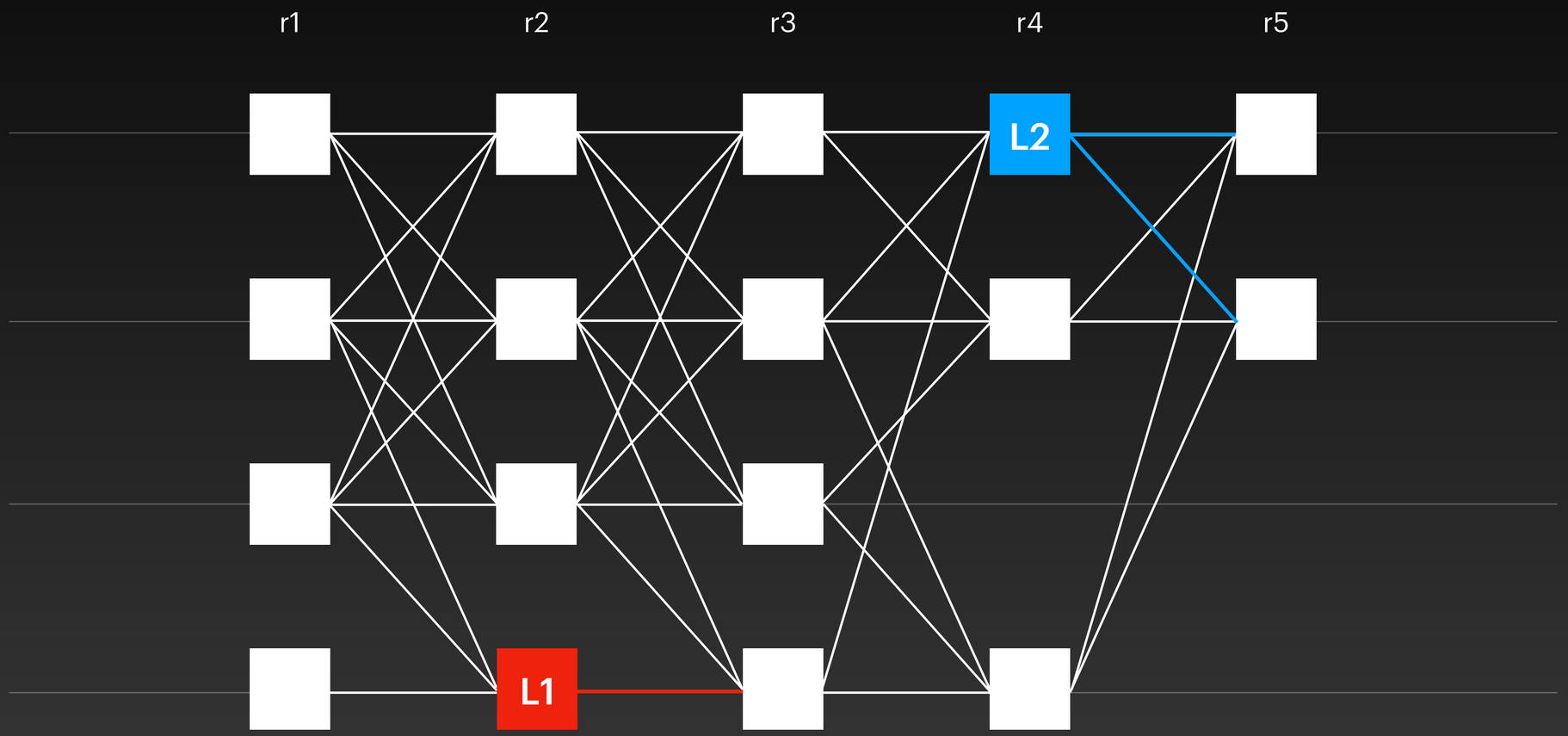
Bullshark

Elect the leader of r4



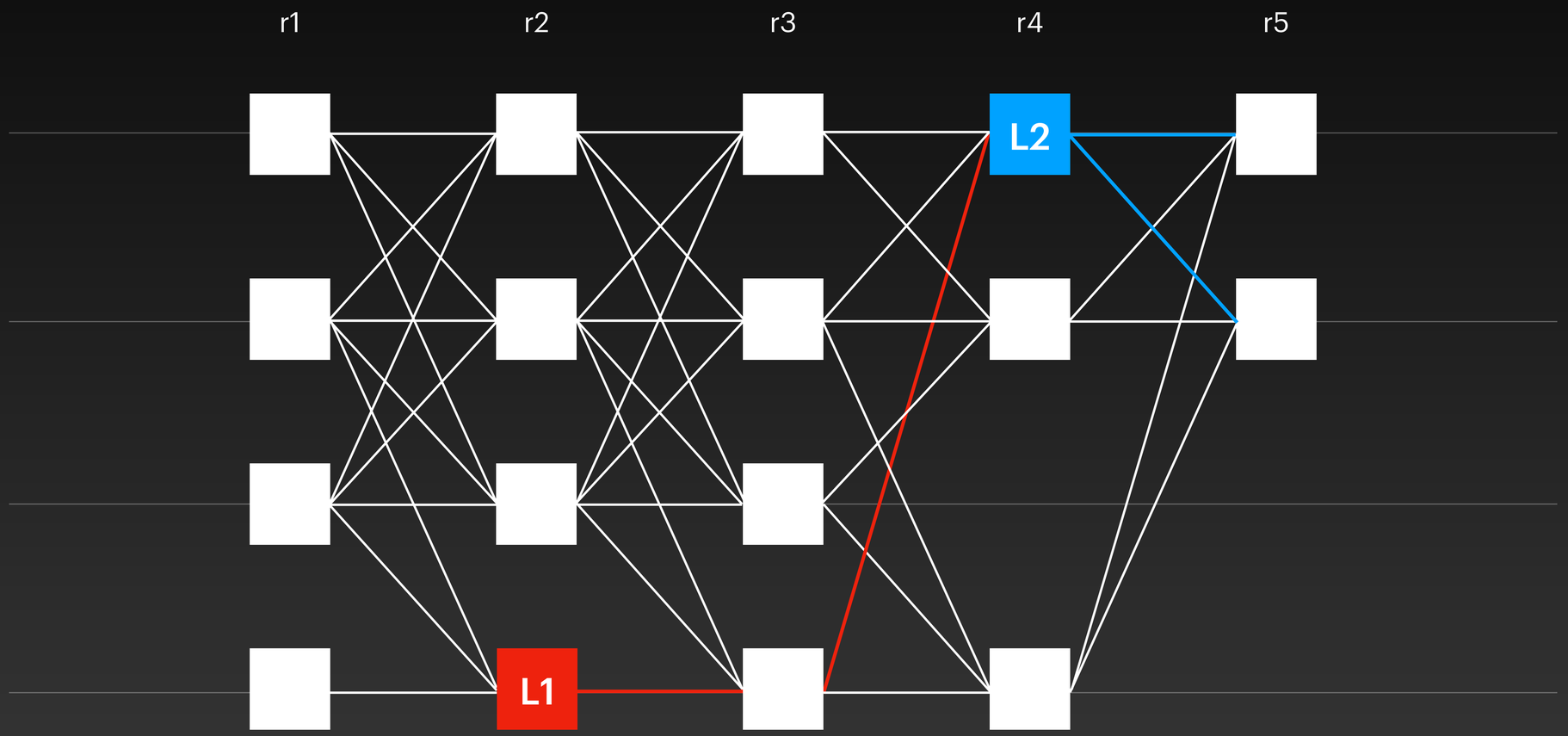
Bullshark

Leader L2 has enough support



Bullshark

Leader L2 has links to leader L1

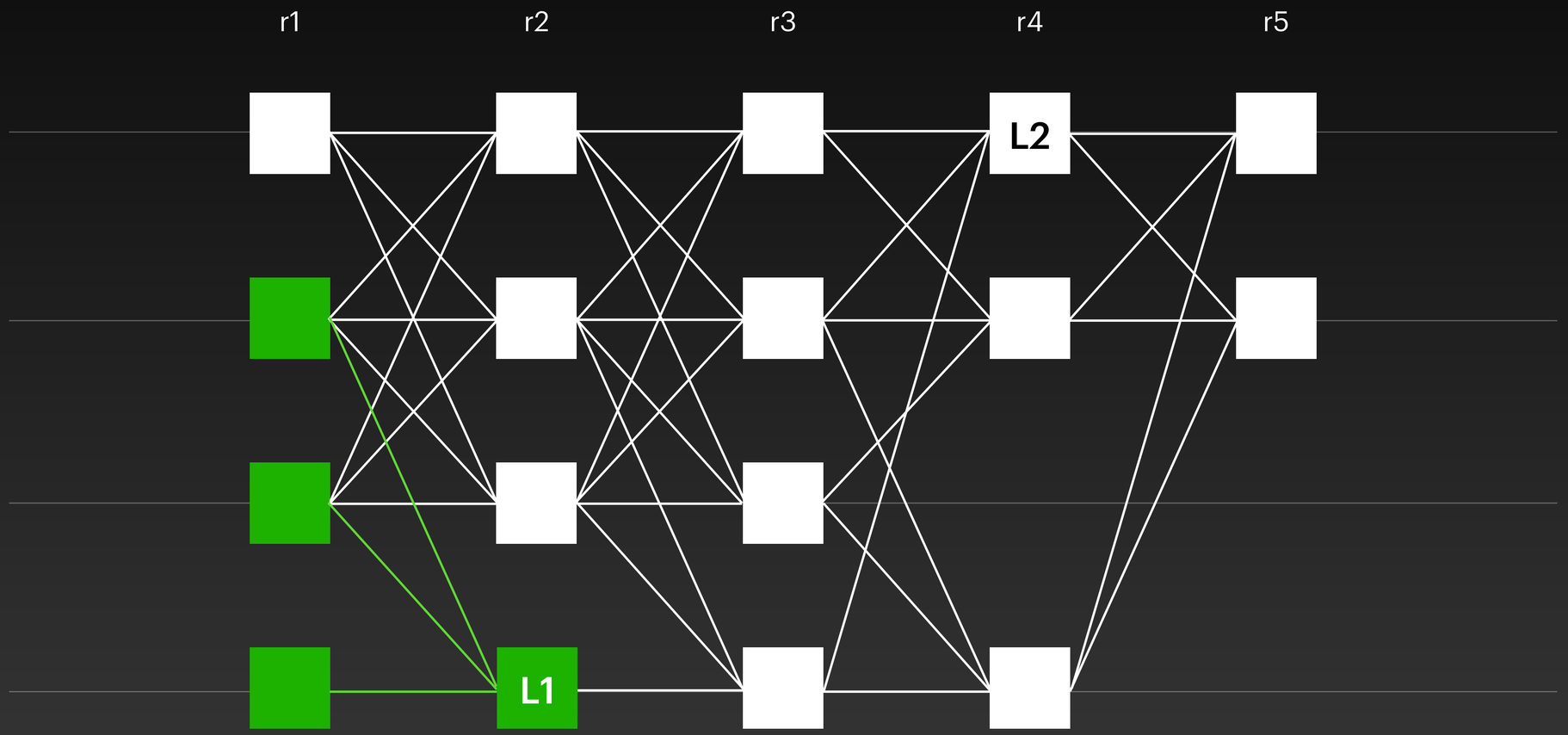


First commit L1

Then commit L2

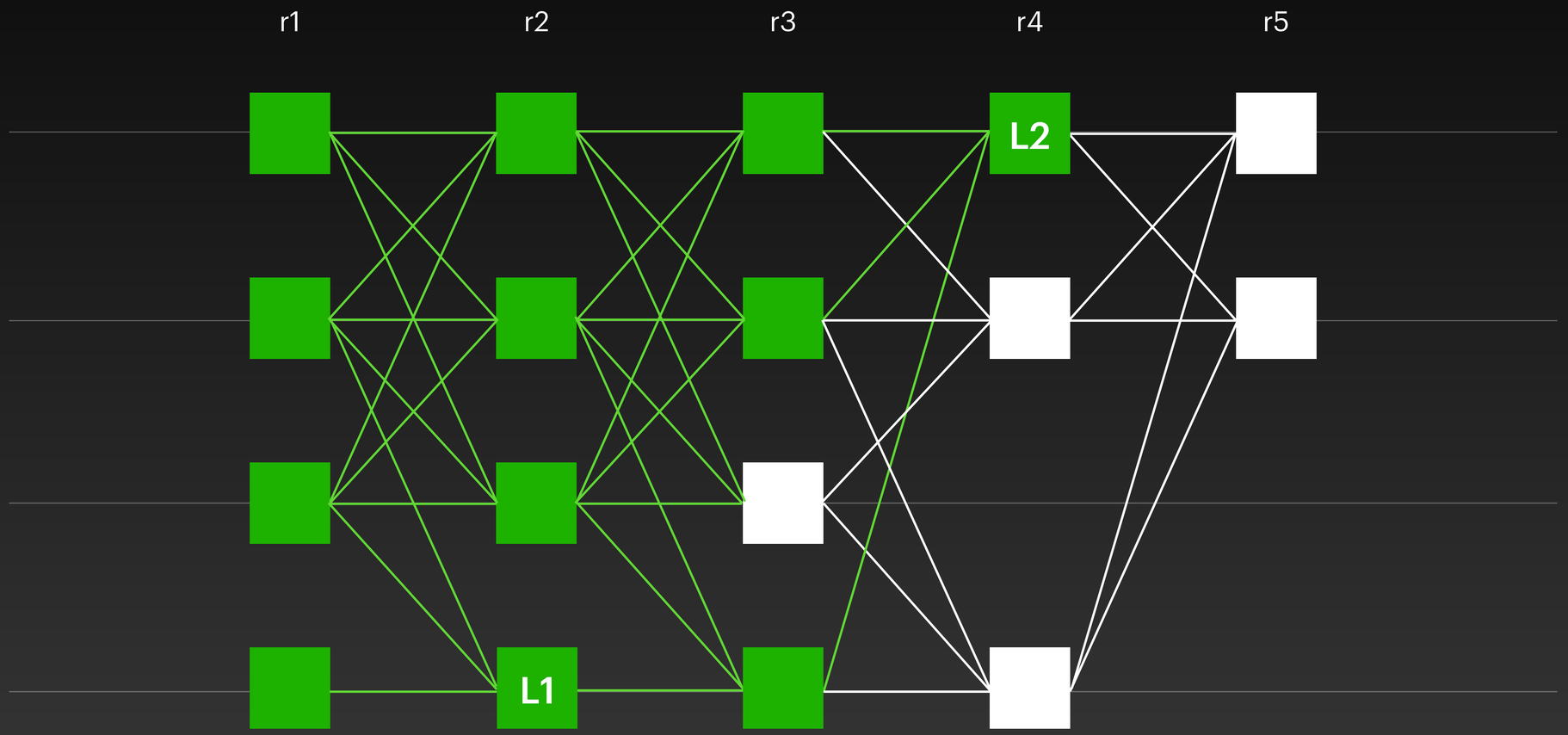
Bullshark

Commit all the sub-DAG of the leader

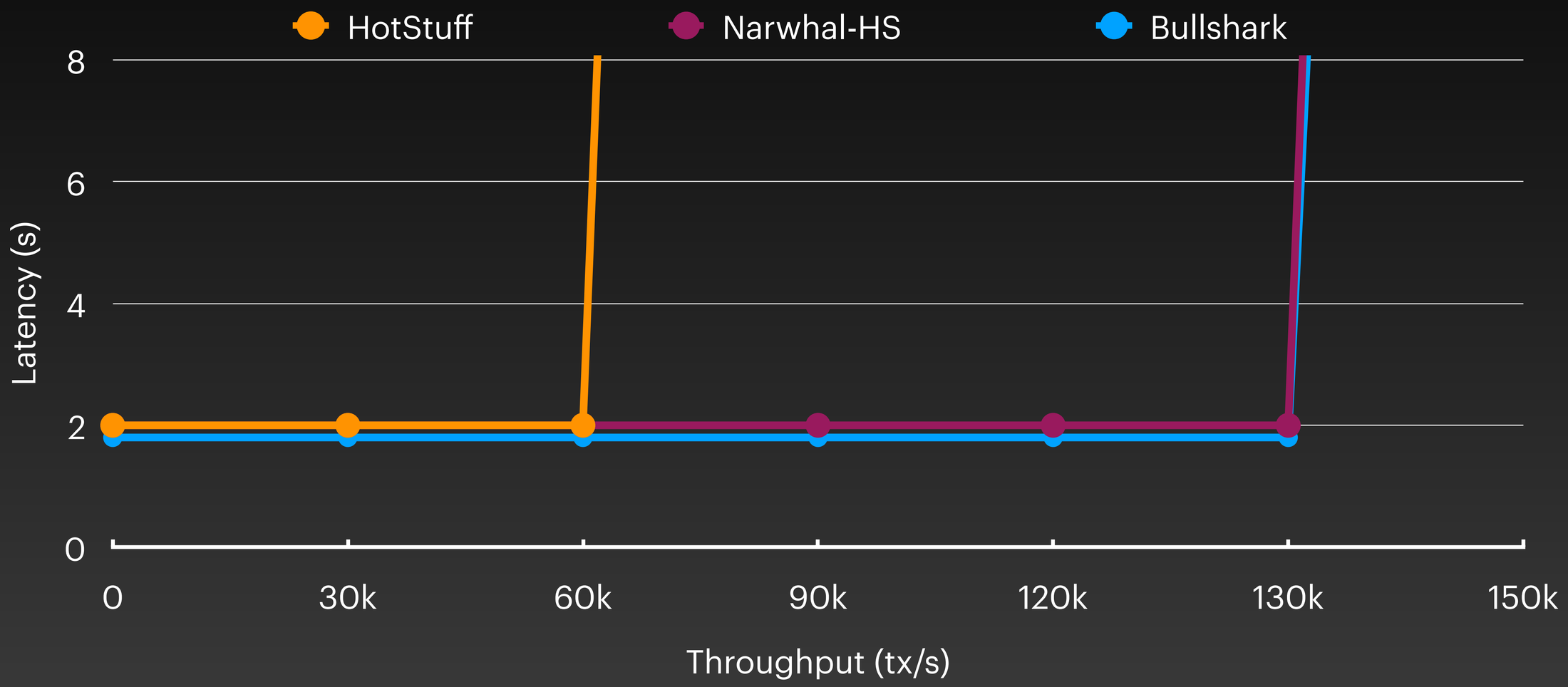


Bullshark

Commit all the sub-DAG of the leader



Performance



Research Questions

1. Network model?
2. BFT testing?
3. Consensus-exec interface?

Lessons Learned

1. Modularisation is a design strategy
2. Tasks-threads relationship
3. Benchmark early
4. Codesign with mem. and storage
5. Core is hard, consensus is easy

By that time...

Sui

Aptos

Linera

...

Fundraising with papers seems to work

Sui, 2022

Over a year for mainnet

- Lack of checkpoints
- Lack of epoch-change
- Lack of crash-recovery

Research Questions

1. Network model?
2. BFT testing?
3. Consensus-exec interface?
4. Storage architecture?

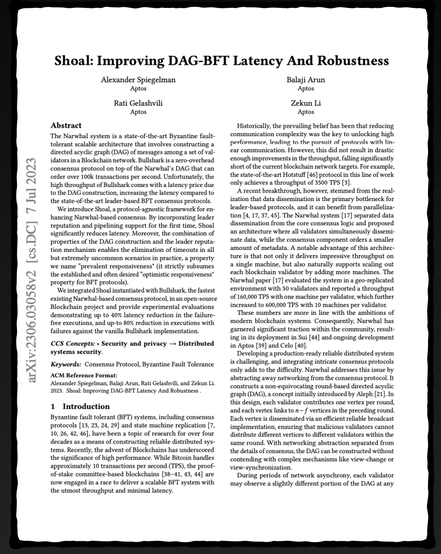
Lessons Learned

1. Modularisation is a design strategy
2. Tasks-threads relationship
3. Benchmark early
4. Codesign with mem. and storage
5. Core is hard, consensus is easy
6. Epoch change is not an add-on

Sui, 2023

- Latency was too high
- Crash faults were predominant
- Building Bullshark was still too complex

Shoal



Shoal: Improving DAG-BFT Latency And Robustness

Alexander Spiegelman
Aptos

Balaji Arun
Aptos

Rati Gelashvili
Aptos

Zekun Li
Aptos

Abstract

The Narwhal system is a state-of-the-art Byzantine fault-tolerant scalable architecture that involves constructing a directed acyclic graph (DAG) of messages among a set of validators in a Blockchain network. Bullshark is a zero-overhead consensus protocol on top of the Narwhal's DAG that can order over 100k transactions per second. Unfortunately, the high throughput of Bullshark comes with a latency price due to the DAG construction, increasing the latency compared to the state-of-the-art leader-based BFT consensus protocols.

We introduce Shoal, a protocol-agnostic framework for enhancing Narwhal-based consensus. By incorporating leader reputation and pipelining support for the first time, Shoal significantly reduces latency. Moreover, the combination of properties of the DAG construction and the leader reputation mechanism enables the elimination of timeouts in all but extremely uncommon scenarios in practice, a property we name "prevalent responsiveness" (it strictly subsumes the established and often desired "optimistic responsiveness" property for BFT protocols).

We integrated Shoal instantiated with Bullshark, the fastest existing Narwhal-based consensus protocol, in an open-source Blockchain project and provide experimental evaluations demonstrating up to 40% latency reduction in the failure-free executions, and up-to 80% reduction in executions with failures against the vanilla Bullshark implementation.

CCS Concepts: • **Security and privacy → Distributed systems security**.

Keywords: Consensus Protocol, Byzantine Fault Tolerance

ACM Reference Format:
Alexander Spiegelman, Balaji Arun, Rati Gelashvili, and Zekun Li. 2023. Shoal: Improving DAG-BFT Latency And Robustness .

1 Introduction

Byzantine fault tolerant (BFT) systems, including consensus protocols [13, 23, 24, 29] and state machine replication [7, 10, 26, 42, 46], have been a topic of research for over four decades as a means of constructing reliable distributed systems. Recently, the advent of Blockchains has underscored the significance of high performance. While Bitcoin handles approximately 10 transactions per second (TPS), the proof-of-stake committee-based blockchains [38–41, 43, 44] are now engaged in a race to deliver a scalable BFT system with the utmost throughput and minimal latency.

Historically, the prevailing belief has been that reducing communication complexity was the key to unlocking high performance, leading to the pursuit of protocols with linear communication. However, this did not result in drastic enough improvements in the throughput, falling significantly short of the current blockchain network targets. For example, the state-of-the-art Hotstuff [46] protocol in this line of work only achieves a throughput of 3500 TPS [3].

A recent breakthrough, however, stemmed from the realization that data dissemination is the primary bottleneck for leader-based protocols, and it can benefit from parallelization [4, 17, 37, 45]. The Narwhal system [17] separated data dissemination from the core consensus logic and proposed an architecture where all validators simultaneously disseminate data, while the consensus component orders a smaller amount of metadata. A notable advantage of this architecture is that not only it delivers impressive throughput on a single machine, but also naturally supports scaling out each blockchain validator by adding more machines. The Narwhal paper [17] evaluated the system in a geo-replicated environment with 50 validators and reported a throughput of 160,000 TPS with one machine per validator, which further increased to 600,000 TPS with 10 machines per validator.

These numbers are more in line with the ambitions of modern blockchain systems. Consequently, Narwhal has garnered significant traction within the community, resulting in its deployment in Sui [44] and ongoing development in Aptos [39] and Celo [40].

Developing a production-ready reliable distributed system is challenging, and integrating intricate consensus protocols only adds to the difficulty. Narwhal addresses this issue by abstracting away networking from the consensus protocol. It constructs a non-equivocating round-based directed acyclic graph (DAG), a concept initially introduced by Aleph [21]. In this design, each validator contributes one vertex per round, and each vertex links to $n-f$ vertices in the preceding round. Each vertex is disseminated via an efficient reliable broadcast implementation, ensuring that malicious validators cannot distribute different vertices to different validators within the same round. With networking abstraction separated from the details of consensus, the DAG can be constructed without contending with complex mechanisms like view-change or view-synchronization.

During periods of network asynchrony, each validator may observe a slightly different portion of the DAG at any

Sailfish

Sailfish: Towards Improving the Latency of DAG-based BFT

Nibesh Shrestha
n.shrestha@supraoracles.com
Supra Research

Rohan Shrothrium
rohan@karalabs.xyz
Kara Labs

Aniket Kate
aniket@purdue.com
Purdue University / Supra Research

Kartik Nayak
kartik@cs.duke.edu
Duke University

***Abstract*—Directed Acyclic Graph (DAG) based BFT protocols balance consensus efforts across different parties and maintain high throughput even when some designated parties fail. However, existing DAG-based BFT protocols exhibit long latency to commit decisions, primarily because they have a *leader every 2 or more "rounds"*. Recent works, such as Shoal (PTC'23) and Mysticeti, have deemed supporting a leader vertex in each round particularly difficult, if not impossible. Consequently, even under honest leaders, these protocols require high latency (or communication complexity) to commit the proposal submitted by the leader (leader vertex) and additional latency to commit other proposals (non-leader vertices).**

In this work, we present Sailfish, the first DAG-based BFT that supports a leader vertex in each round. Under honest leaders, Sailfish maintains a commit latency of one reliable broadcast (RBC) round plus 1δ to commit the leader vertex (where δ is the actual transmission latency of a message) and only an additional RBC round to commit non-leader vertices. We also extend Sailfish to Multi-leader Sailfish, which facilitates multiple leaders within a single round and commits all leader vertices in a round with a latency of one RBC round plus 1δ. Our experimental evaluation demonstrates that our protocols introduce significantly lower latency overhead compared to existing DAG-based protocols, with similar throughput.

1. Introduction

Byzantine fault-tolerant state machine replication (BFT SMR) protocols form the core underpinning for blockchains. At a high level, a BFT-SMR enables a group of n parties to agree on a sequence of values, even if a bound of up to f of these parties is Byzantine (arbitrarily malicious). Owing to the need for efficient blockchains in practice, there has been a lot of recent progress in improving the key efficiency metrics namely, latency, communication complexity, and throughput under various network conditions. Assuming the network is partially synchronous, existing SMR protocols can commit with a latency overhead of 3δ (where δ represents the actual network delay) [11], [12], [22] and also achieve linear communication complexity [19], [31] under optimistic conditions (such as an honest leader).

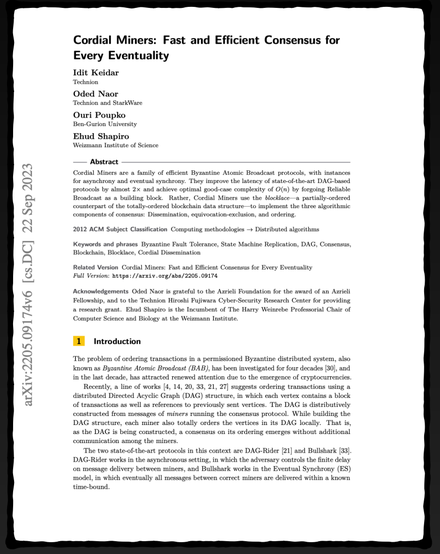
Most of these protocol designs rely on a designated leader who is the party responsible for proposing transactions and driving the protocol forward while other parties agree on the proposed values and ensure that the leader keeps making progress. From an efficiency standpoint, this approach results in two key drawbacks. First, there is an uneven scheduling of work among the parties. While the leader is sending a proposal, the other parties' processors and their network are not used, leading to uneven resource usage across parties. Second, in typical leader-based protocols progress stops if the leader fails and until it is replaced. Several techniques proposed in the literature can potentially mitigate these concerns. These include the use of erasure coding techniques [2], [41] or the data availability committees [26], [27], [49] to disseminate the data more efficiently.

Recently, a novel approach known as DAG-based BFT has emerged [5], [18], [28], [33], [34], [36], [47]. These protocols enable all participating parties to propose in parallel, maximizing bandwidth utilization and ensuring equitable distribution of workload. Additionally, because each party is responsible for disseminating its own transactions, the protocol continues to progress in constructing the DAG even if a party fails during a round. Consequently, these protocols have demonstrated improved throughput compared to their leader-based counterparts under moderate network sizes [19], [46]. However, existing DAG-based protocols incur a high latency compared to their "leader-heavy" counterparts [12], [22], [30], [37], [43]. Is high latency inherent for such DAG-based protocols? Addressing this question is the key goal of this paper.

All existing DAG-based protocols progress in *rounds*. In each round, every party can create a potential DAG vertex containing transactions, with edges pointing to vertices from previous rounds. These protocols rely on committing a designated "leader vertex" and order other non-leader vertices in the DAG. Therefore, *the frequency with which leaders are designated and how fast the leader vertices are committed* directly influences the commit latency.

Supporting a leader vertex in each round. State-of-the-art protocols designate leaders once every two or more rounds, and in fact, deem supporting a leader vertex in each round particularly difficult. In their words, Shoal [43] writes, *"Our attempts to solve the problem by delving into the inner workings of the protocol and exploring complex quorum intersection ordering rules have not been fruitful. Intuitively, this is because ...* ". Similarly, Mysticeti [4]

CM



Cordial Miners: Fast and Efficient Consensus for Every Eventuality

Idit Keidar
Technion

Oded Naor
Technion and StarkWare

Ouri Poupko
Ben-Gurion University

Ehud Shapiro
Weimmann Institute of Science

Abstract

Cordial Miners are a family of efficient Byzantine Atomic Broadcast protocols, with instances for asynchrony and eventual synchrony. They improve the latency of state-of-the-art DAG-based protocols by almost $2\times$ and achieve optimal good-case complexity of $O(n)$ by forgoing Reliable Broadcast as a building block. Rather, Cordial Miners use the *blocklace*—a partially-ordered counterpart of the totally-ordered blockchain data structure—to implement the three algorithmic components of consensus: Dissemination, equivocation-exclusion, and ordering.

2012 ACM Subject Classification Computing methodologies → Distributed algorithms

Keywords and phrases Byzantine Fault Tolerance, State Machine Replication, DAG, Consensus, Blockchain, Blocklace, Cordial Dissemination

Related Version Cordial Miners: Fast and Efficient Consensus for Every Eventuality
Full Version: https://arxiv.org/abs/2205.09174

Acknowledgements Oded Naor is grateful to the Azrieli Foundation for the award of an Azrieli Fellowship, and to the Technion Hiroshi Fujiwara Cyber-Security Research Center for providing a research grant. Ehud Shapiro is the Incumbent of The Harry Weinrebe Professorial Chair of Computer Science and Biology at the Weizmann Institute.

1 Introduction

The problem of ordering transactions in a permissioned Byzantine distributed system, also known as *Byzantine Atomic Broadcast (BAB)*, has been investigated for four decades [30], and in the last decade, has attracted renewed attention due to the emergence of cryptocurrencies.

Recently, a line of works [4, 14, 20, 33, 21, 27] suggests ordering transactions using a distributed Directed Acyclic Graph (DAG) structure, in which each vertex contains a block of transactions as well as references to previously sent vertices. The DAG is distributively constructed from messages of *miners* running the consensus protocol. While building the DAG structure, each miner also totally orders the vertices in its DAG locally. That is, as the DAG is being constructed, a consensus on its ordering emerges without additional communication among the miners.

The two state-of-the-art protocols in this context are DAG-Rider [21] and Bullshark [33]. DAG-Rider works in the asynchronous setting, in which the adversary controls the finite delay on message delivery between miners, and Bullshark works in the Eventual Synchrony (ES) model, in which eventually all messages between correct miners are delivered within a known time-bound.

Mysticeti

MYSTICETI: Reaching the Latency Limits with Uncertified DAGs

Kushal Babel*†, Andrey Chursin‡, George Danezis§¶, Anastasios Kichidis§, Lefteris Kokoris-Kogias‖¶, Arun Koshy‡, Alberto Sonnino§¶, Mingwei Tian‡

*Cornell Tech, †IC3, ‡Mysten Labs, §University College London (UCL), ¶IST Austria

***Abstract*—We introduce MYSTICETI-C, the first DAG-based Byzantine consensus protocol to achieve the lower bounds of latency of 3 message rounds. Since MYSTICETI-C is built over DAGs it also achieves high resource efficiency and censorship resistance. MYSTICETI-C achieves this latency improvement by avoiding explicit certification of the DAG blocks and by proposing a novel commit rule such that every block can be committed without delays, resulting in optimal latency in the steady state and under crash failures. We further extend MYSTICETI-C to MYSTICETI-FPC, which incorporates a fast commit path that achieves even lower latency for transferring assets. Unlike prior fast commit path protocols, MYSTICETI-FPC minimizes the number of signatures and messages by weaving the fast path transactions into the DAG. This frees up resources, which subsequently result in better performance. We prove the safety and liveness in a Byzantine context. We evaluate both MYSTICETI protocols and compare them with state-of-the-art consensus and fast path protocols to demonstrate their low latency and resource efficiency, as well as their more graceful degradation under crash failures. MYSTICETI-C is the first Byzantine consensus protocol to achieve WAN latency of 0.5s for consensus commit while simultaneously maintaining state-of-the-art throughput of over 200k TPS. Finally, we report on integrating MYSTICETI-C as the consensus protocol into the Sui blockchain [67], resulting in over 4x latency reduction.**

I. Introduction

Several recent blockchains, such as Sui [67], [12], have adopted consensus protocols based on certified directed acyclic graphs (DAG) of blocks [25], [55], [56], [34], [30], [70], [52], [58], [44]. By design, these consensus protocols scale well in terms of throughput, with a performance of 100k tx/s of raw transactions and are robust against faults and network asynchrony [33], [25]. This, however, comes at a high latency of around 2-3 seconds, which can hinder user experience and prevent low-latency applications.

MYSTICETI-C: the power of uncertified DAGs Certified DAGs [34], [25], where each vertex is delivered through consistent broadcast [14], have high latency for three main reasons: (1) the certification process requires multiple round-trips to broadcast each block between validators, get signatures, and re-broadcast certificates. This leads to higher latency than traditional consensus protocols [31], [64], [15]; (2) blocks commit on a "per-wave" basis, which means that only once every two rounds (for Bullshark [55]) there is a chance to commit. Hence, some blocks have to wait for the wave to finish increasing the latency of transactions proposed by the block. This phenomenon is similar to committing big batches of $2f+1$ blocks. Finally, (3) since all certified blocks need to

Fig. 1: P50 latency of a major blockchain switching from Bullshark (1900ms) to MYSTICETI-C (390ms) consensus on 106 independently run validators

be signed by a supermajority of validators, signature generation and verification consume a large amount of CPU on each validator, which grows with the number of validators [42], [16]. This burden is particularly heavy for a crash-recovered validator that typically needs to verify thousands of signatures when trying to catch up with the rest. Although at a first glance, certification seems to have the benefit that in adversarial cases nodes can advance the DAG without needing to synchronize the full-history, production experience of deploying Bullshark shows that this benefit is negated when needing to execute the committed transactions. As a result, the certification benefits only Byzantine Atomic Broadcast protocols but not if used for the common case of powering a State Machine Replication system (e.g., a blockchain).

This comes in stark contrast to the early protocols for BFT consensus, such as PBFT [15], which requires only 3 message delays to commit a proposal (instead of the 6 in Bullshark) and facilitates the pipeline of proposals to commit one block every round [38]. They, however, require a high number of authenticated messages to coordinate, which consumes a lot of resources and results in low throughput. Additionally, they are fragile to faults and implementation mistakes due to their complexity, especially the view-change sub-protocols.

This work presents MYSTICETI, a family of DAG-based protocols allowing to safely commit distributed transactions in a Byzantine setting that focuses on low-latency and low-CPU operation, achieving the best of both worlds. MYSTICETI-C is a consensus protocol based on a threshold logical clock [29] DAG of blocks, that commits every block as early as it can be decided. MYSTICETI-C solves all of the above challenges as (1) it is the first safe DAG-based consensus protocol that does not require explicit certificates, committing blocks within the

Techniques

- Many leaders per round
- Leaders ever round
- Uncertified DAG

Discussion

Shoal/shoal++

- Low latency
- Easier synchroniser
- Leverage existing code

Sailfish/BBCA

- Lower latency
- Easy synchroniser
- Flexible

CM/Mysticeti

- Even Lower latency
- Graceful crash faults
- Simpler, less CPU

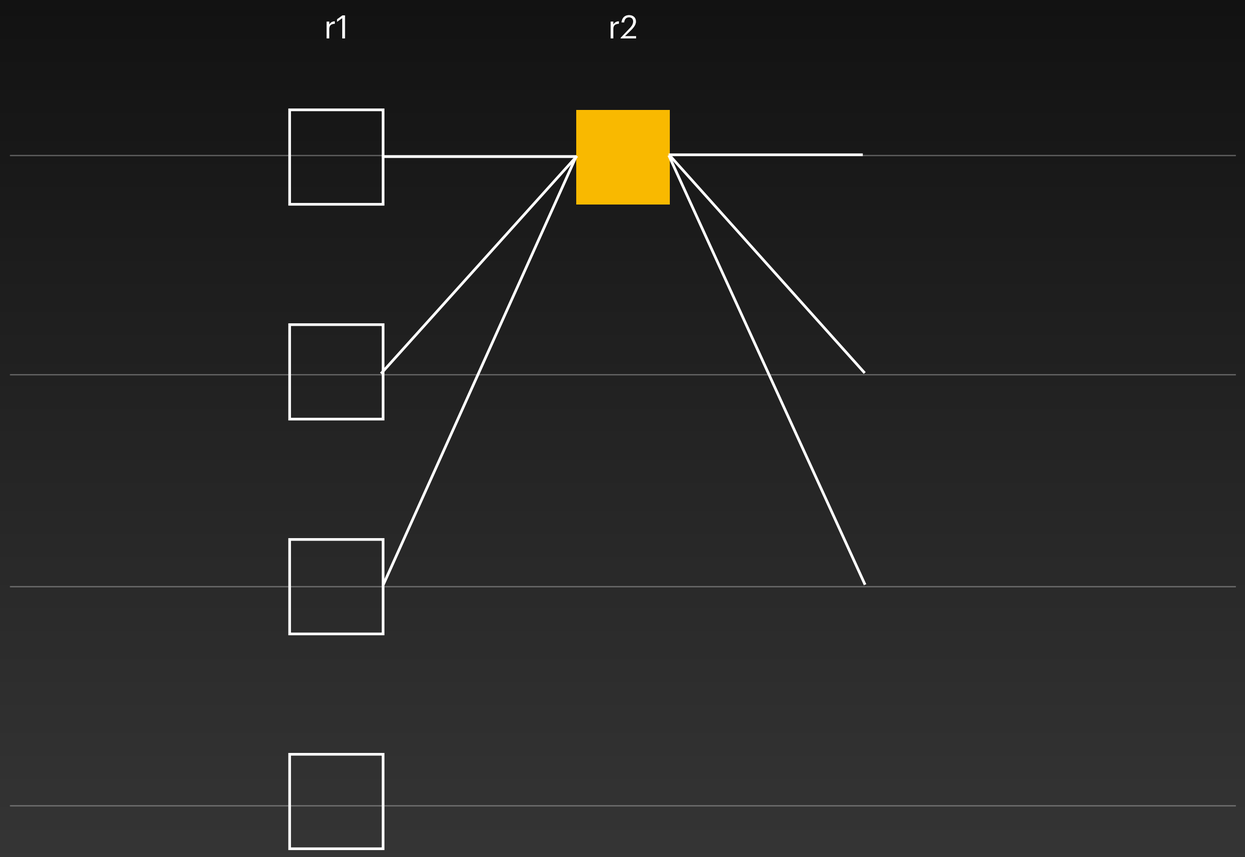
Research Questions

1. Network model?
2. BFT testing?
3. Consensus-exec interface?
4. Storage architecture?
5. Block synchroniser?

Lessons Learned

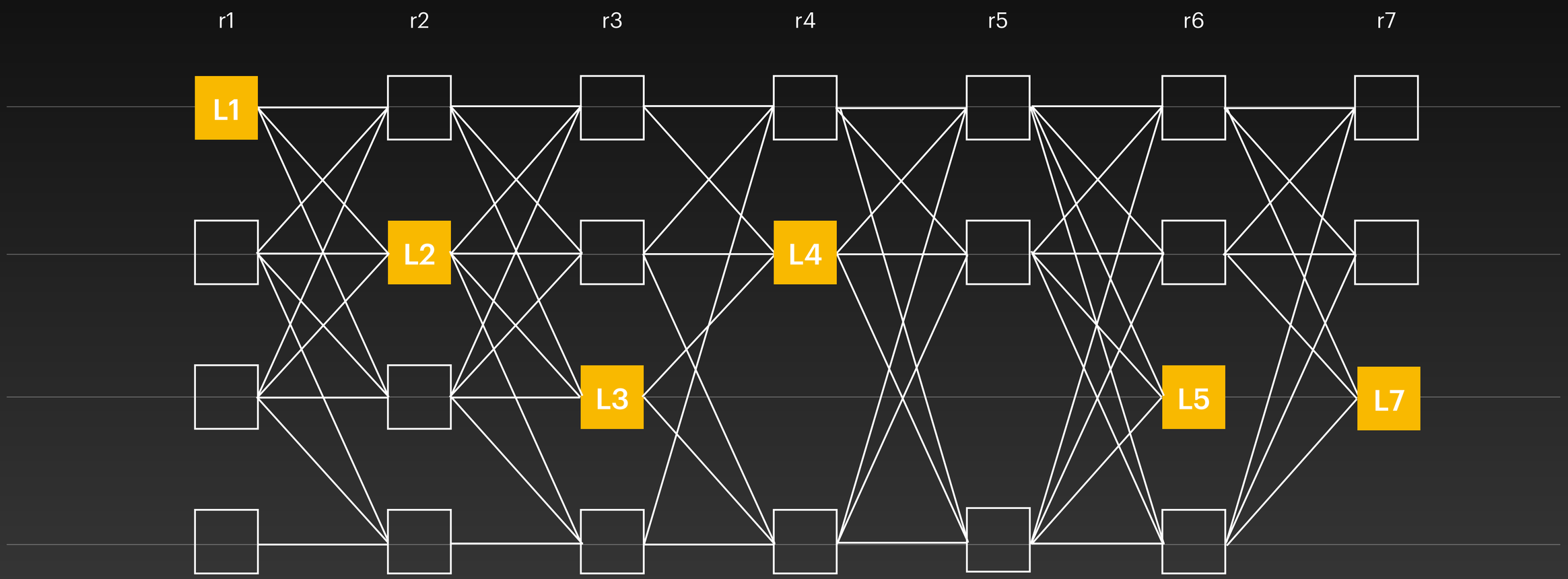
1. Modularisation is a design strategy
2. Tasks-threads relationship
3. Benchmark early
4. Codesign with mem. and storage
5. Core is hard, consensus is easy
6. Epoch change is not an add-on

Uncertified DAG

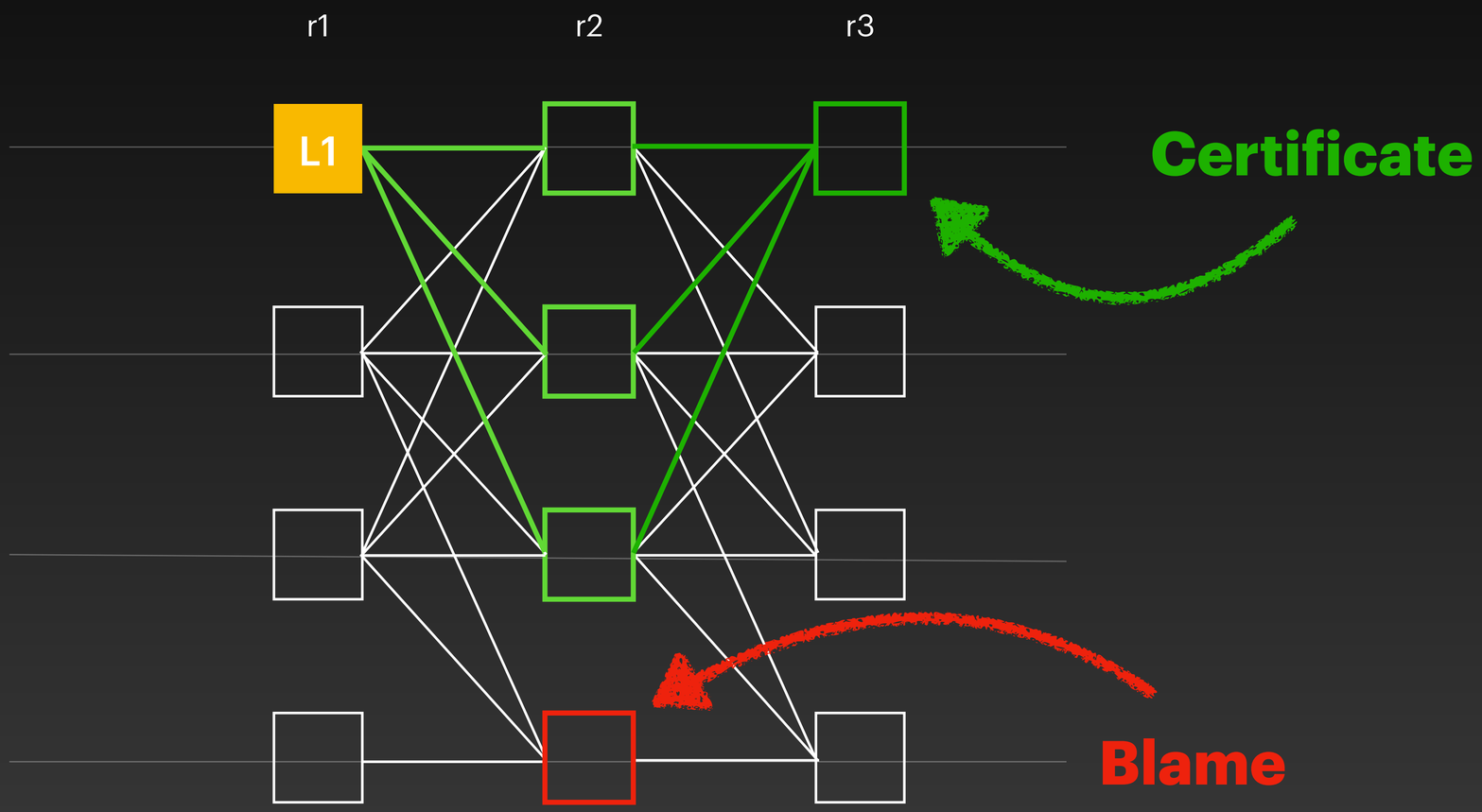


- Round number
- Author
- Payload (transactions)
- Signature

Uncertified DAG



Interpreting DAG Patterns



Direct Decision Rule

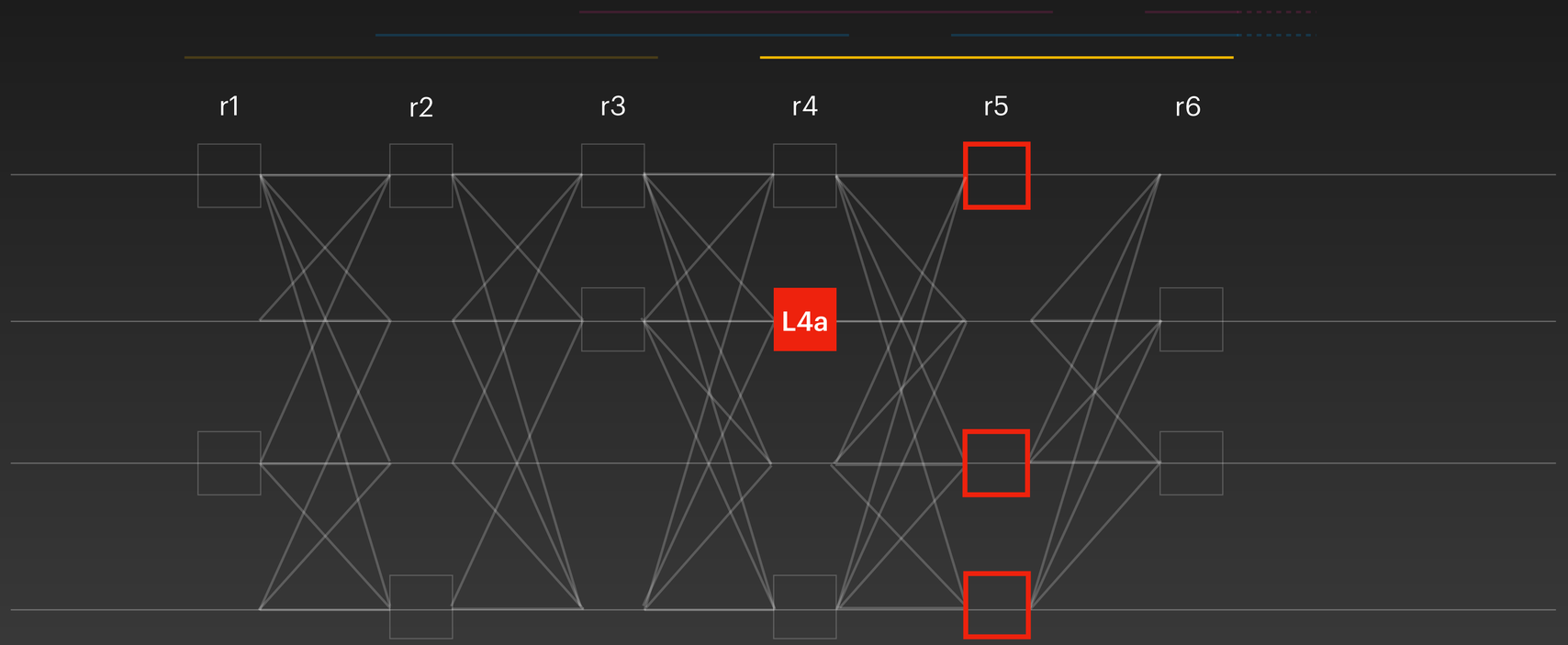
On each leader starting from highest round:

- **Skip** if 2f+1 blames
- **Commit** if 2f+1 certificates
- **Undecided** otherwise

Direct Decision Rule

On each leader starting from highest round:

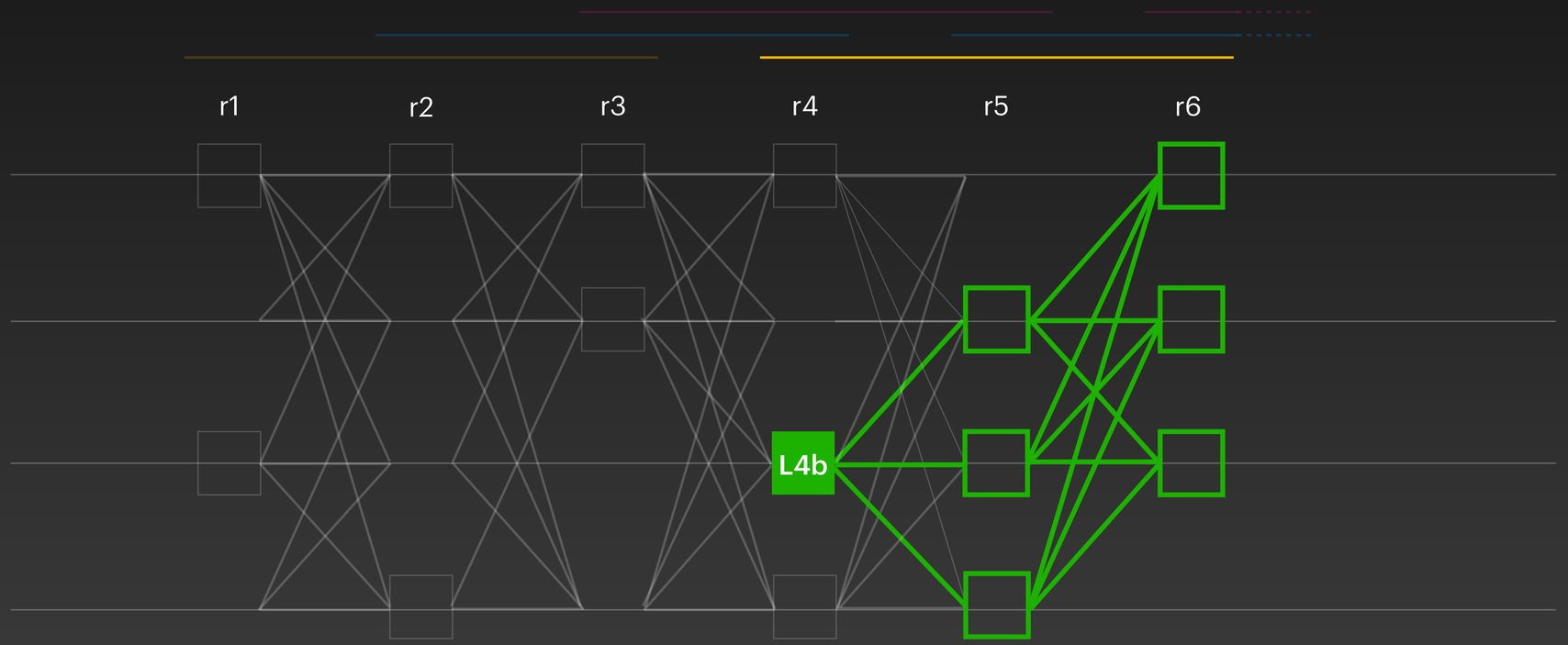
- **Skip** if 2f+1 blames
- **Commit** if 2f+1 certificates
- **Undecided** otherwise



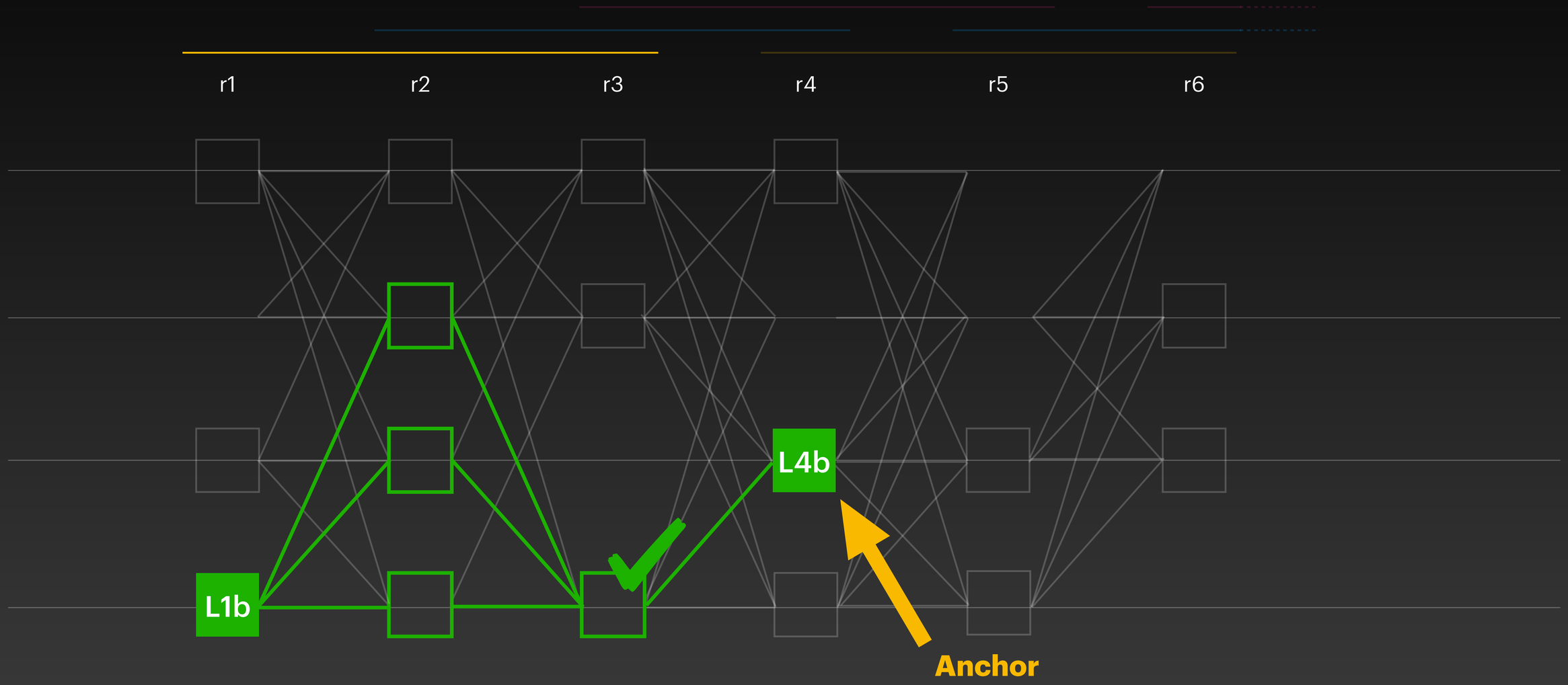
Direct Decision Rule

On each leader starting from highest round:

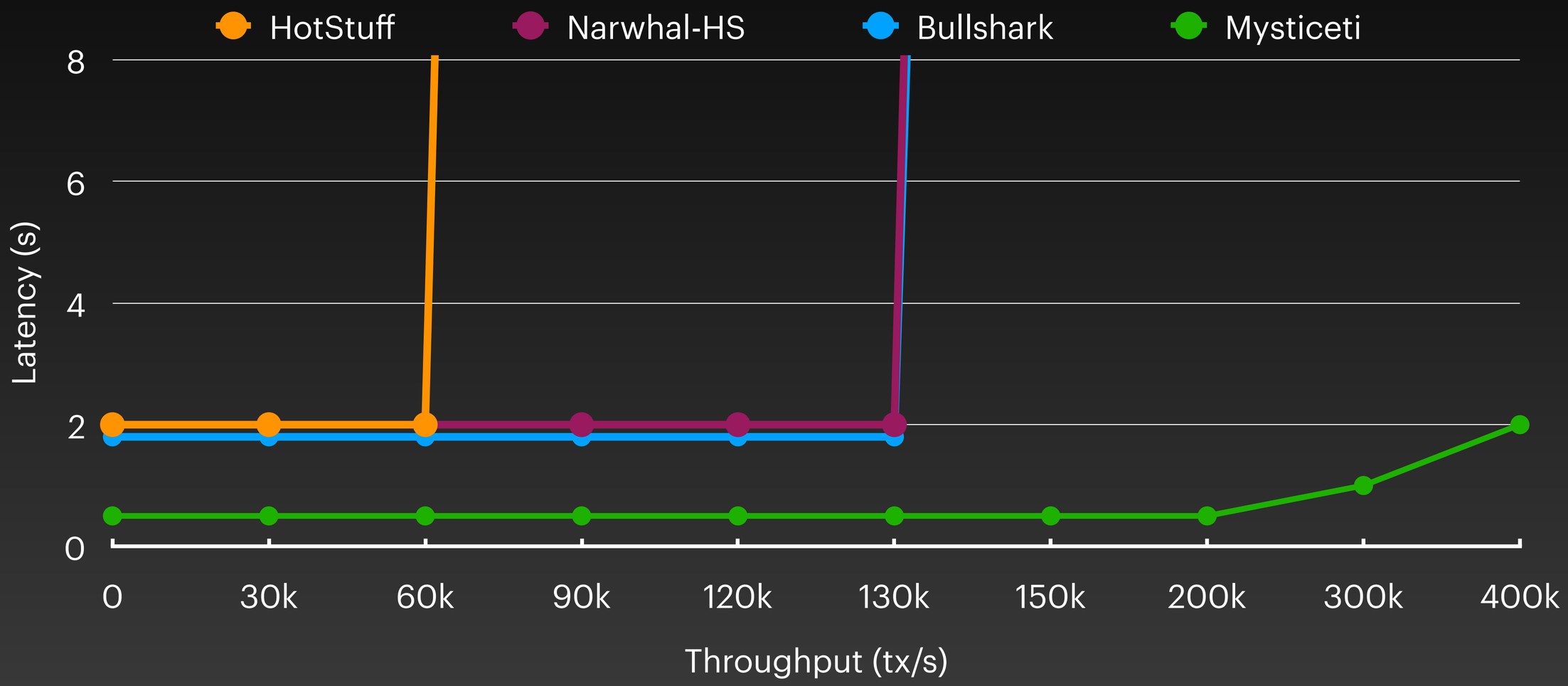
- **Skip** if 2f+1 blames
- **Commit** if 2f+1 certificates
- **Undecided** otherwise



Apply Indirect Rule



Performance



Engineering Benchmarks

Protocol	Committee	Load/TPS	P50	P95
Bullshark	137	5k	2.89 s	4.60 s
Mysticeti	137	5k	397 ms	690 ms

We ran it for 24h and it looks good 👍

Research Questions

1. Network model?
2. BFT testing?
3. Consensus-exec interface?
4. Storage architecture?
5. Block synchroniser?
6. Realistic benchmarks?
7. Efficient reads?

Lessons Learned

1. Modularisation is a design strategy
2. Tasks-threads relationship
3. Benchmark early
4. Codesign with mem. and storage
5. Core is hard, consensus is easy
6. Epoch change is not an add-on

Testing Strategy

- Compare performance & robustness
- Test mainnet change `bullshark -> mysticeti`
- Prepare for the worst `mysticeti -> bullshark`

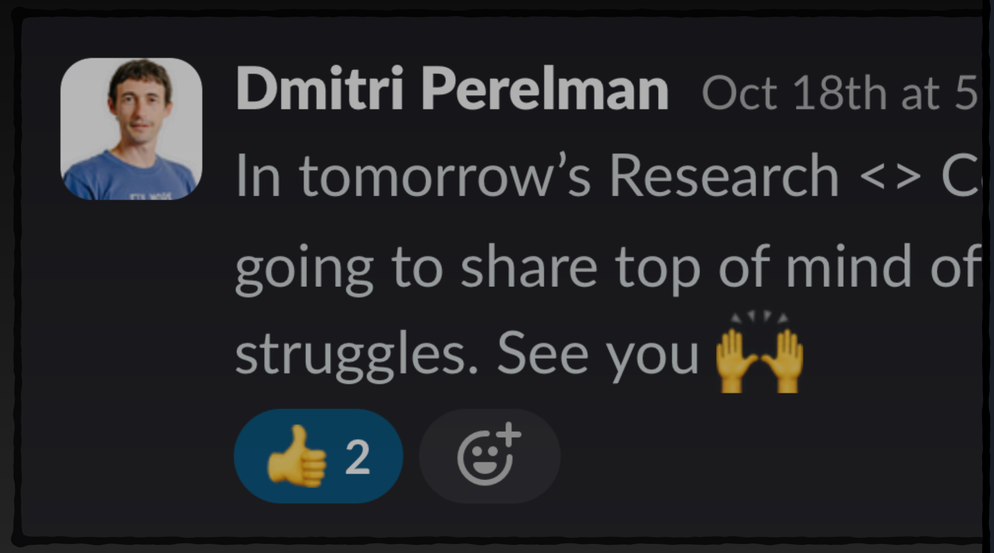
Projects Roadmap

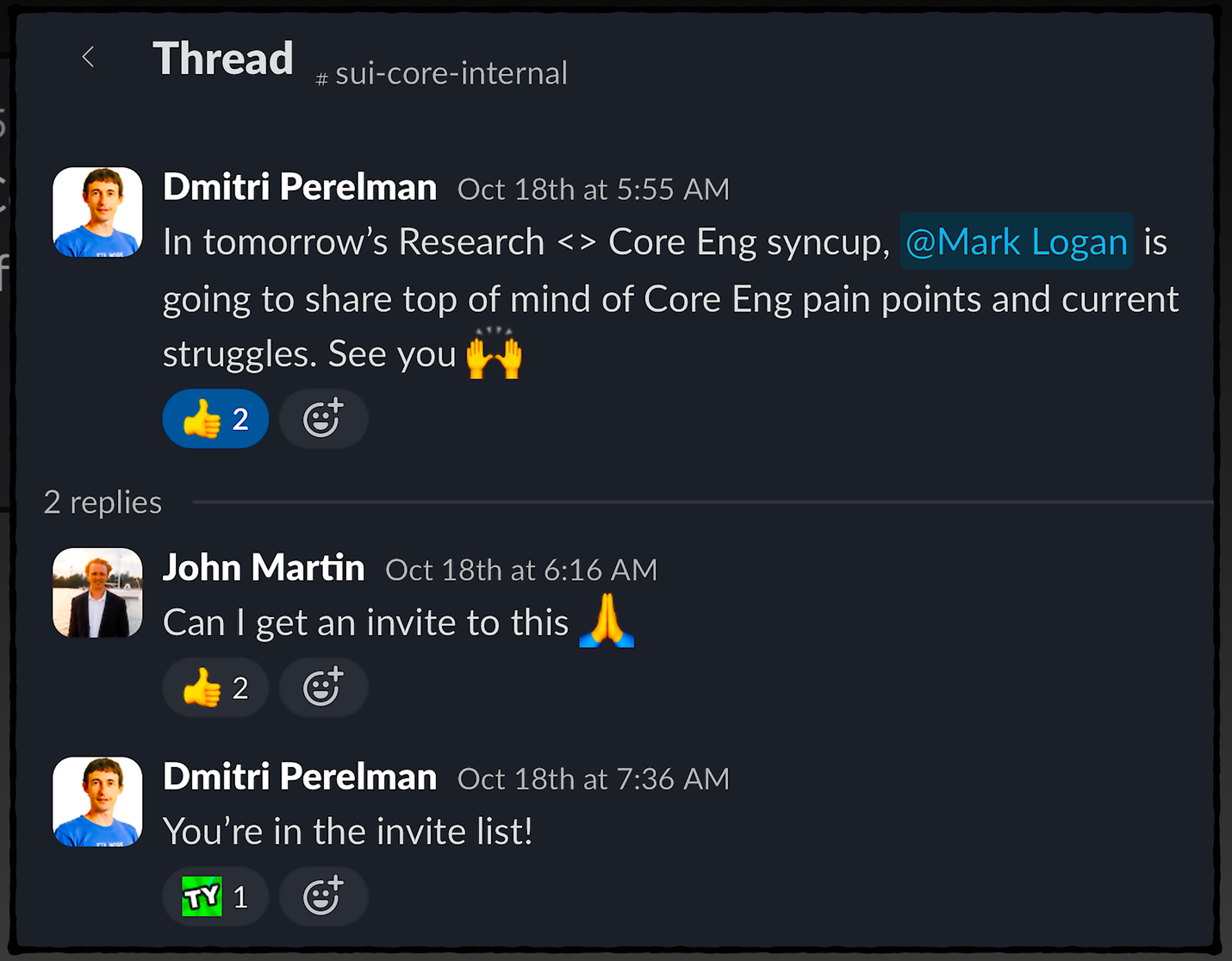
Dmitri Perelman Oct 18th at 5:55 AM

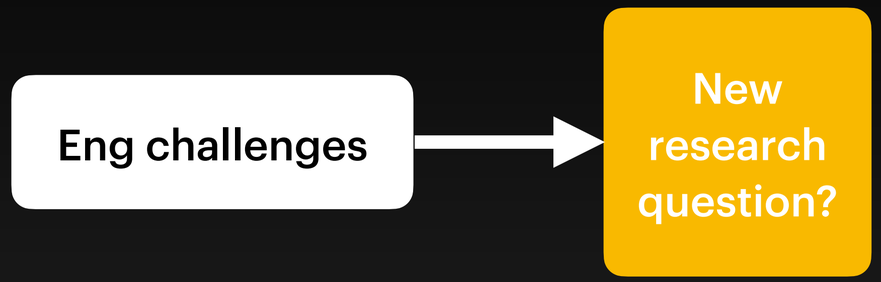
In tomorrow’s Research <> Core Eng syncup, @Mark Logan is going to share top of mind of Core Eng pain points and current struggles. See you 🙌

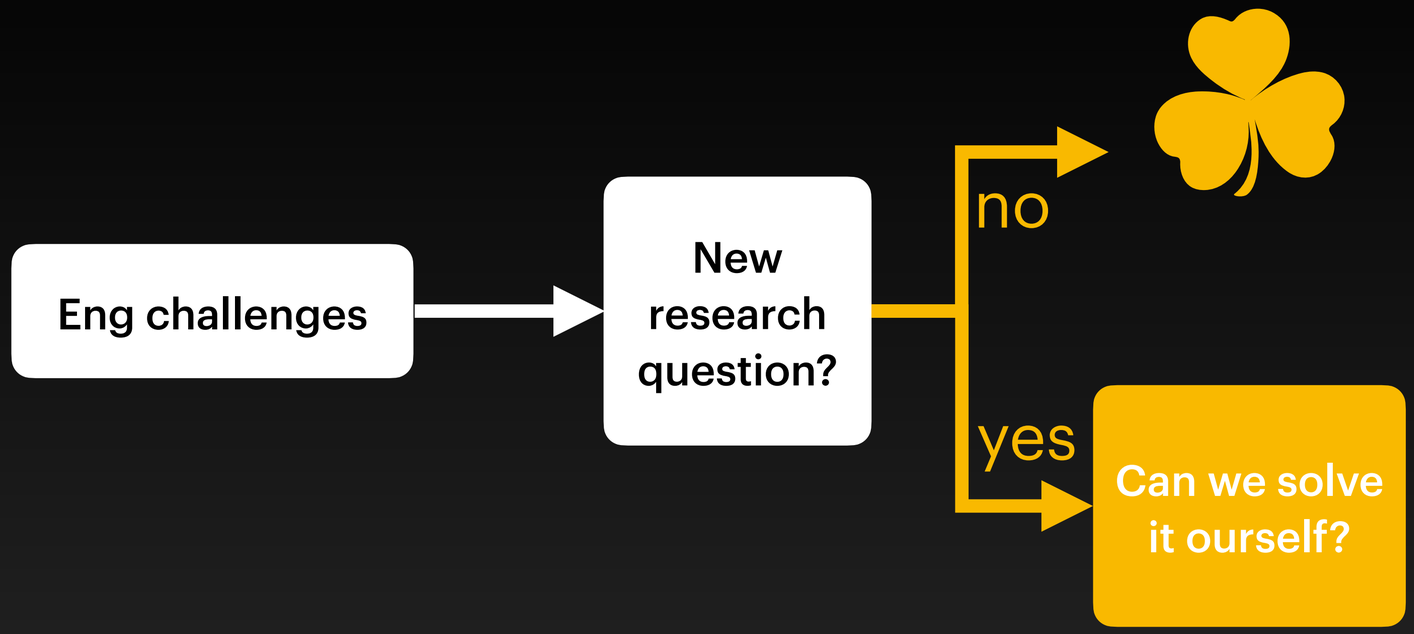
👍 2

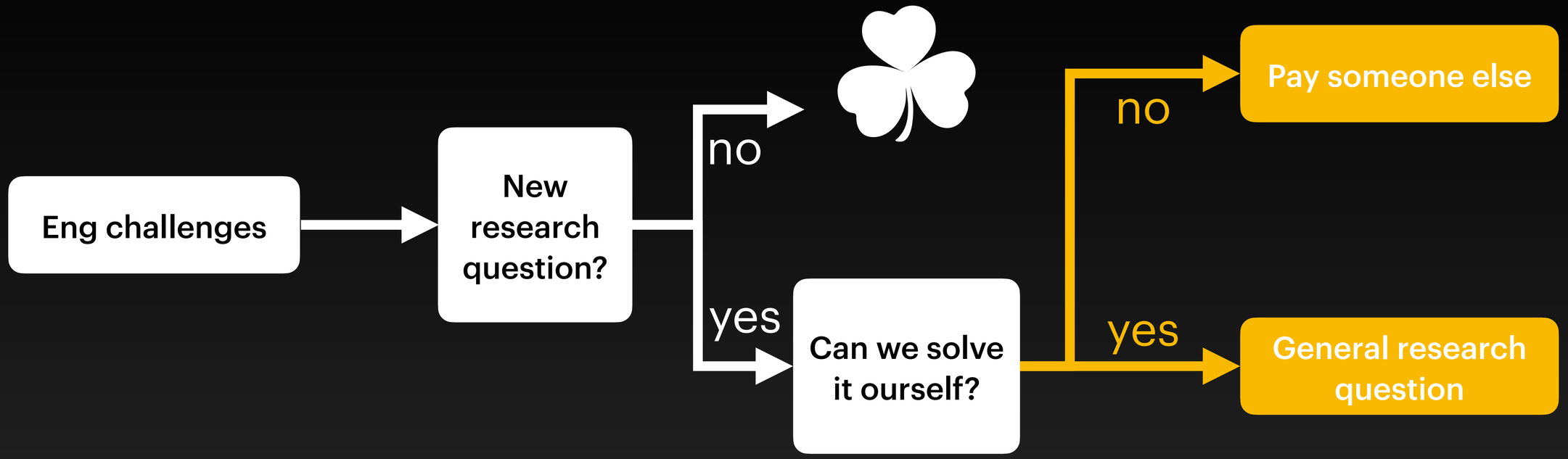
Projects Roadmap

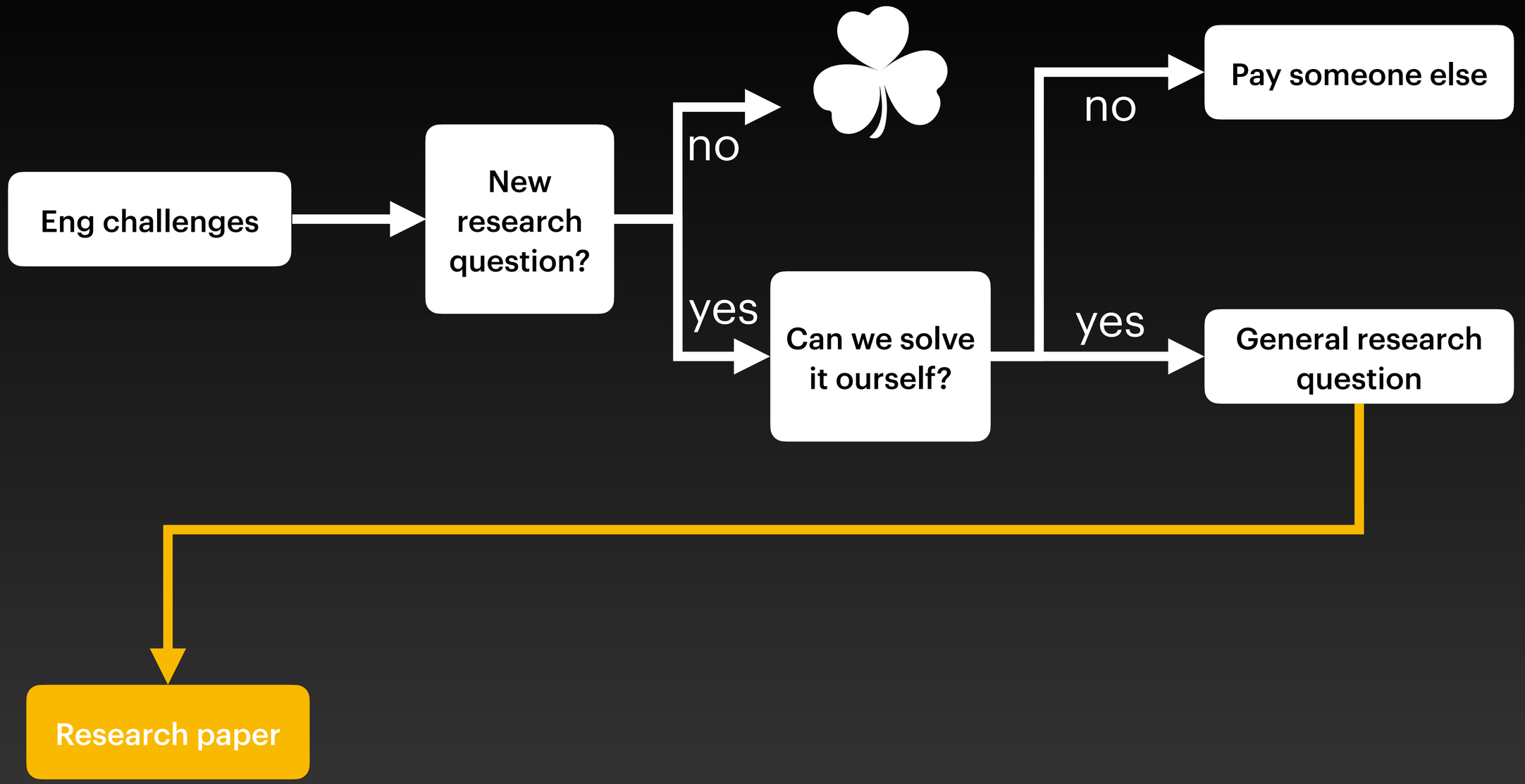


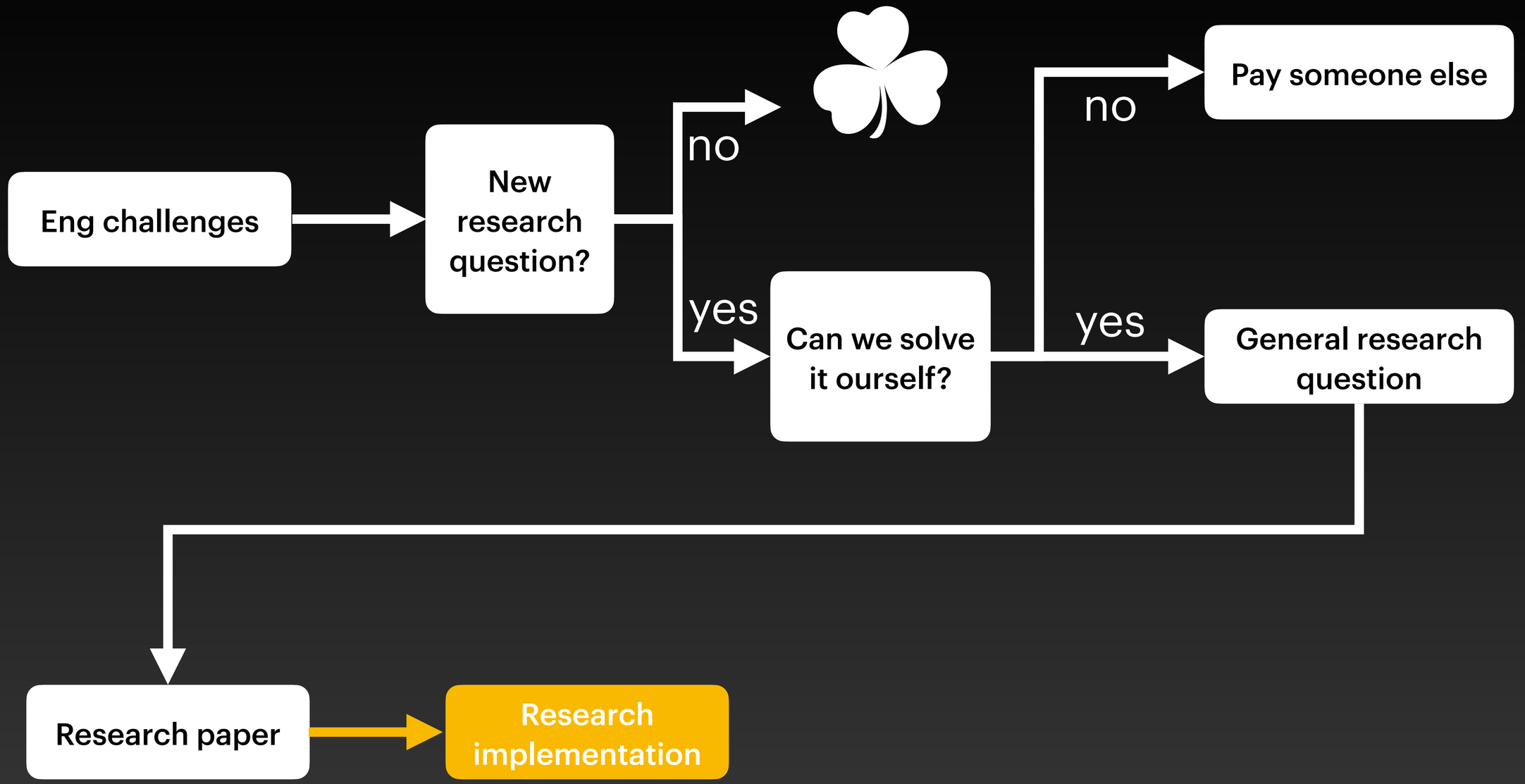


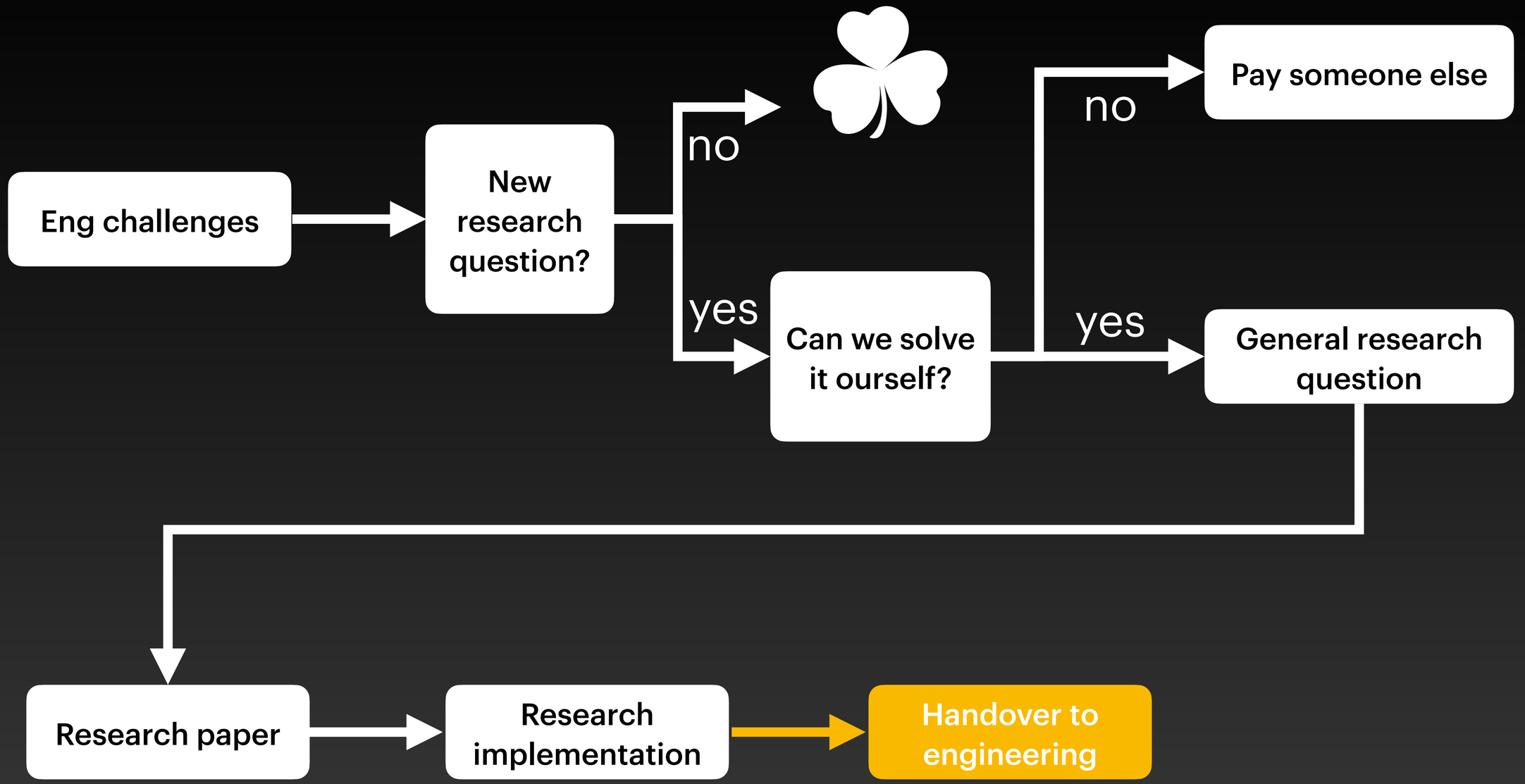

Eng challenges
New research question?

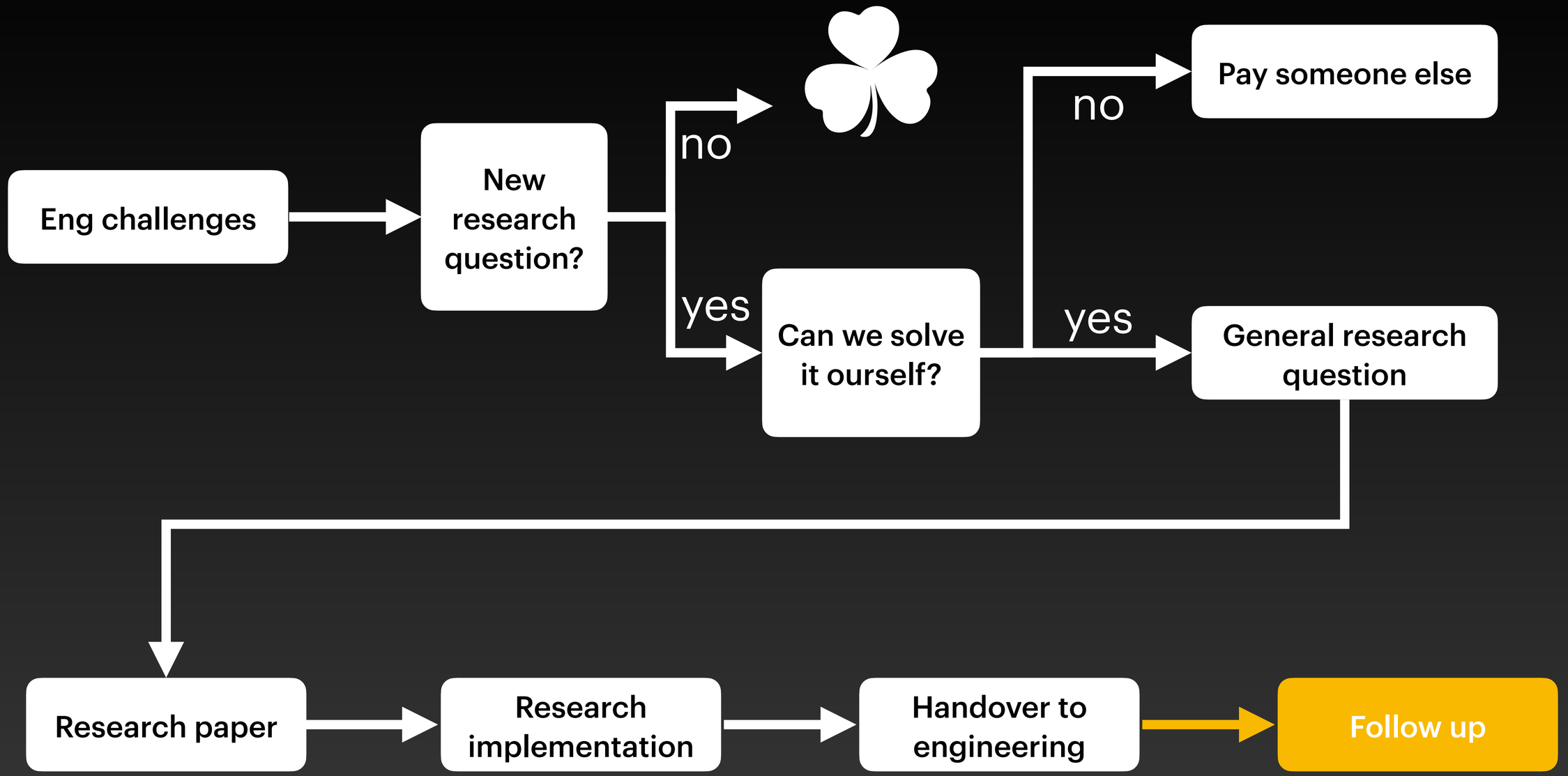

Eng challenges
New research question?
no
yes
Can we solve it ourself?


Eng challenges
New research question?
no
yes
Can we solve it ourself?
no
Pay someone else
yes
General research question


Eng challenges
New research question?
no
yes
Can we solve it ourself?
no
Pay someone else
yes
General research question
Research paper


Eng challenges
New research question?
no
yes
Can we solve it ourself?
no
Pay someone else
yes
General research question
Research paper
Research implementation


Eng challenges
New research question?
no
yes
Can we solve it ourself?
no
Pay someone else
yes
General research question
Research paper
Research implementation
Handover to engineering


Eng challenges
New research question?
no
yes
Can we solve it ourself?
no
Pay someone else
yes
General research question
Research paper
Research implementation
Handover to engineering
Follow up

Chainspace: A Sharded Smart Contracts Platform
NDSS • Adopted by chainspace.io

Coconut: Threshold Issuance Selective Disclosure …
NDSS • Adopted by chainspace.io, KetI, Nym, …

Replay Attacks and Defenses against Cross-shard …
EuroS&P • Adopted by chainspace.io

FastPay: High-Performance Byzantine Fault Tolerant …
AFT • Adopted by Sui, Linera

Twins: BFT Systems Made Robust
OPODIS • Adopted by Diem, Aptos, Chainlink

Fraud Proofs: Maximising Light Client Security and …
FC • Adoped by Ethereum, Celestia

Jolteon and Ditto: Network-Adaptive Efficient Consensus …
FC • Adopted by Flow, Diem, Aptos, Monad

Be Aware of Your Leaders
FC • Adopted by Diem, Aptos

Subset-optimized BLS Multi-signature with Key Aggregation
FC • Adopted by Fastcrypto

Narwhal and Tusk: A DAG-based Mempool and Efficient …
EuroSys • Adopted by Sui, Aptos, Fleek, Aleo
Best paper award

Bullshark: DAG BFT Protocols Made Practical
CCS • Adopted by Sui, Aleo, Fleek

Zef: Low-latency, Scalable, Private Payments
WPES • Adopted by Linera

Parakeet: Practical Key Transparency for End-to-End …
NDSS • Adopted by WhatsApp
IETF Applied Networking Research Prize

HammerHead: Leader Reputation for Dynamic Scheduling
ICDCS • Adopted by Sui

Fastcrypto: Pioneering Cryptography via Continuous …
LTB • Adopted by Fastcrypto

Sui Lutris: A Blockchain Combining Broadcast and …
CCS • Adopted by Sui
Distinguished paper award

Mysticeti: Reaching the Limits of Latency with Uncertified …
NDSS • Adopted by Sui

Research Questions

1. Network model?
2. BFT testing?
3. Consensus-exec interface?
4. Storage architecture?
5. Block synchroniser?
6. Realistic benchmarks?
7. Efficient reads?

Lessons Learned

1. Modularisation is a design strategy
2. Tasks-threads relationship
3. Benchmark early
4. Codesign with mem. and storage
5. Core is hard, consensus is easy
6. Epoch change is not an add-on
7. Writing papers to explore designs

alberto@mystenlabs.com

EXTRA

Implementation

- Written in Rust
- Networking: Tokio (TCP)
- Storage: custom WAL
- Cryptography: ed25519-consensus

https://github.com/mystenlabs/mysticeti

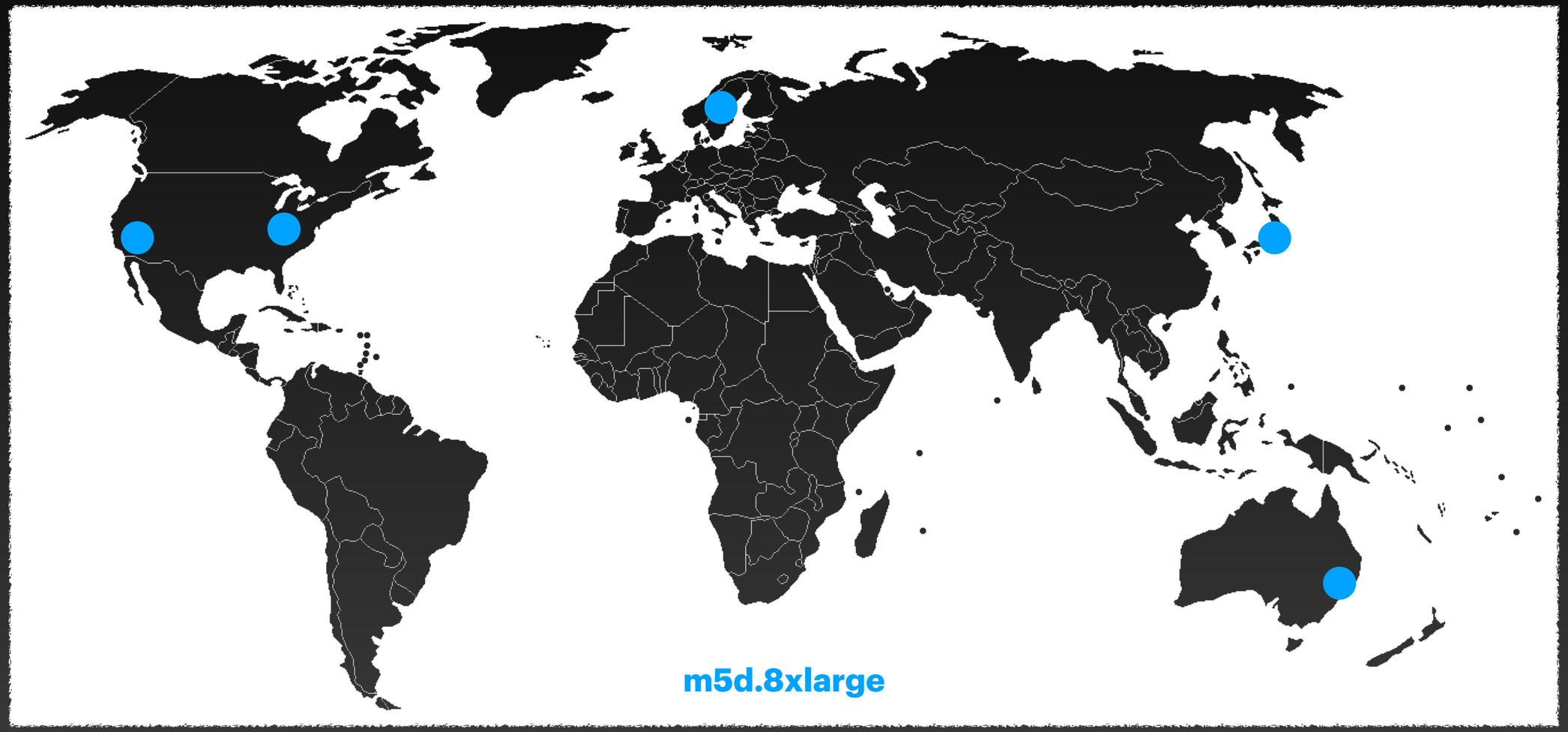
Implementation

- Synchronous core
- One Tokio task per peer (limiting resource usage)
- DTE simulator

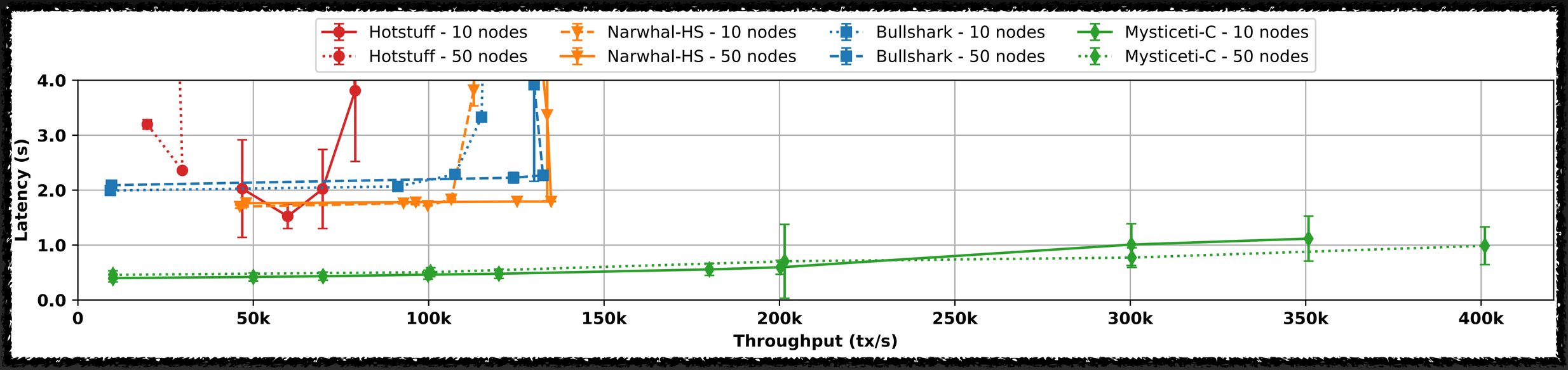
https://github.com/mystenlabs/mysticeti

Evaluation

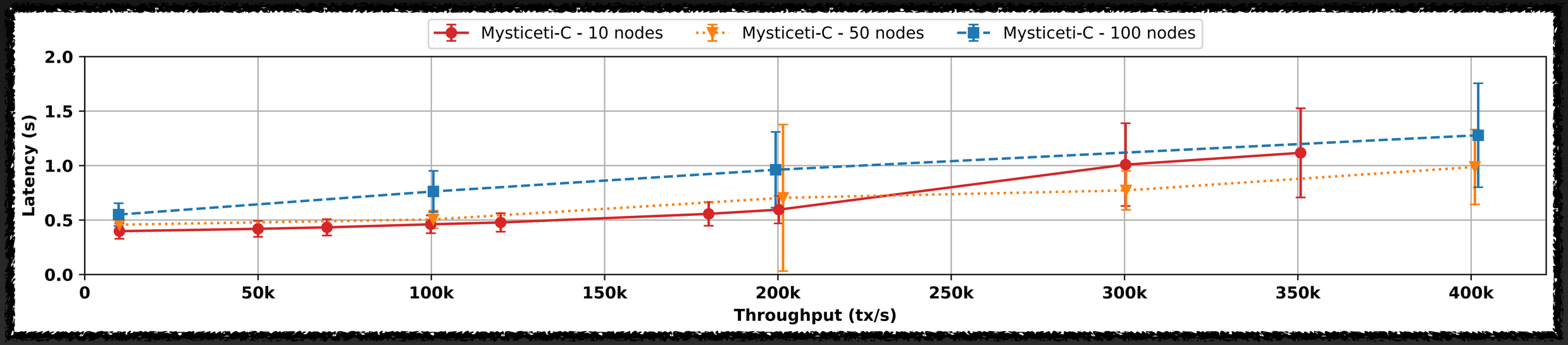
Experimental setup on AWS



Prototype Benchmarks



Prototype Benchmarks



Research Questions

1. Network model?
2. BFT testing?
3. Consensus-exec interface?
4. Storage architecture?
5. Block synchroniser?
6. Realistic benchmarks?
7. Efficient reads?

Lessons Learned

1. Modularisation is a design strategy
2. Tasks-threads relationship
3. Benchmark early
4. Codesign with mem. and storage
5. Core is hard, consensus is easy
6. Epoch change is not an add-on
7. Writing papers to explore designs