Stellar

# Federated Byzantine Agreement

Giuliano Losa,
Researcher, Stellar Development Foundation
SPTDC 2026

April 2026

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real gold bar

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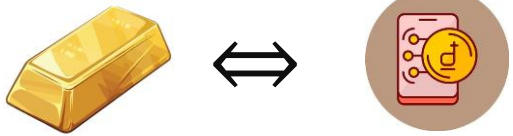

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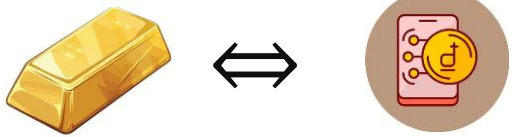

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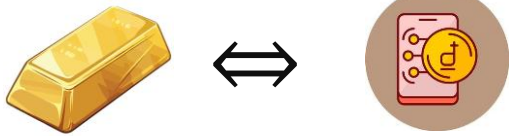

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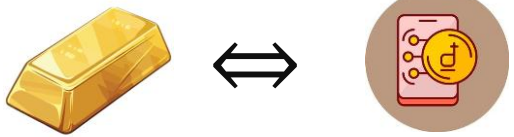

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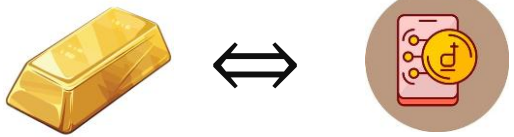

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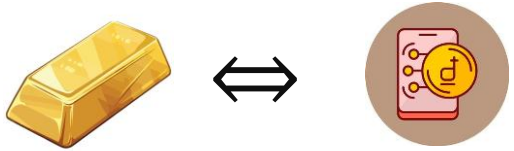

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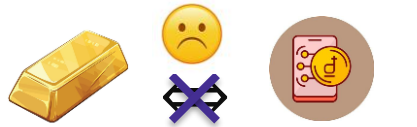

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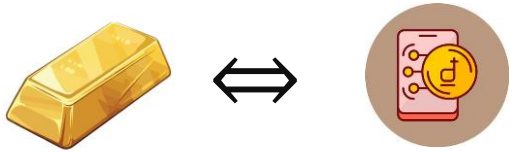

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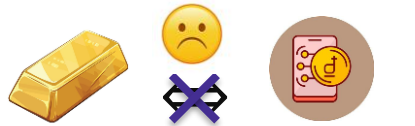

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Stakers have economic incentive not to do that (~USD $100 Billion staked), but what if the assets are worth more?

# A problem with real-world assets on blockchains

Say the central bank of a country wants to issue 10 trillion USD worth of digital currency (a CBDC) on Ethereum

*$10 trillion*

⇔

digital DOLLART token

Total ETH staked is in the order of USD $100 Billion

Now stakers' economic incentives might not be enough to secure the system

# How to safely tokenize 10 trillion USD worth of assets?

We want:

- **Open access:** anyone can issue and trade digital tokens representing real-world assets
- **Cross-issuer atomicity:** tokens from multiple issuers can be exchanged and traded atomically
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(Note that this is about protecting issuers from anonymous miners or stakers, and not about protecting users from issuers; the latter is done by courts of law in the real world)

# Can private payment systems do it?

Examples: PayPal, WeChat Pay, Venmo, etc.

- ✓ Have issuer-enforced finality (PayPal can block transactions and controls its ledger)
- ▪ Not open access (cannot issue new tokens)
- ▪ Cross-issuer atomic transactions are impossible (one cannot atomically swap Paypal USD for WeChat Pay CNY)

# Can domestic payment networks do it?

Examples: PIX (Brazil), FedNow (USA), SEPA (EU), etc.

- ✓ Have issuer-enforced finality
- ✓ Have cross-issuer atomic transactions
- ▪ Not open access (limited to one jurisdiction)


# Can public PoW/PoS blockchains do it?

Example: Bitcoin, Ethereum, Solana, Sui, Aptos, etc.

- ✓ Have open access
- ✓ Have cross-issuer atomicity
- ▪ But not issuer-enforced finality: miners or stakers are in control of finality

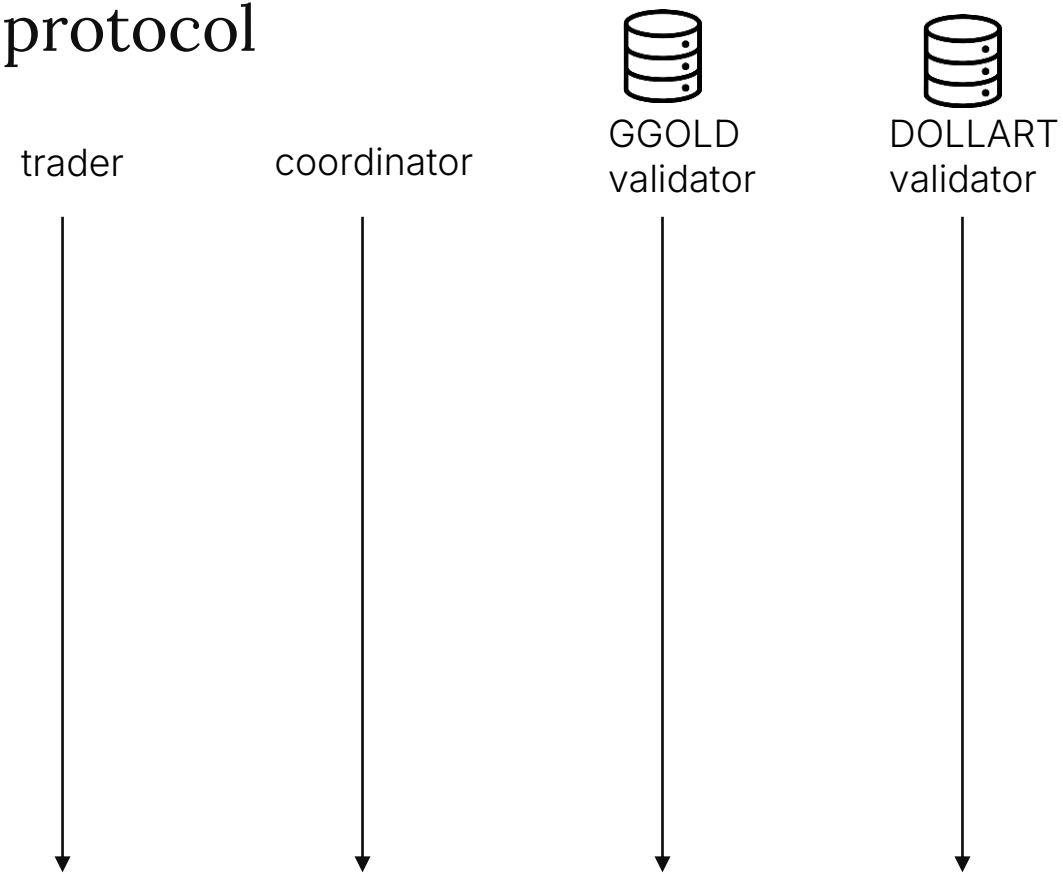
# Idea: let token issuers host their own authoritative ledgers

- I run my own transaction *validator* with the authoritative copy of the GGOLD ledger
- The central bank runs its own *validator* with the authoritative copy of its DOLLART ledger

⇒ *We have issuer-enforced finality*

How do we coordinate cross-issuer transactions?

# Idea: coordinate cross-issuer transactions with a 2-phase commit protocol



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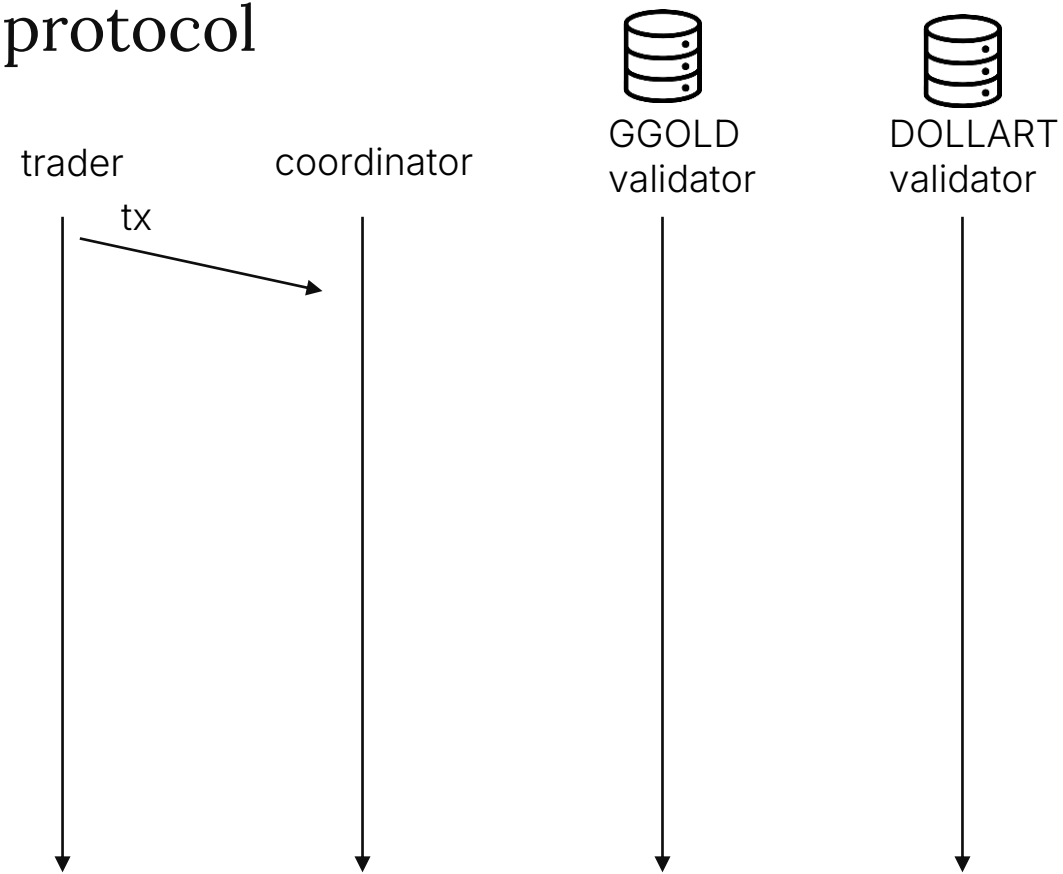

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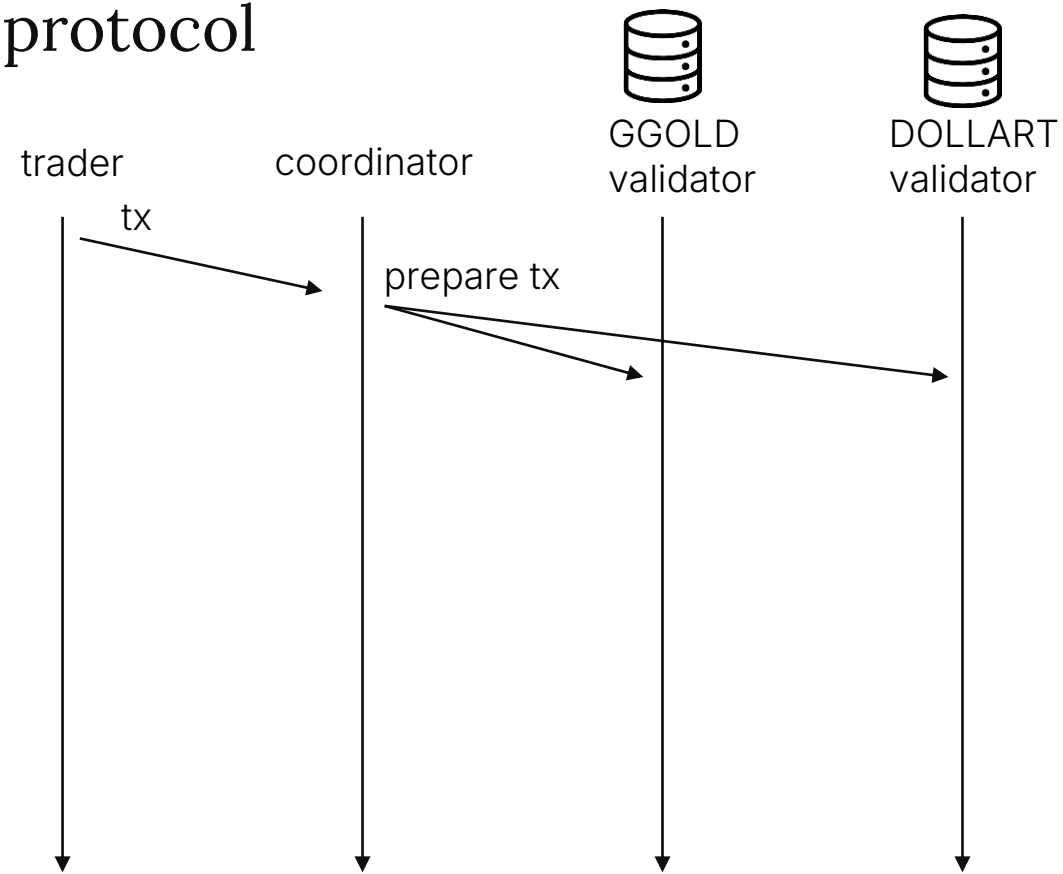

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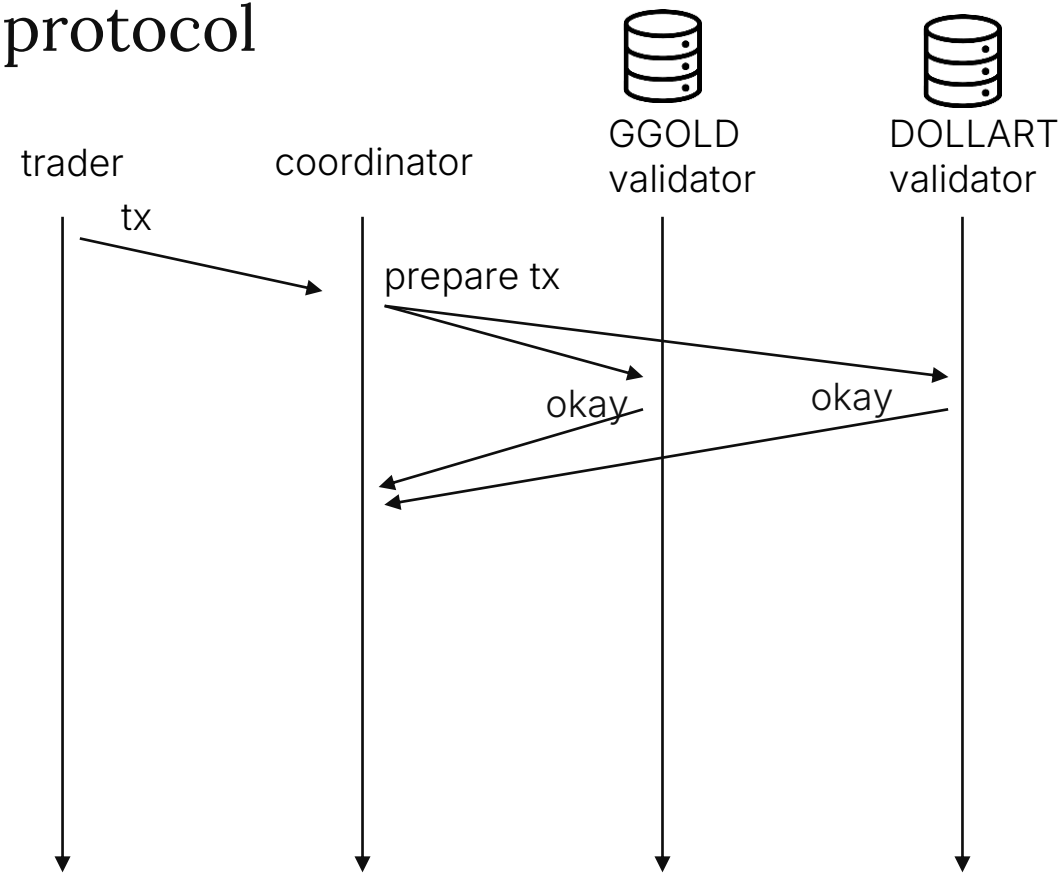

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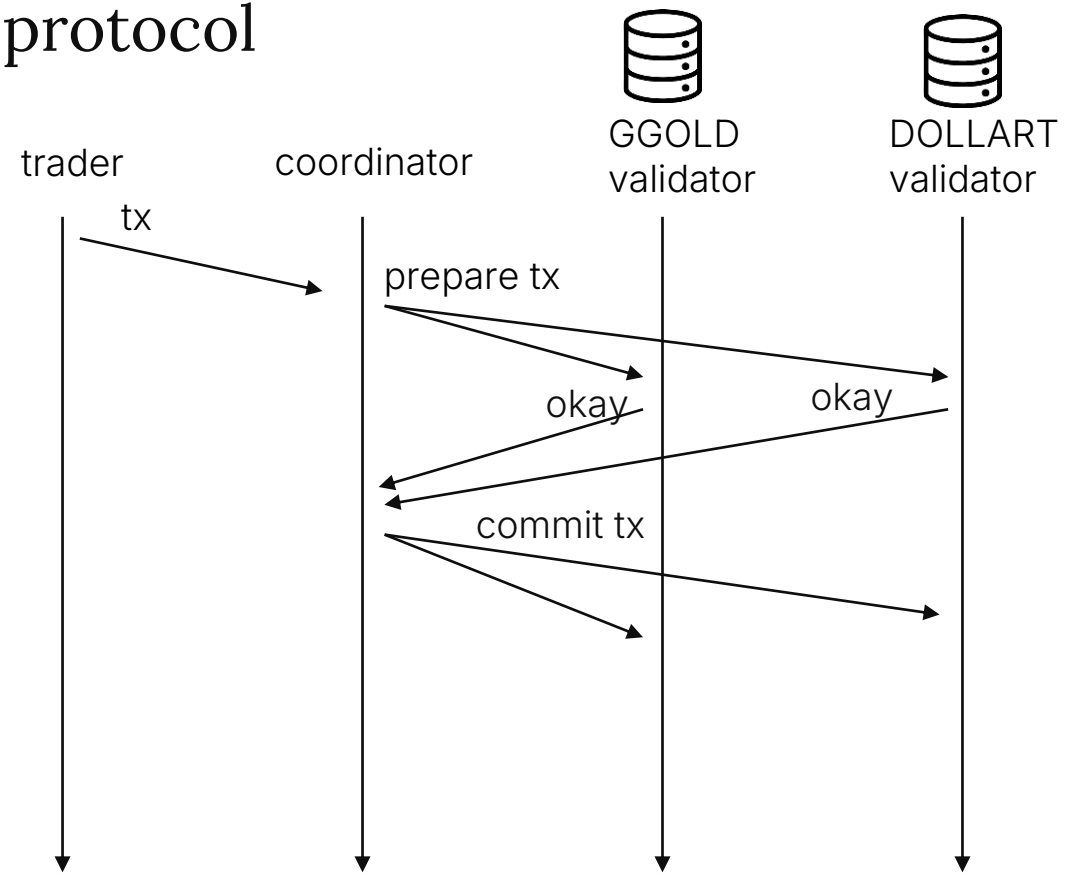

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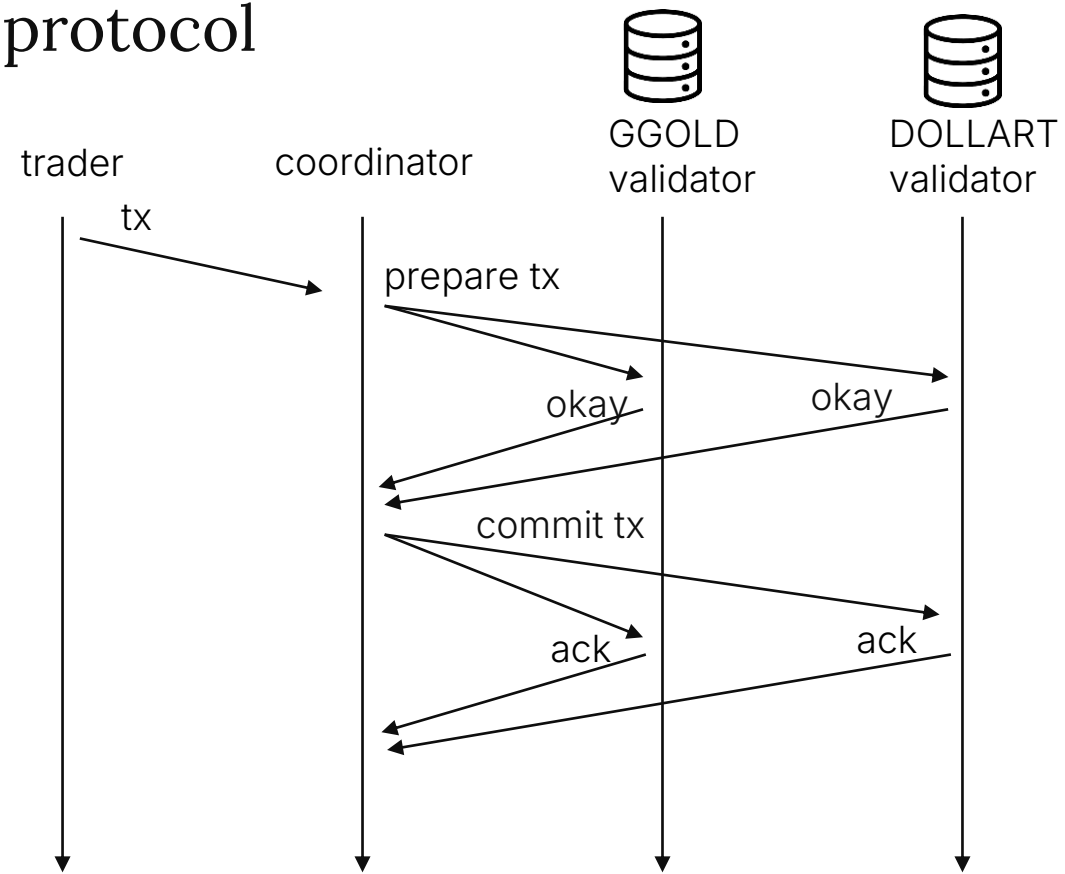

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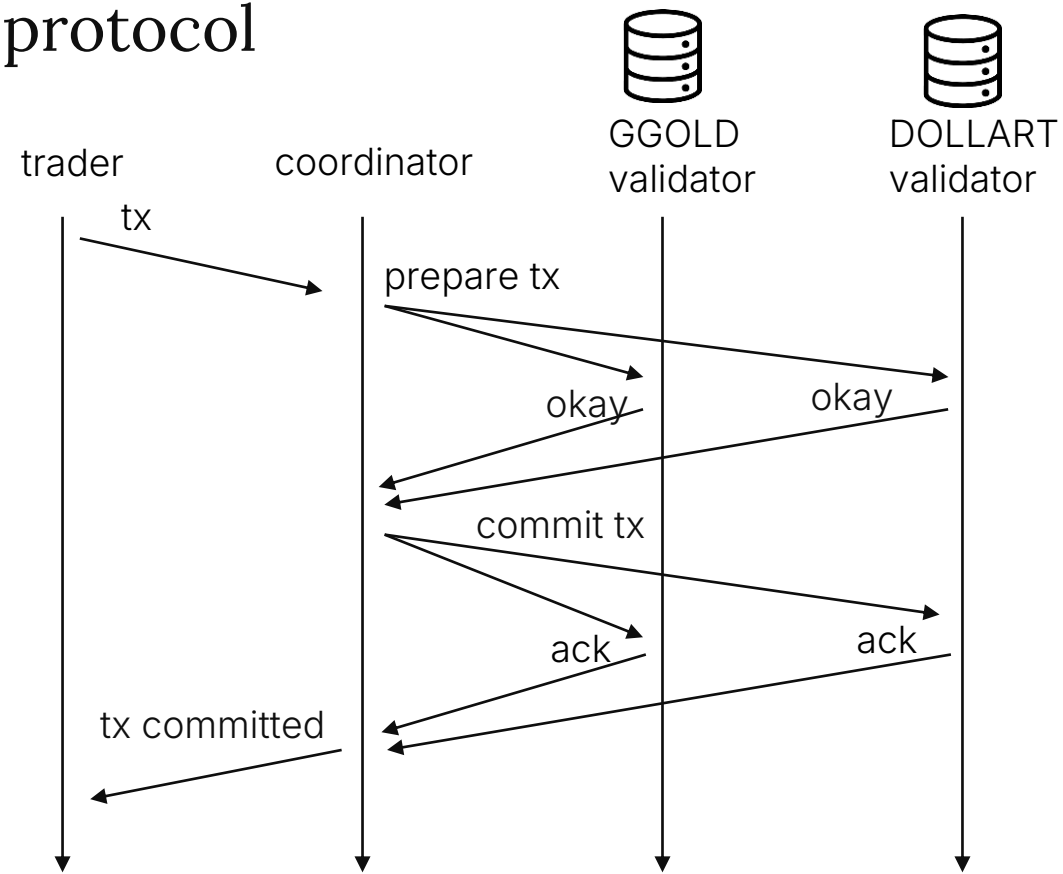

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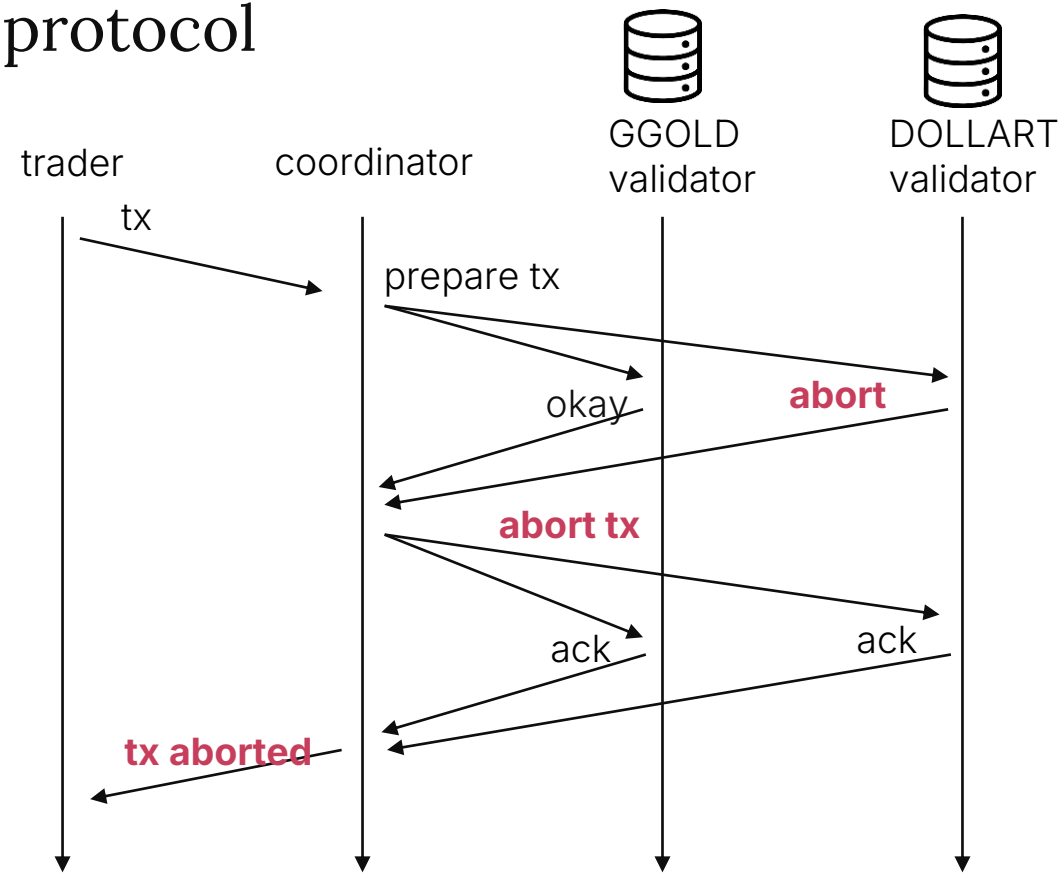

# Problems with the 2-phase commit approach

- ✓ Issuer-enforced finality
- ✓ Cross-issuer atomic transactions
- Not open access
  - We need to agree in advance on who will participate and who will be the coordinator
  - What about designating a global coordinator? Now we have a dictator...

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# Roadmap

- ✓ Intro: the problem of issuer-enforced finality
- ➢ Background: Partial Synchrony, Total-Order Broadcast, BFT quorum systems, Reliable Voting
- Quorums in Federated Byzantine Agreement systems
- Reliable Voting in Federated Byzantine Agreement systems
- Total-Order Broadcast by porting Simplex to FBA

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- Validators have accurate local clocks

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> Dwork, Lynch, and Stockmeyer. ***Consensus in the Presence of Partial Synchrony***. Journal of the ACM, 1988.

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*Progress:* If the system remains synchronous long enough, every well-behaved validator eventually adds one more value proposed by a well-behaved validator to its committed log

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# We can think of TOB as filling consecutive positions in local arrays

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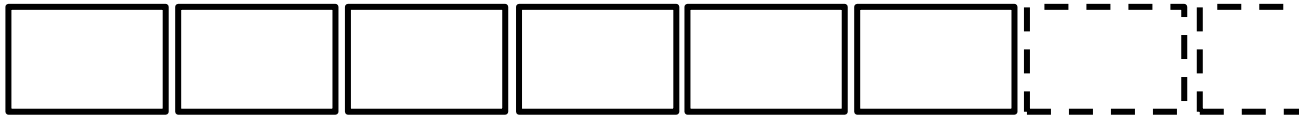


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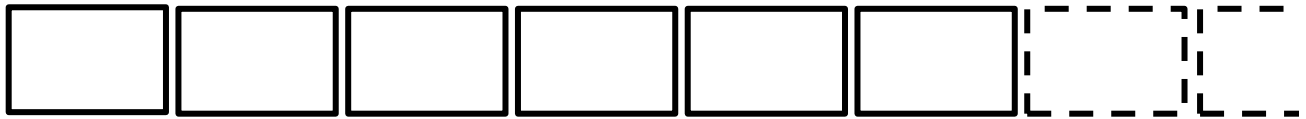

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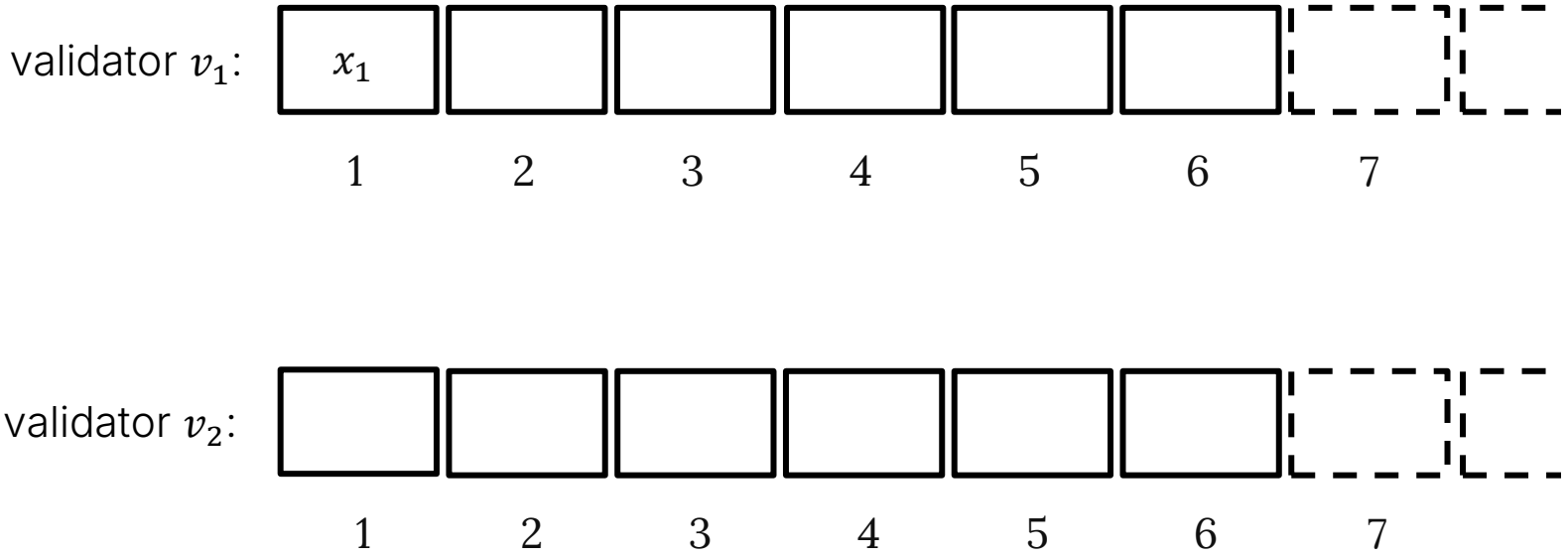

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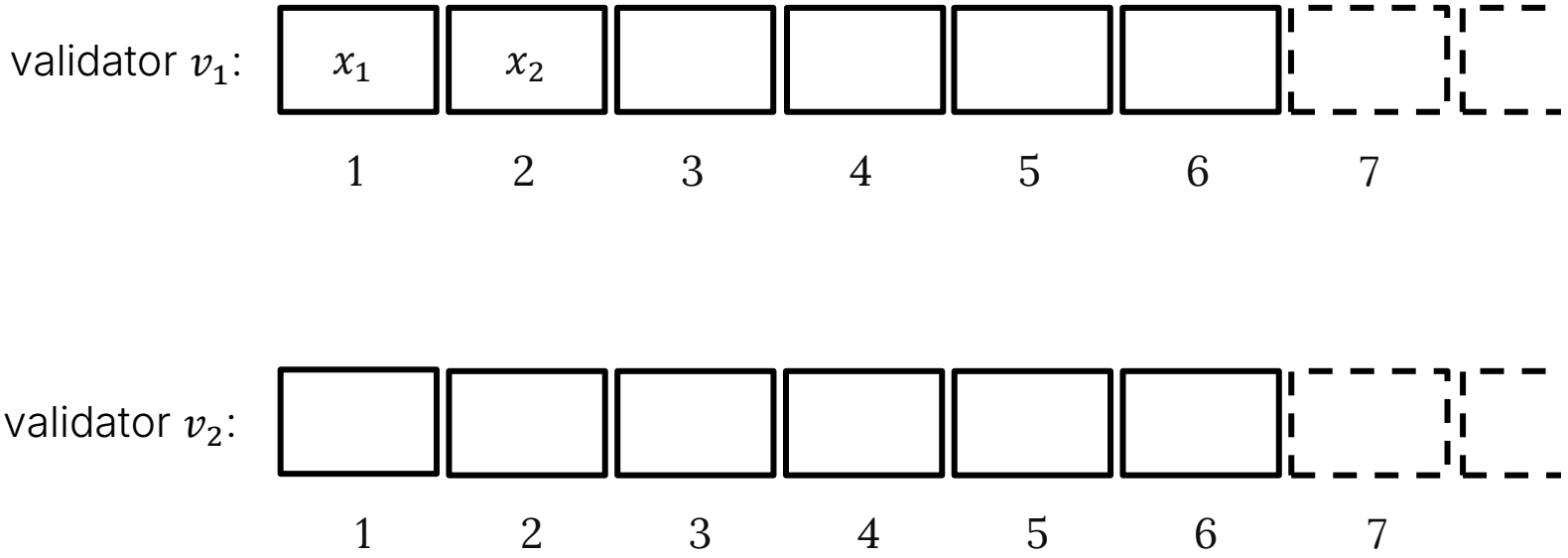

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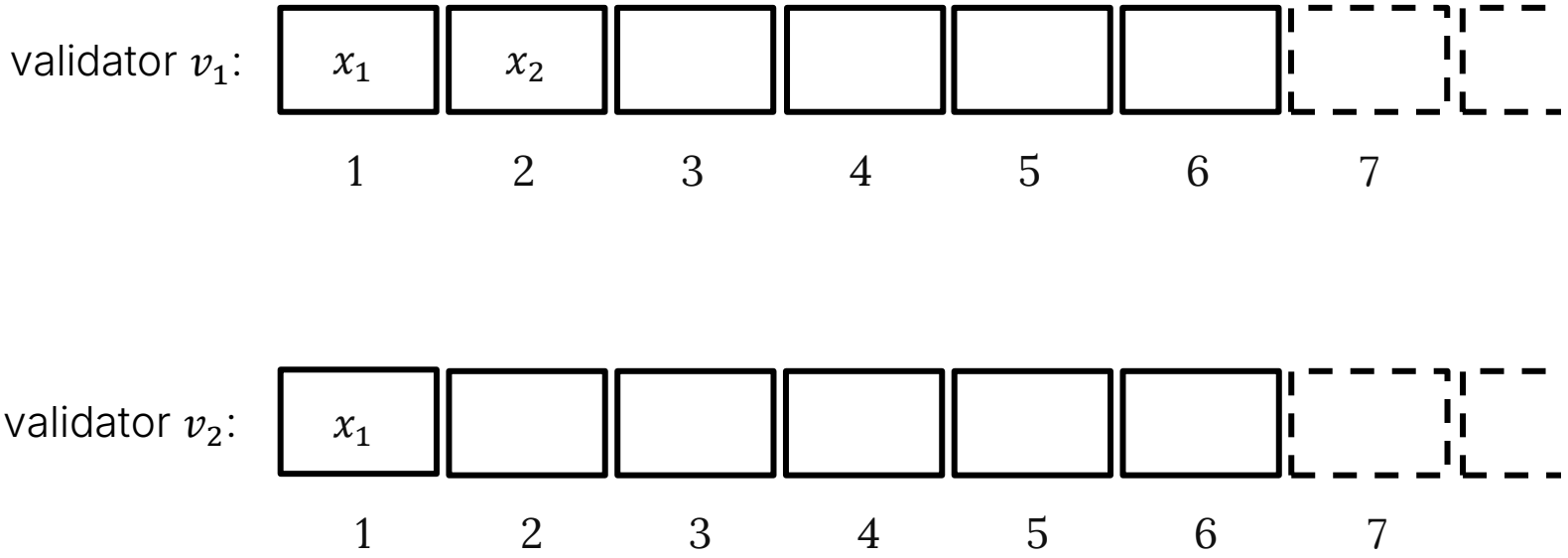

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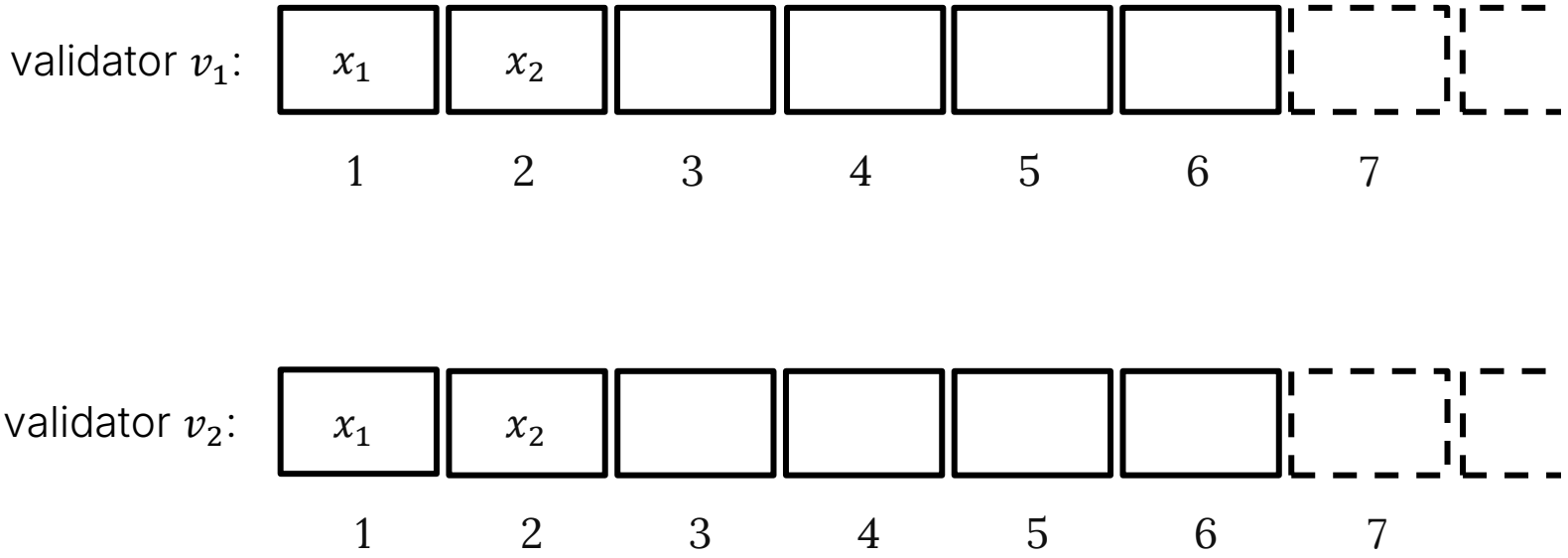

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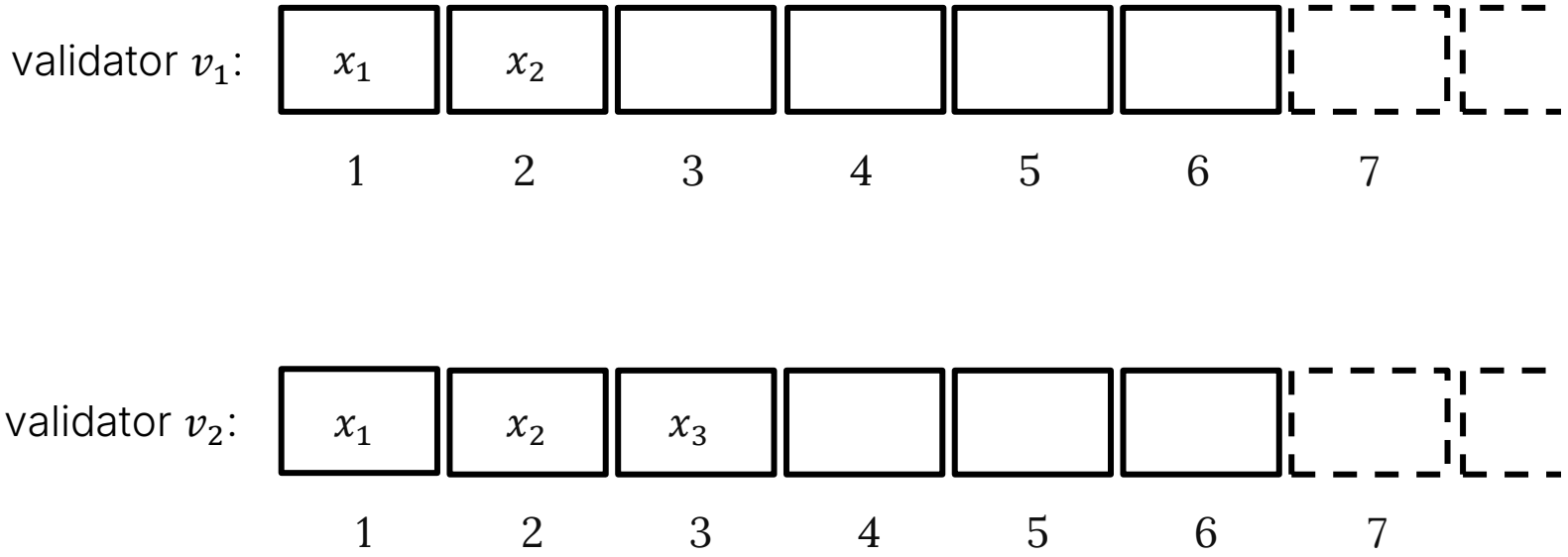

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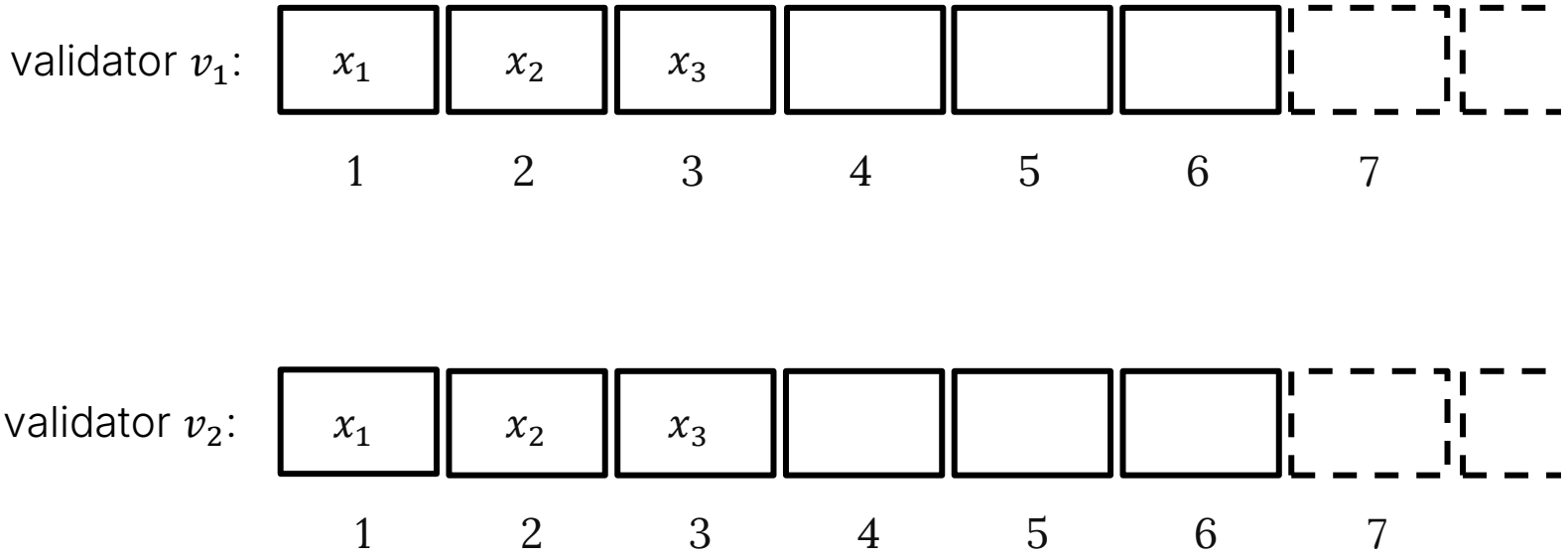

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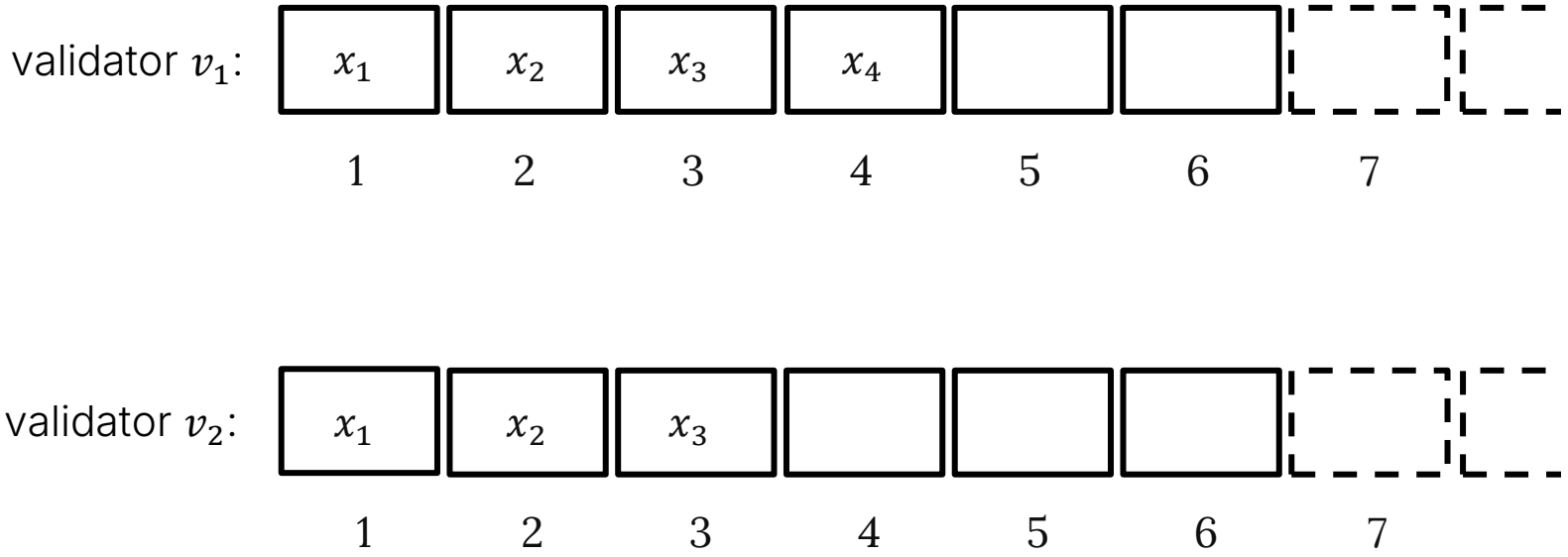

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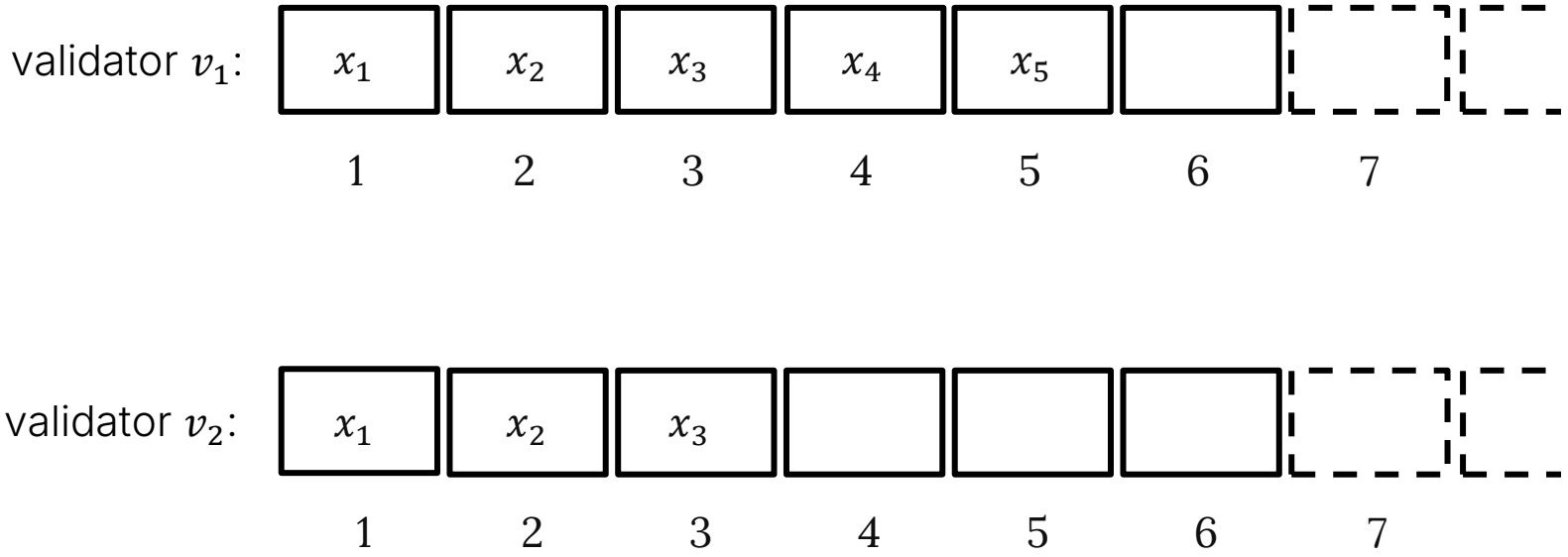

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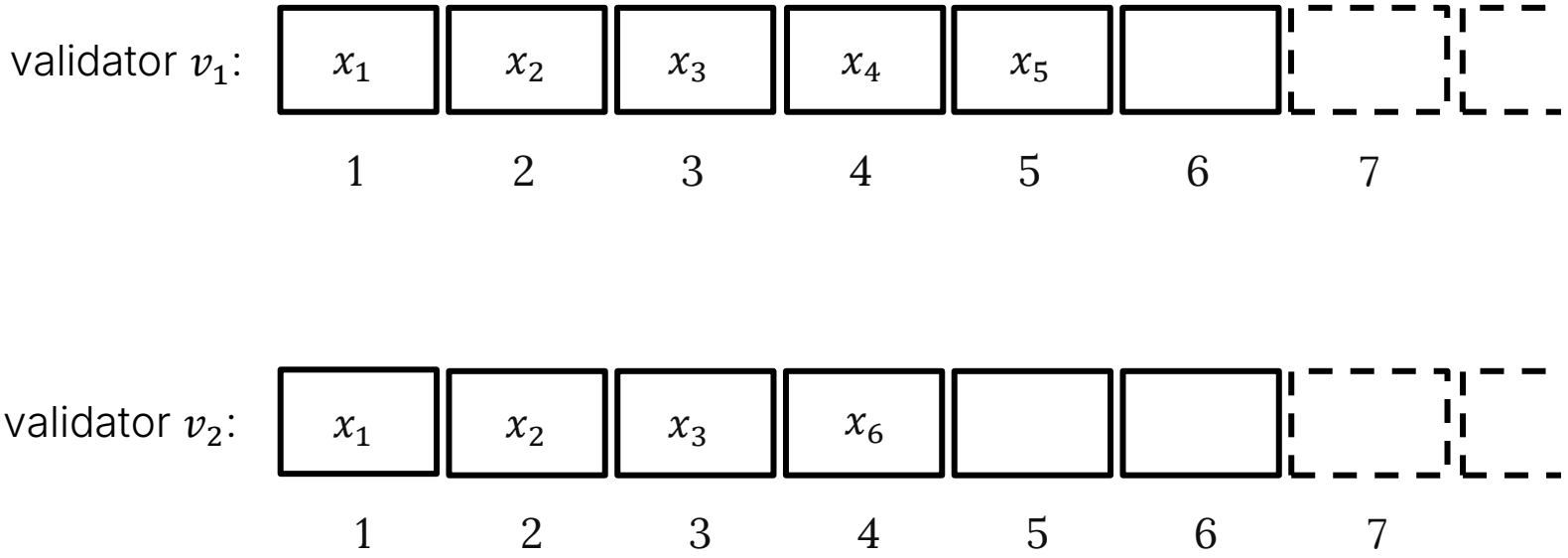

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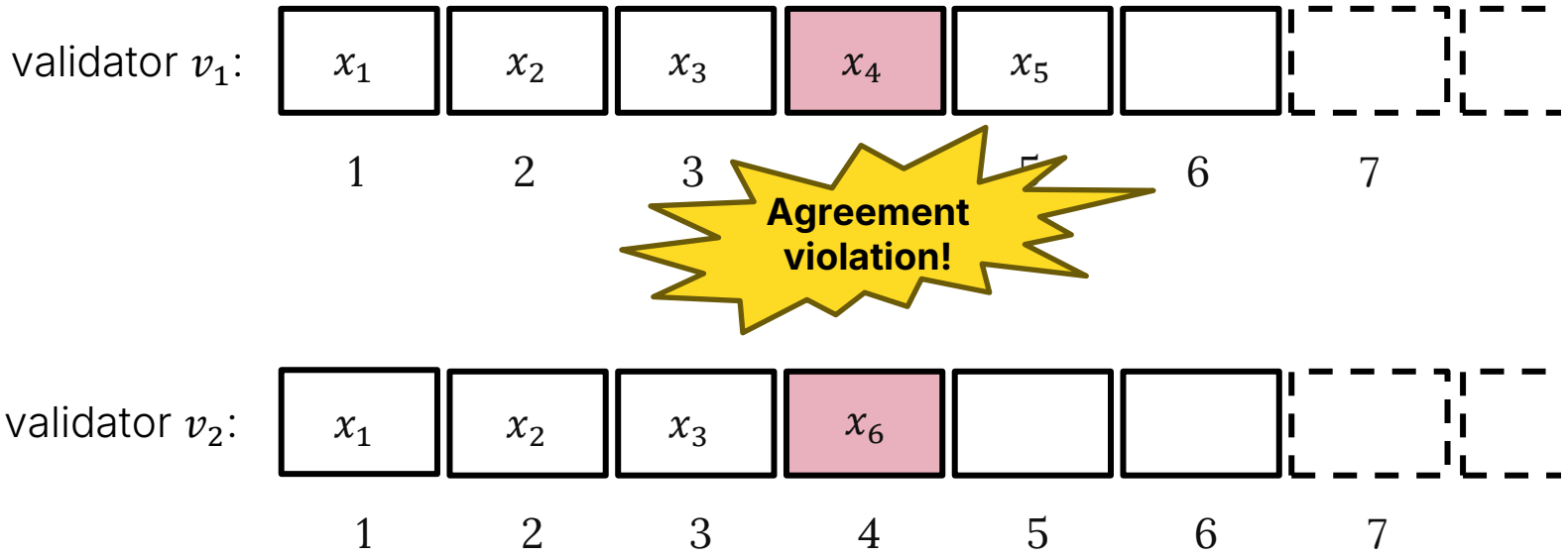
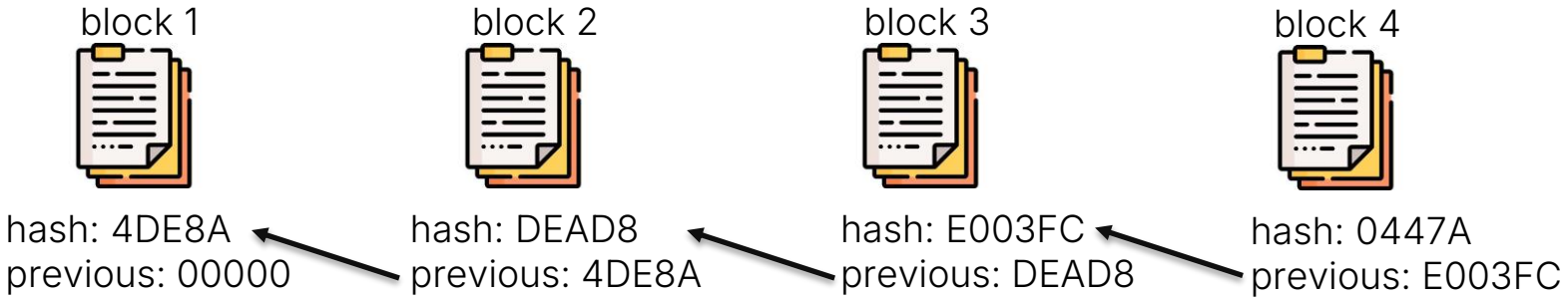


# With Total-Order Broadcast (TOB), we can implement blockchains



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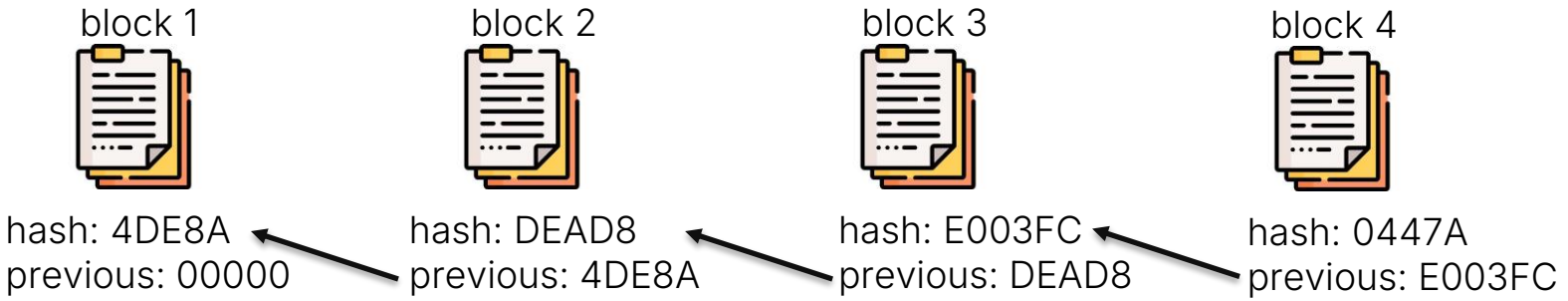

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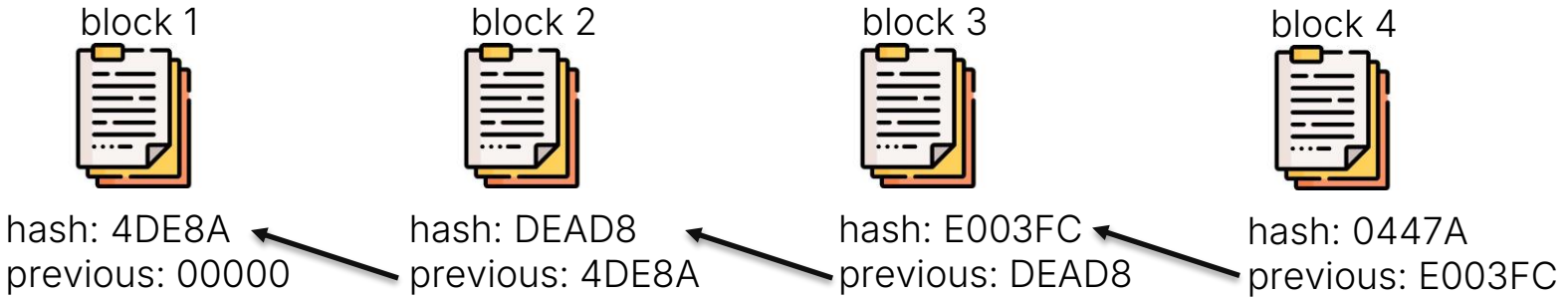

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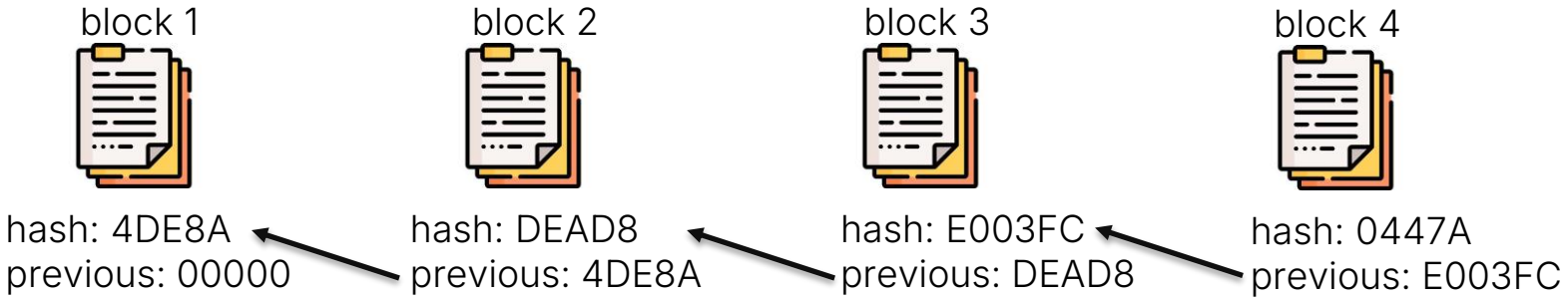

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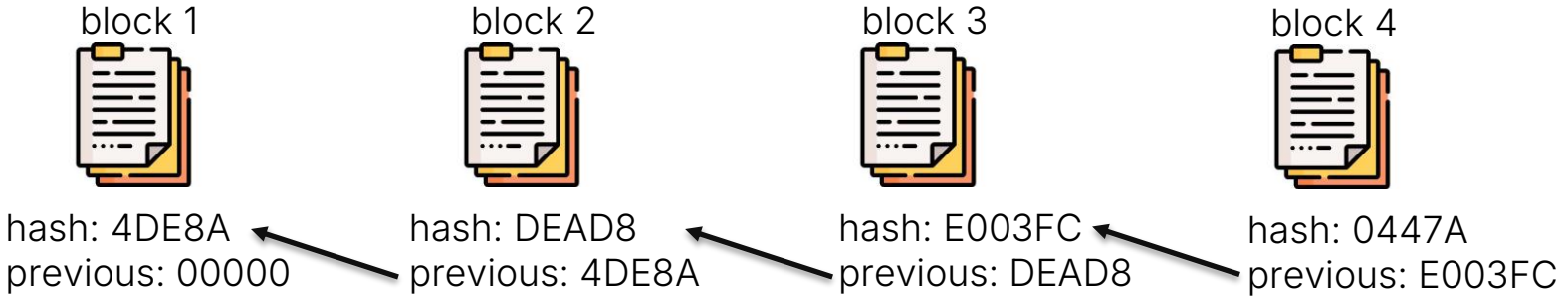
- The system inherits the fault tolerance of the TOB protocol



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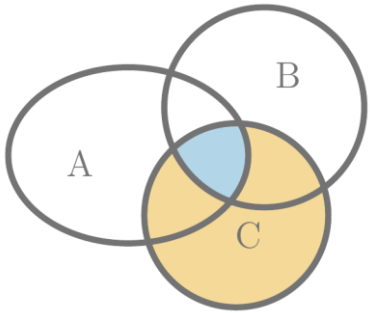


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Example:
3 out of 4

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In PoS we have weighted validators and any set of collective weight > 2/3 is a quorum

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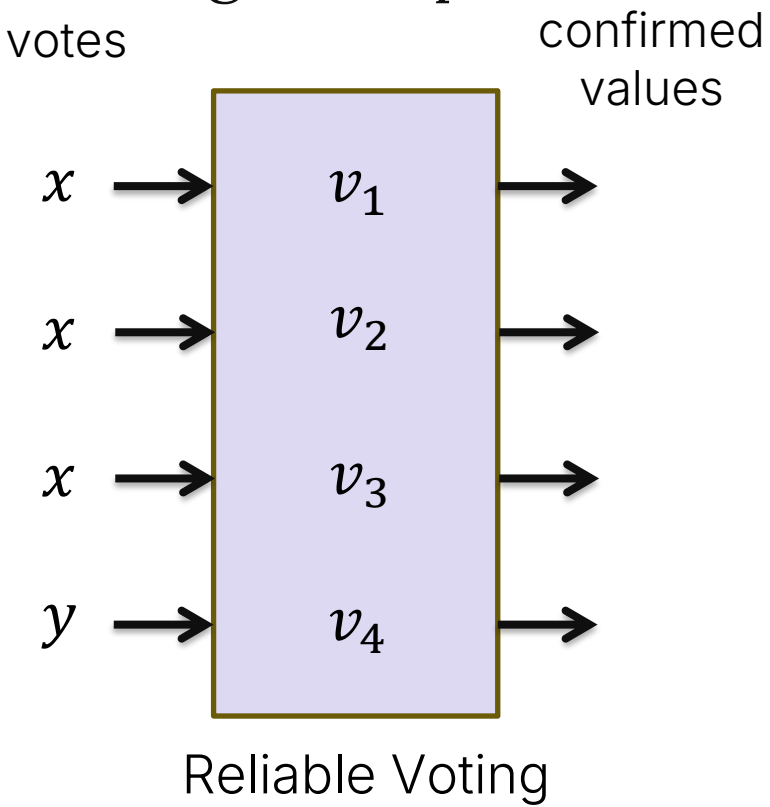
Notes*:*

- Reliable Voting is allowed to get stuck
- This is like Reliable Broadcast but without a broadcaster

# Reliable Voting: examples



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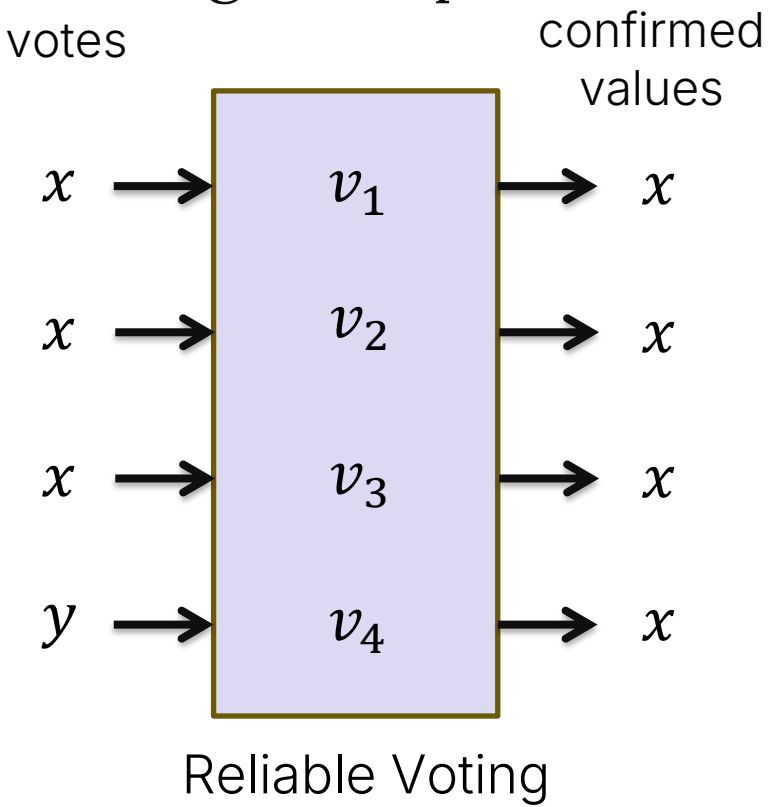


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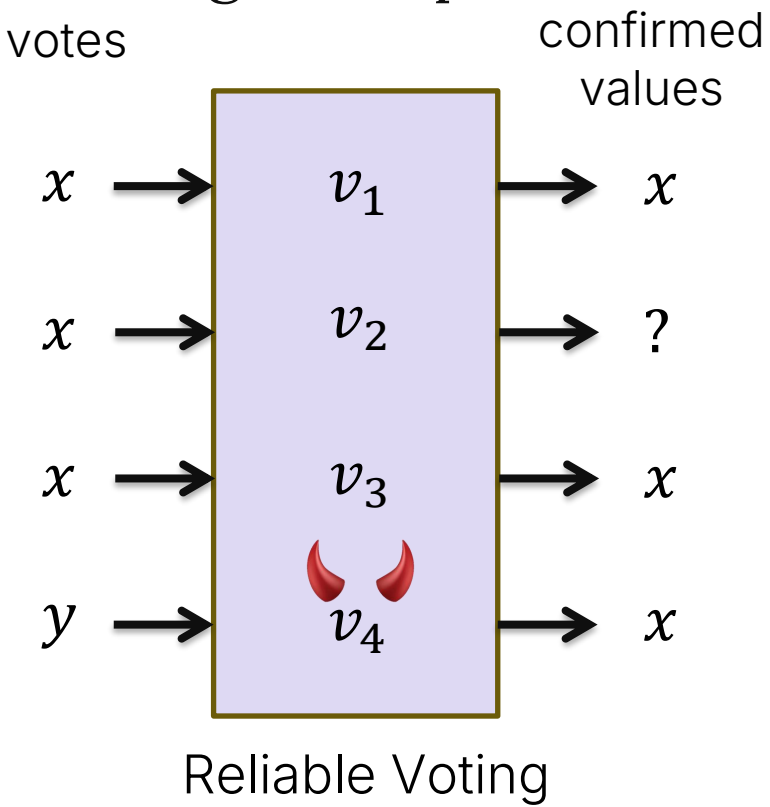

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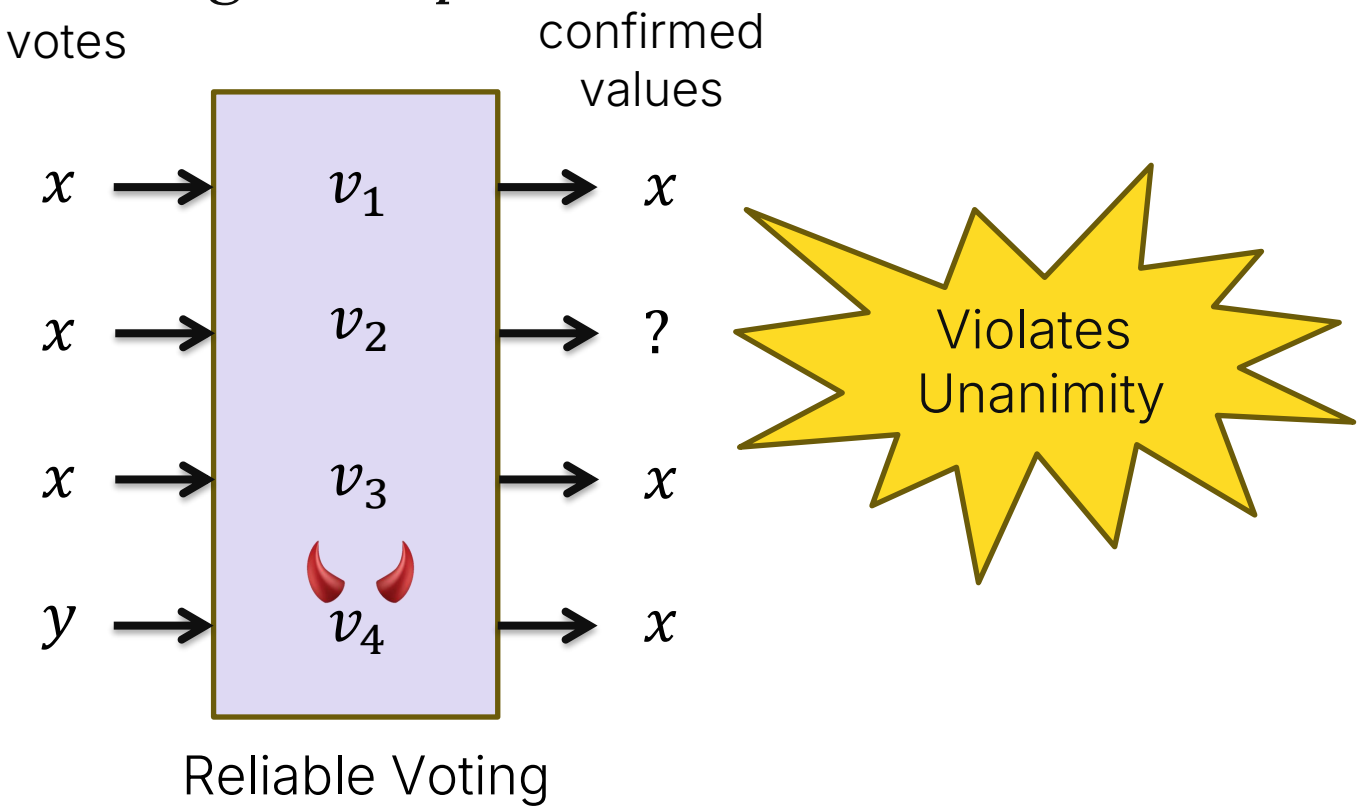

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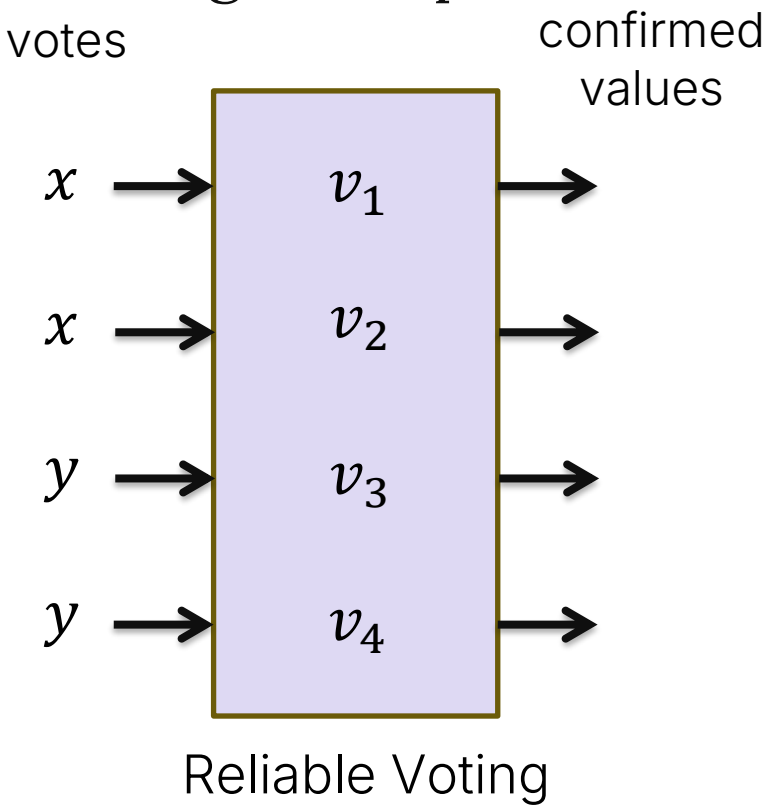

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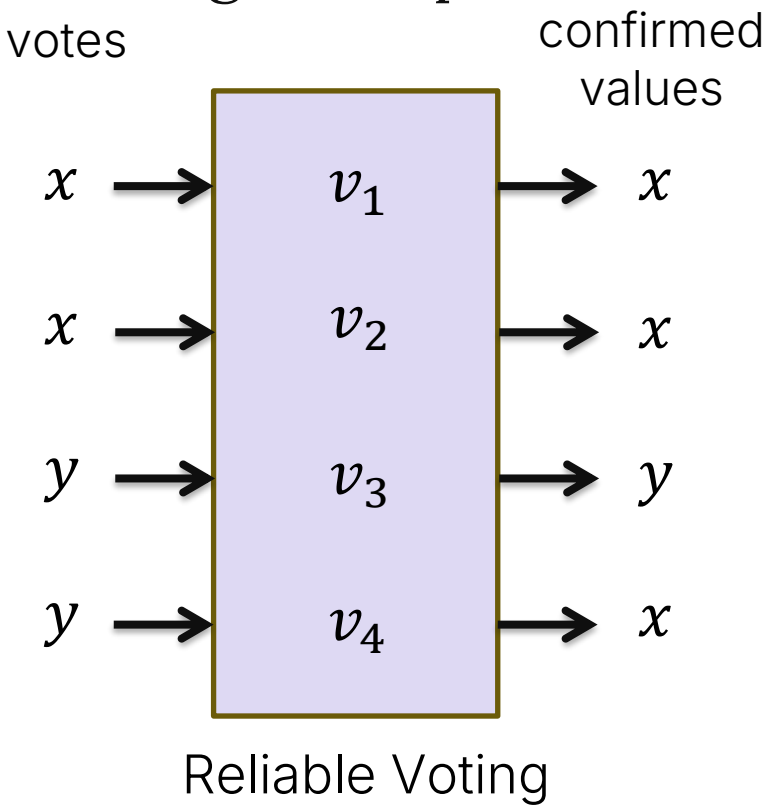

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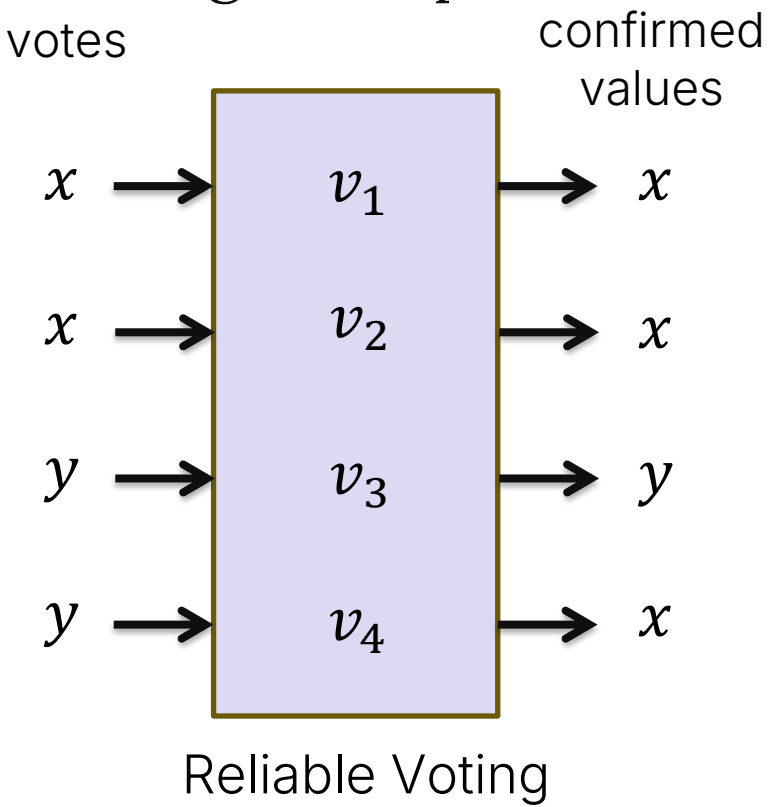


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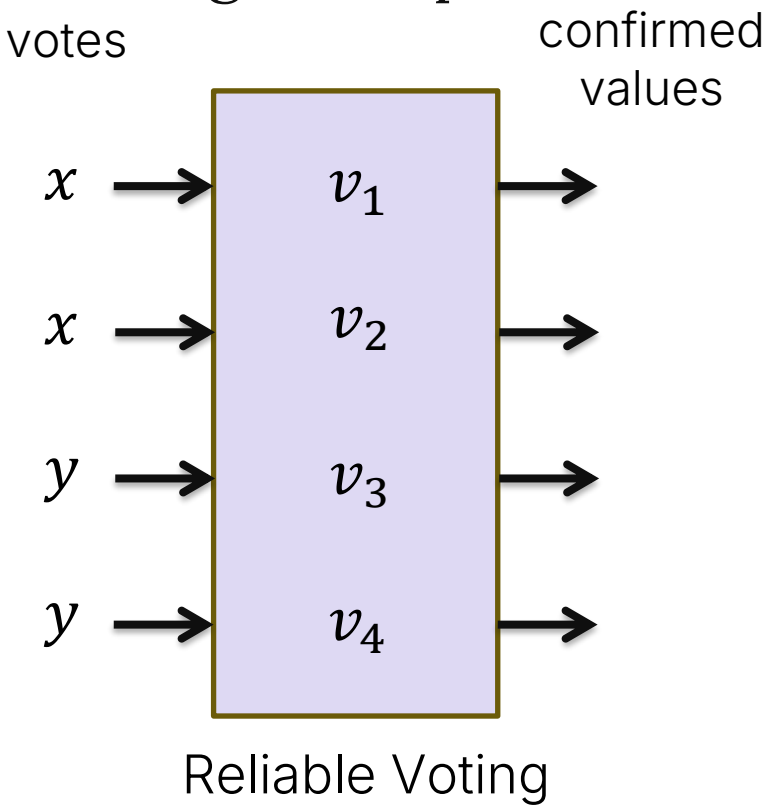

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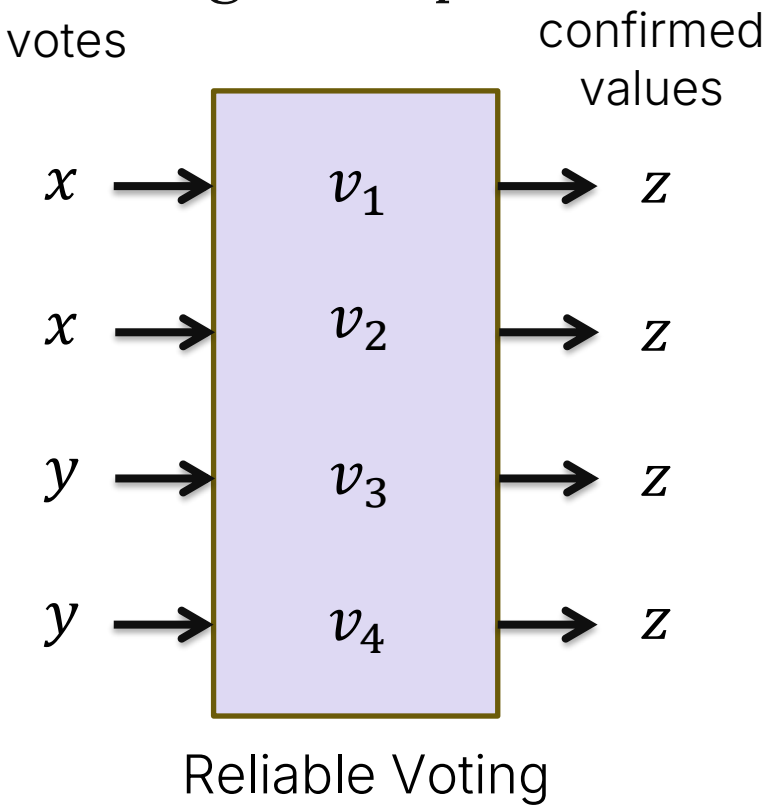

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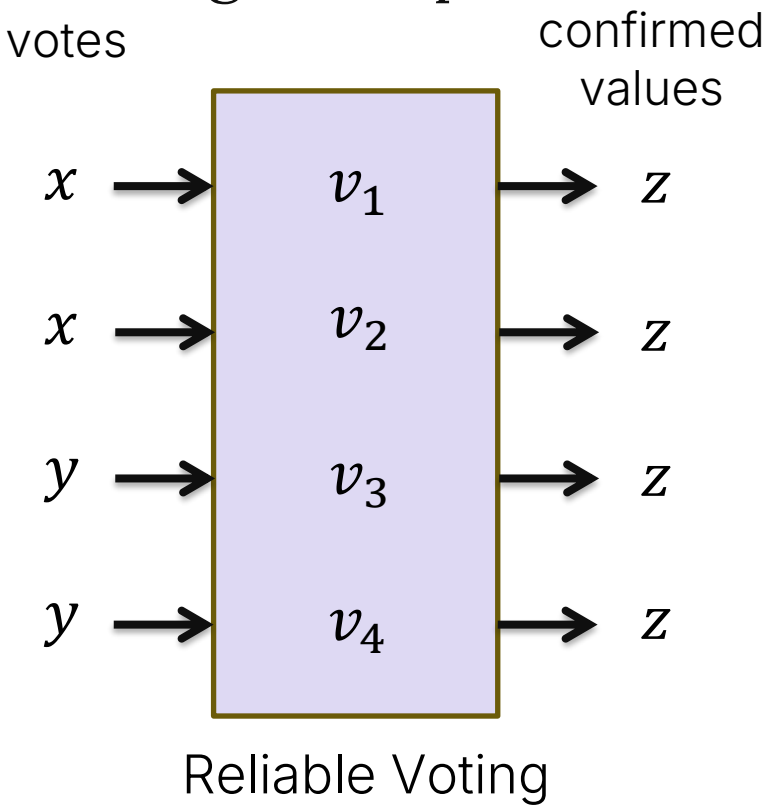


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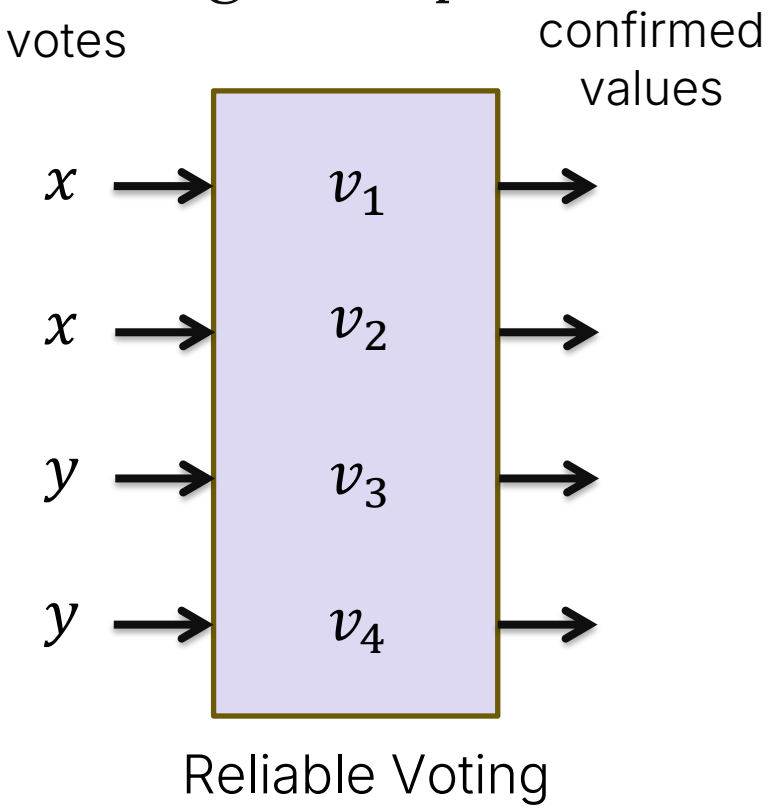

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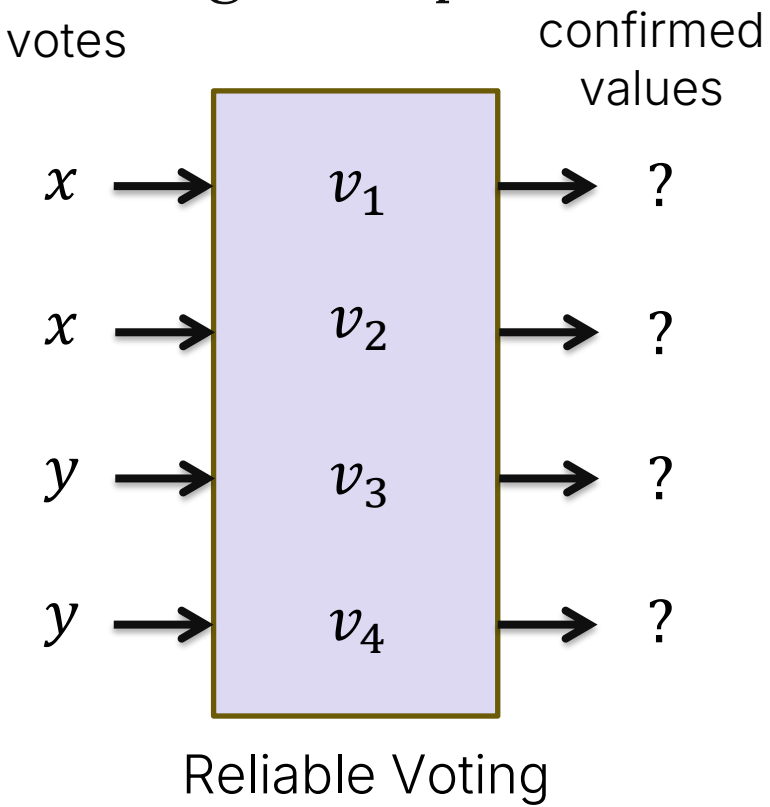

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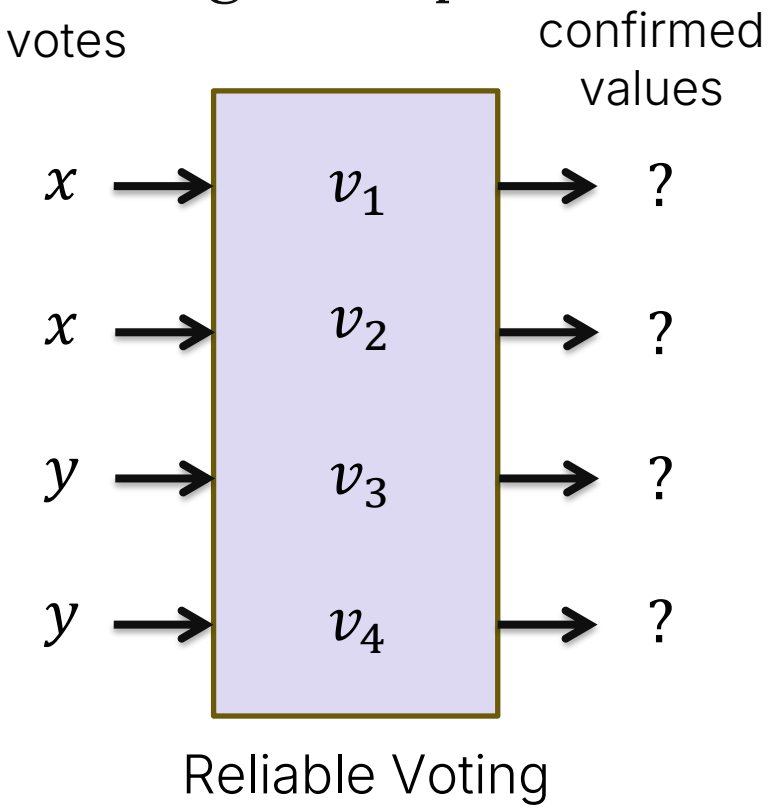


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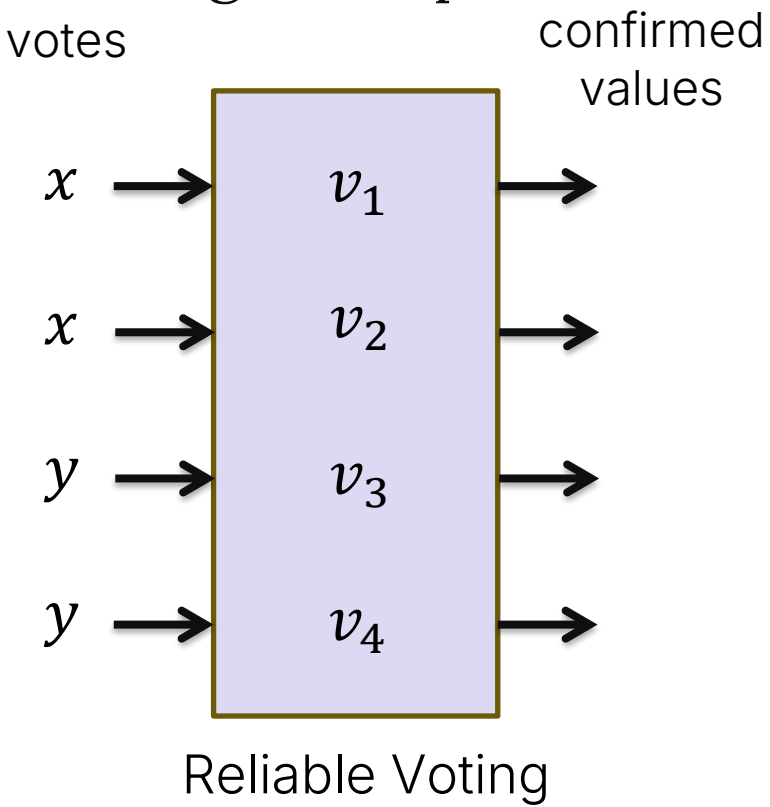

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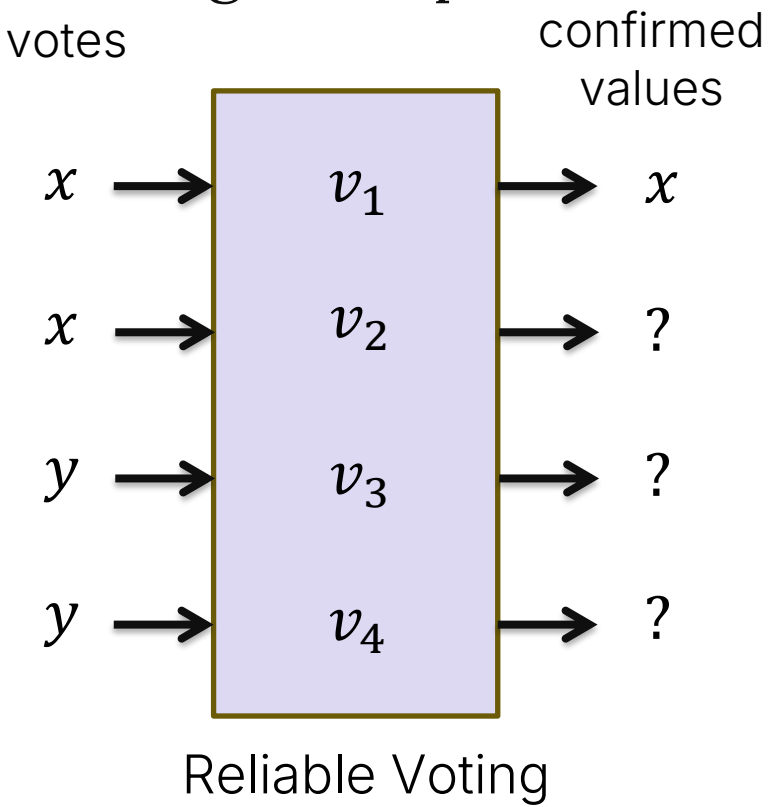

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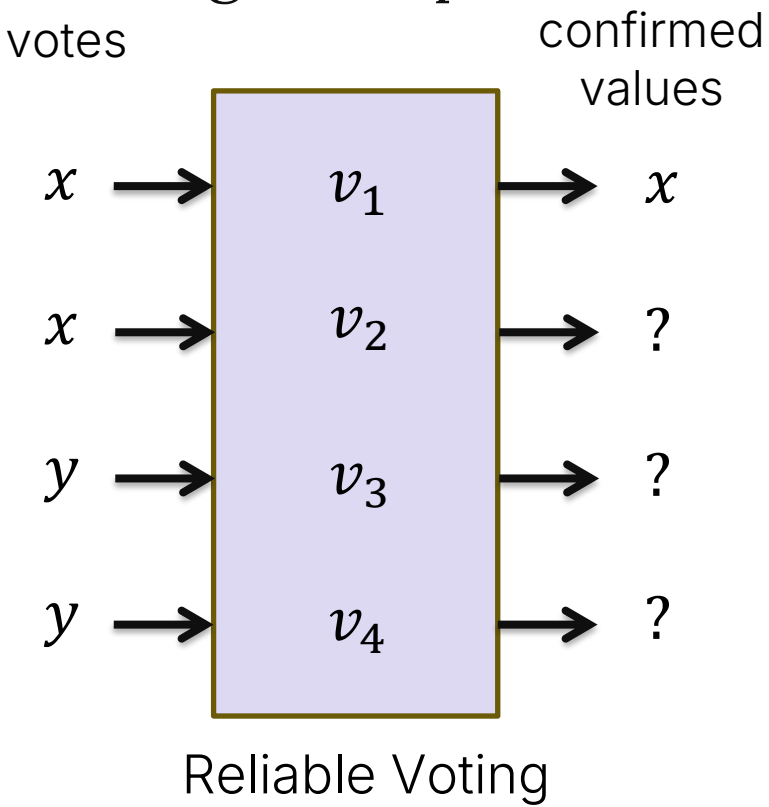


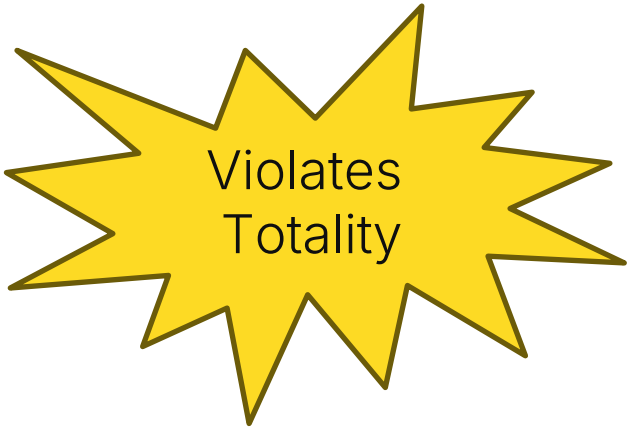

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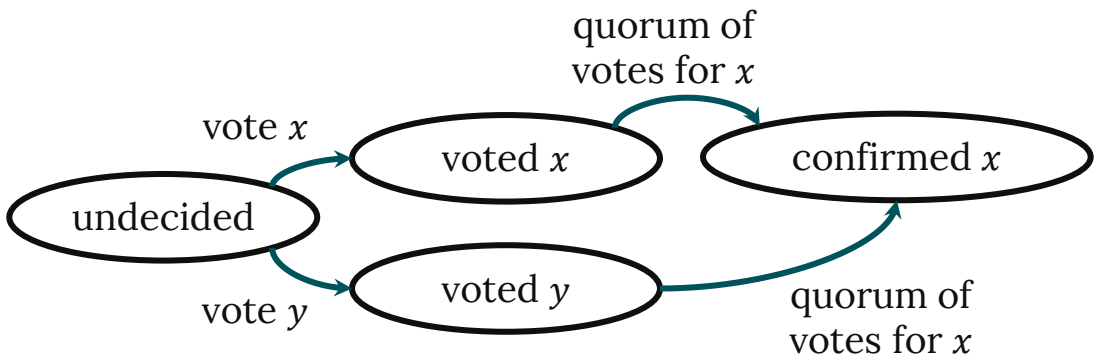

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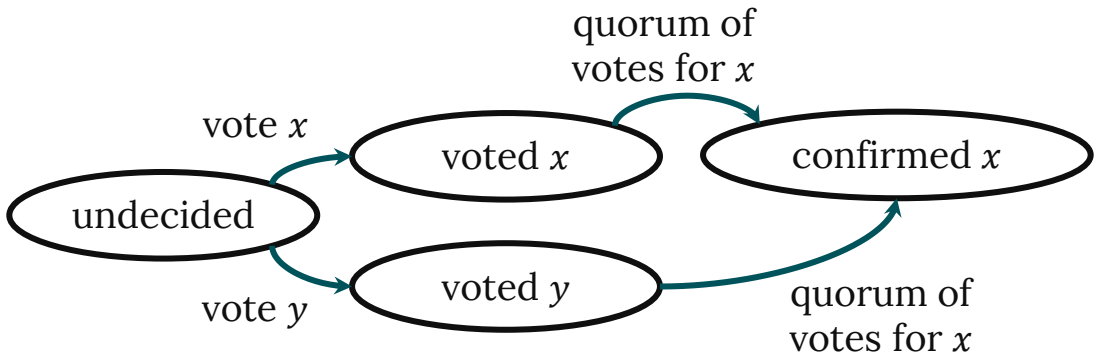
- Quorum Intersection ⇒ Agreement
- Agreement + Quorum availability ⇒ Unanimity + Totality
- Quorum intersection + Quorum availability ⇒ Validity



# From Reliable Voting to TOB with Simplex

Simplex is a popular and simple blockchain consensus algorithm

- Chan and Pass, ***Simplex consensus: A simple and fast consensus protocol***, TCC 2023
- Shoup, ***Sing a song of Simplex***, DISC 2024

We will see how we can phrase Simplex in terms of Reliable Voting + Leader Election, which then makes it easy to port Simplex to the FBA model

# Roadmap

- ✓ Intro: the problem of issuer-enforced finality
- ✓ Background: Partial Synchrony, Total-Order Broadcast, BFT quorum systems, Reliable Voting
- ➢ Quorums in Federated Byzantine Agreement systems
- • Reliable Voting in FBA systems
- • Total-Order Broadcast by porting Simplex to FBA

# In FBA, validators declare local, unilateral agreement requirements

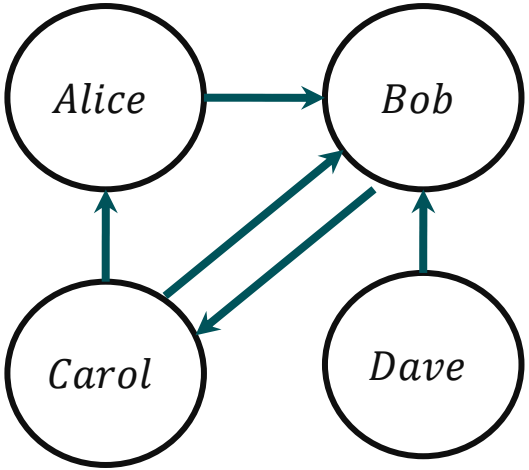
Example

Alice requires agreement from Bob

Bob requires agreement from Carol

Carol requires agreement from Alice and Bob

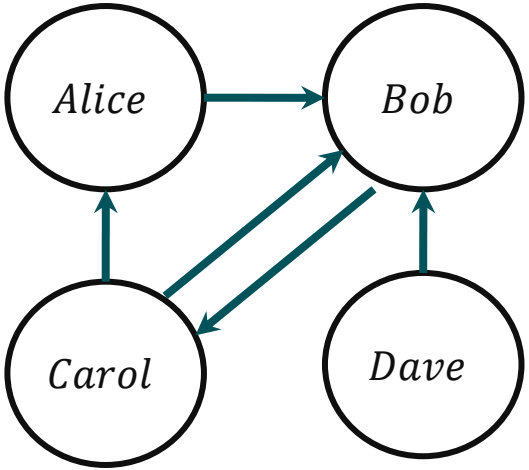
Dave requires agreement from Bob




"Alice → Bob" means Alice requires agreement from Bob

# Quorums emerge from the local agreement requirements of each validator

We call the sets that can make a decision together *quorums*



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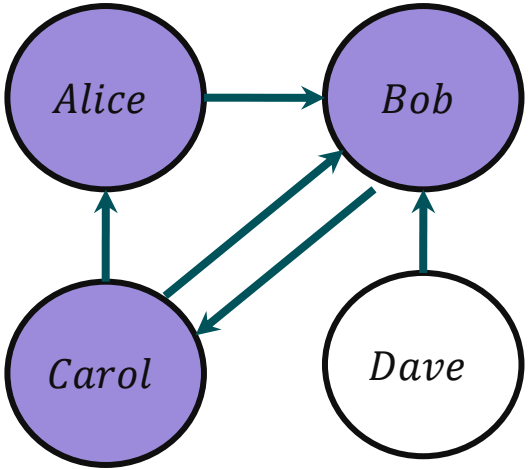


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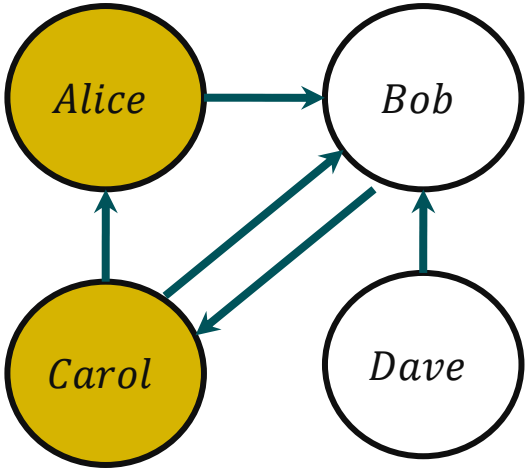


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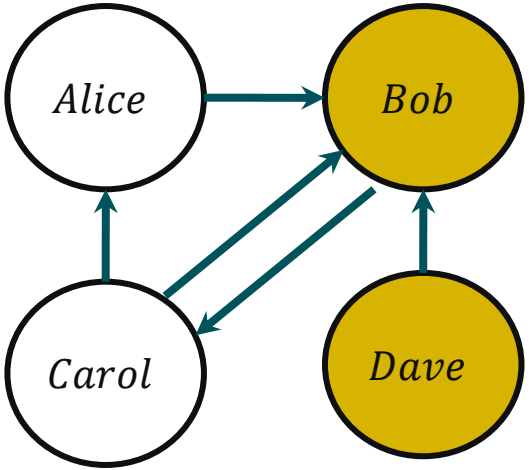


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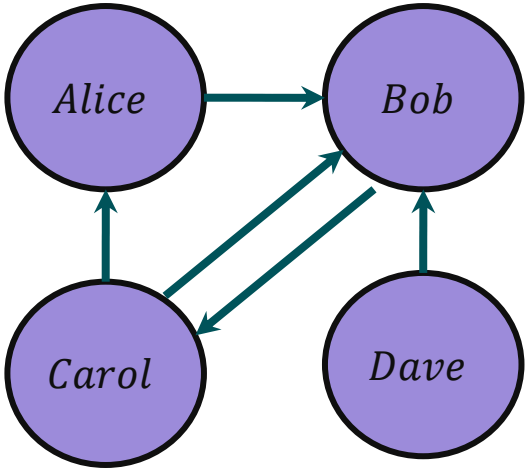


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# For fault-tolerance, we allow specifying multiple alternative agreement requirements, called quorum slices

Every validator $v$ picks a set of **quorum slices** (**slices** for short)
$\mathbf{S}_v = \{S_1, S_2, \ldots, S_N\}$ where each slice is a set of validators

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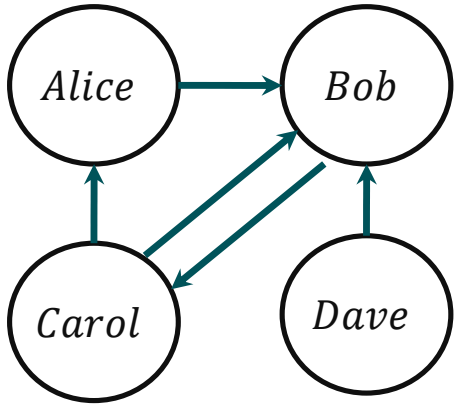
$$\boldsymbol{S}_{Alice} = \{\{Bob\}\}$$

$$\mathbf{S}_{Bob} = \{\{Carol\}\}$$

$$\boldsymbol{S}_{Carol} = \{\{Alice, Bob\}\}$$

$$\boldsymbol{S}_{Dave} = \{\{Bob\}\}$$



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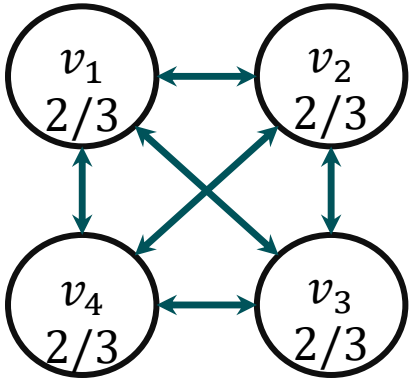
$$\mathbf{S}_{v_i} = \{S \subseteq \boldsymbol{\mathcal{V}} \setminus \{v_i\}. |S| = 2\}$$

e.g. $\boldsymbol{S}_{v_1} = \{\{v_2, v_3\}, \{v_3, v_4\}, \{v_2, v_4\}\}$




2/3 means requires agreement from 2 out of the 3 outgoing edges

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$$\boldsymbol{S}_{Alice} = \{\{Bob\}\}$$
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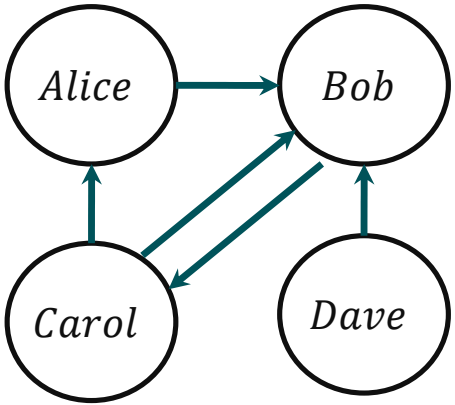
$$\boldsymbol{S}_{Carol} = \{\{Alice, Bob\}\}$$
$$\boldsymbol{S}_{Dave} = \{\{Bob\}\}$$



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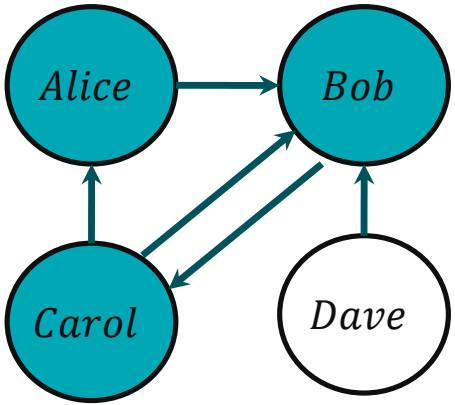


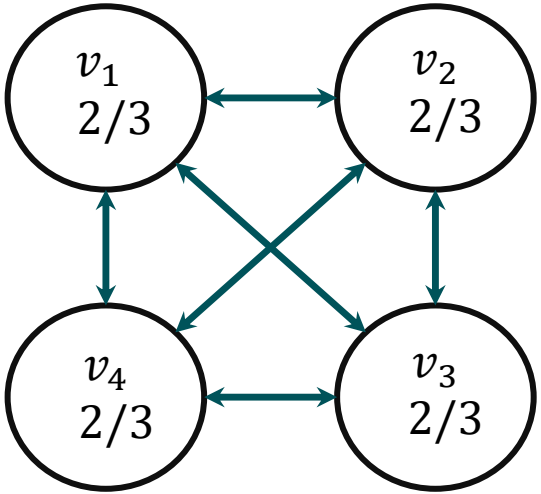

$\{Alice, Bob, Carol\}$ is the minimal quorum

$\{Alice, Bob, Carol, Dave\}$ is also a quorum

# Example 2

Take $\mathcal{V} = \{v_1, v_2, v_3, v_4\}$, each requiring agreement from 2 others:

$$\mathbf{S}_{v_i} = \{S \subseteq \boldsymbol{\mathcal{V}} \setminus \{v_i\}. |S| = 2\}$$

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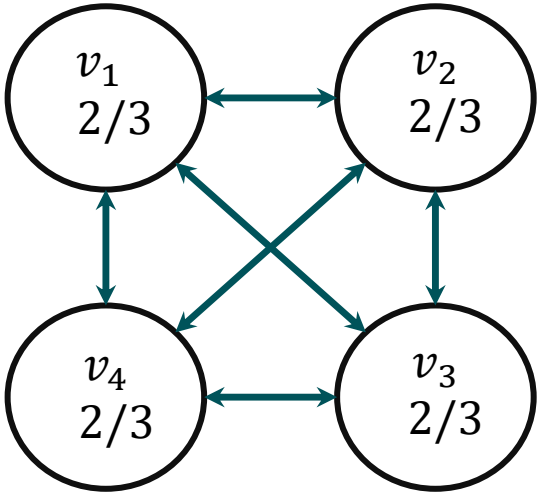


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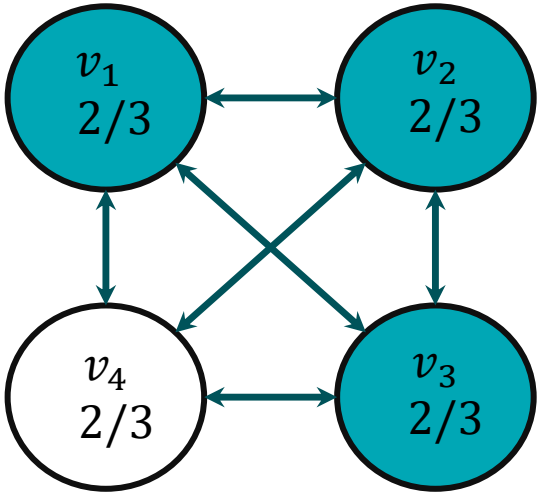


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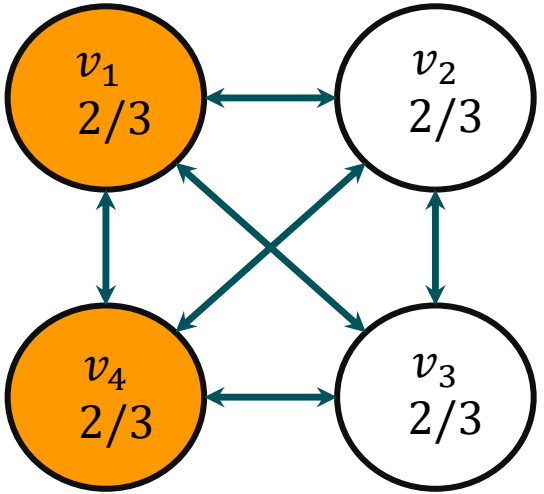


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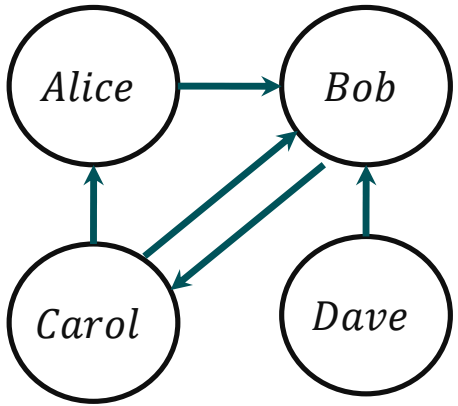
# Quorums are subjective and local

A quorum $Q$ is a ***quorum of*** a validator $v$ when $v \in Q$



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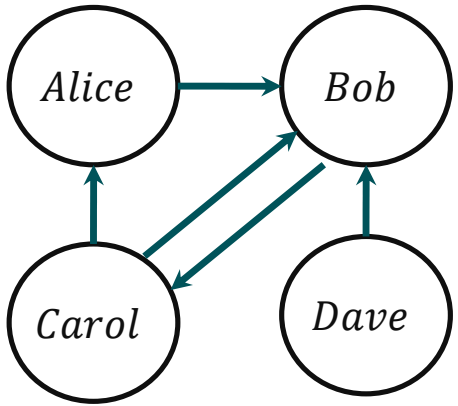

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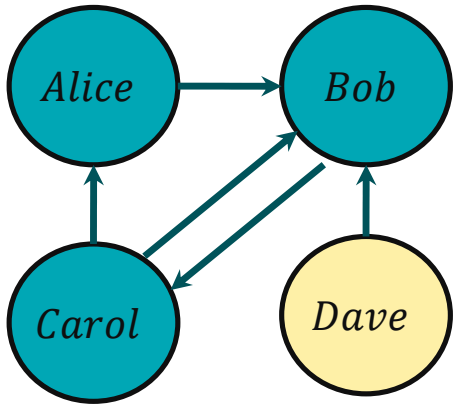

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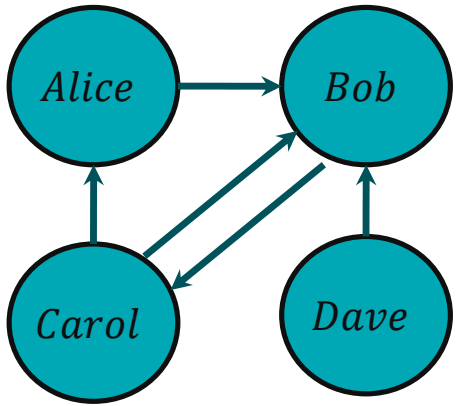

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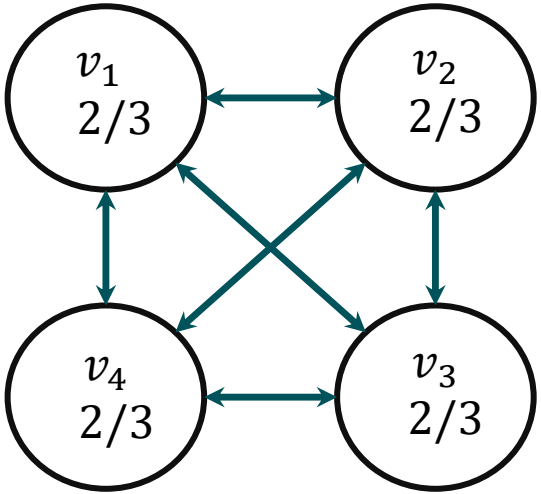


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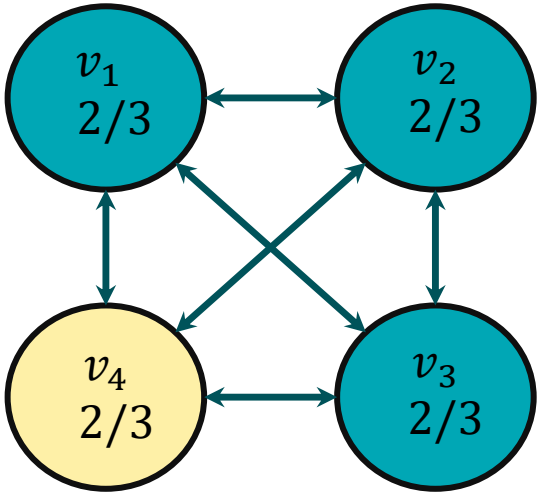
- Not all quorums are quorums of every validator
  - $\{v_1, v_2, v_3\}$ is a quorum but not a quorum of $v_4$

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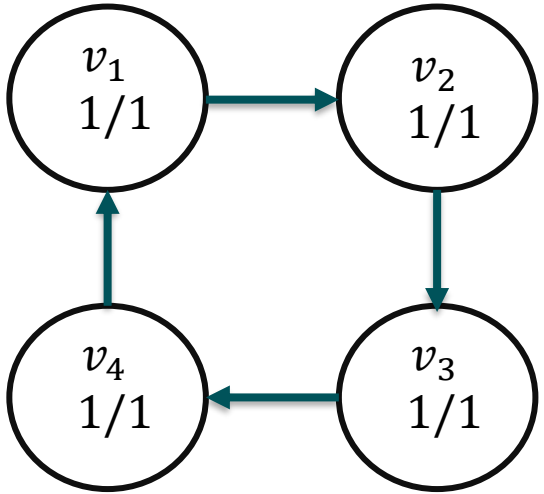
# Example 3

Now each validator has a single singleton slice consisting of the next validator in the ring: $\boldsymbol{S}_{v_i} = \{\{v_{(i\%4)+1}\}\}$



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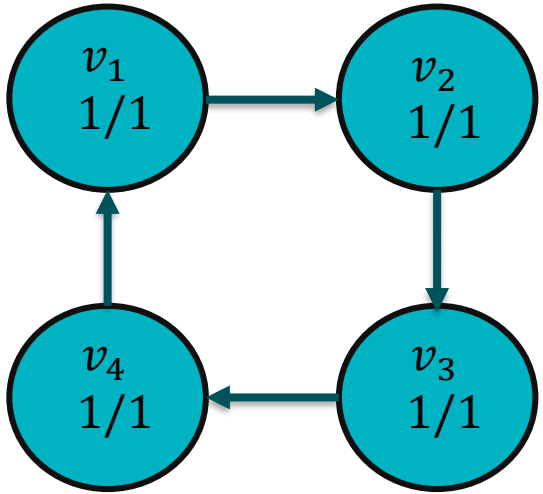
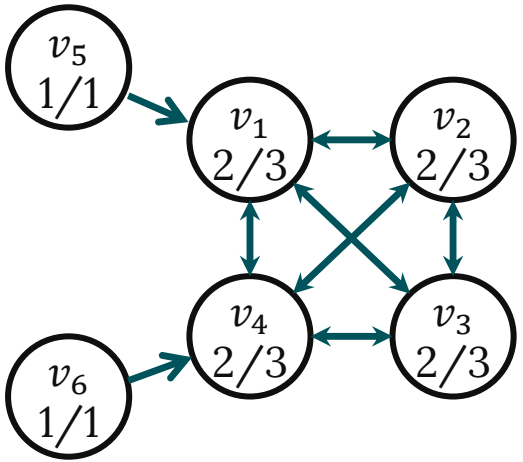
The only quorum is $\boldsymbol{\mathcal{V}}$ itself



# Example 4

We add $v_5$ and $v_6$ with
$S_{v_5} = \{\{v_1\}\}$ and $S_{v_6} = \{\{v_4\}\}$

The minimal quorums are still every 3 out of $\{v_1, v_2, v_3, v_4\}$



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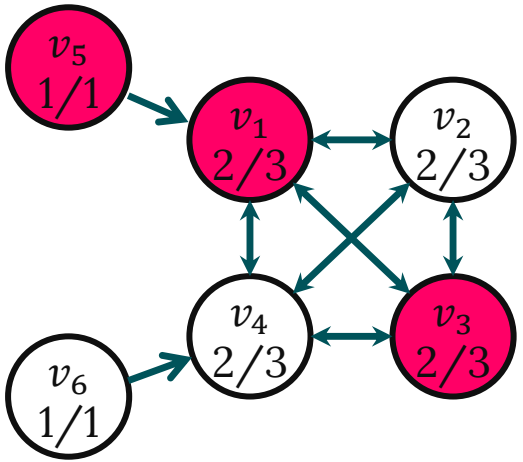

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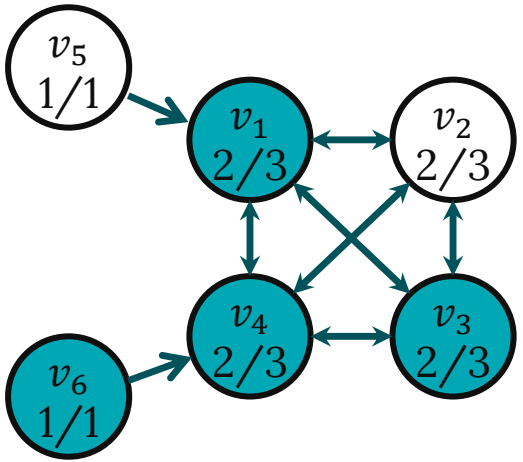

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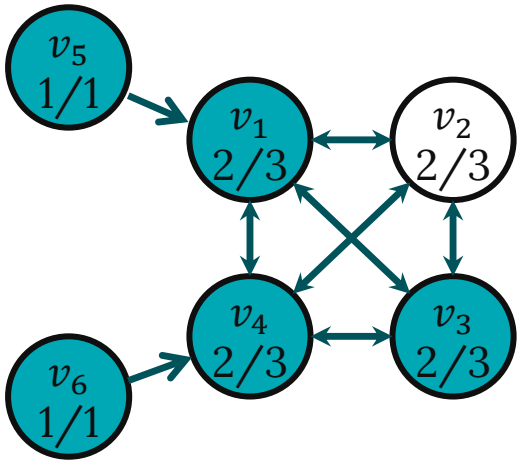

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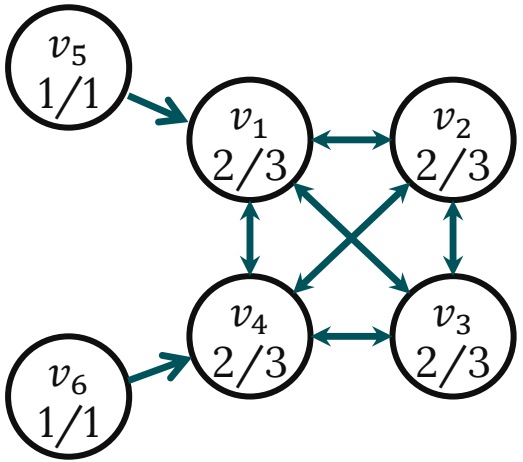
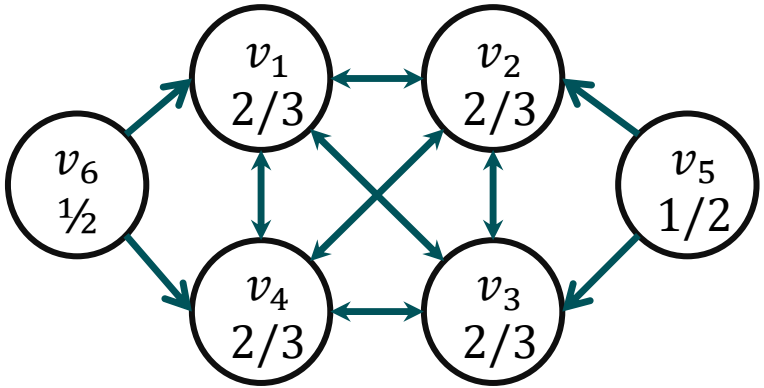



Note $v_5$ and $v_6$ have disjoint slices but all their quorums intersect

# Example 5

Now assume $\boldsymbol{S}_{v_5} = \{\{v_1\}, \{v_4\}\}$ and $\boldsymbol{S}_{v_6} = \{\{v_2\}, \{v_3\}\}$



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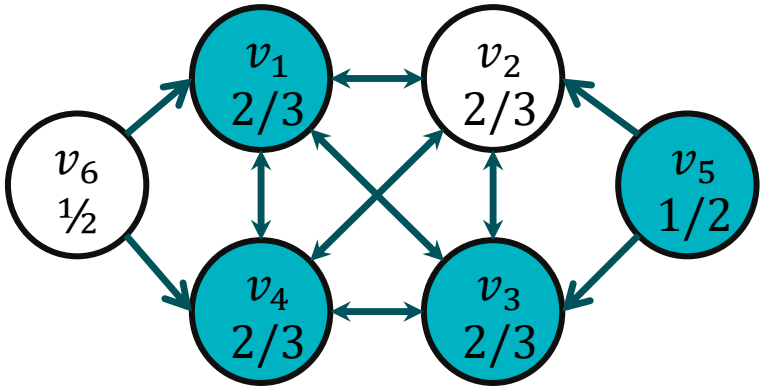

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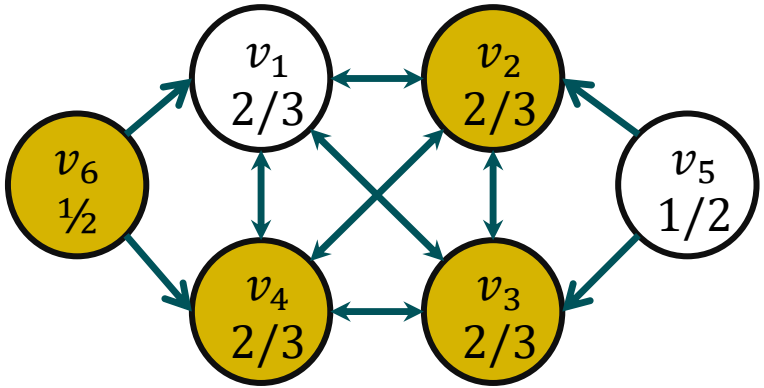

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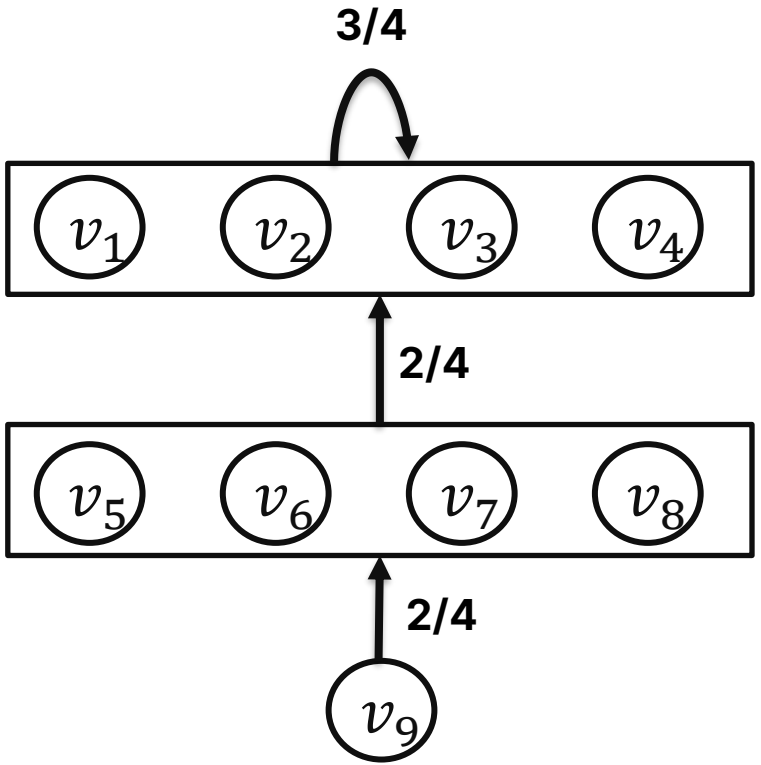
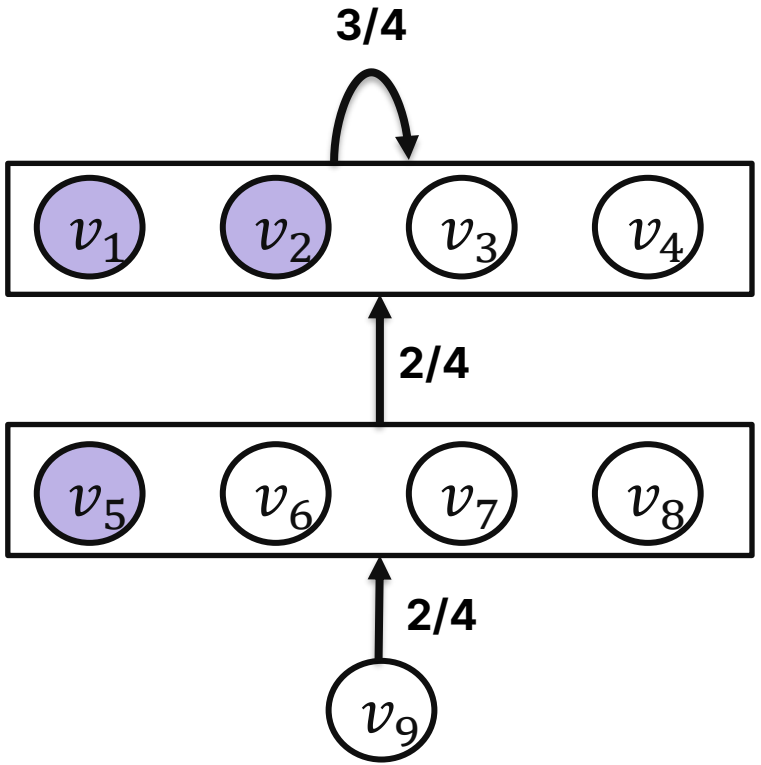


# Example 6

- Is $\{v_5, v_1, v_2\}$ a quorum?



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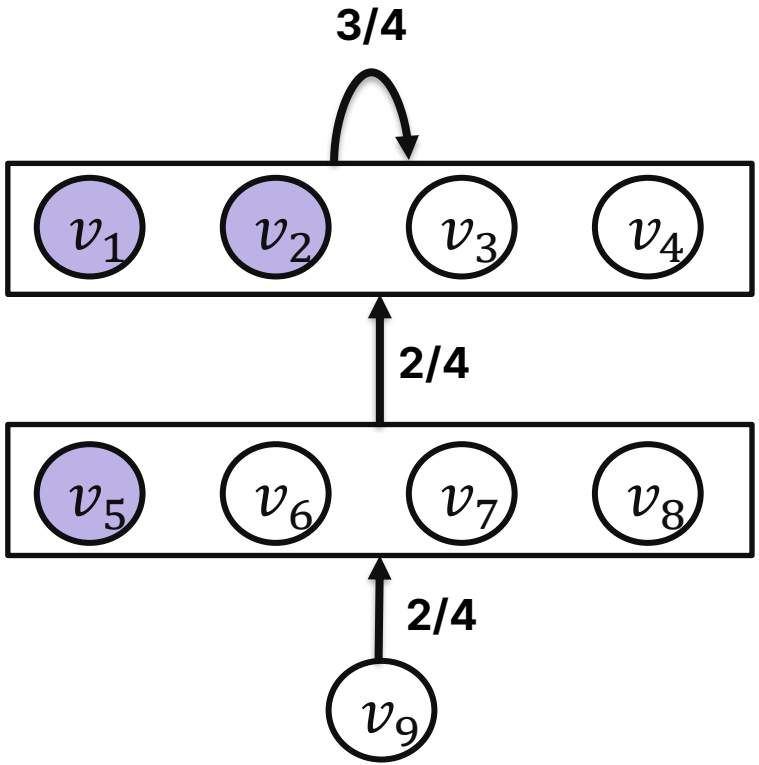

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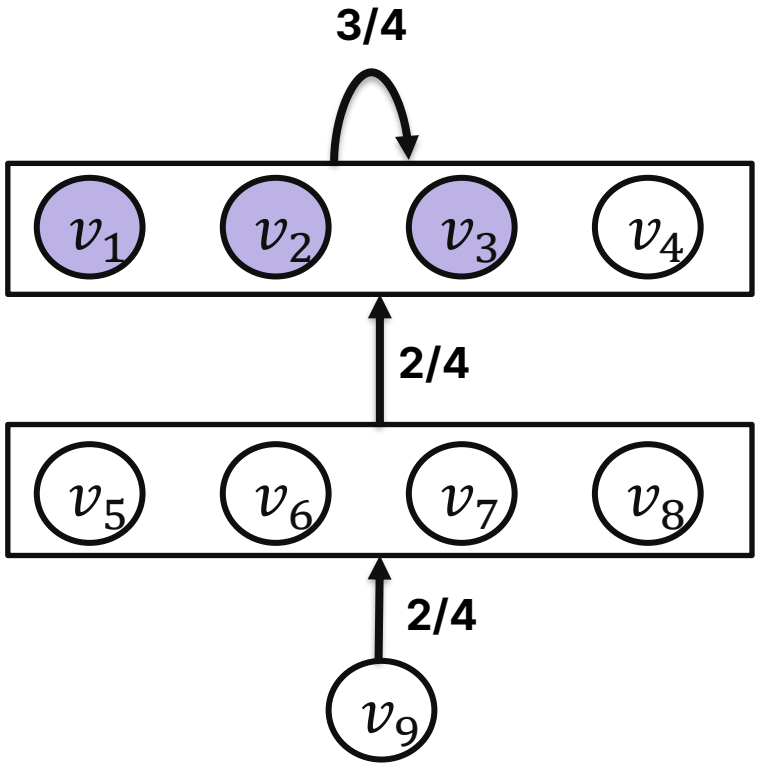

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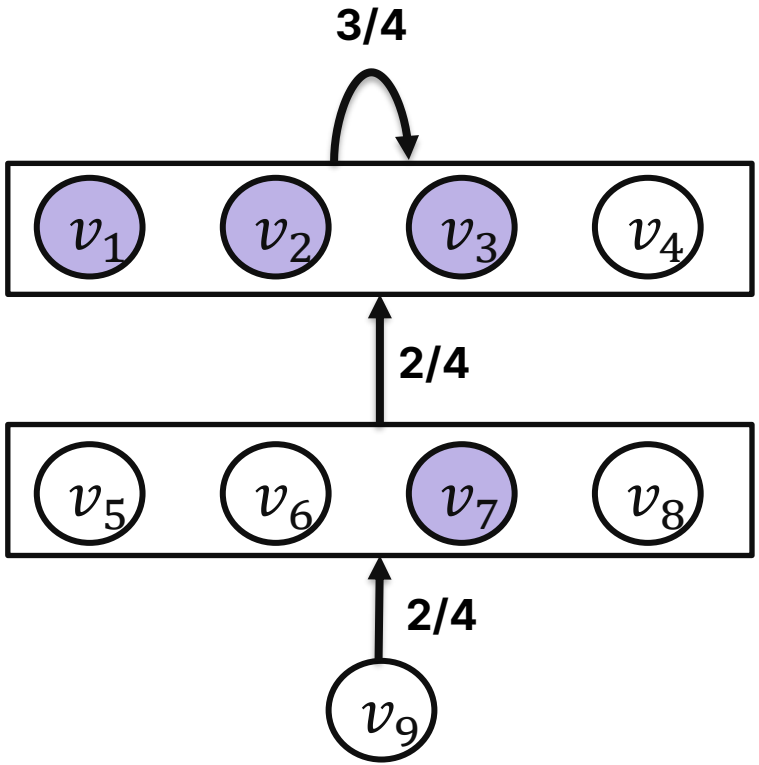
- Is $\{v_1, v_2, v_3, v_7\}$ a quorum?



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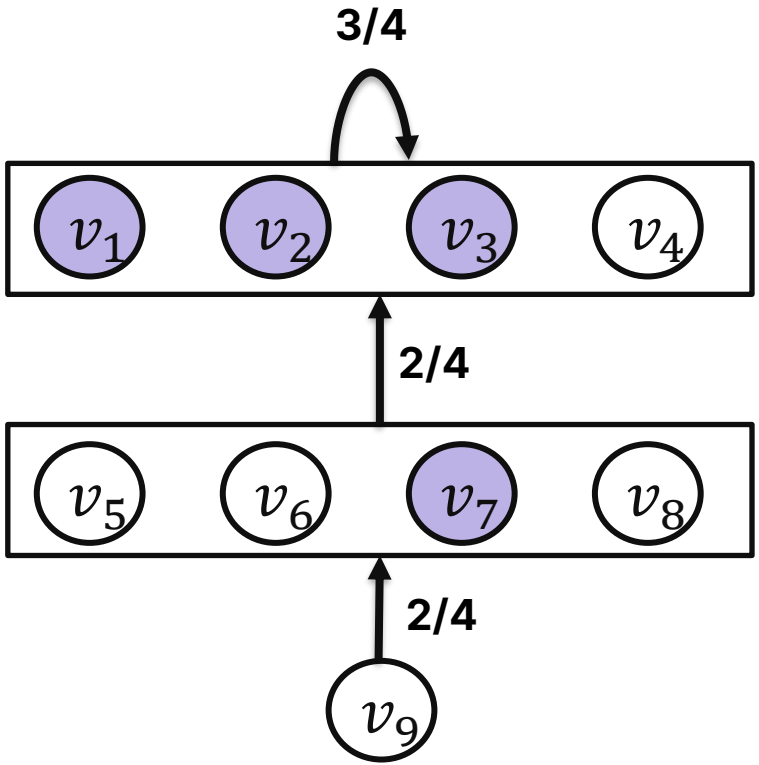

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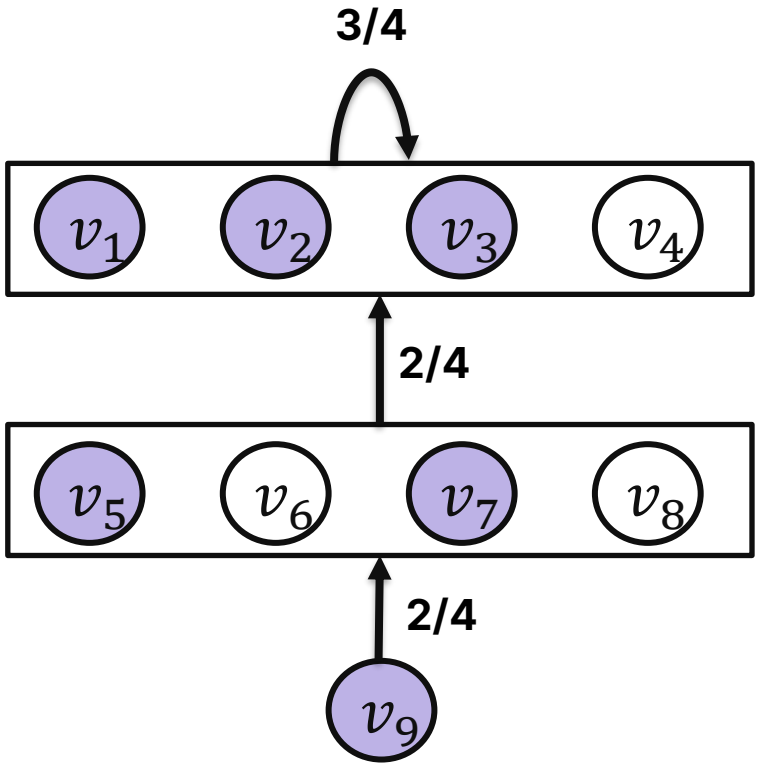
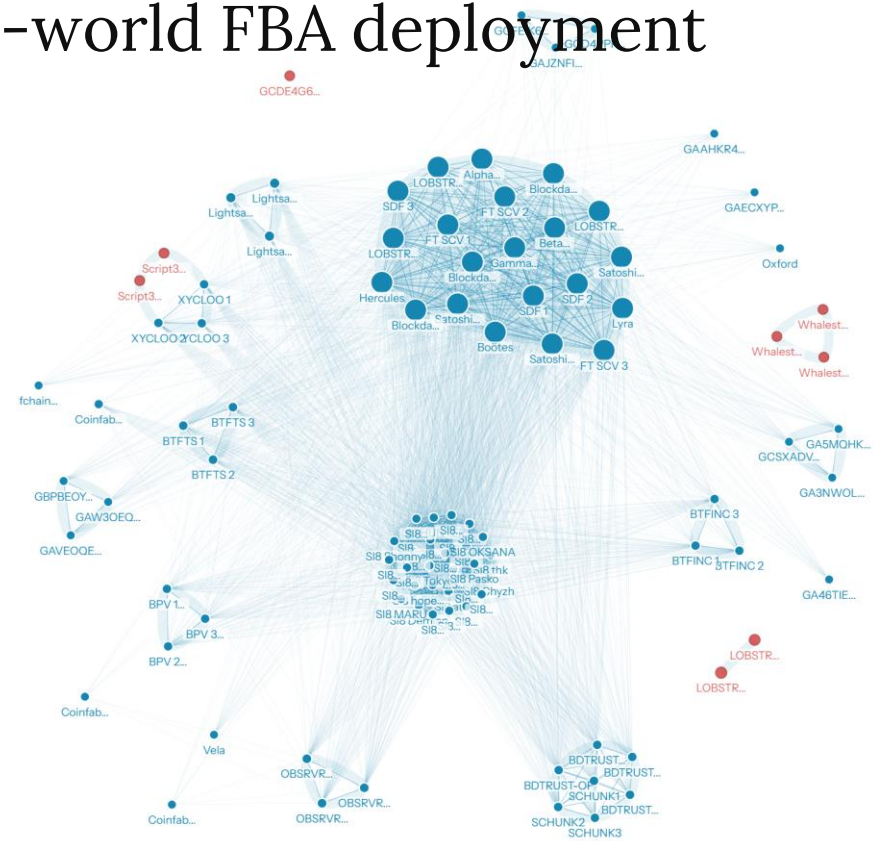
  - Yes
- $\{v_1, v_2, v_3, v_5, v_7, v_8\}$ is a quorum



# The Stellar network is a real-world FBA deployment

Currently 92 validators belonging to 17 organizations.

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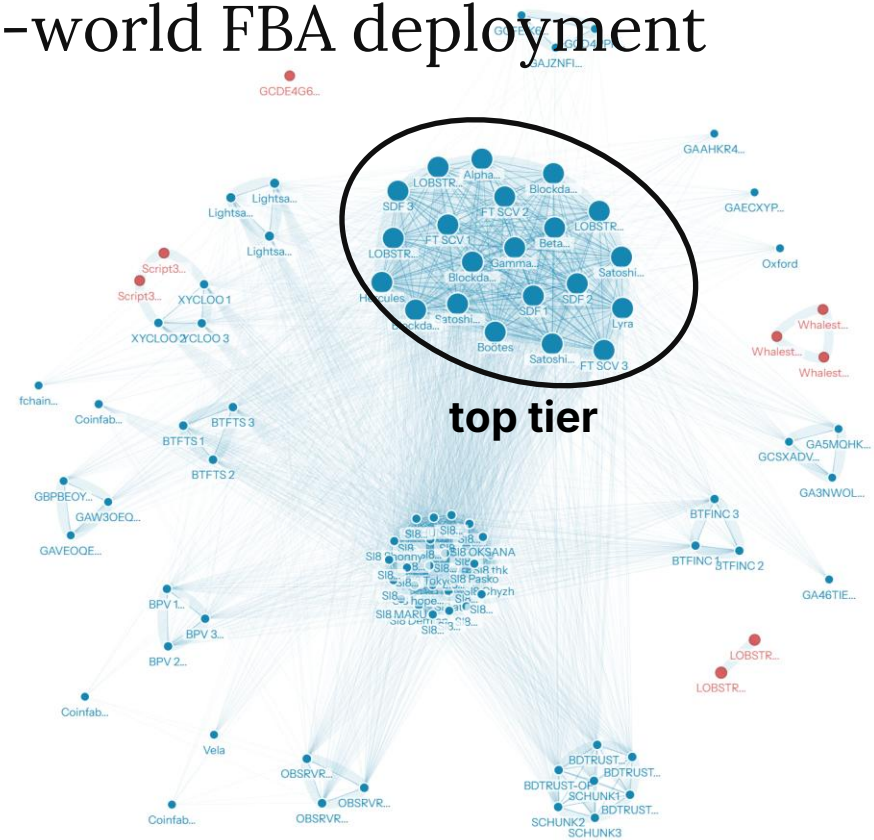


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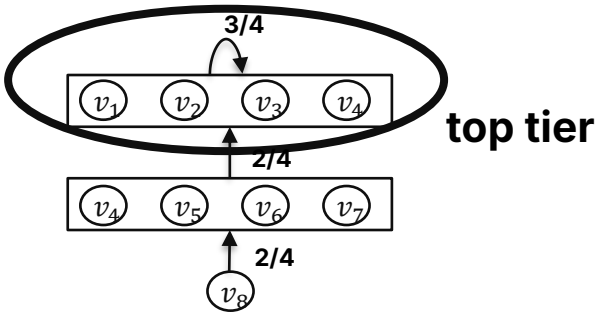
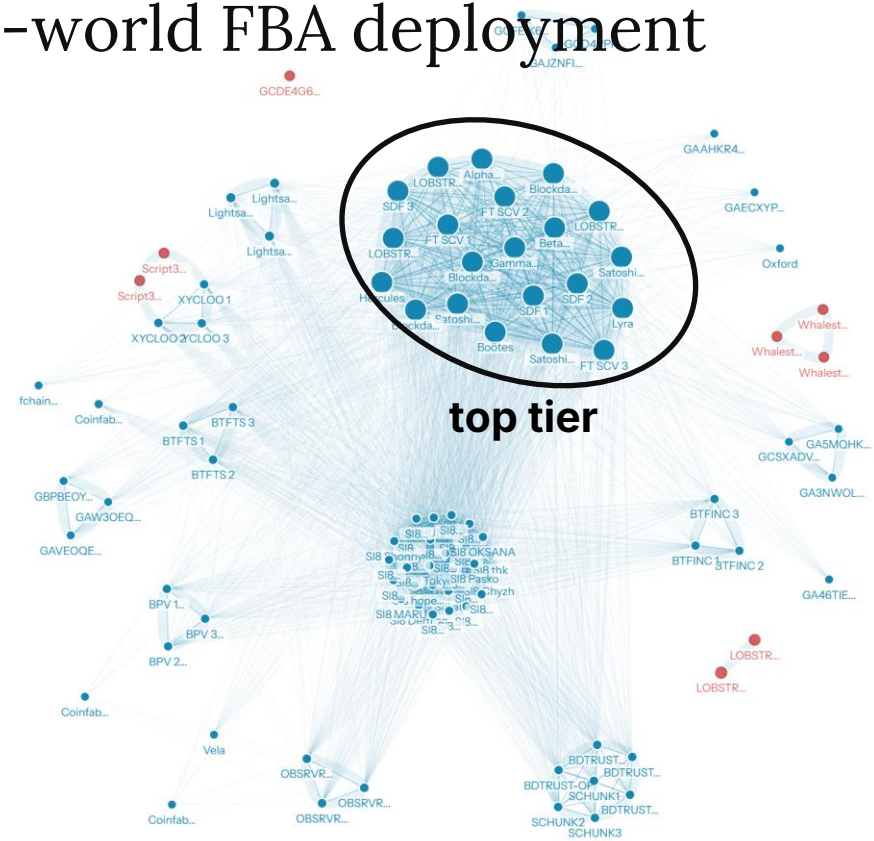



top tier

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# Issuer-enforced finality in the Stellar network and the Internet Hypothesis

- In practice today, few asset issuers run validators (only one major issuer runs validators)...
- Nevertheless, validators have incentives to require agreement with other validators they deem trustworthy to ensure quorum intersection
- The Internet Hypothesis: like the Internet, a global FBA system will be highly connected and fault tolerant
  - Currently, all quorums intersect with some margin (3 organizations)

# Deployment experience

- Deployed in 2015
- For a few years, all validators just configured their quorum slices as ½ of the validators of the Stellar Development Foundation (SDF)
- The SDF pushed the community towards decentralization, but this led to a problem in 2019:
  - Many validators picked quorum slices that were too big
  - A popular monitoring tool underreported validator down-time
  - ➢ Unreliable validators caused the whole system to stop because no quorum was available
  - ➢ Chaotic, manual reconfiguration ensued and the system lost quorum intersection and validators diverged, requiring manual restart to a know good state
- As a result, SDF implemented a slice-generator tool, and monitoring tools improved

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Organizations run multiple validators (typically 3)

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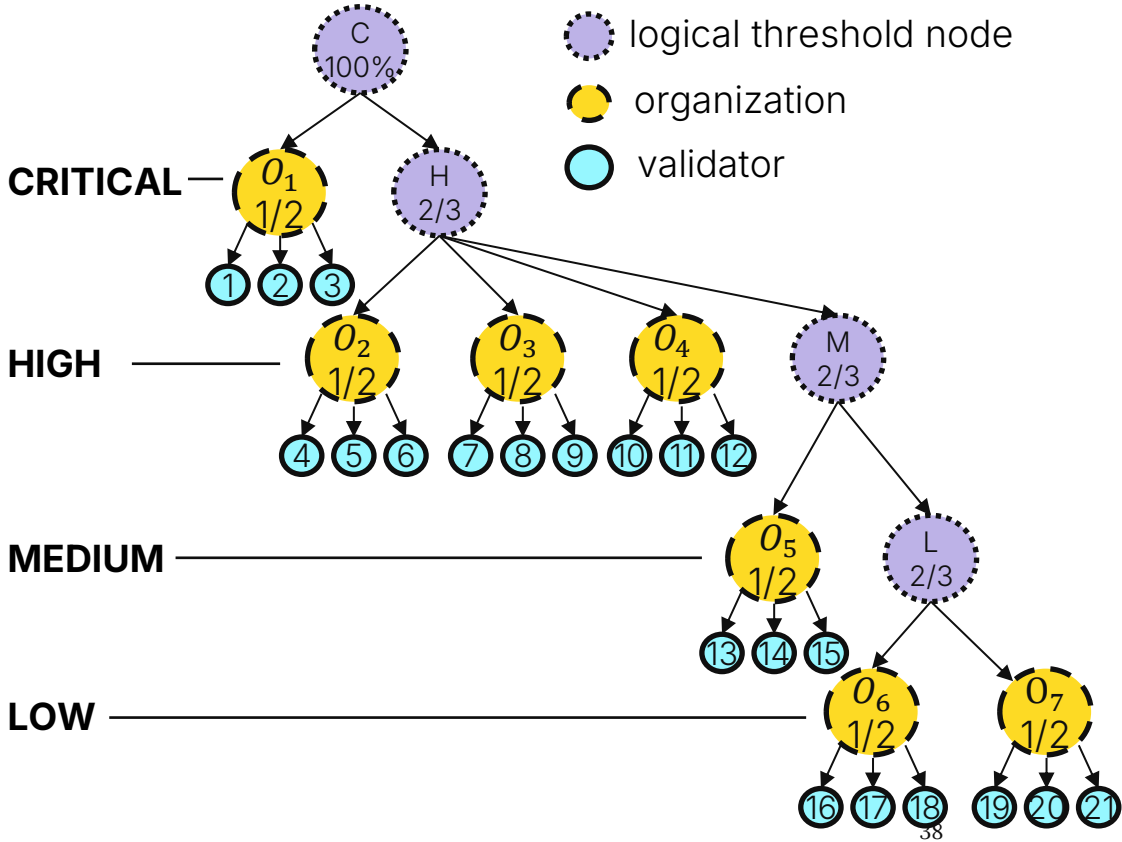
The inter-organization threshold is set to ½ and the per-level threshold is set to 2/3



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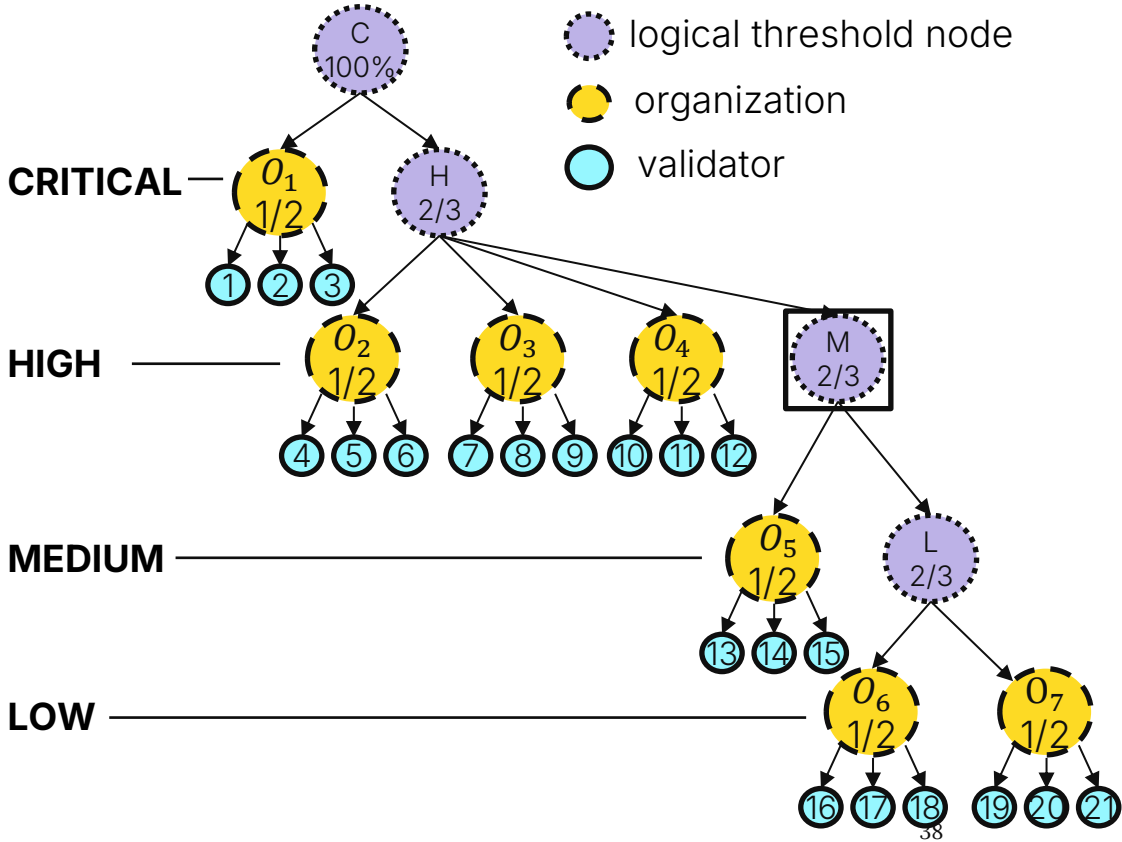
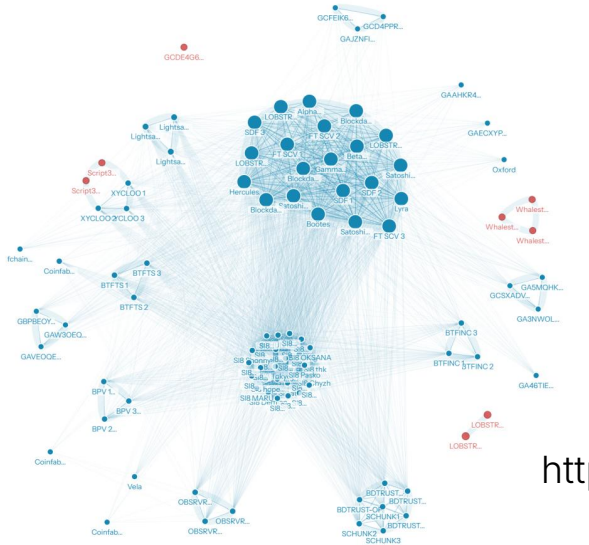
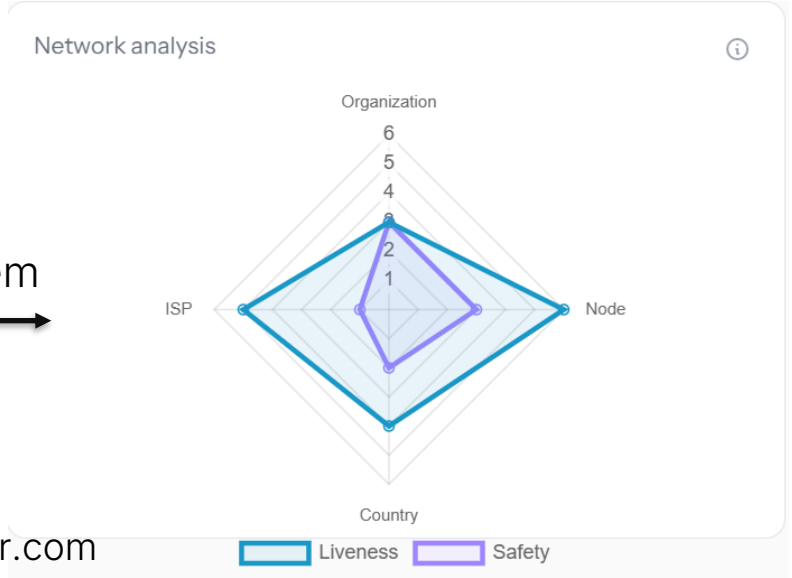


# We can compute the minimal “splitting sets” and “blocking sets”



NP-hard problem

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Uses search algorithms from
https://github.com/trudi-group/fbas_analyzer

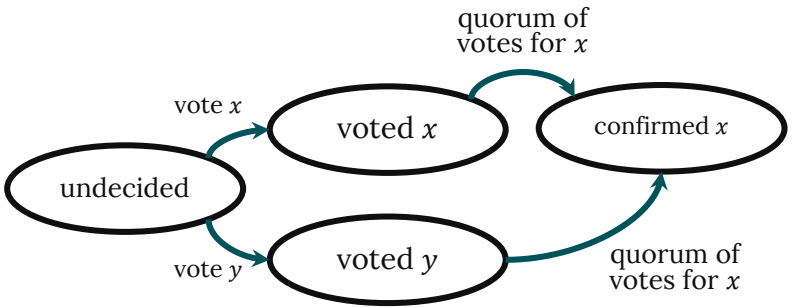
Alternative SAT-based implementation at
https://github.com/nano-o/python-fbas

# Roadmap

- ✓ Intro: the problem of issuer-enforced finality
- ✓ Background: Partial Synchrony, Total-Order Broadcast, BFT quorum systems, Reliable Voting
- ✓ Quorums in Federated Byzantine Agreement systems
- ➢ Reliable Voting in FBA systems
  - ➢ A simple, safe straw-man protocol
  - Quorum intersection is not that simple
  - Consensus clusters
  - Obtaining Totality: the Federated Voting protocol
- Total-Order Broadcast by porting Simplex to FBA

# How do we implement Reliable Voting in FBA?

Assuming quorum intersection and availability, can we reuse the Reliable Voting algorithm to ensure Unanimity, Validity, Agreement, Totality?



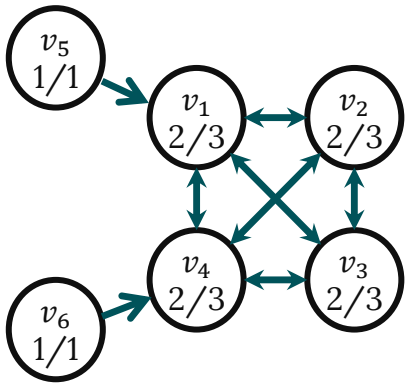

+ Re-broadcast all received votes

Does this algorithm still work?

# Two initial issues

How do validators learn each other's slices?

Slices are local and ***a priori*** unknown to other validators




How do validators compute quorums from slices?

We have a definition, not an algorithm

$$\mathrm{v} \in \mathrm{Q} \wedge \forall v' \in Q. \exists S \in \boldsymbol{S}_{v\prime}. S \subseteq Q$$

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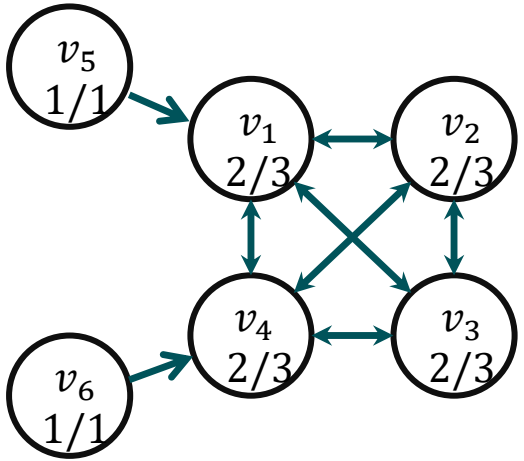
  4. Else set $candidates := remaining$ and go to 2

# Example 1

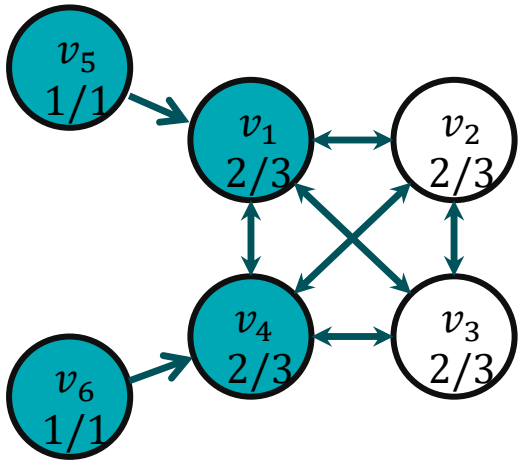
Consider at $v_5$:



# Example 1

Consider at $v_5$:

- $candidates = \{v_6, v_5, v_1, v_4\}$



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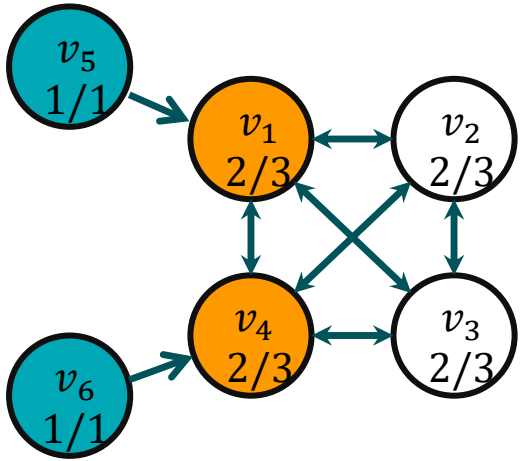

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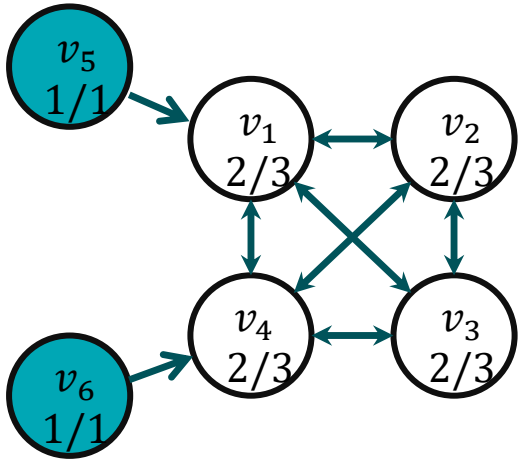

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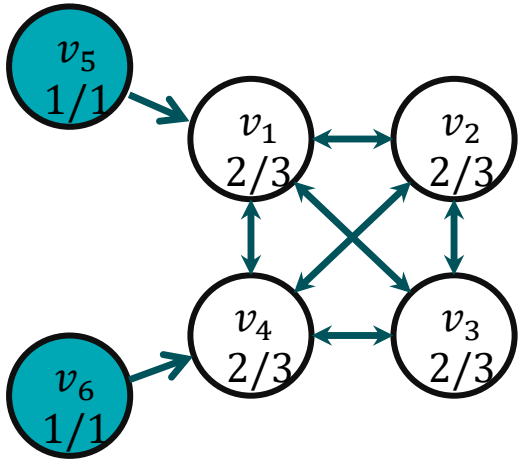

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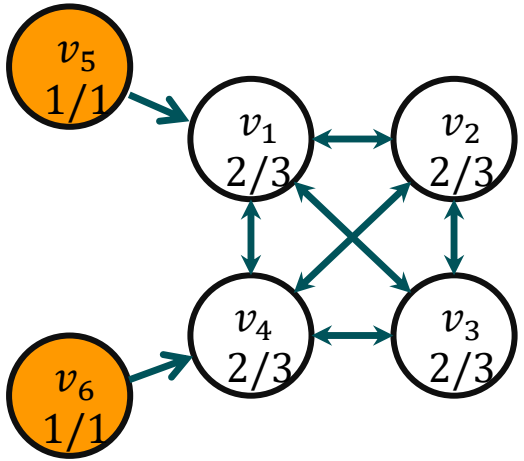

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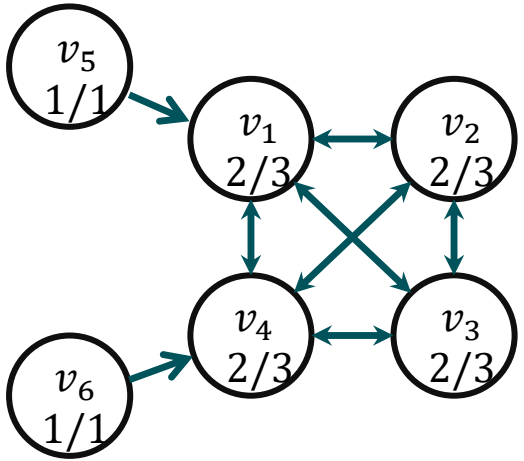

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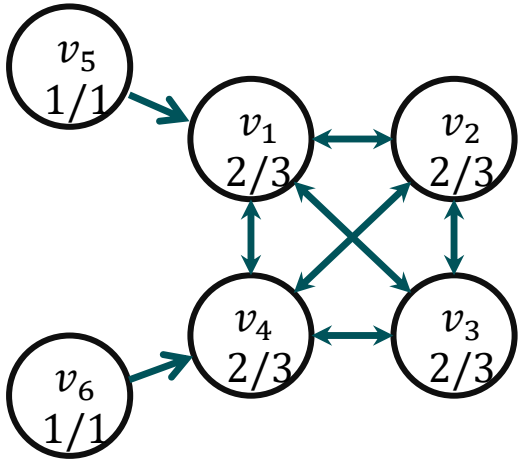
  - return false



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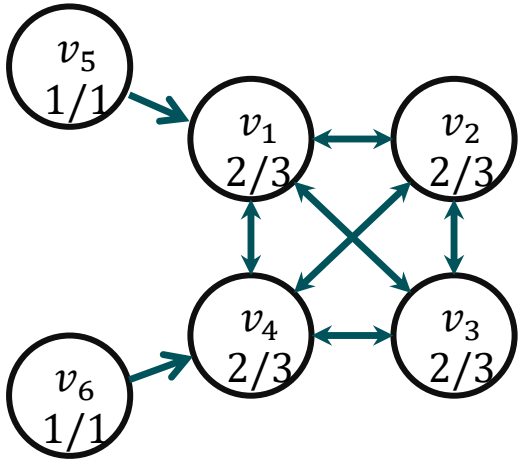

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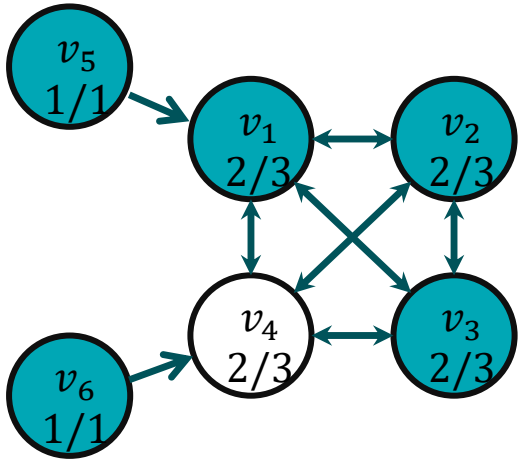

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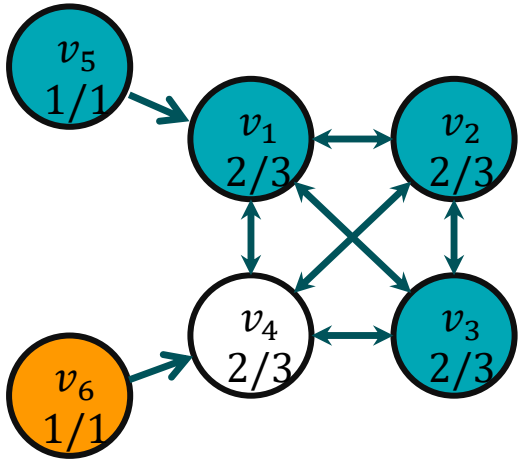

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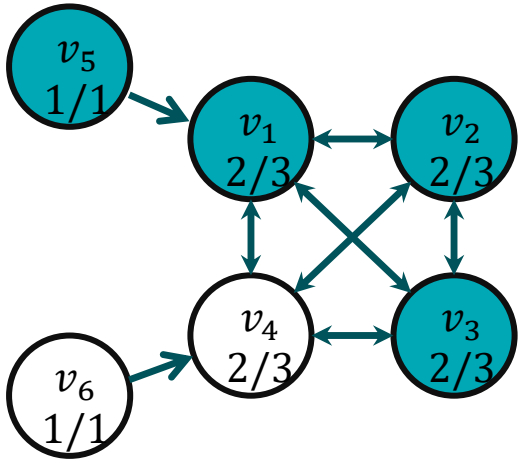

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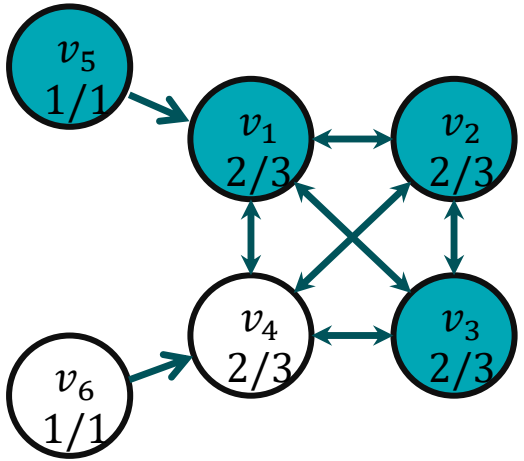

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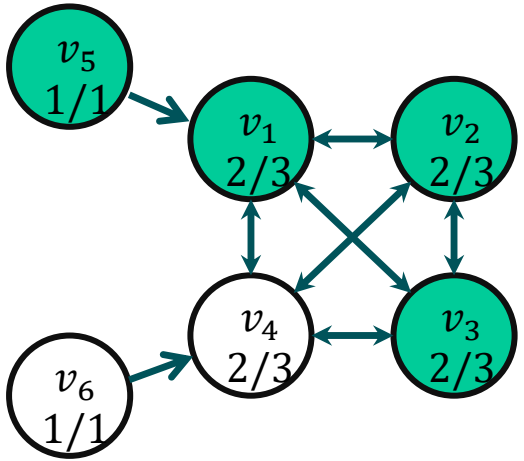
  - return true



# We solved our two initial issues

## How do validators learn each other's slices?

Validators attach their slices to every message they send

## How do validators compute quorums from slices?

We check whether a set of vote messages reached quorum threshold using a linear-time elimination procedure

# Roadmap

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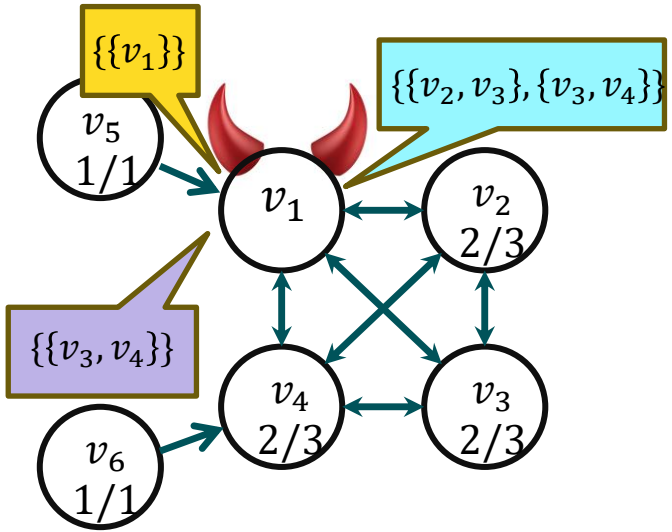
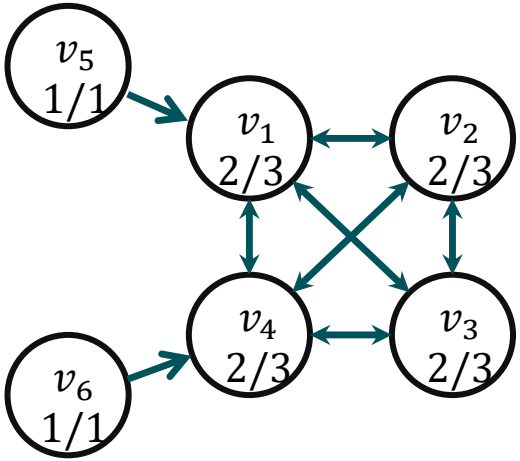
- Faulty validators can manipulate this by forging or lying about their slices
- “Perceived” quorums depend on Byzantine behavior



# Example: faulty validators can “cut” quorums

- Initially, every quorum includes 3 validators out of $\{v_1, v_2, v_3, v_4\}$
- So, one Byzantine failure among $\{v_1, v_2, v_3, v_4\}$ should be okay



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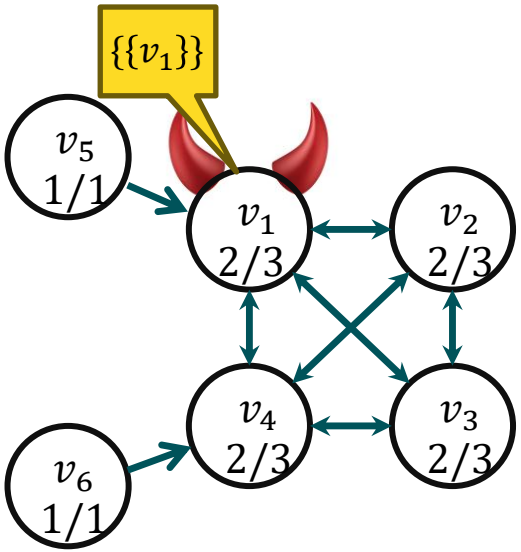

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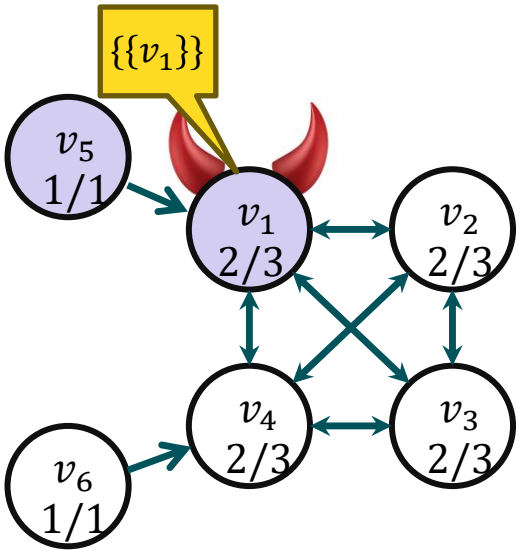

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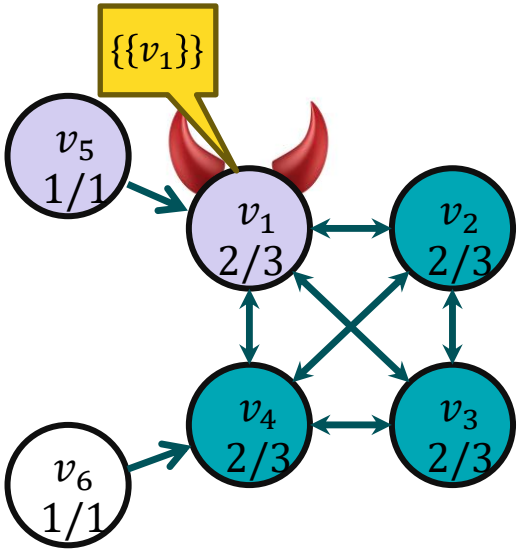
- $\{v_2, v_3, v_4\}$ is a disjoint quorum
- Quorum intersection actually fails!



# “Possible quorums” account for worst-case Byzantine behavior

Definition: $Q$ is a possible quorum when

- $Q$ contains a well-behaved member
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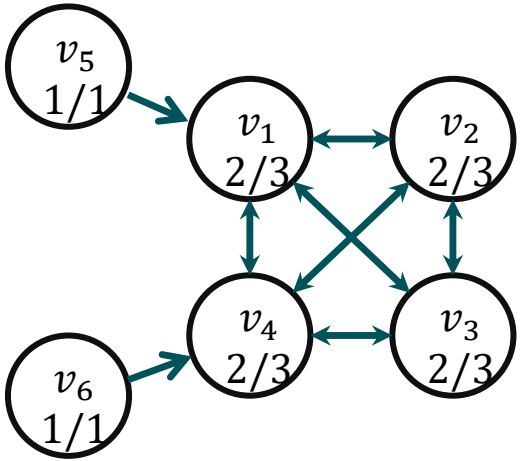

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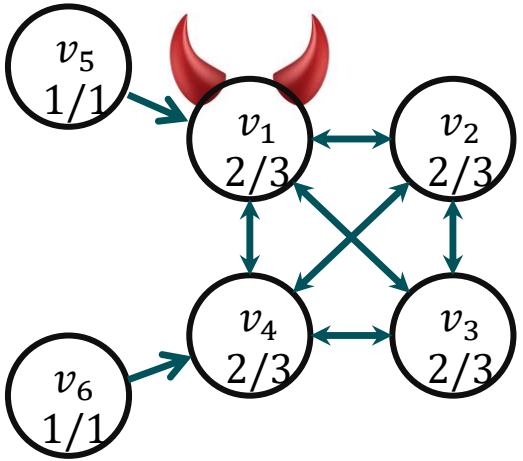

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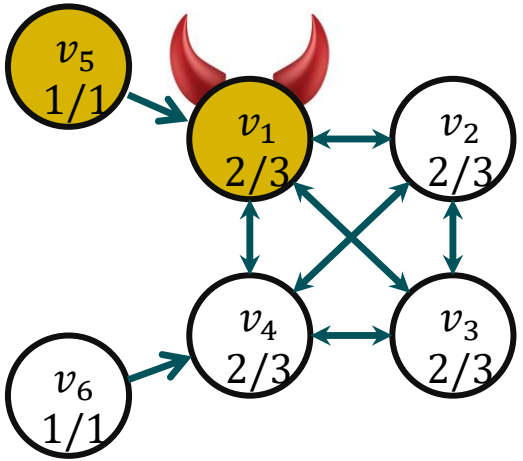

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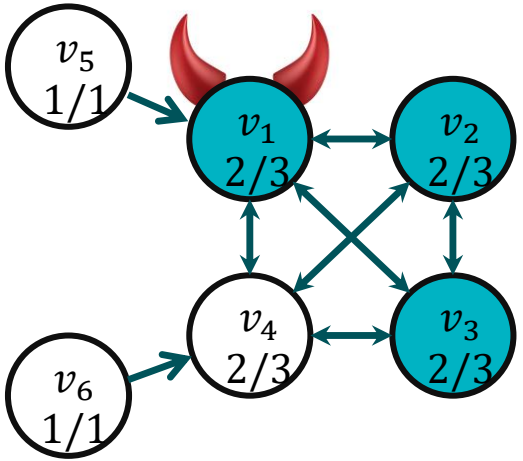

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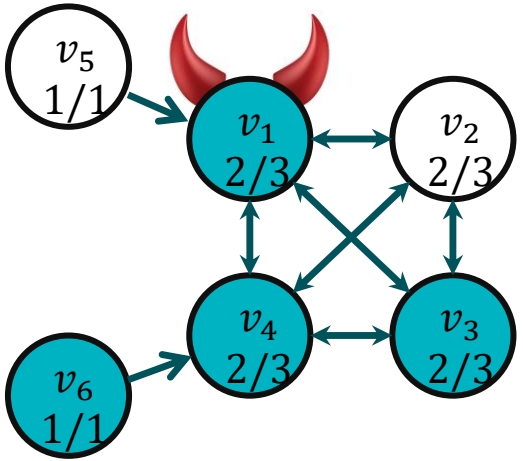
- $\{v_6, v_4\}$ and any two out of $\{v_1, v_2, v_3\}$ are a possible quorum



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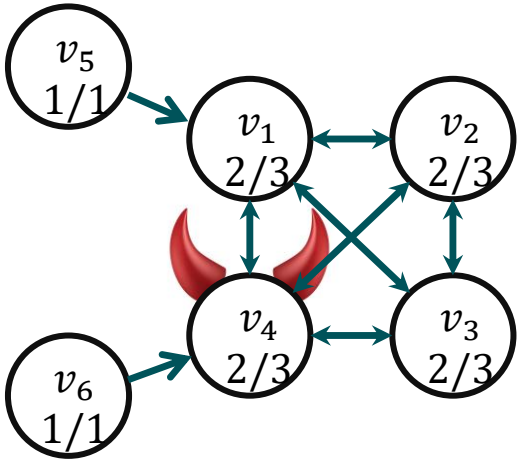
If $v_2$ is faulty then



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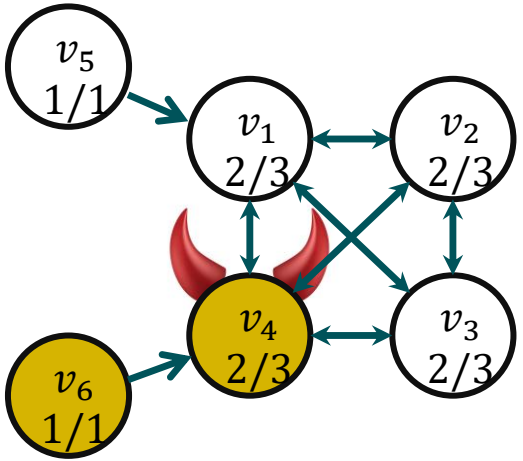
If $v_2$ is faulty then

- $\{v_6, v_2\}$ is now a possible quorum



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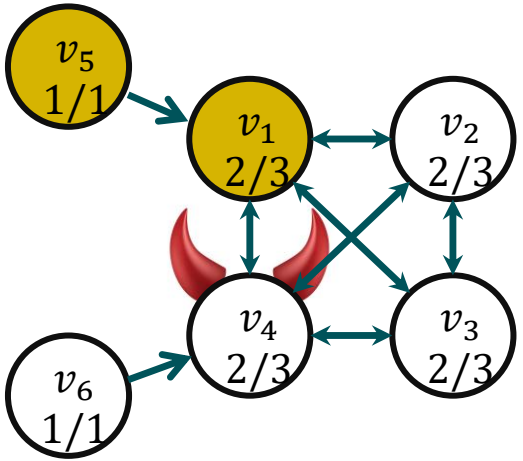

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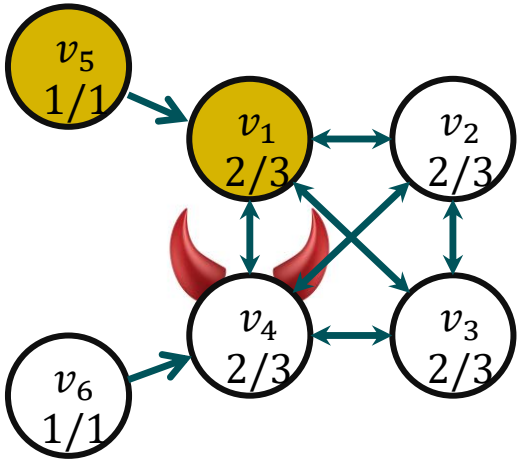
- What about $\{v_5, v_6\}$?
  - Not a possible quorum



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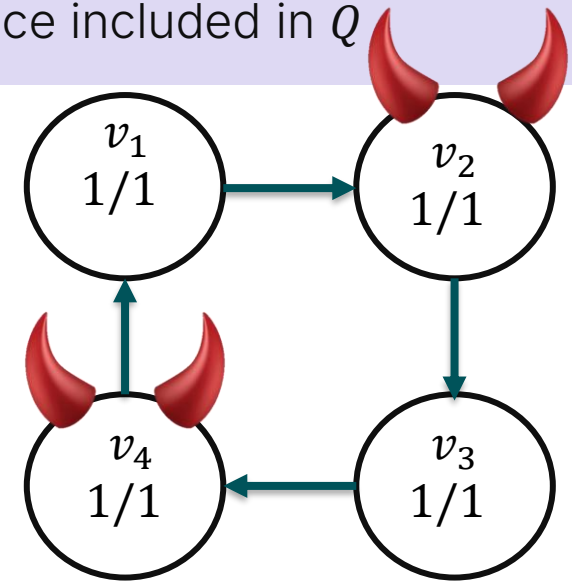

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- $\{v_1, v_2\}$ is a possible quorum
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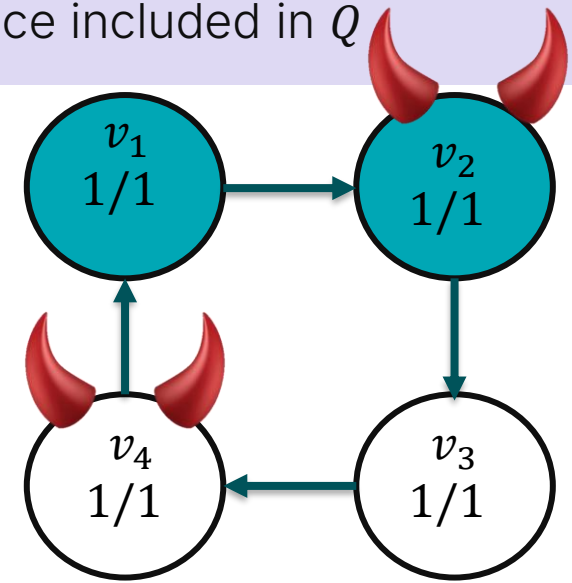
  - ✓ $v_2$ is faulty



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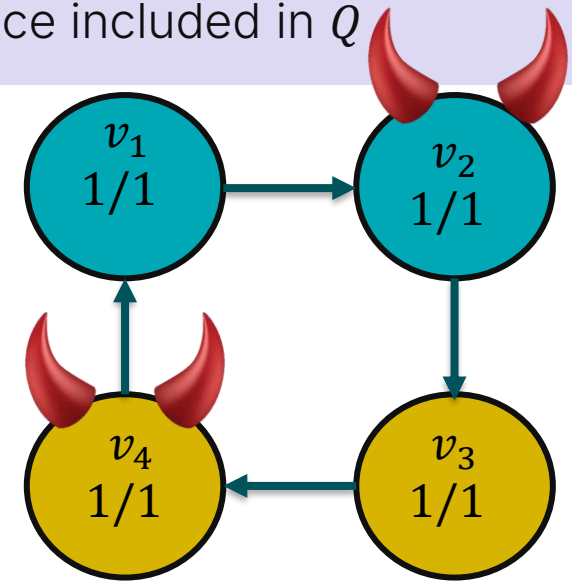
- $\{v_3, v_4\}$ is a possible quorum
  - ✓ $v_3$ has a slice included in $\{v_3, v_4\}$
  - ✓ $v_4$ is faulty



# We can now analyze the system in terms of possible quorums

Assuming that

- Every two ***possible quorums*** have a well-behaved member in common
- Every validator has a well-behaved quorum

The voting algorithm ensures Unanimity, Agreement, and Validity

*What about Totality?*

# Roadmap

- ✓ Intro: the problem of issuer-enforced finality
- ✓ Background: Partial Synchrony, Total-Order Broadcast, BFT quorum systems, Reliable Voting
- ✓ Quorums in Federated Byzantine Agreement systems
- ➢ Reliable Voting in FBA systems
  - ✓ A simple, safe straw-man protocol
  - ✓ Quorum intersection is not that simple (possible quorums)
  - ➢ Consensus clusters
  - Obtaining Totality: the Federated Voting protocol
- Total-Order Broadcast by porting Simplex to FBA

# In an open system, we cannot assume possible quorums will suitably intersect

Validators are free to choose their agreement requirements

- Some might choose to agree with the “wrong” validators
- Too many validators get hacked
- Some validators might genuinely not want to agree with others and form their own community

Does the system devolve into chaos?

# Consensus Clusters

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Fix a faulty set $\mathcal{F}$

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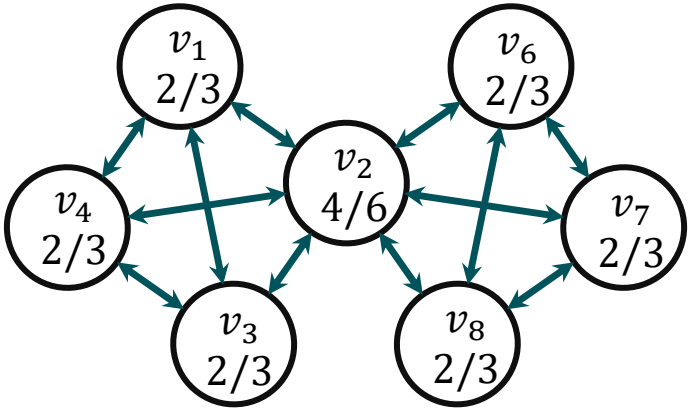
Notation: we will use capital $\mathbf{C}$ for clusters ($\mathbf{C}$, $\mathbf{C}$', $C_1$)

# Example



# Example

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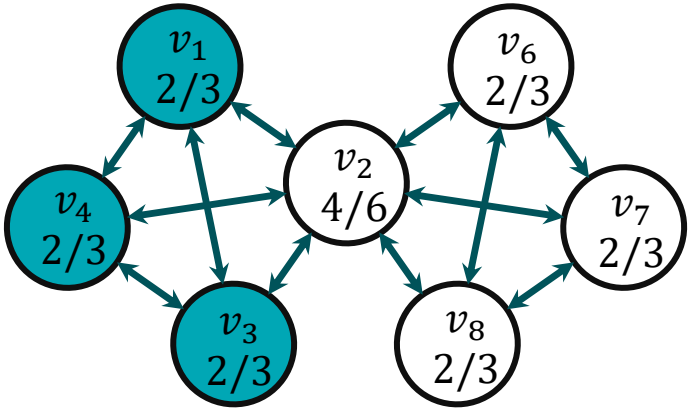

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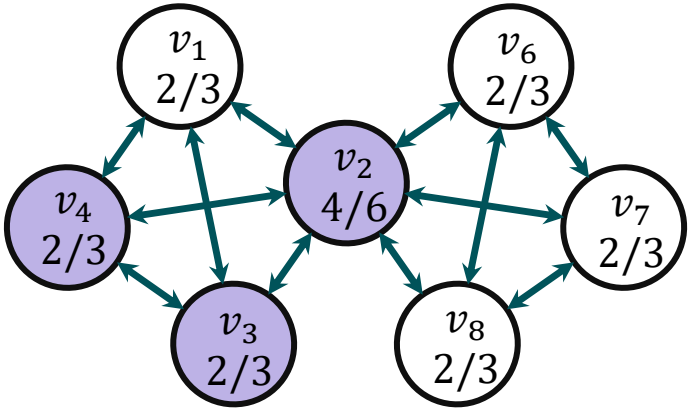
- $\{v_1, v_3, v_4\}$ is a cluster
- $\{v_2, v_3, v_4\}$ is not a cluster



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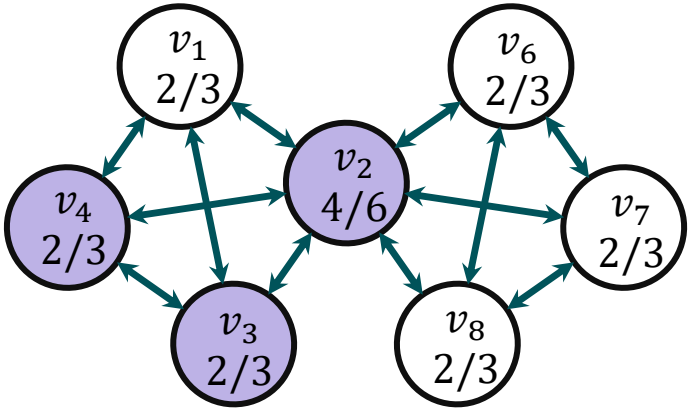

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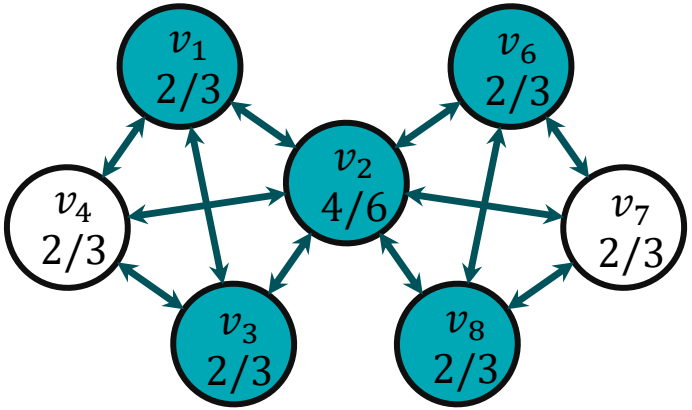
- $\{v_1, v_2, v_3, v_6, v_8\}$ is not a cluster



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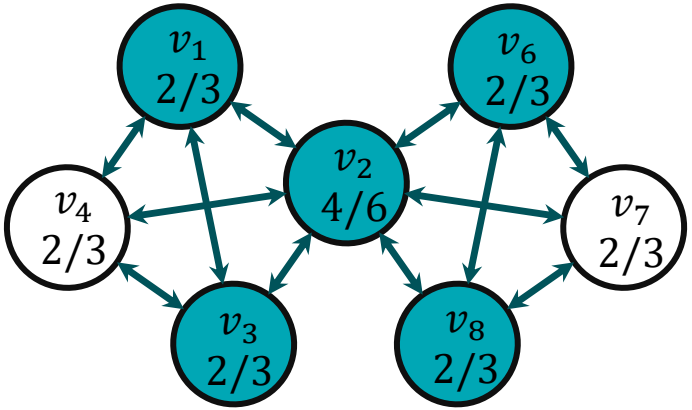

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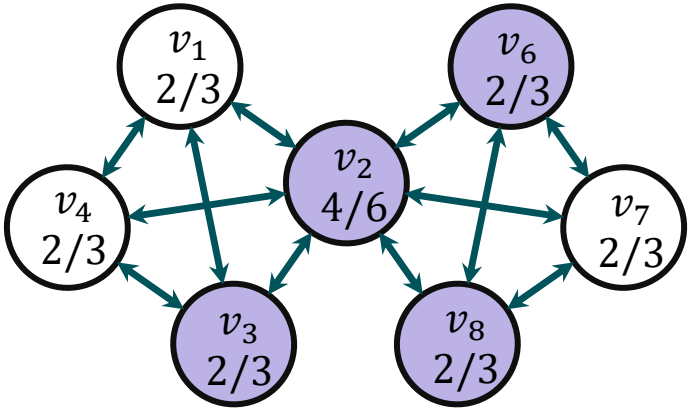

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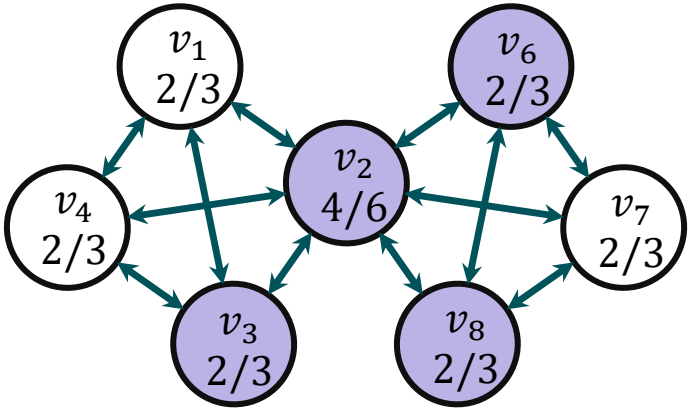

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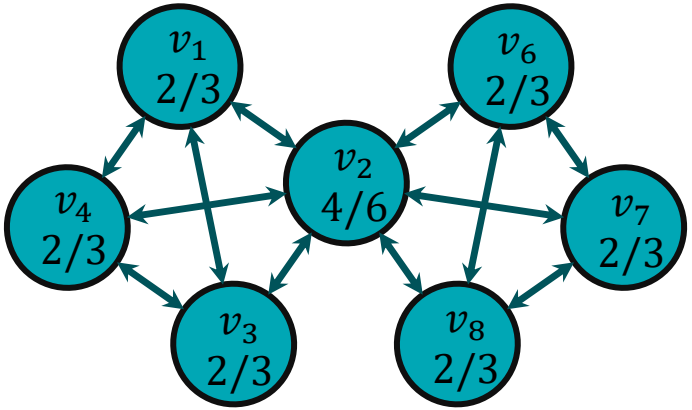
  - It is not a quorum
- The whole system is a cluster



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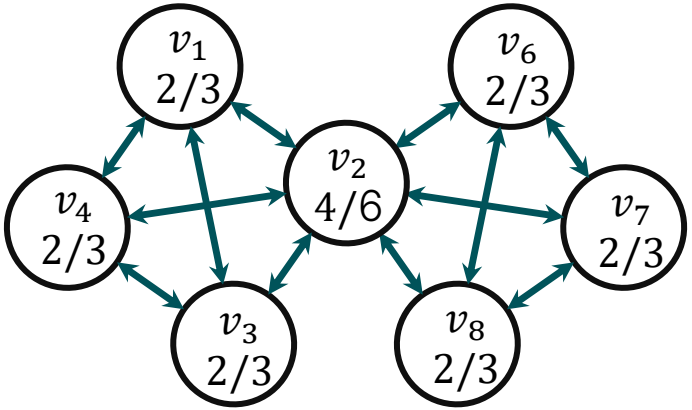
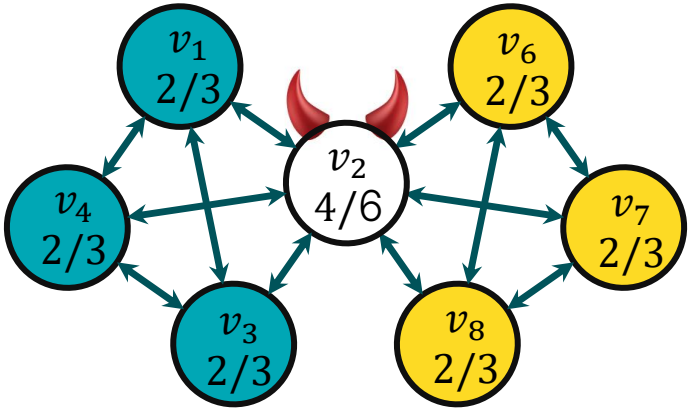


# Example

Suppose $\mathcal{F} = \{v_2\}$



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Suppose $\mathcal{F} = \{v_2\}$

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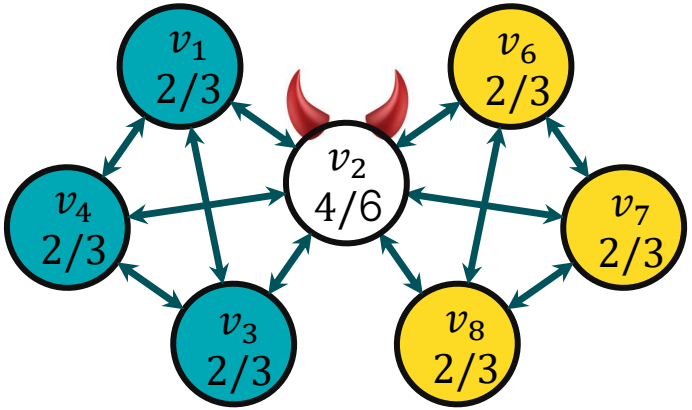

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Suppose $\mathcal{F} = \{v_2\}$

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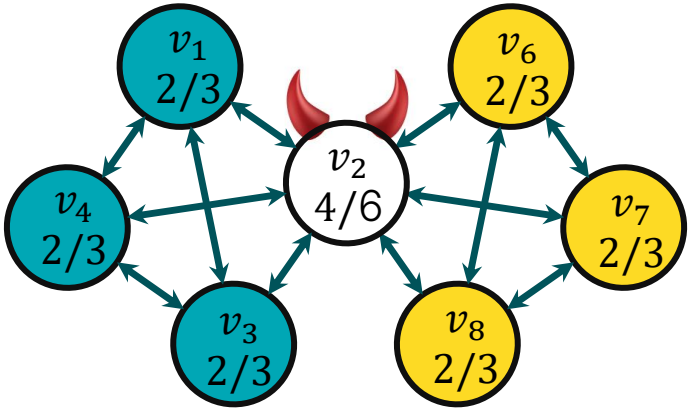
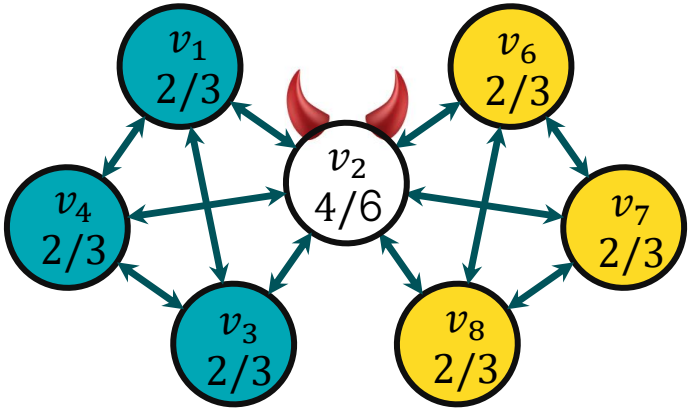
- $\{v_6, v_7, v_8\}$ is a cluster



# Example

Suppose $\mathcal{F} = \{v_2\}$

- $\{v_1, v_3, v_4\}$ is a cluster
- $\{v_6, v_7, v_8\}$ is a cluster
- Those are the only two clusters



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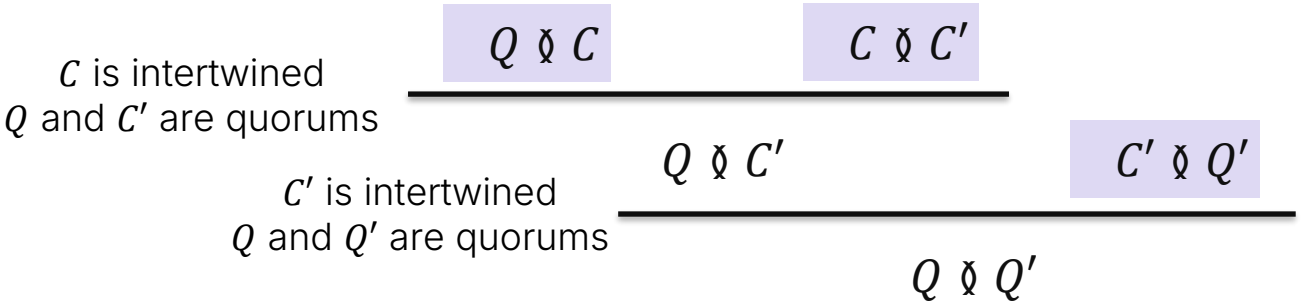

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# Roadmap

- ✓ Intro: the problem of issuer-enforced finality
- ✓ Background: Partial Synchrony, Total-Order Broadcast, BFT quorum systems, Reliable Voting
- ✓ Quorums in Federated Byzantine Agreement systems
- ➢ Reliable Voting in FBA systems
  - ✓ A simple straw-man protocol
  - ✓ Quorum intersection is not that simple (possible quorums)
  - ✓ Consensus clusters
  - ➢ Obtaining Totality: the Federated Voting protocol
- Total-Order Broadcast by porting Simplex to FBA

# New goal: Reliable Voting *for clusters*

New Specification:

For every value $x$ and every cluster $C$:

***Unanimity:*** If all members of $C$ vote for $x$, then they all eventually confirm $x$

***Validity:*** If a member of $C$ confirms $x$, then a member of $C$ voted for $x$

***Agreement:*** No two members of $C$ confirm different values

***Totality:*** If a member of $C$ confirms $x$, then all members of $C$ eventually confirm $x$

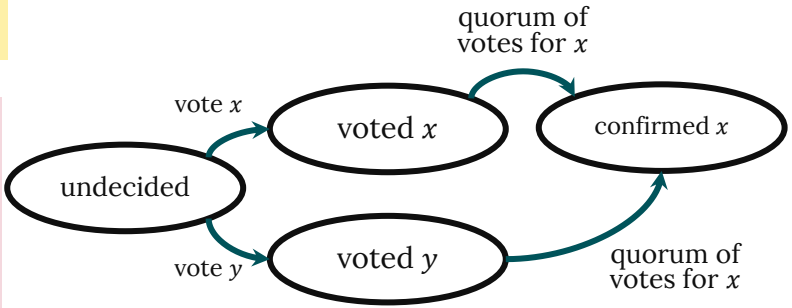
***Note***: We do not know in advance which set will be clusters

# Does the voting algorithm implement Reliable Voting in the FBA model?

Validity, Agreement, and Unanimity hold

Problem: Totality

Because quorums are subjective, a quorum that convinces $v_1$ may not convince $v_2$



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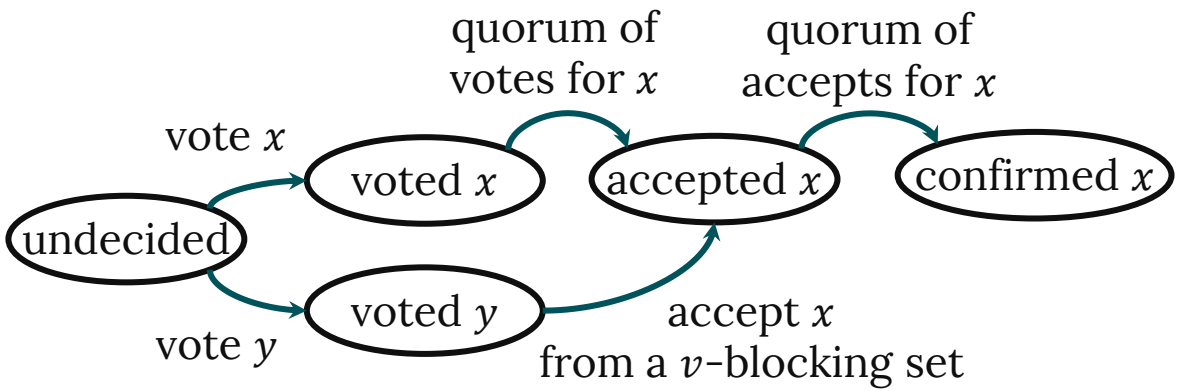

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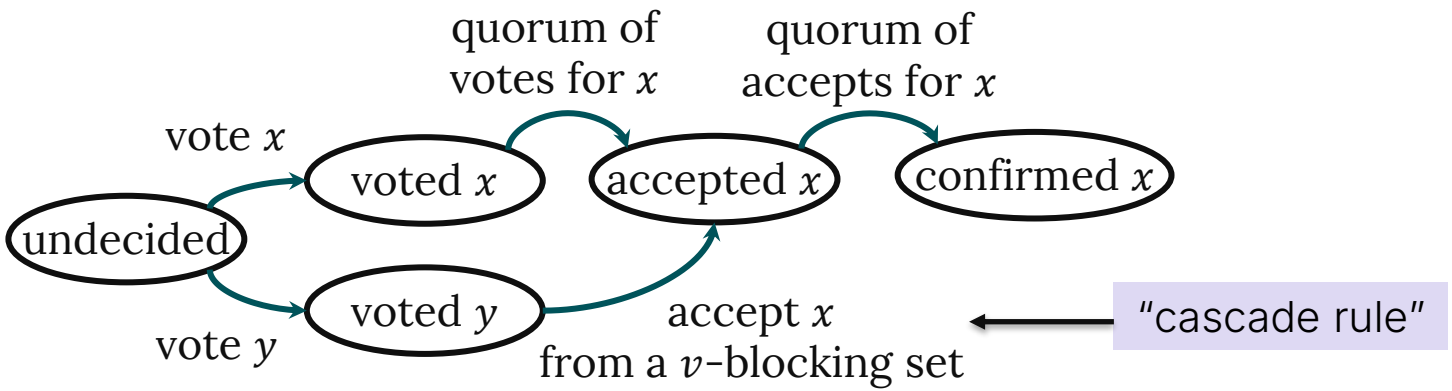

# If a cluster member confirms, then "accept" and "confirm" cascade to the entire cluster

Say $v_2$ confirmed $x$ because $v_1, v_2, v_3$ accepted $x$, but $v_5, v_6, v_4$ voted for $y$

1. $v_4$ and $v_5$ are blocked by accept $x$, but not $v_6$
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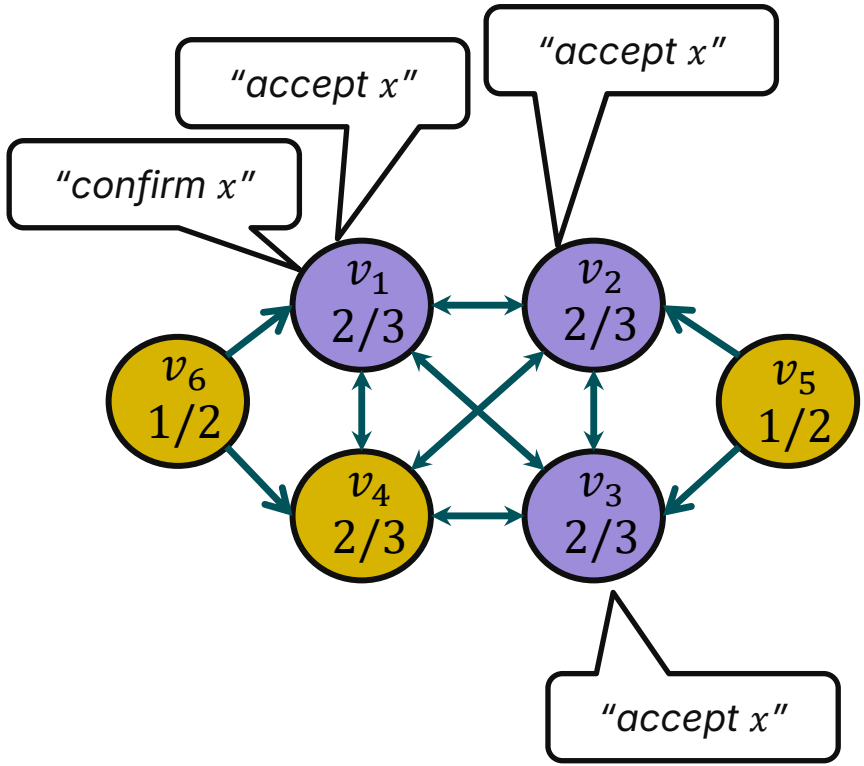

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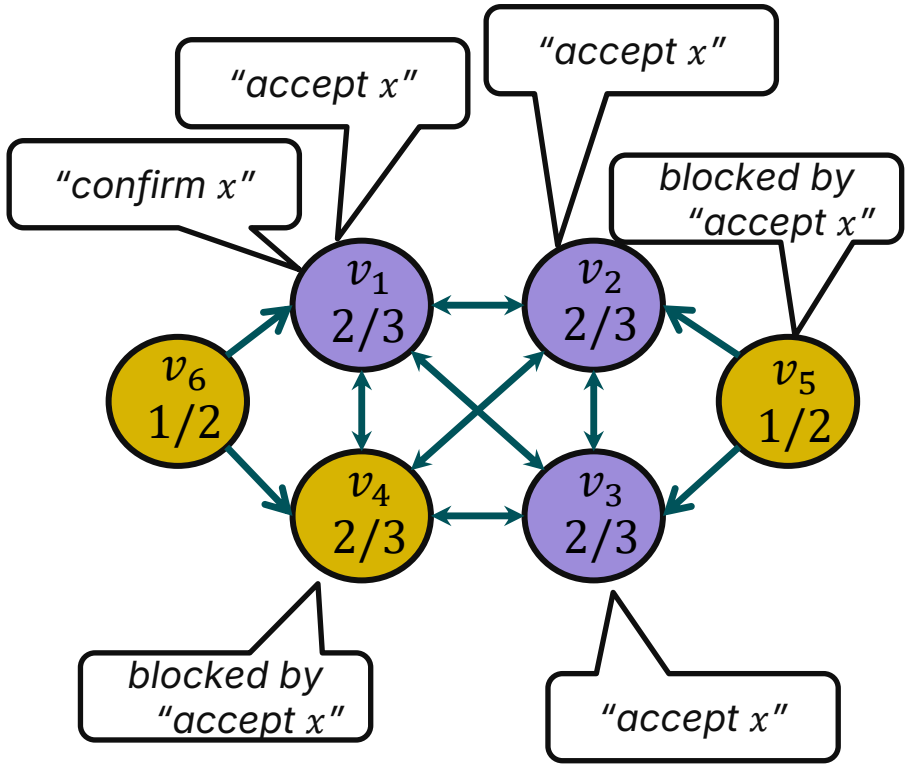

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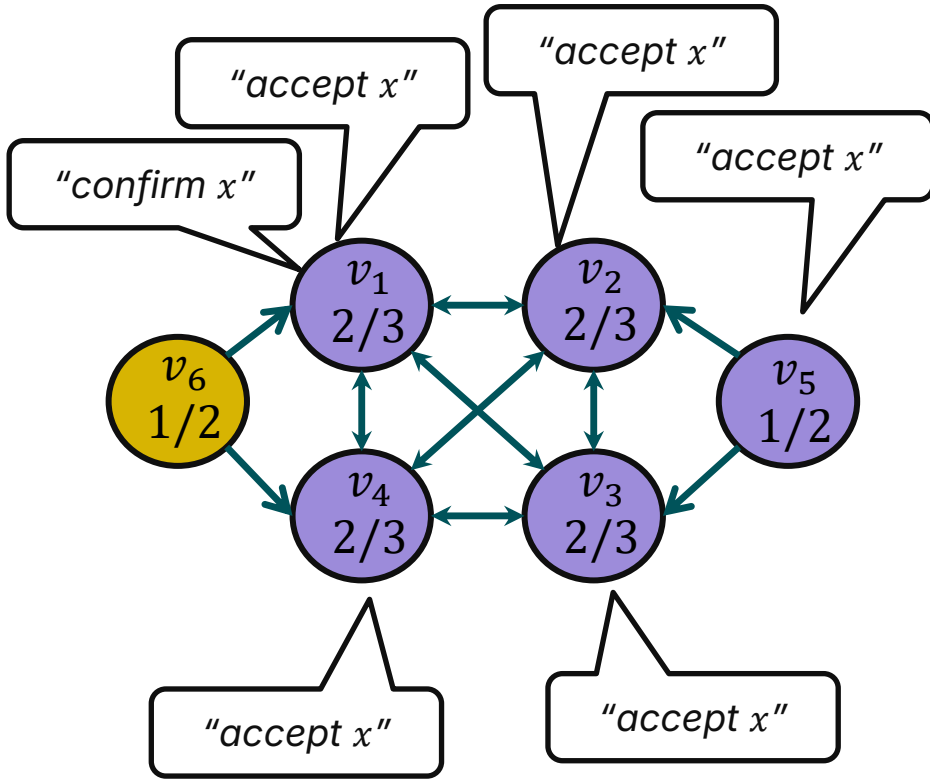

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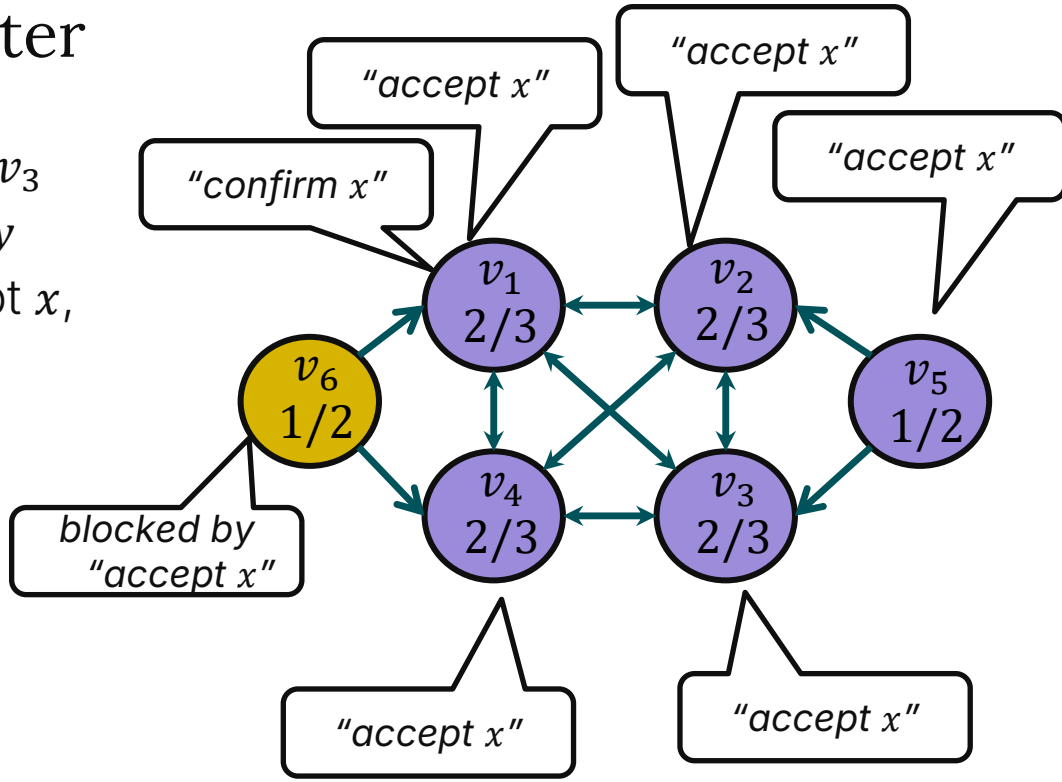

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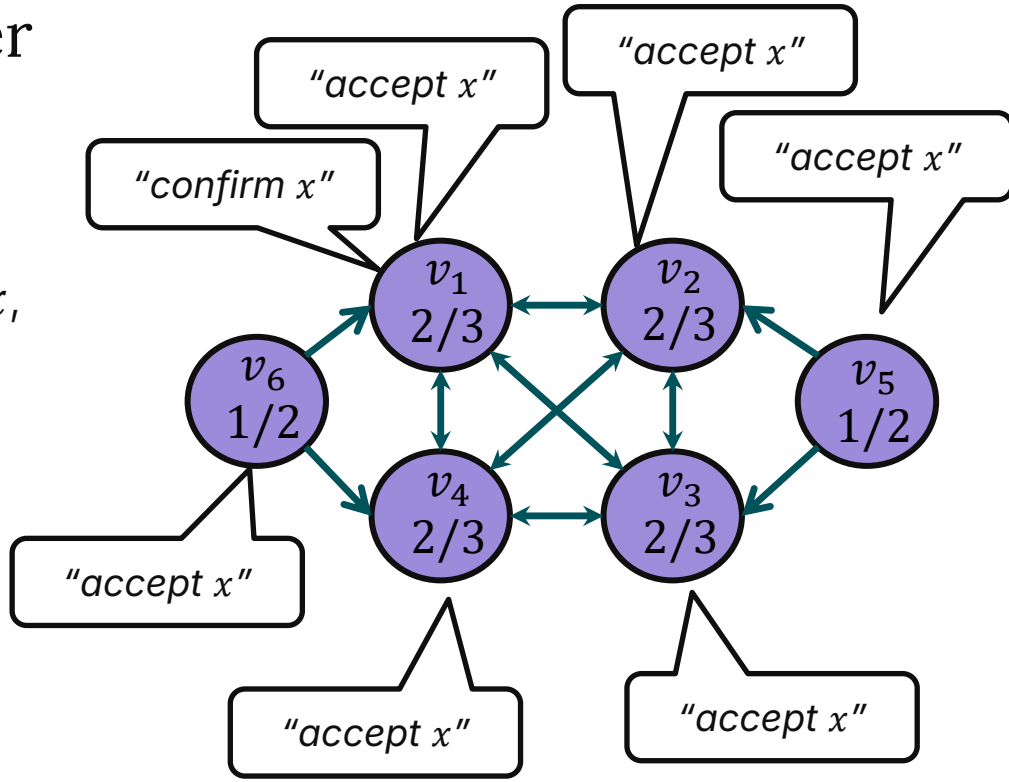

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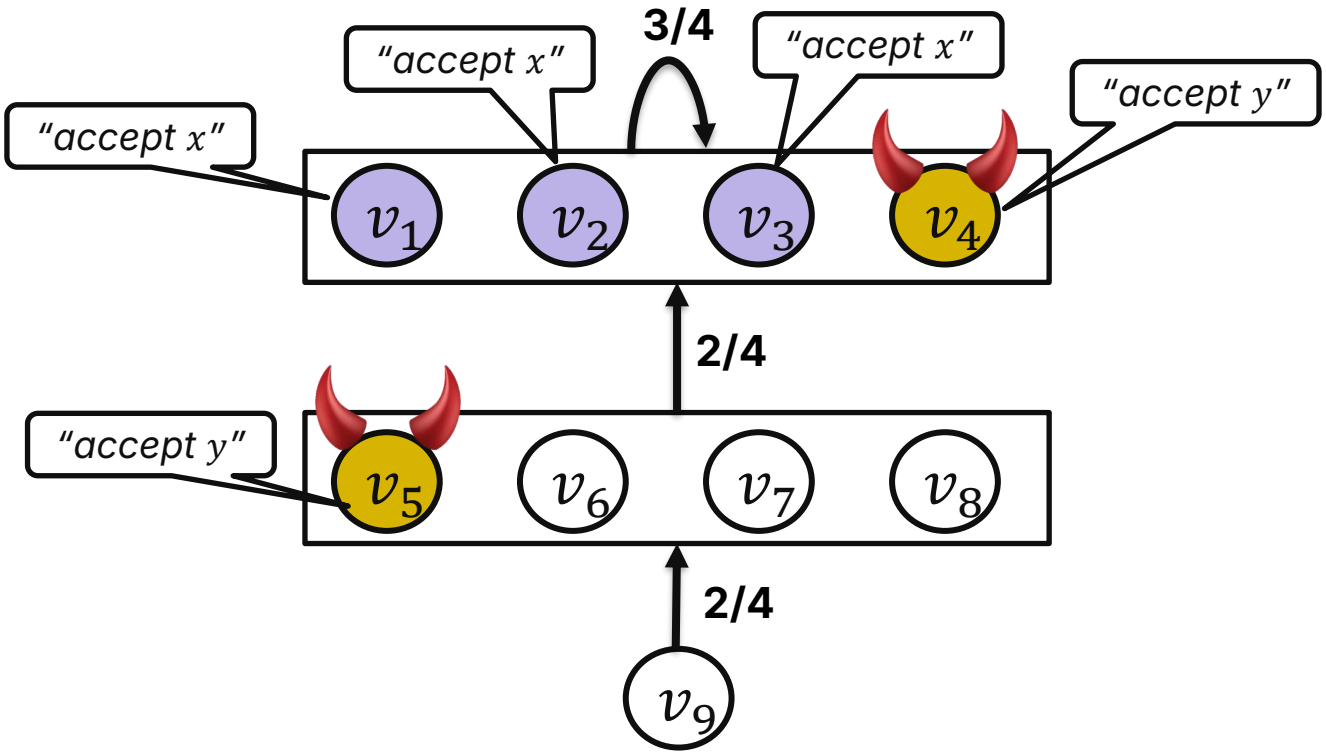

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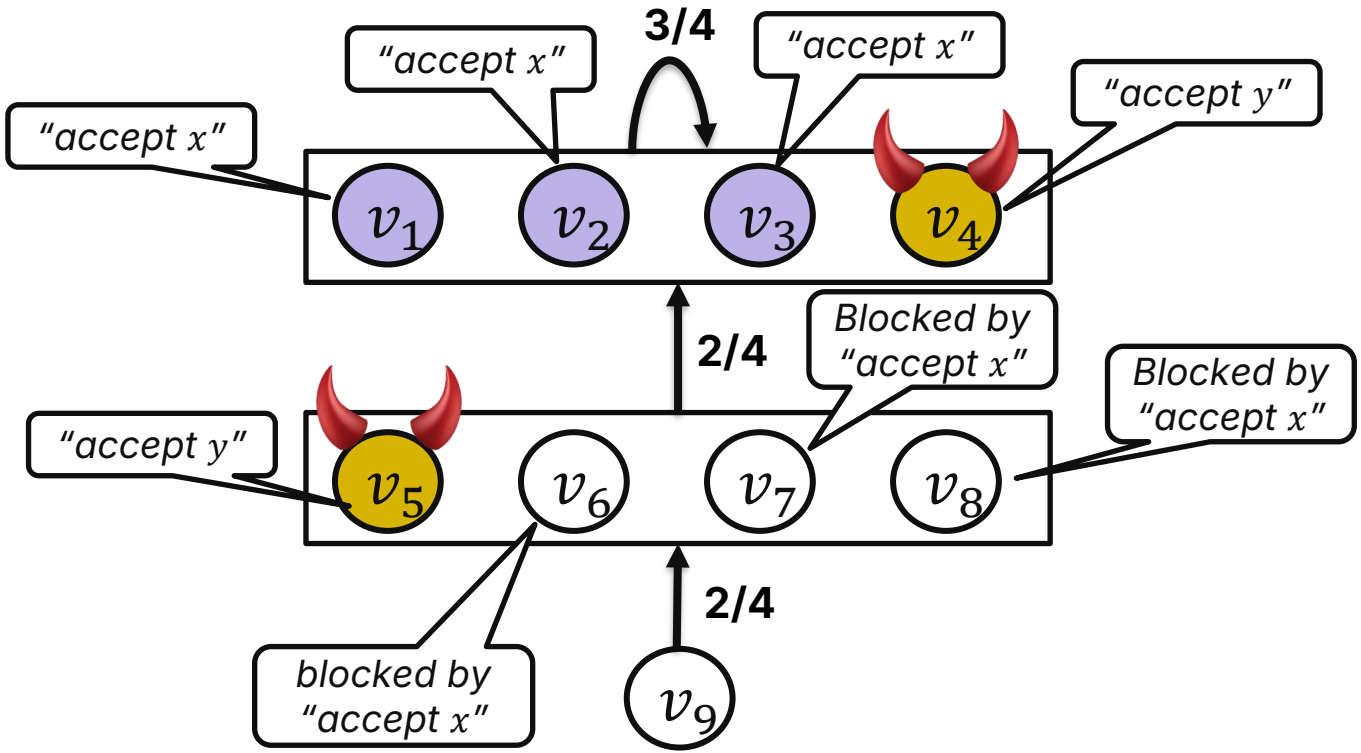

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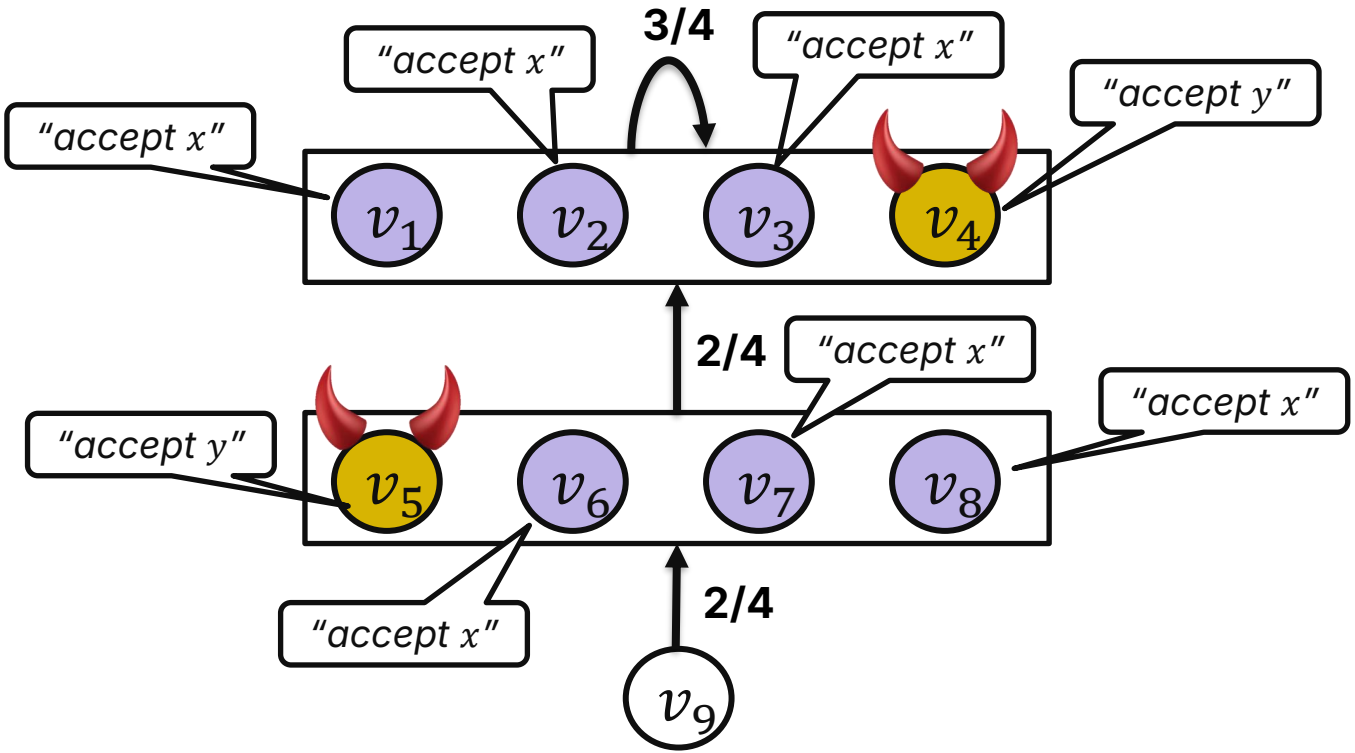

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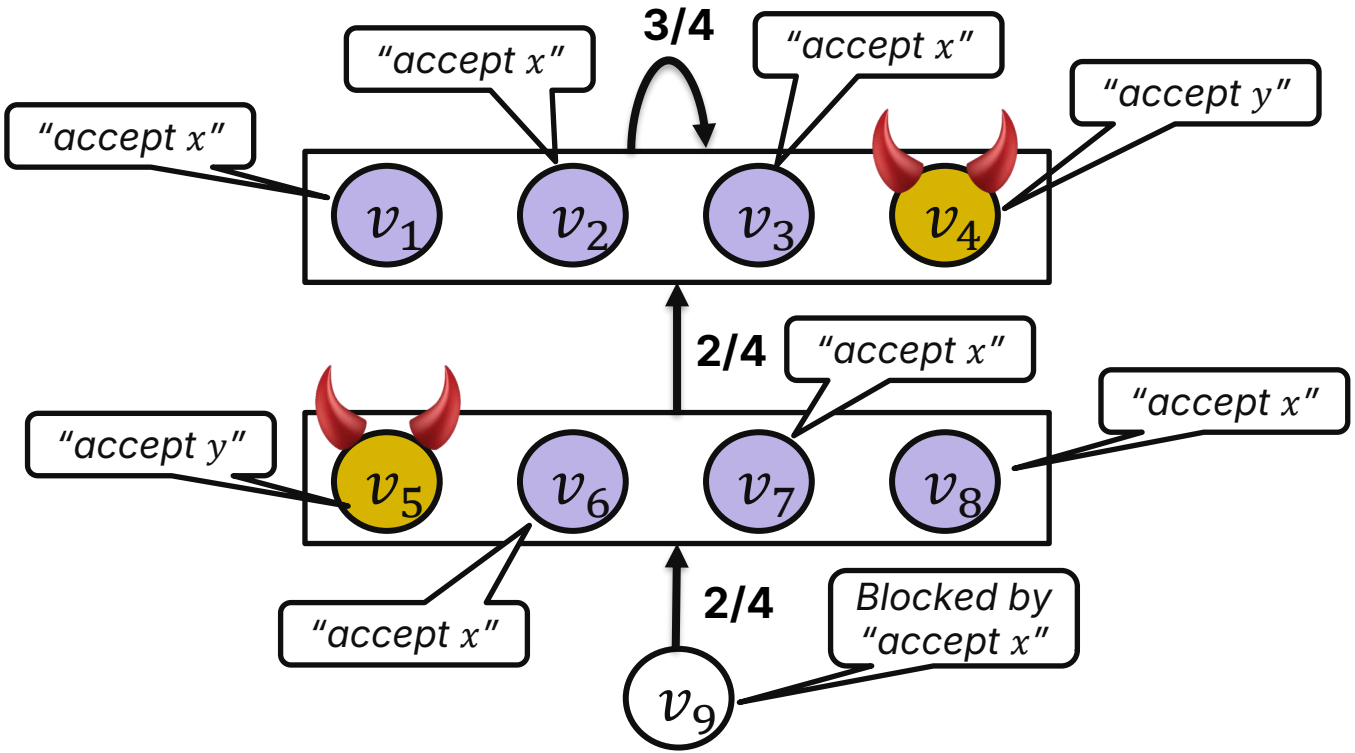

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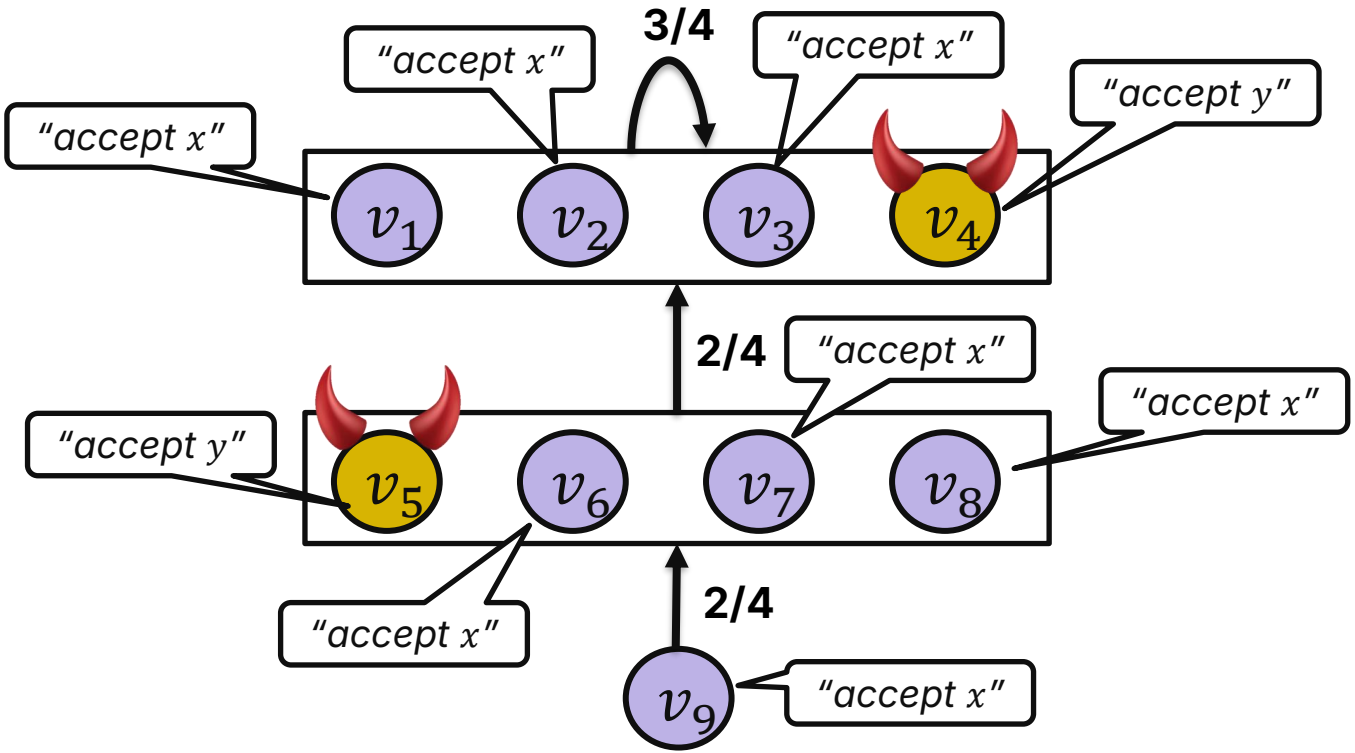

# The cascade rule preserves Agreement and ensures Totality

It suffices to show:

1. **For Agreement**: If a validator $v \in C$ accepts $x$, then a member of $C$ accepted $x$ through the quorum rule
2. **For Totality**: If a quorum $Q$ of a validator $v \in C$ accepts $x$, then "accept $x$" cascades to all members of $C$

# Notion of “possibly cascades”

Definition: a set $U$ of validators **possibly cascades** to $v$:

- If $v \in U$, then $U$ possibly cascades to $v$
- If every slice of $v$ contains a validator $v'$ such that $U$ possibly cascades to $v'$ or $v'$ is faulty, then $U$ possibly cascades to $v$

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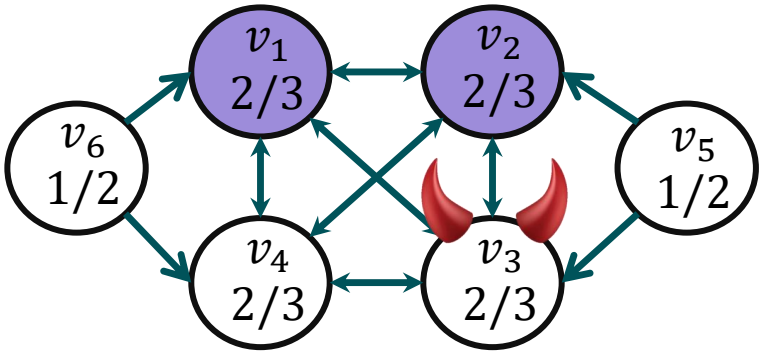
$U = \{v_1, v_2\}$ possibly cascades to $v_6$ and $v_5$ because: if $U \cup \boldsymbol{\mathcal{F}} = \{\boldsymbol{v_1, v_2, v_3}\}$ accepts $x$, the “accept $x$” cascades to the whole system



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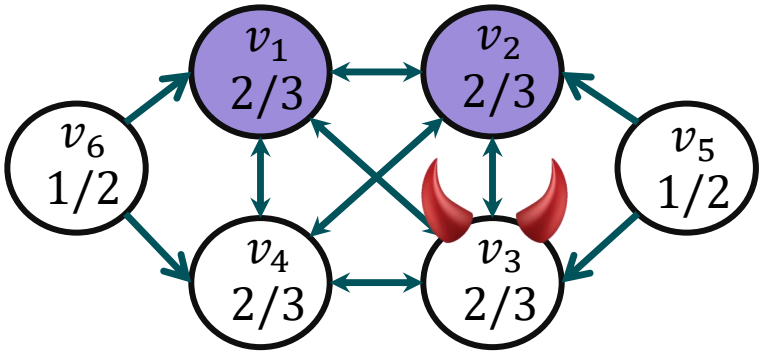
$U = \{v_1, v_2\}$ does not surely cascade to $v_6$ and $v_5$: if $\boldsymbol{\mathcal{F} = \{v_3\}}$ remains silent, no cascade occurs



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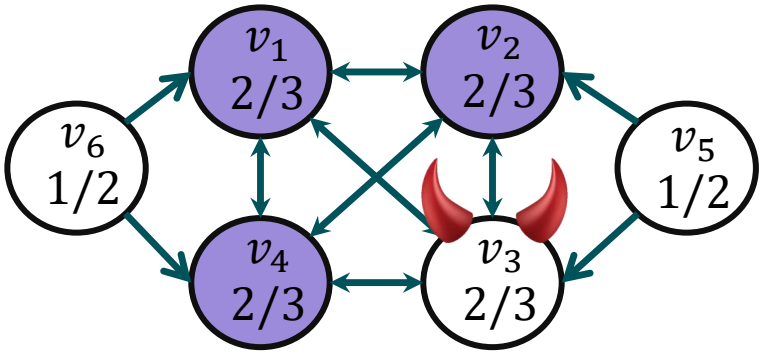
$U = \{v_1, v_2, v_4\}$ surely cascade to $v_6$ but not $v_5$



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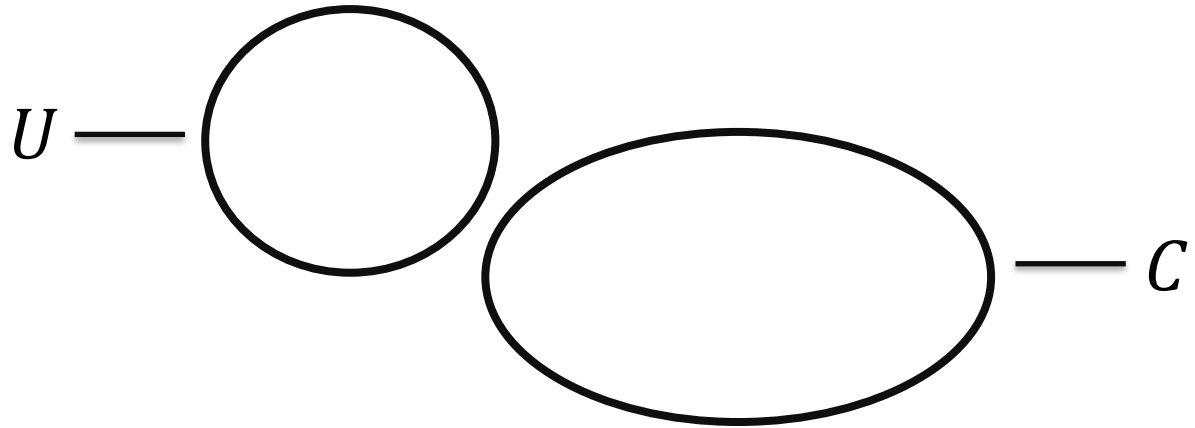

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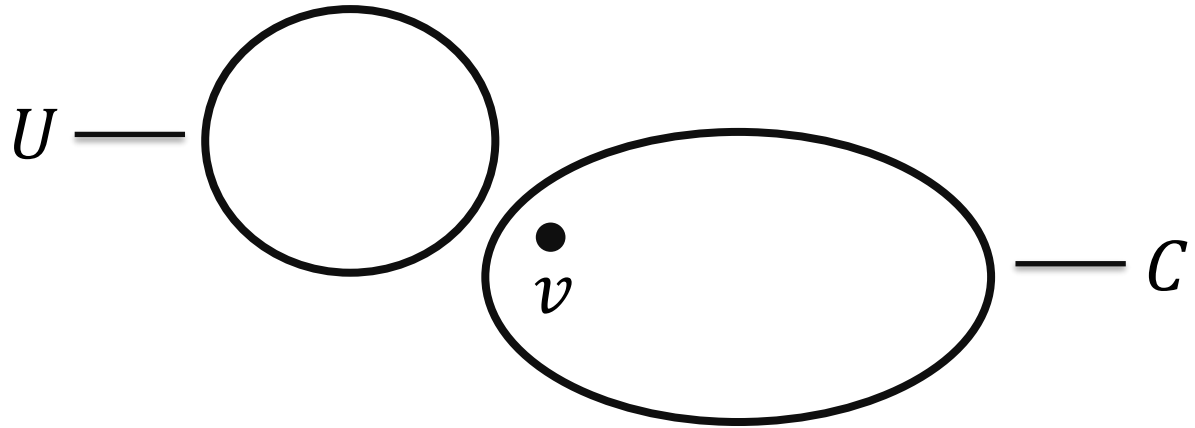

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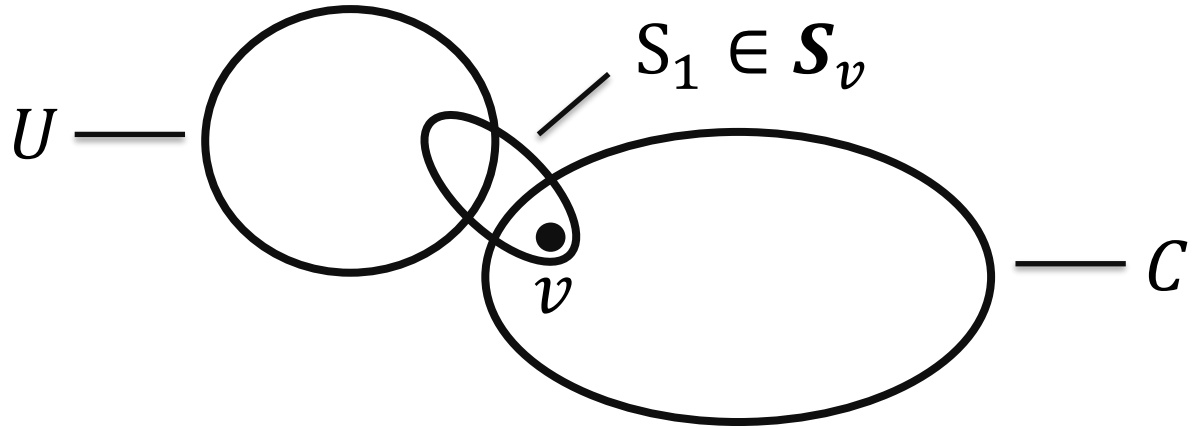

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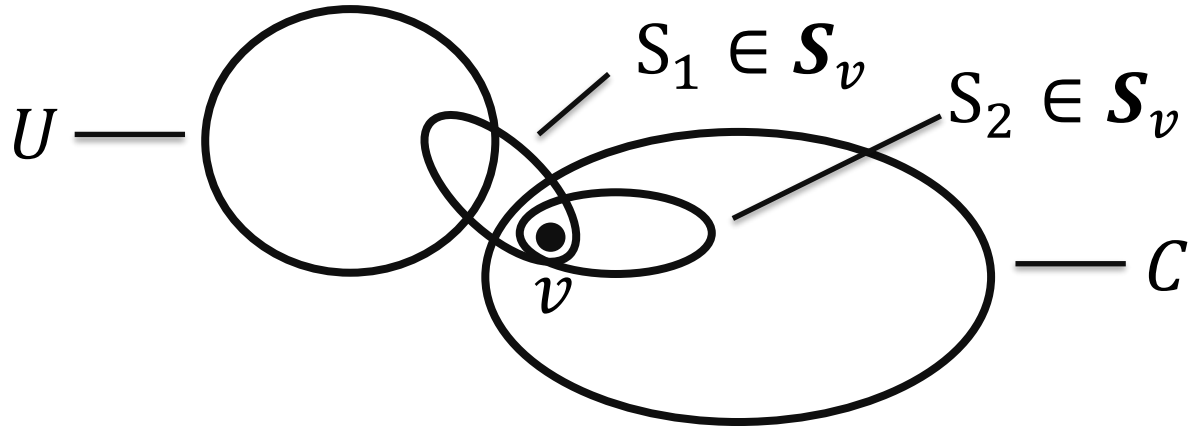

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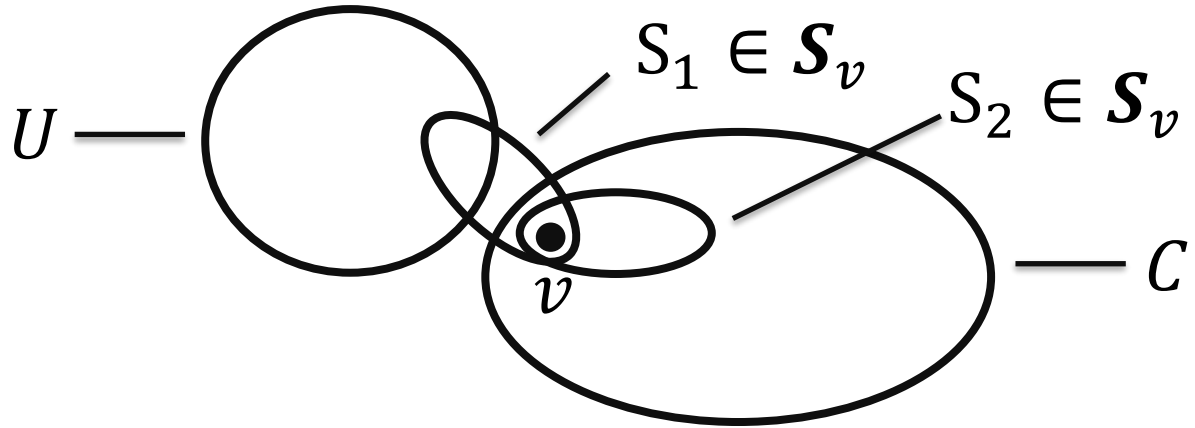

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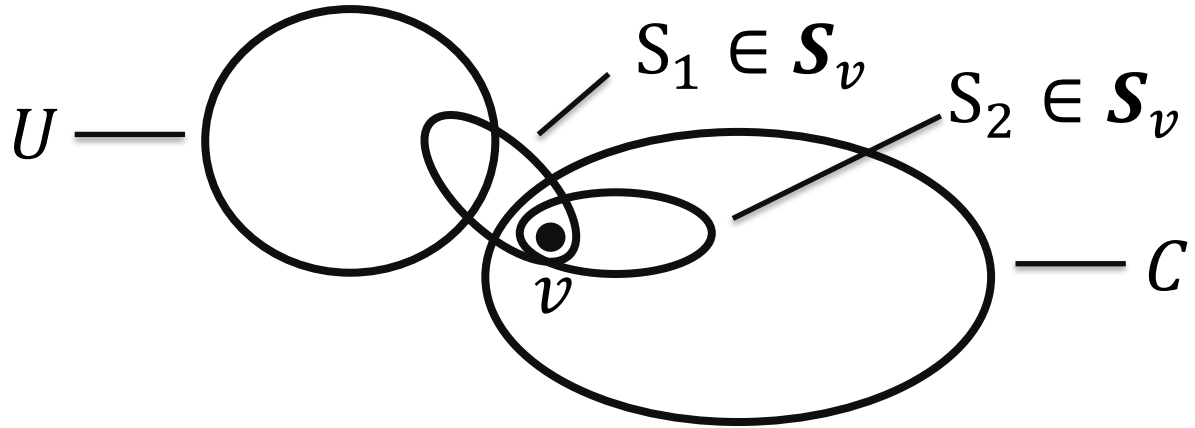
Proof: $C$ is a well-behaved quorum, so every member of $C$ has a well-behaved slice inside $C$. Thus, the cascade cannot start from outside $C$.



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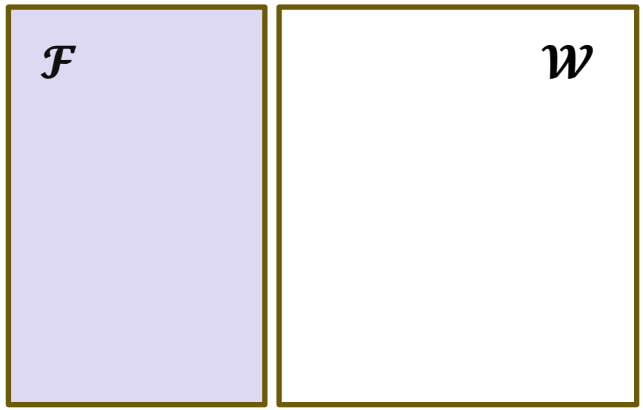

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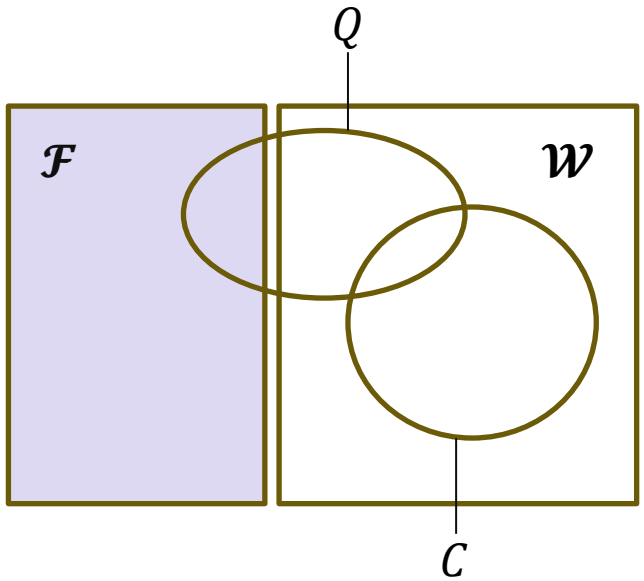

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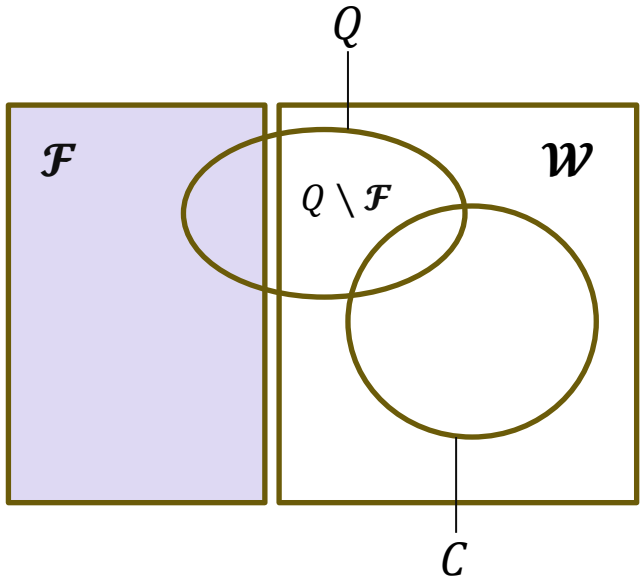

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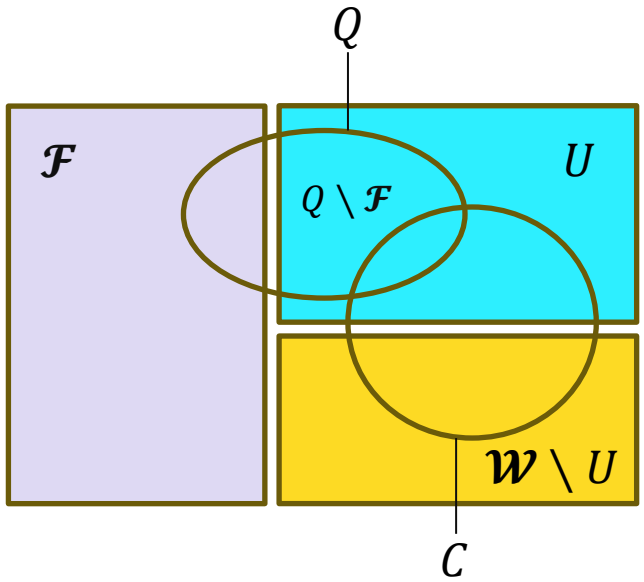

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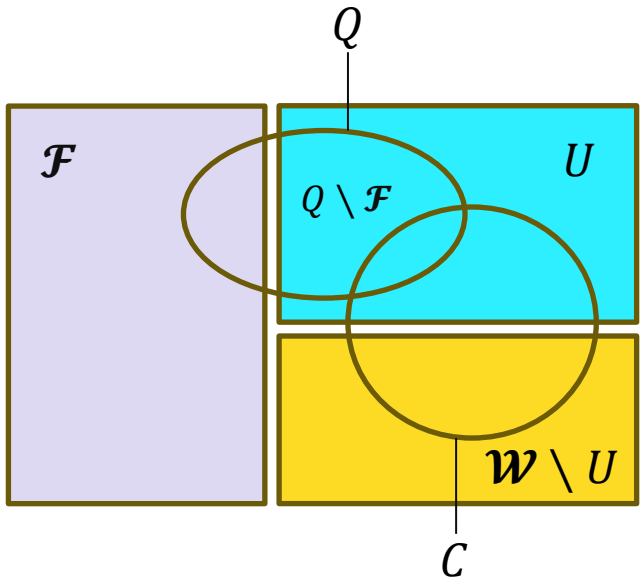

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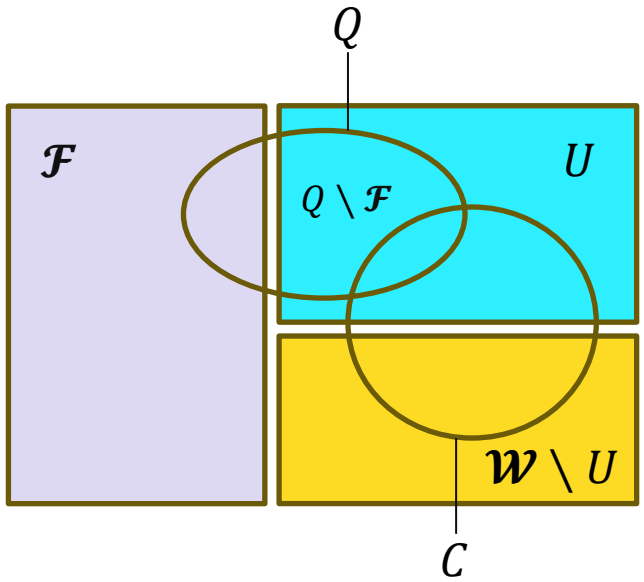

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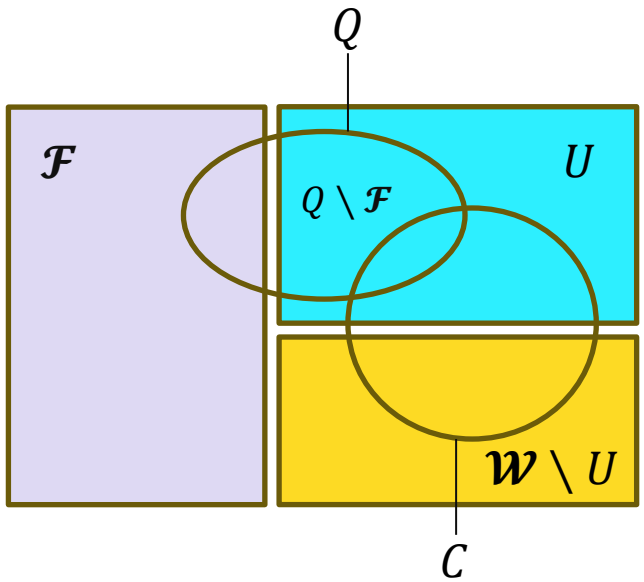

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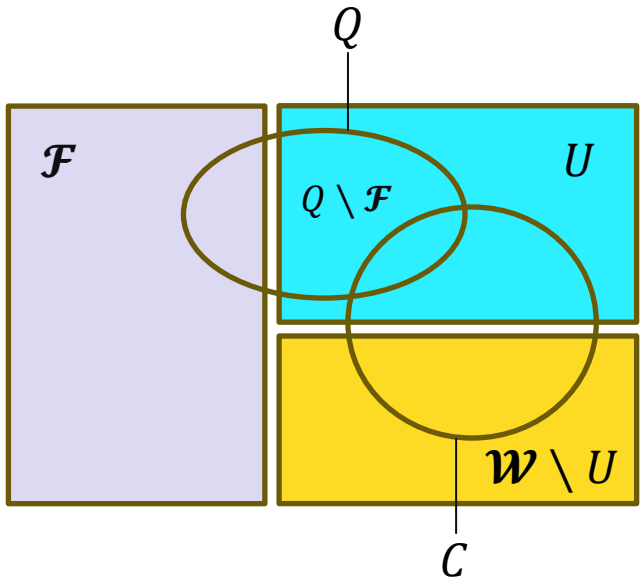

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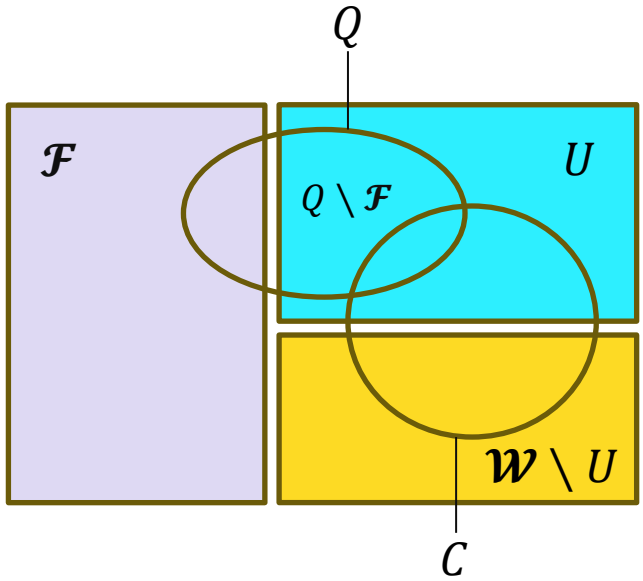
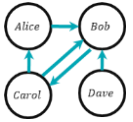
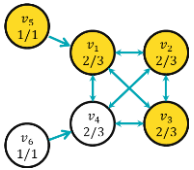
6. Thus, $C$ is not intertwined. Contradiction!

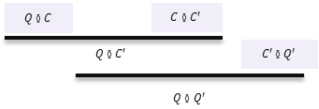


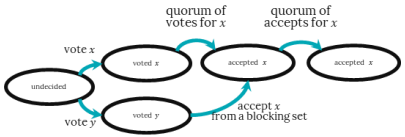
# Recap: Reliable Voting in FBA

1. Validators declare local agreement requirements
2. Subjective quorums emerge as sets that satisfy the requirements of all their members
3. Byzantine validators can “cut” the quorums of well-behaved validators
4. The system partitions itself into disjoint clusters
5. The Federated Voting algorithm solves Reliable Voting for consensus clusters
    - Without initial knowledge of who participates
    - Without knowing which sets are clusters



# Roadmap

- ✓ Intro: the problem of issuer-enforced finality
- ✓ Background: Partial Synchrony, Total-Order Broadcast, BFT quorum systems, Reliable Voting
- ✓ Quorums in Federated Byzantine Agreement systems
- ✓ Reliable Voting in FBA systems
  - ✓ A simple, safe straw-man protocol (attaching slices to vote messages)
  - ✓ Quorum intersection is not that simple (possible quorums)
  - ✓ Consensus clusters (maximal disjoint clusters are disjoint)
  - ✓ Obtaining Totality: the Federated Voting protocol
- ➢ Total-Order Broadcast by porting Simplex to FBA

# Total-Order Broadcast in FBA with the Simplex algorithm

Simplex is a popular and simple blockchain consensus algorithm

- Chan and Pass, ***Simplex consensus: A simple and fast consensus protocol***, TCC 2023
- Shoup, ***Sing a song of Simplex***, DISC 2024

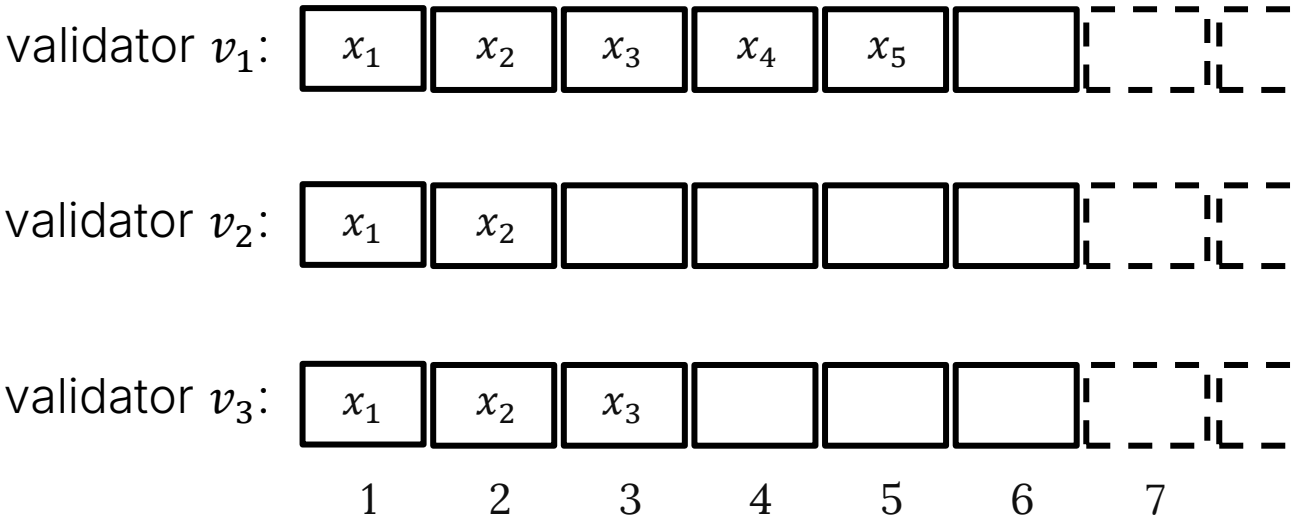
We will now see how we can phrase Simplex in terms of two building blocks: Reliable Voting and leader-election

This will make it easy to port Simplex to FBA

Note: for historical reasons, the Stellar network uses the Stellar Consensus Protocol (SCP), but Simplex is simpler to explain

# Remember Total-Order Broadcast

Each validator has a local copy of a shared log of values $x_1$, $x_2$, $x_3$, etc. and we must guarantee Validity, Agreement, and Progress



# First attempt: agree on which value to assign to each successive slot of the log using Reliable Voting

For slot $s$ from $0$ to $\infty$:

1. Arm a slot timer
2. Wait for a proposal from the pre-assigned slot leader (e.g., from validator number $(s\%N) + 1$, if we know $N$)
3. Vote for the leader's proposal using Reliable Voting
4. Upon confirming $x$ or timing out, go to the next slot

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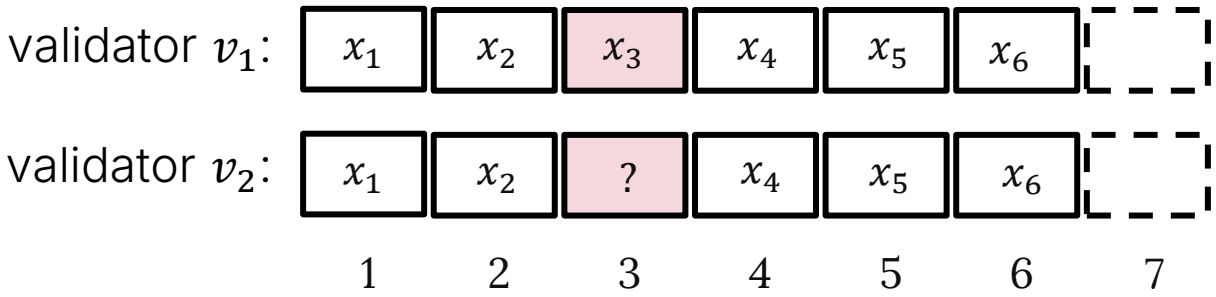
Problem: no agreement on whether a slot timed out or not



# The simplex solution

Each slot $s$, arm a timer and then vote twice:

1. On a pair $(x, s')$, proposed by the slot leader, where $s'$ is the slot's parent
2. On whether the first vote completed timely (before the timer) or late (timed out)

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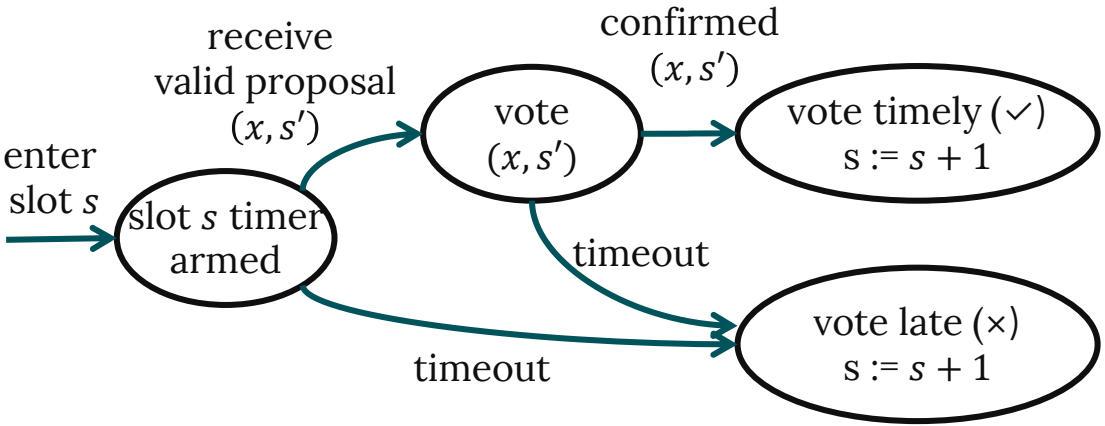


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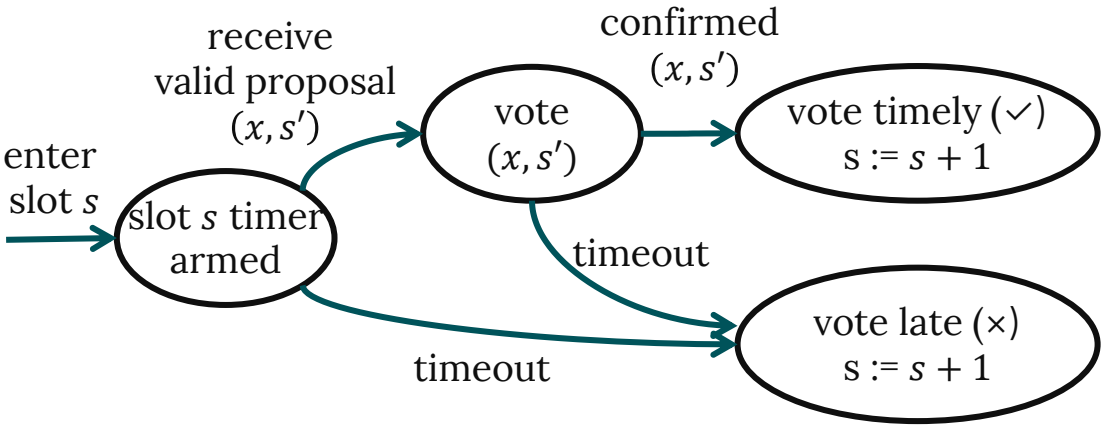



slot $s$

4 possible slot states:

$(x, s')$ ✓

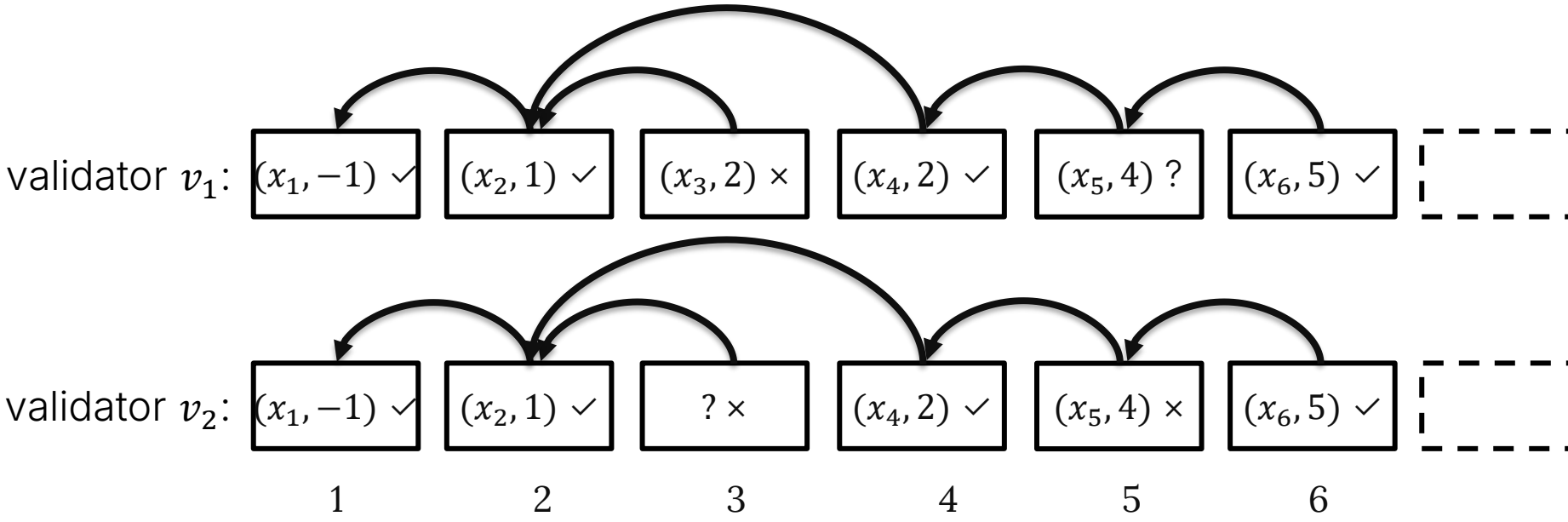
$(x, s')$ ?

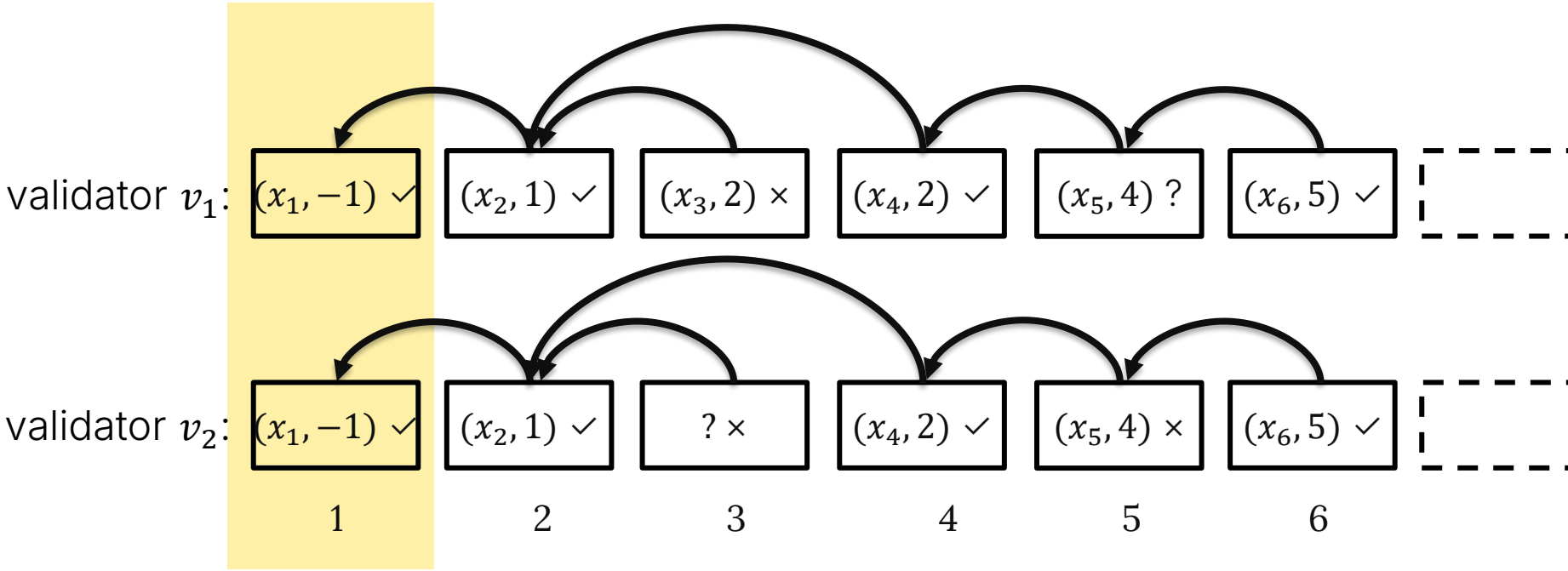
$(x, s')$ ×

? ×

Impossible slot state:

? ✓


validator $v_1$:
$(x_1, -1)$ ✓
$(x_2, 1)$ ✓
$(x_3, 2)$ ×
$(x_4, 2)$ ✓
$(x_5, 4)$ ?
$(x_6, 5)$ ✓
validator $v_2$:
$(x_1, -1)$ ✓
$(x_2, 1)$ ✓
? ×
$(x_4, 2)$ ✓
$(x_5, 4)$ ×
$(x_6, 5)$ ✓
1
2
3
4
5
6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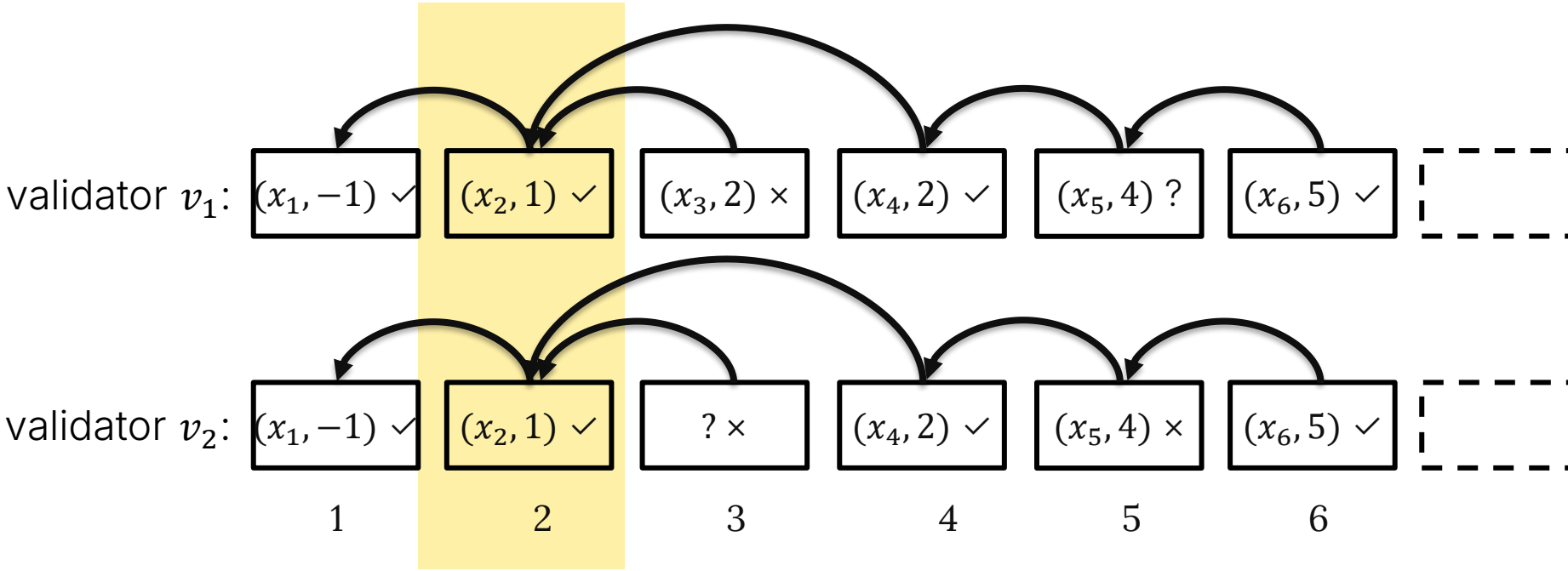
log: $x_1$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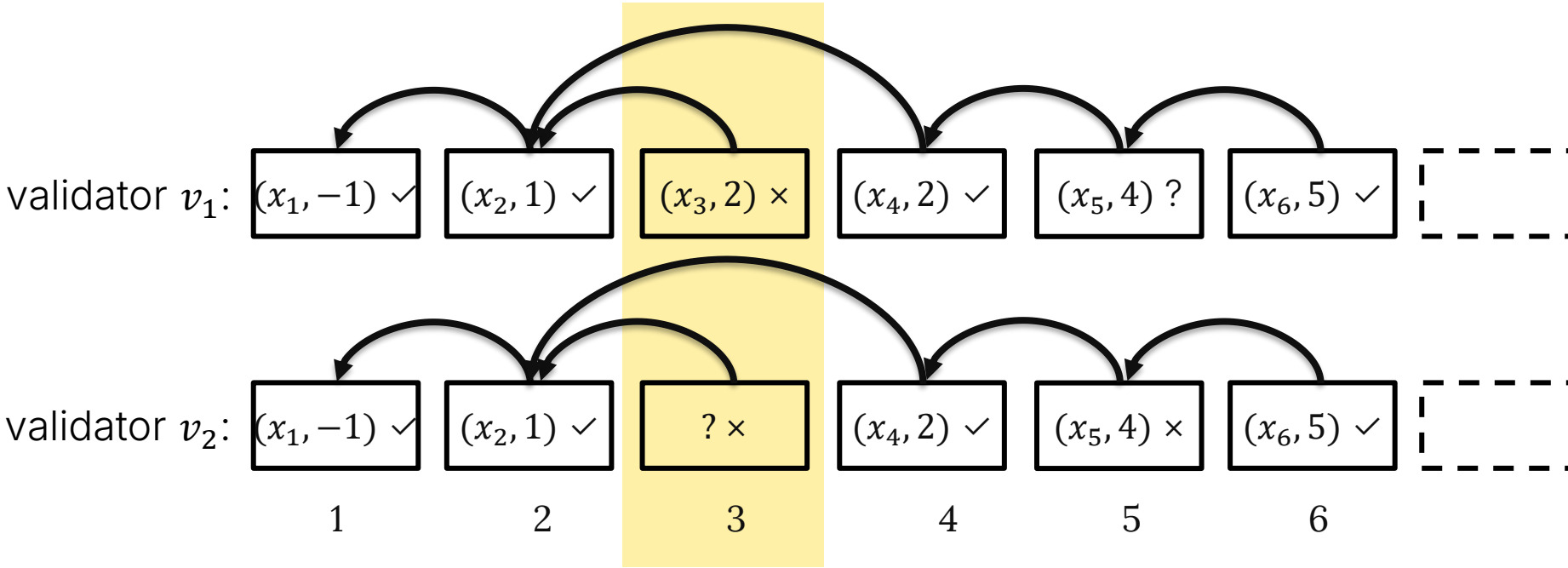
log: $x_1, x_2$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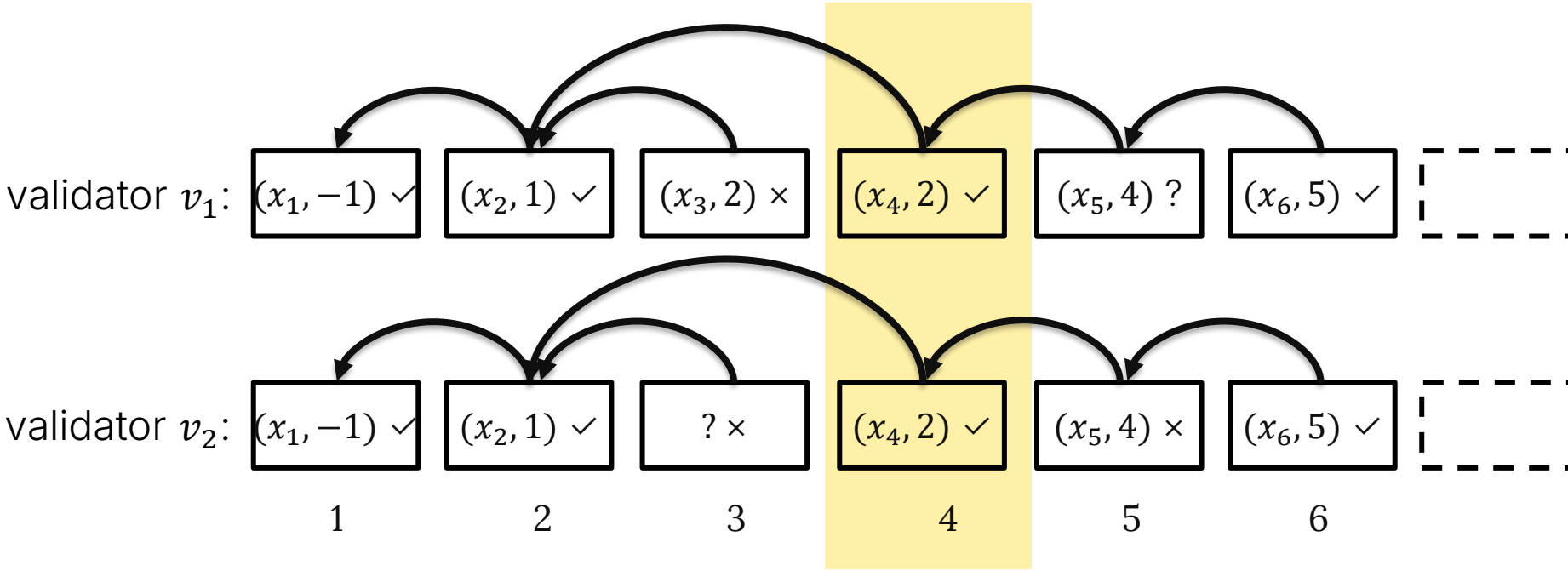
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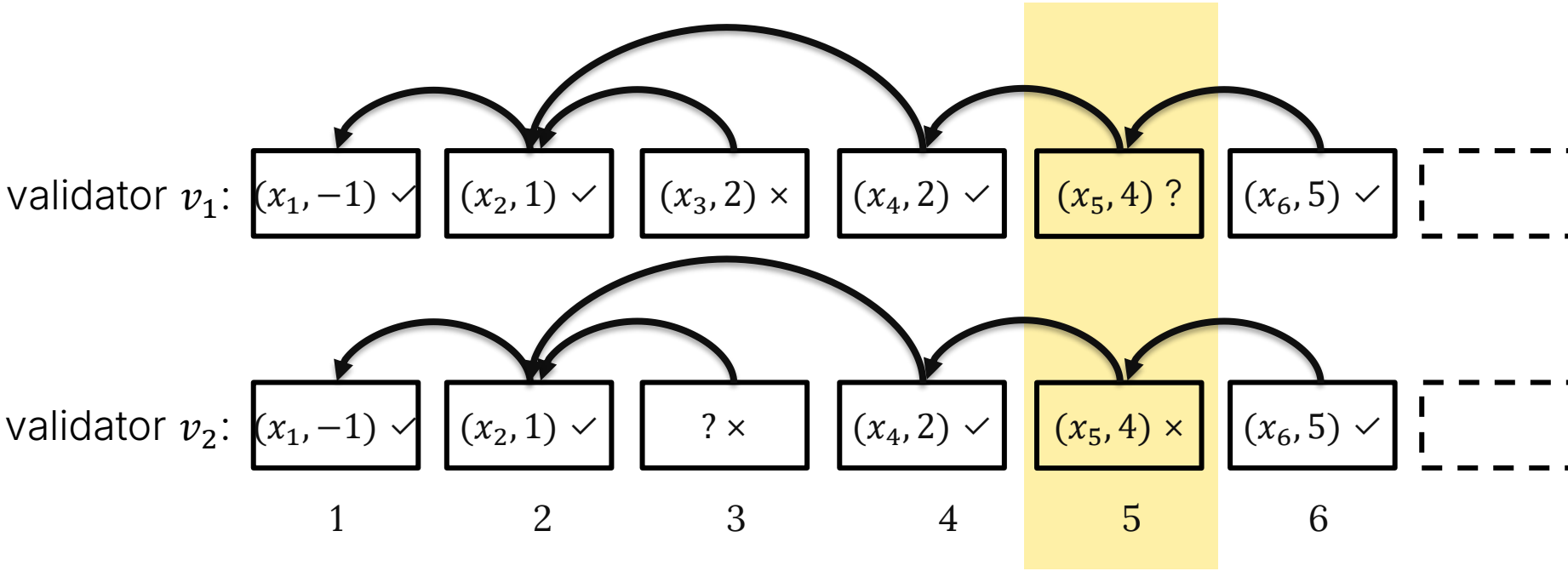
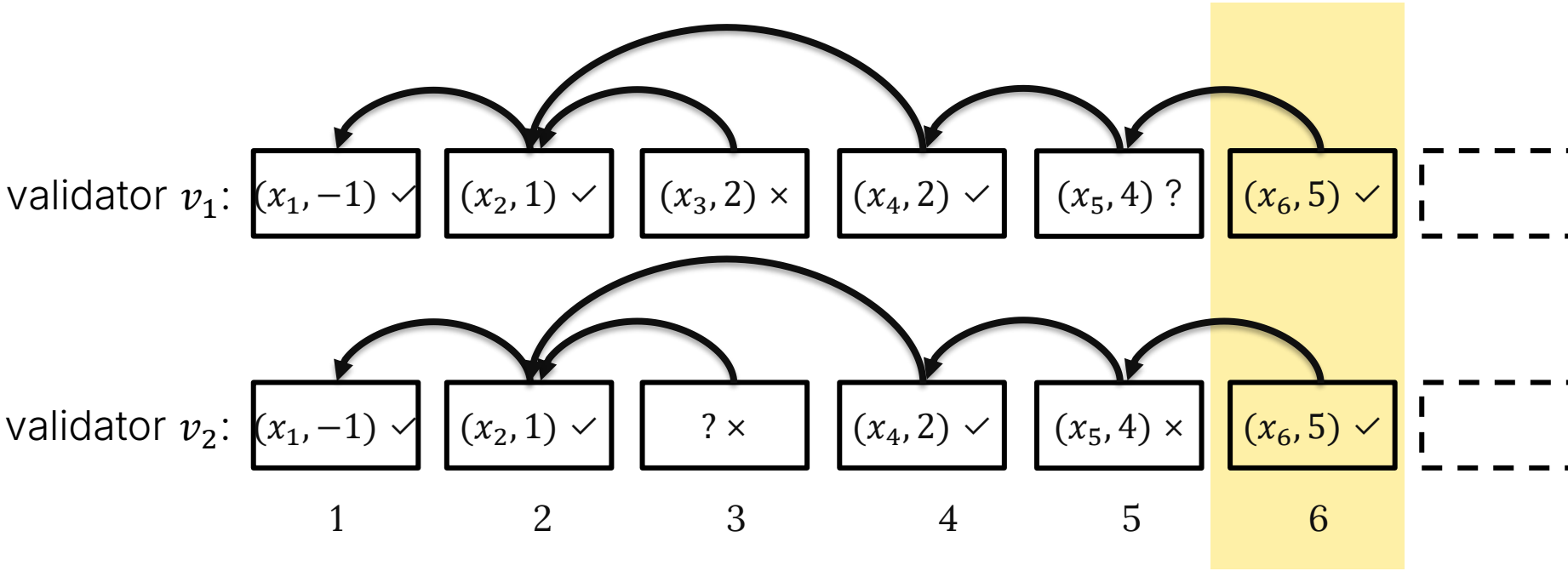
6

log: $x_1, x_2, x_4$

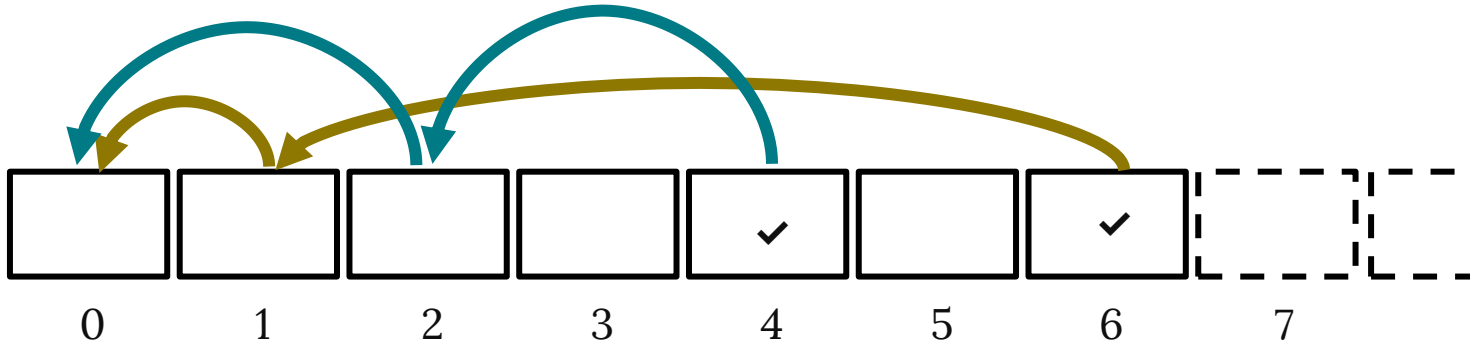



log: $x_1, x_2, x_4, x_5$




log: $x_1, x_2, x_4, x_5, x_6$

# Agreement is guaranteed



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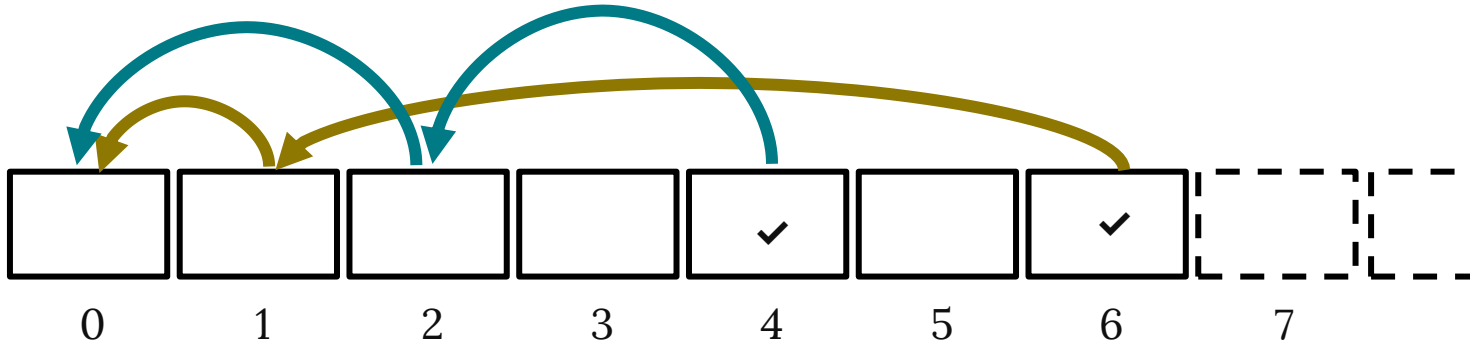
If we have a fork, consider the two confirmed-timely slots *s* and *s'* at the tips.



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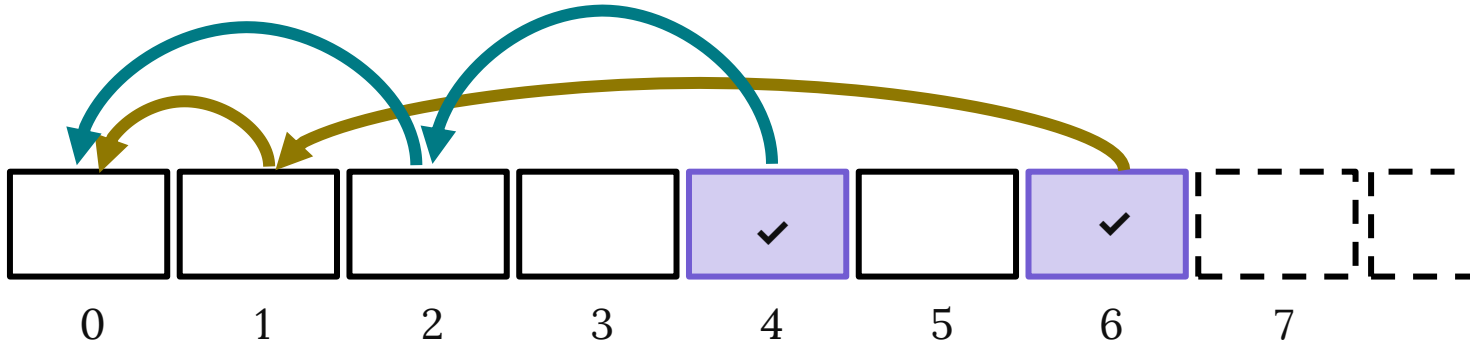

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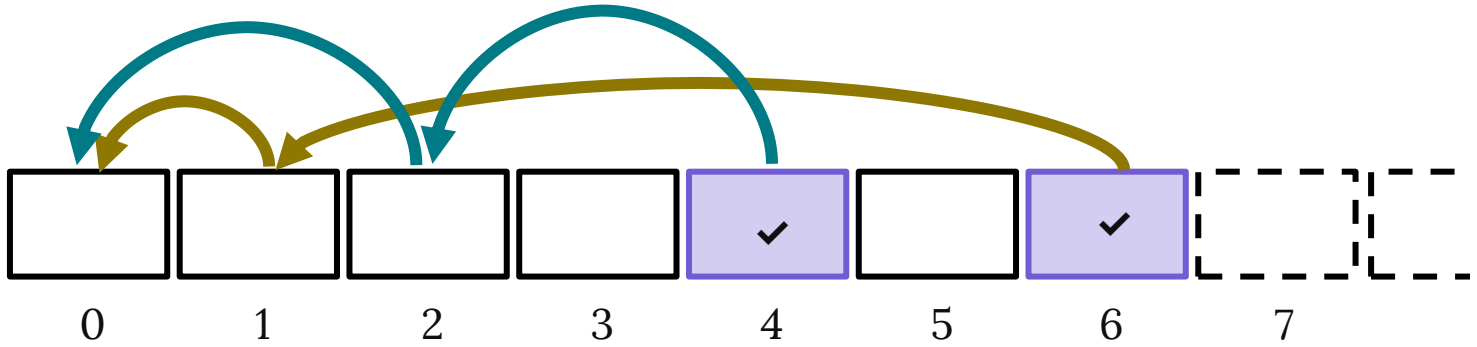
The branch of the higher tip must jump over the lower tip



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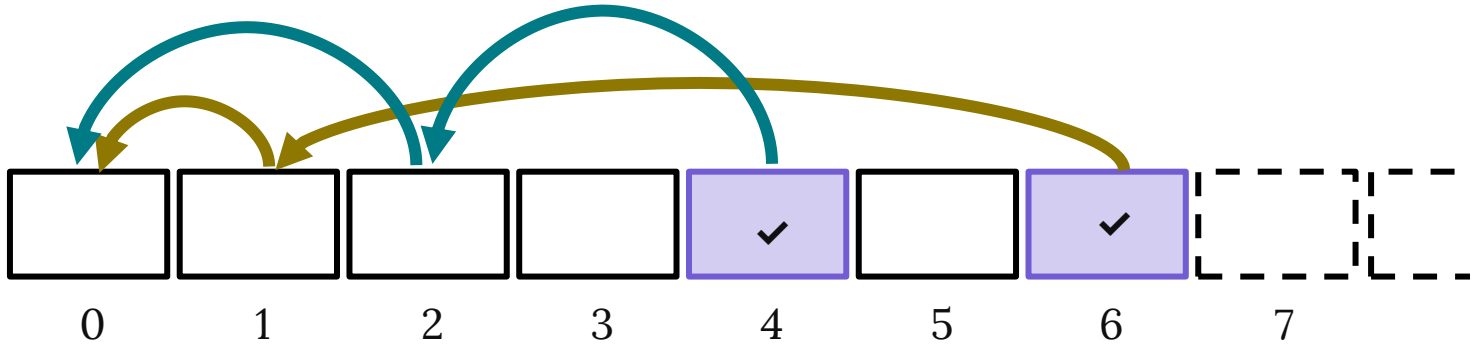
If we have a fork, consider the two confirmed-timely slots *s* and *s'* at the tips.

The branch of the higher tip must jump over the lower tip

This contradicts the fact that slots between a slot and its parent must be confirmed late



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**Lemma**:
At least one of the two votes terminates

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**Lemma**:
At least one of the two votes terminates

**Proof**:

Suppose that the first vote gets stuck

Then all well-behaved validators time out and vote for “skip” in the second vote

By Unanimity of Reliable Voting, they all confirm the slot skipped

# In periods of synchrony, slots commit

If validators' timers are large enough compared to the network delay and the slot leader is well-behaved, then all well-behaved validators commit

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# In periods of synchrony, slots commit

If validators' timers are large enough compared to the network delay and the slot leader is well-behaved, then all well-behaved validators commit

- Under asynchrony, we can keep starting new slots (we won't get stuck), until...
- Under synchrony, new slots that have a well-behaved leader commit

# Simplex in FBA

We have seen that simplex relies on two building blocks:

- Reliable Voting
- Assigning leaders to slots

✓ We have already seen how to implement Reliable Voting

▪ We need a way to assign leaders to slots!

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If validators know $N$, we can say validator number $(s\%N) + 1$ is leader of slot $s$

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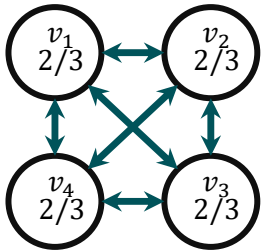

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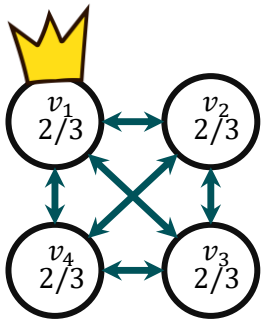

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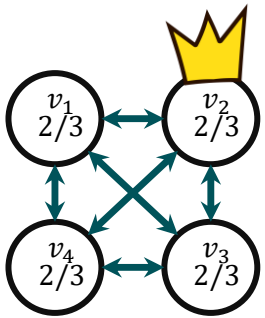

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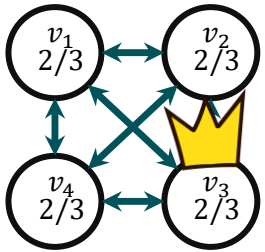

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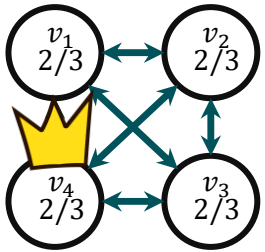

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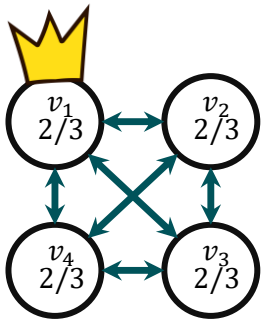

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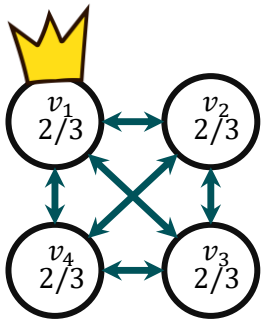

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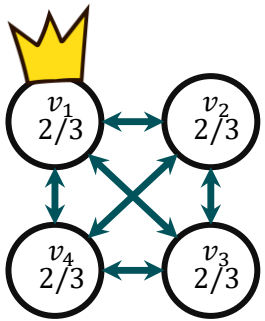


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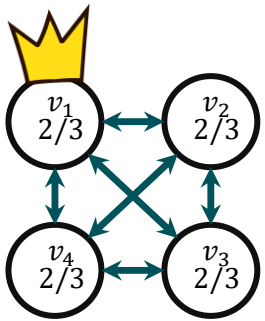


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In synchronous, crash-only periods, this avoids electing crashed validators, guarantees agreement on the slot leader, and achieves fair rotation

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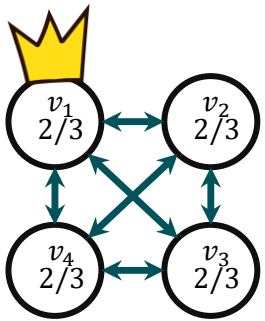


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*Problem: Does not work in FBA because attackers can pollute $K$ with as many validators as they want (often called a Sybil attack)*

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We want to assign a leader to each slot $s$ such that:

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- If a validator has crashed, it is not assigned as leader of new slots
- Disagreement on the leader is okay if it is unlikely under normal conditions (validators disagreeing on the slot leader can prevent committing, but is not a safety issue)

# Assigning leaders to slots in FBA

Idea: Just adapt the BFT solution

- Derive a pseudorandom ranking from the slot number (e.g., hash validator ID + slot number)
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Problem

If validators have significantly different sets of quorum slices, agreement is unlikely because their $K$s will be significantly different

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- This forms a set of disjoint, rooted trees
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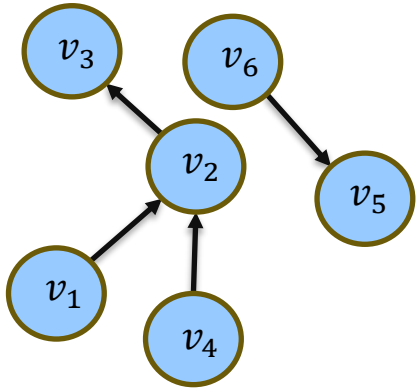

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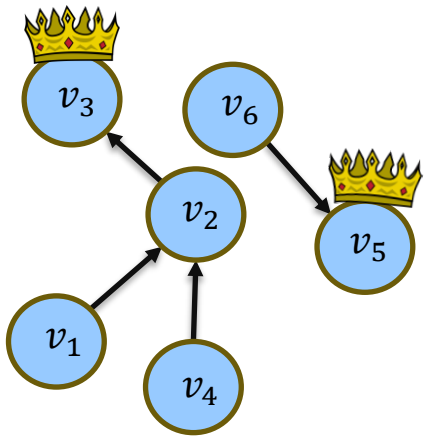

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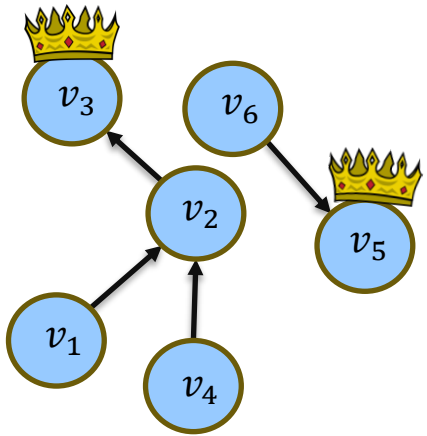
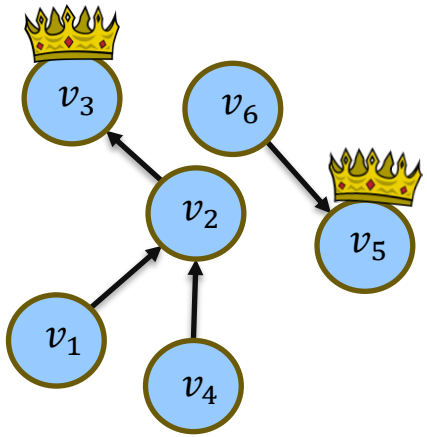
This reduces the number of leaders, but disagreement is still too likely



# Assigning leaders to slots: second improvement

Use Federated Voting to reach agreement on the leader

✓ If a quorum of a cluster initially agrees, then the full cluster will confirm the leader



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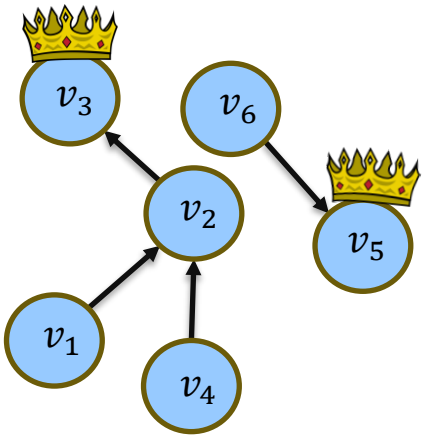
Problem

- Federated Voting can get stuck
- Then could we just repeat?
- Same problem as with the TOB non-solution: there is no agreement on whether a vote got stuck or not



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Observation: initial leader votes are determined pseudo-randomly using a common seed, so the result of  Federated Voting is deterministic and can be simulated locally “in the head”

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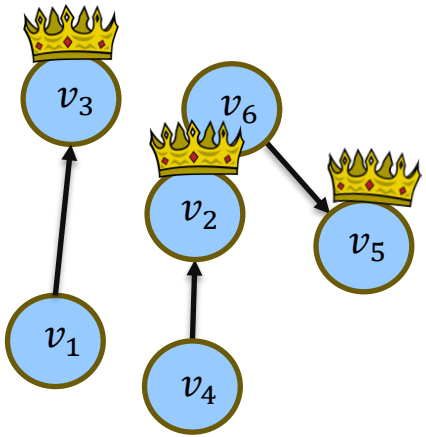


round 1: no leader confirmed

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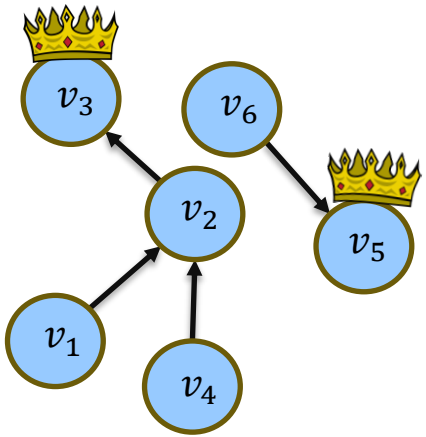


round 2: leader confirmed

# Roadmap

- ✓ Intro: the problem of issuer-enforced finality
- ✓ Background: Partial Synchrony, Total-Order Broadcast, BFT quorum systems, Reliable Voting
- ✓ Quorums in Federated Byzantine Agreement systems
- ✓ Reliable Voting in FBA systems
  - ✓ A simple, safe straw-man protocol (attaching slices to vote messages)
  - ✓ Quorum intersection is not that simple (possible quorums)
  - ✓ Consensus clusters (maximal clusters are disjoint)
  - ✓ Obtaining Totality: the Federated Voting protocol (and the cascade theorem)
- ✓ Total-Order Broadcast by porting Simplex to FBA
  - ✓ Simplex in terms of Reliable Voting
  - ✓ Leader election in FBA systems

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8. Malkhi and Reiter. *Byzantine quorum systems.* Distributed Computing, 1998.

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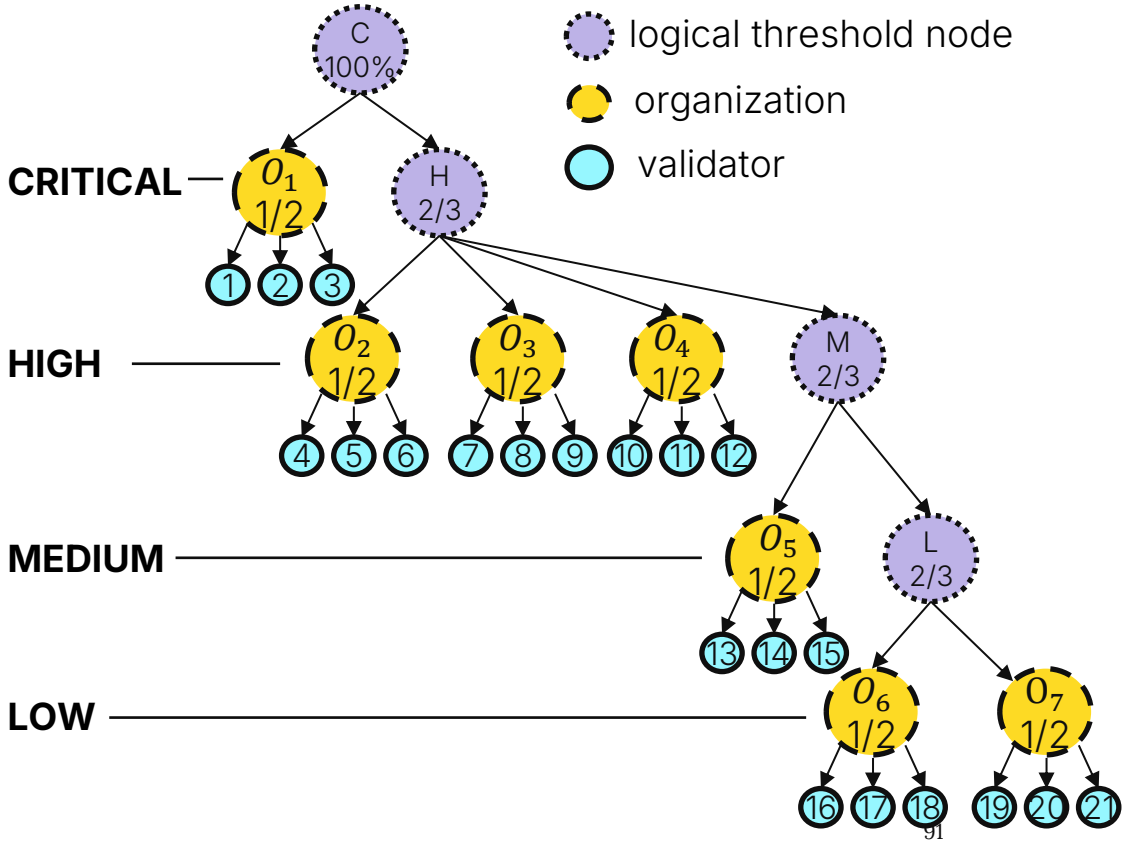

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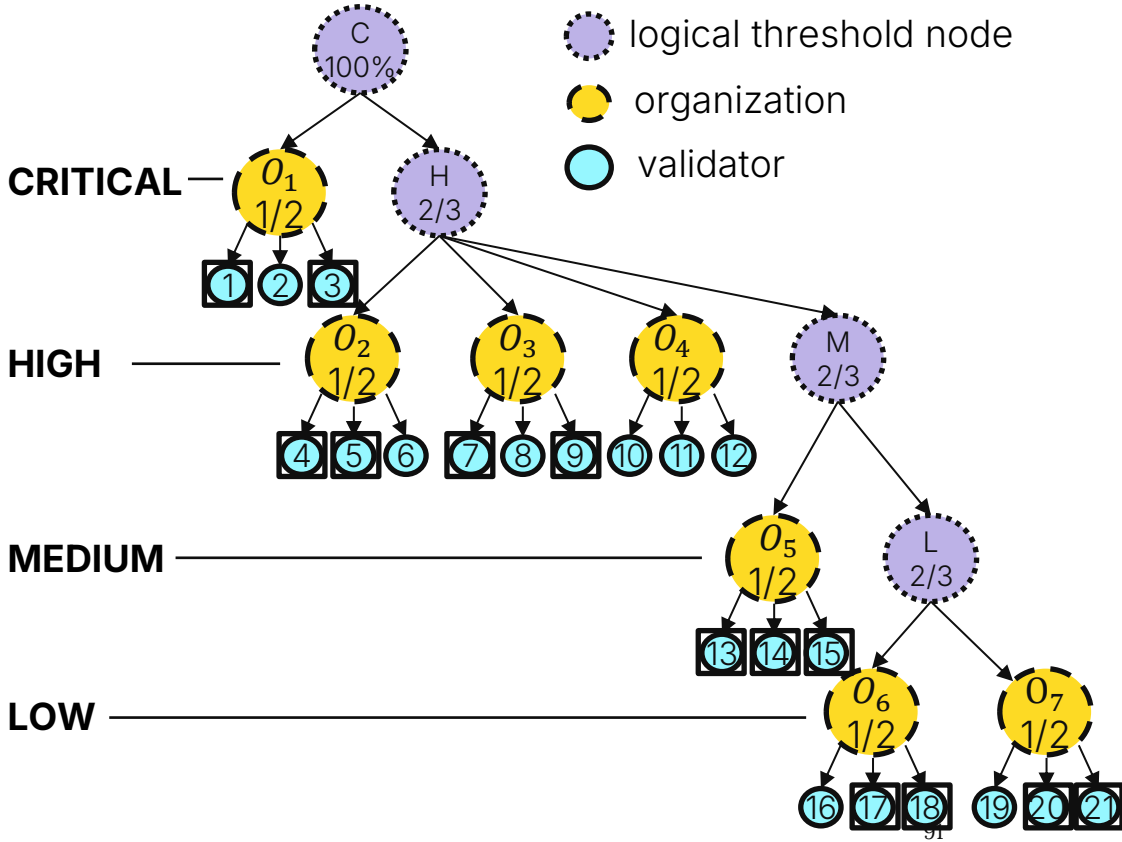

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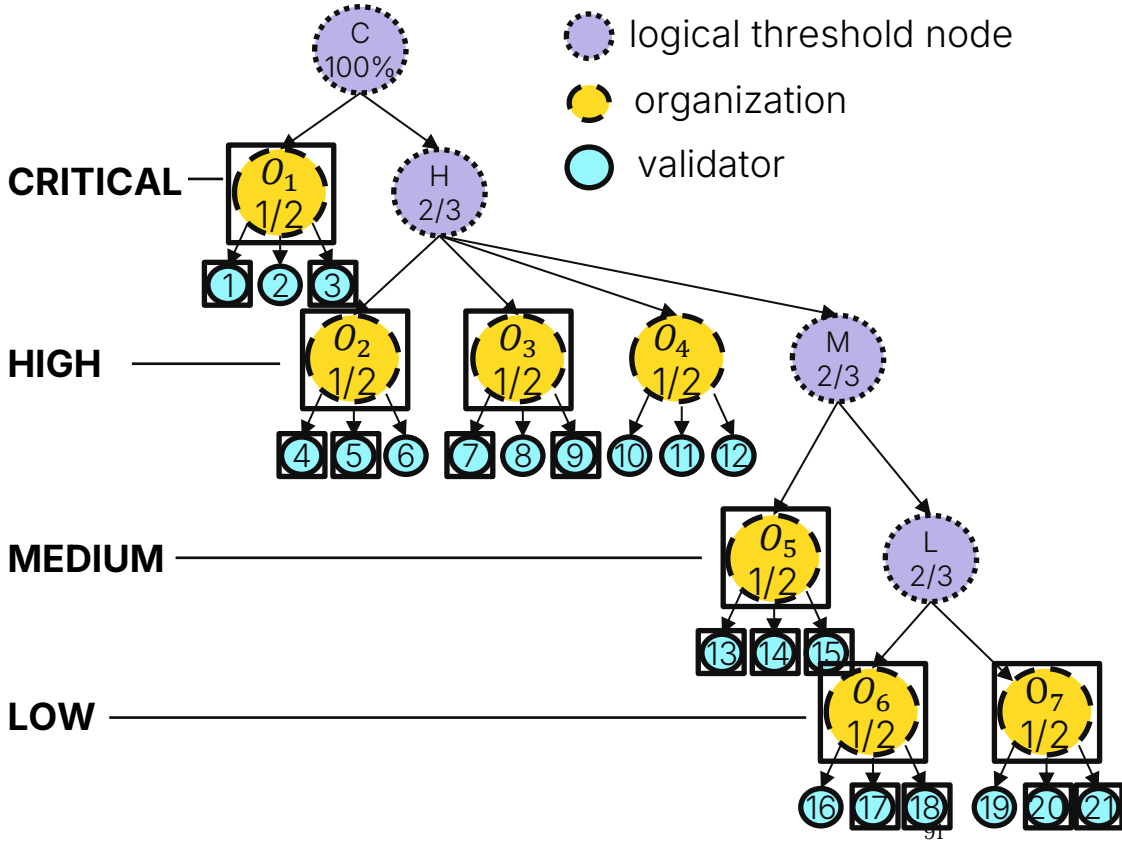

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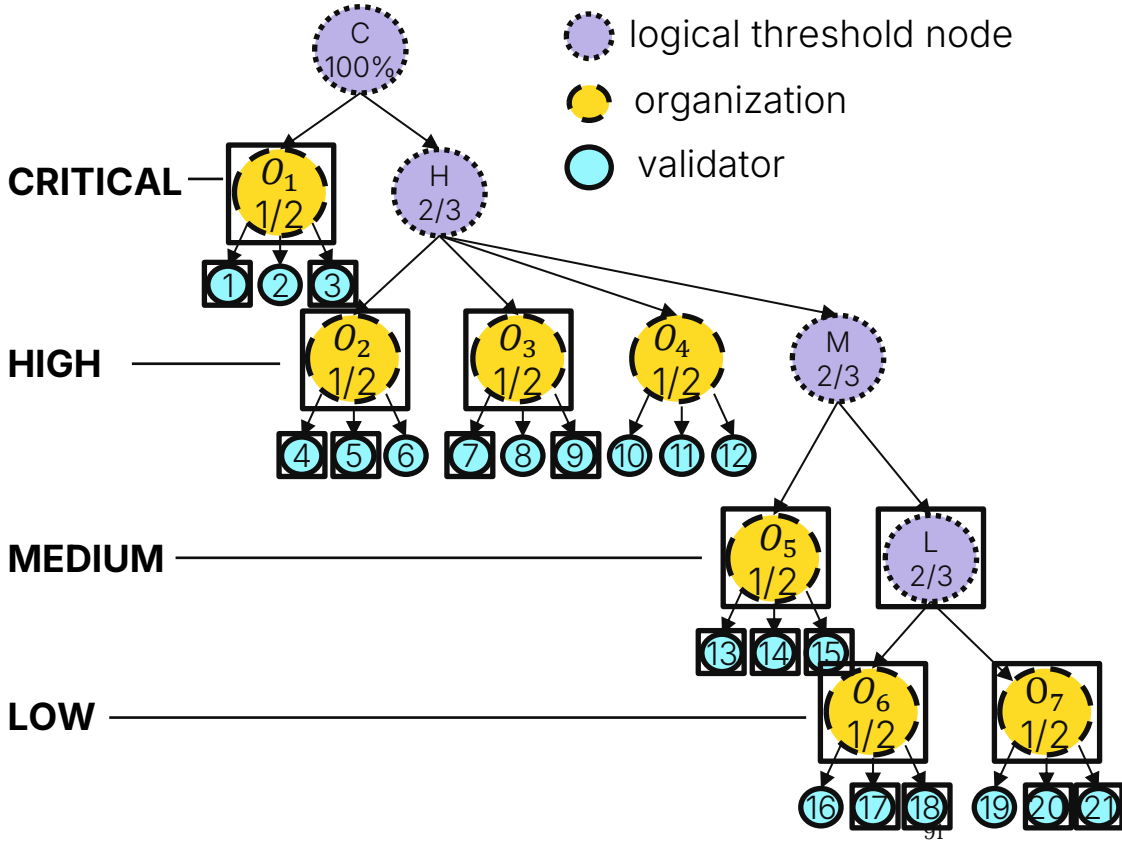

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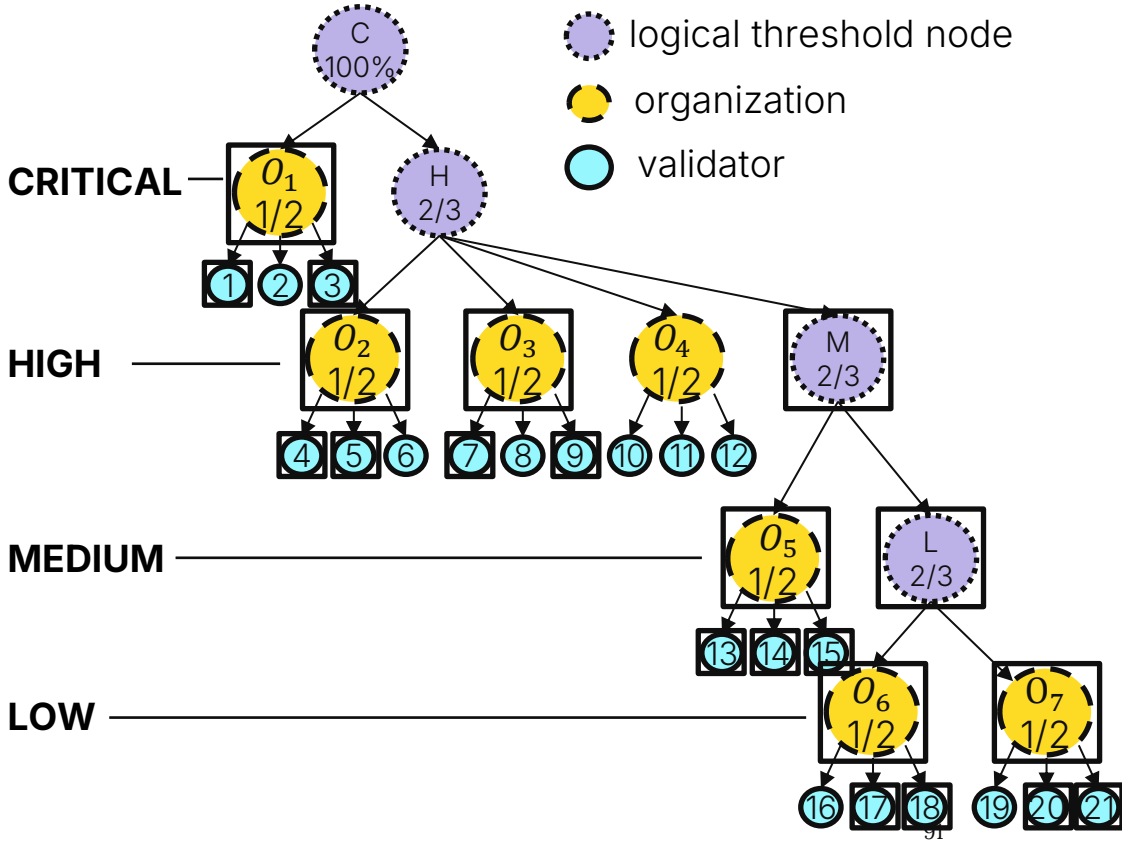

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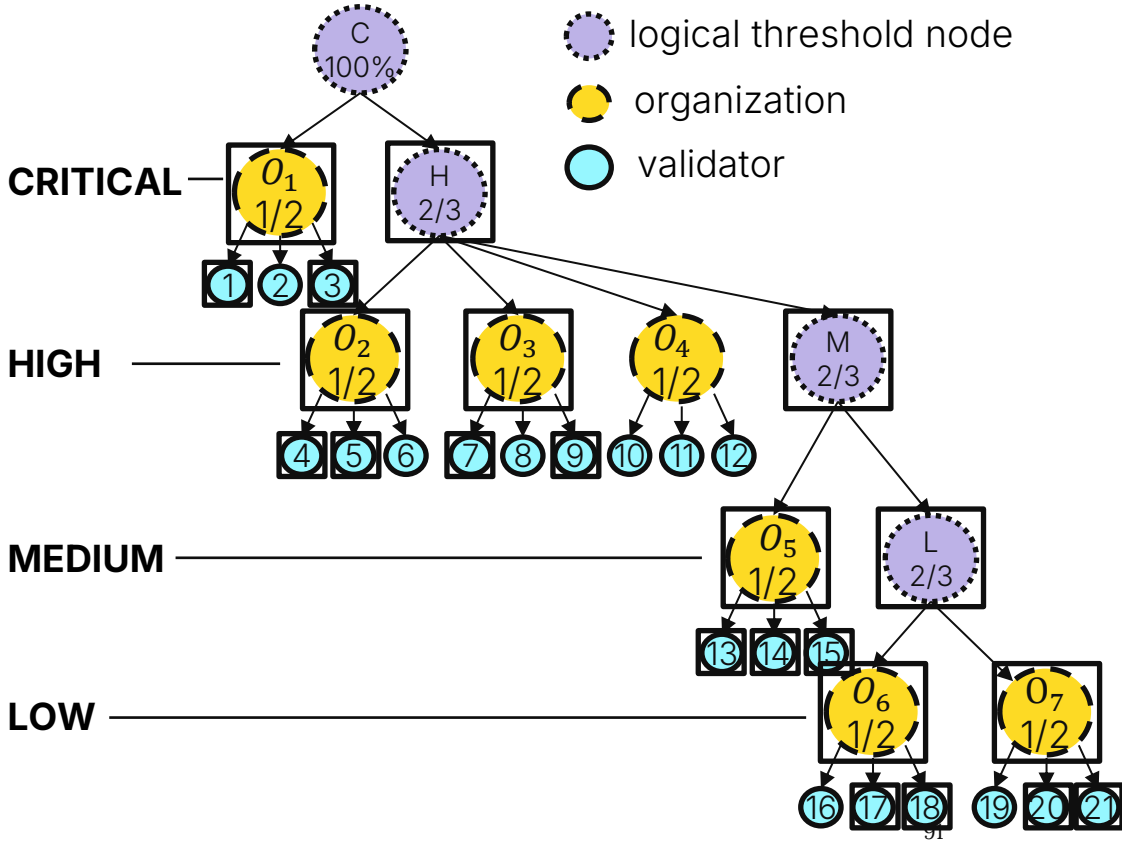

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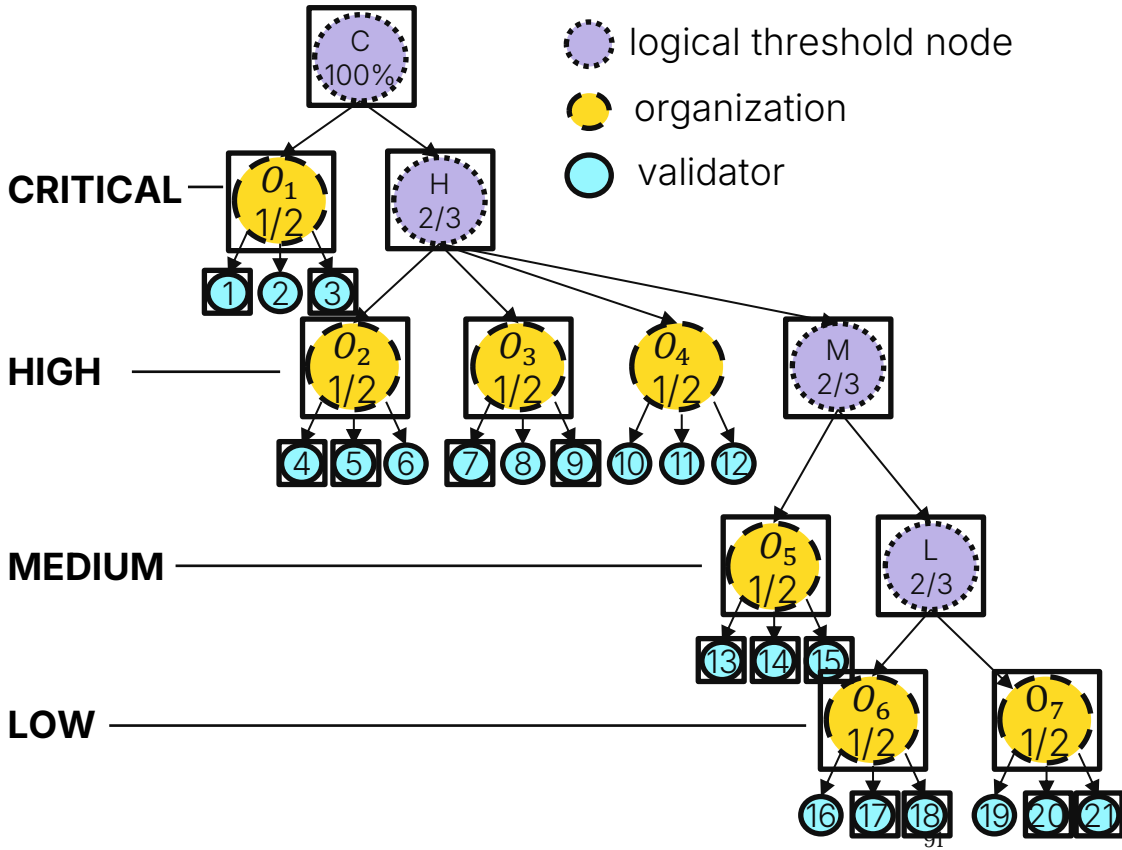

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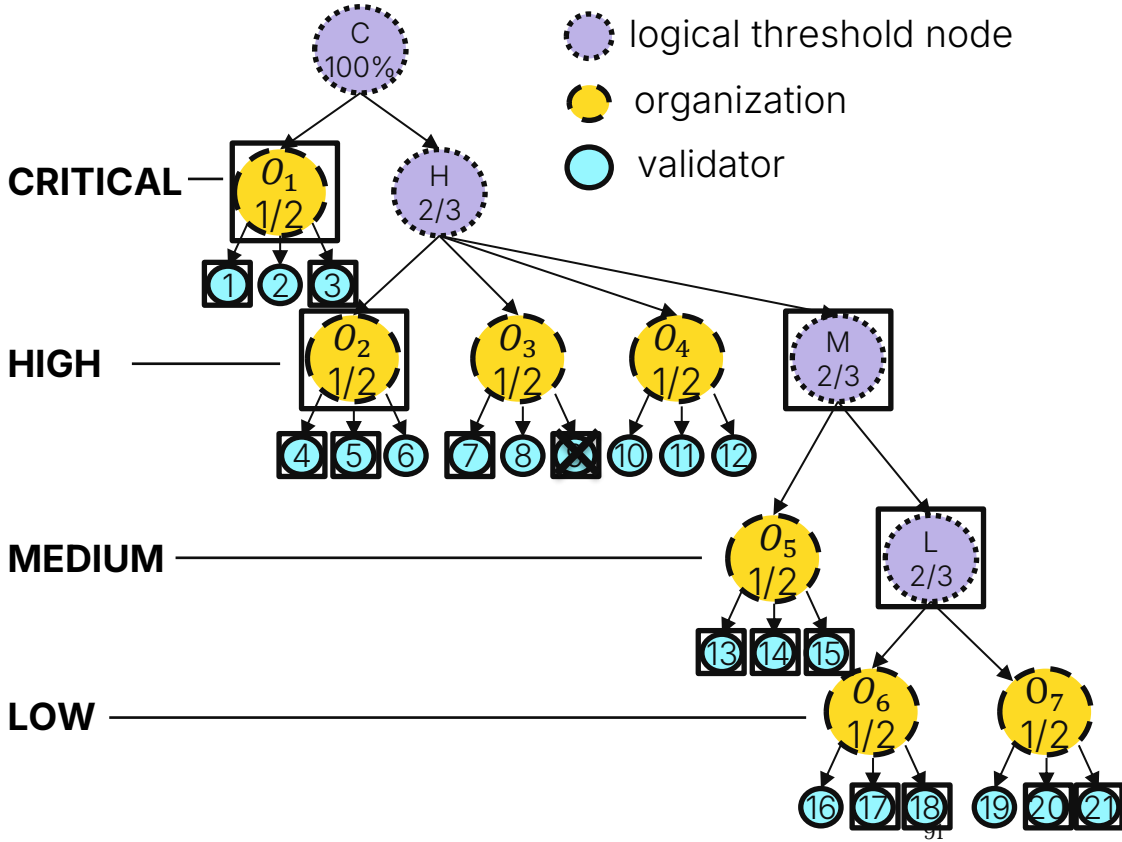

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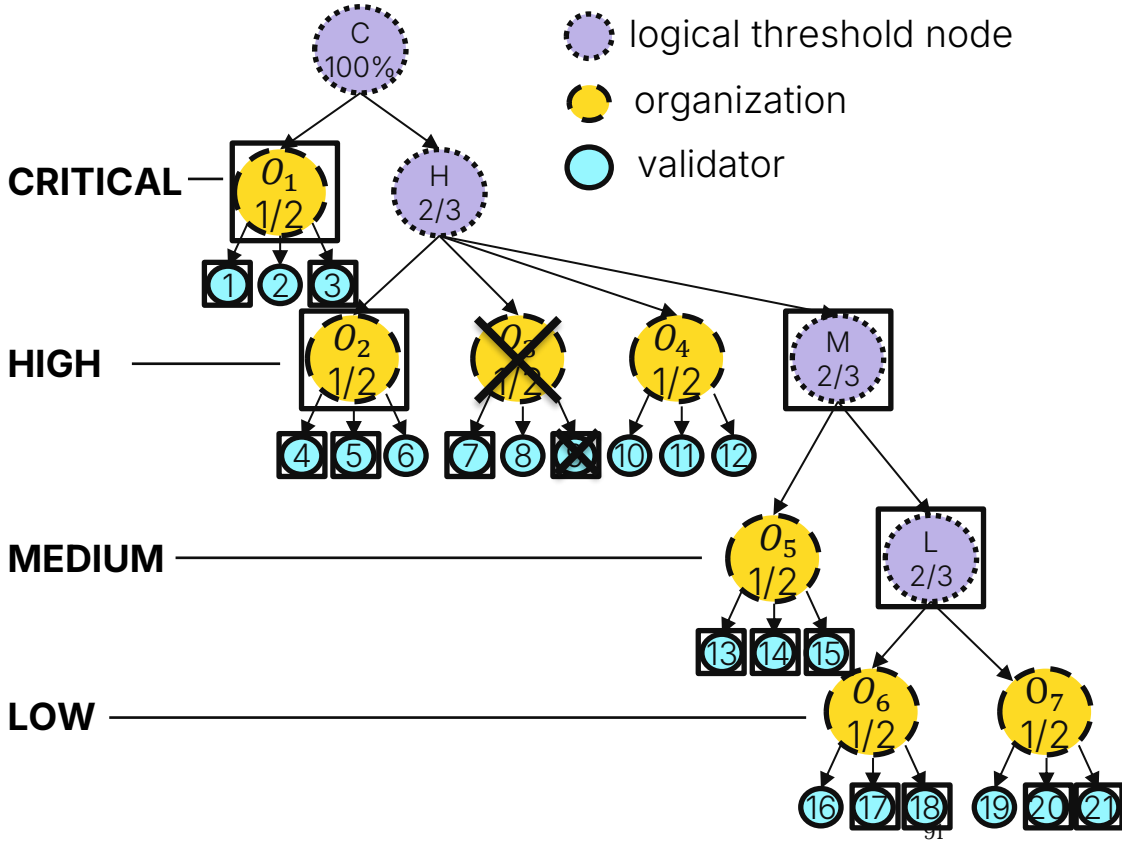

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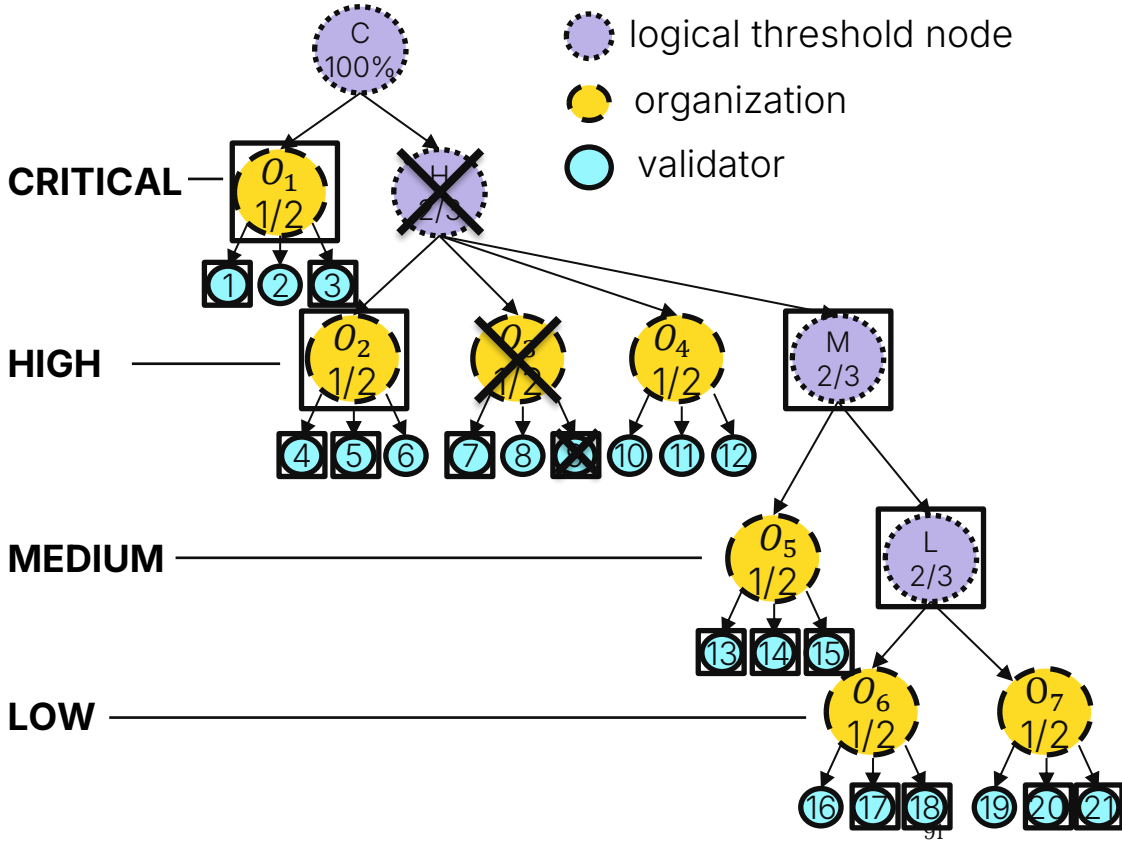

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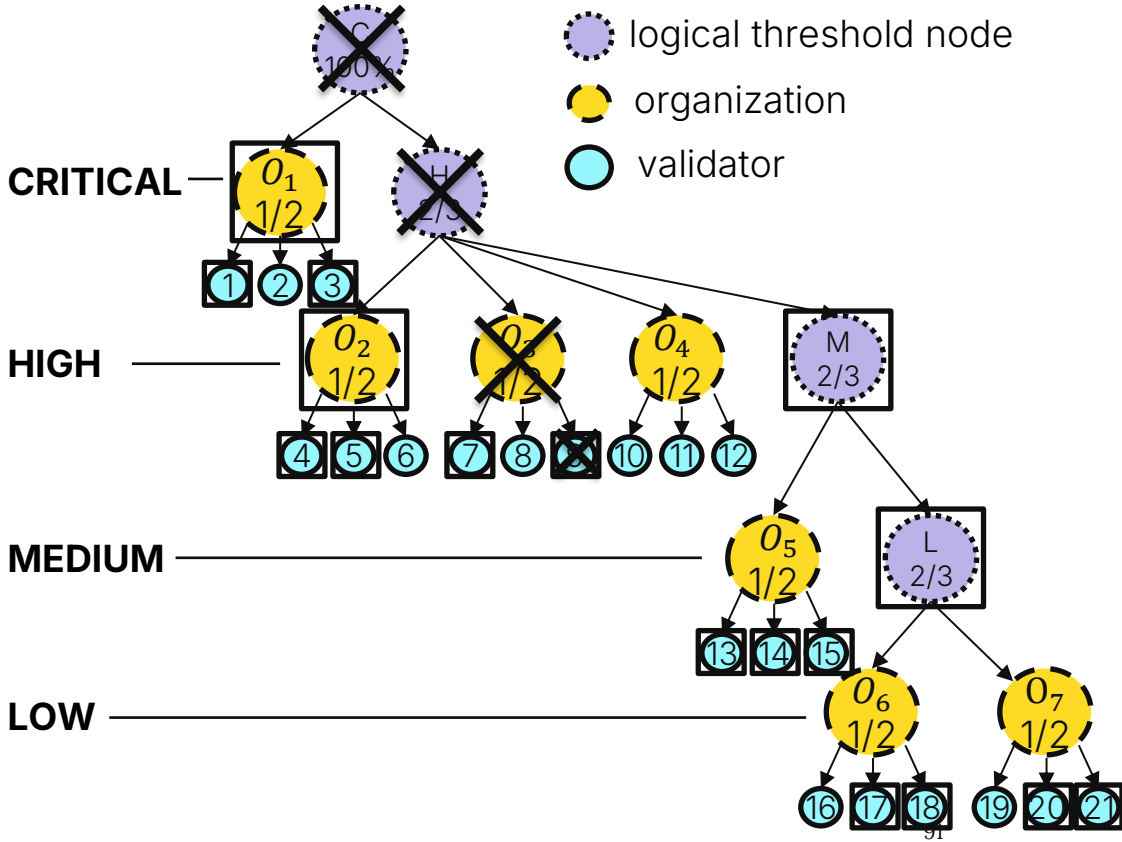
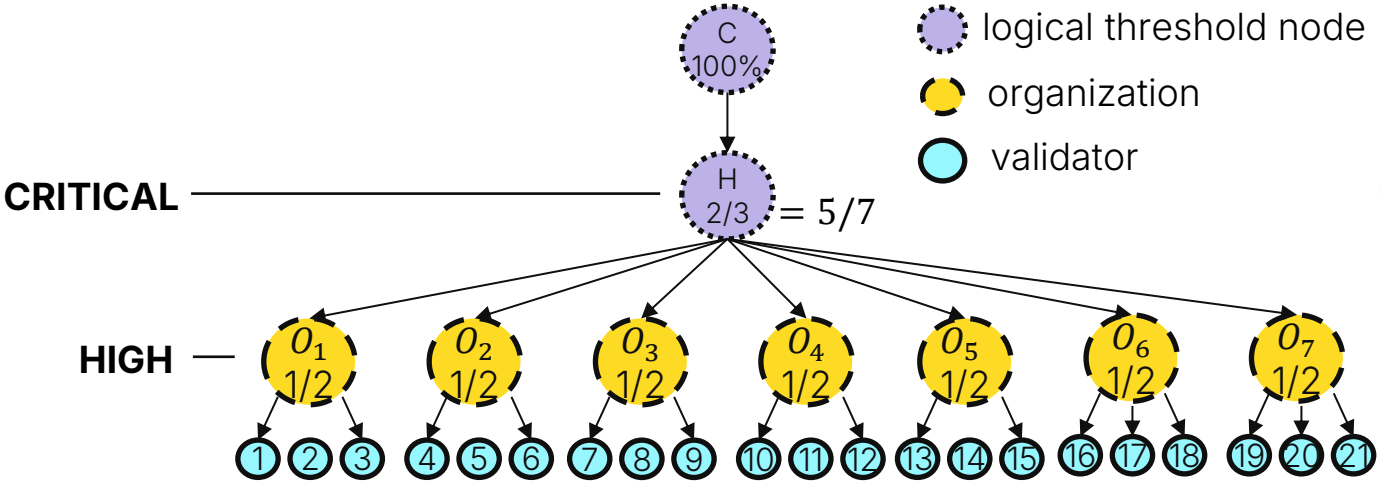
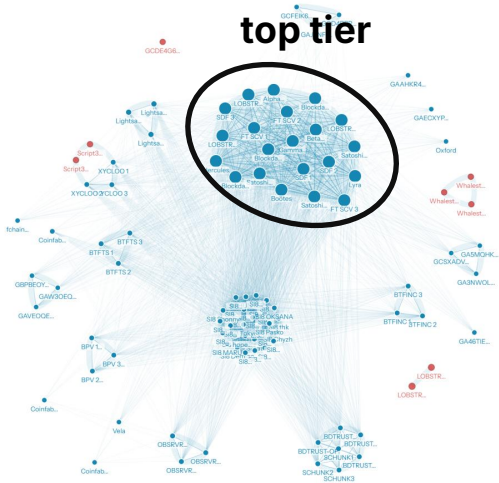


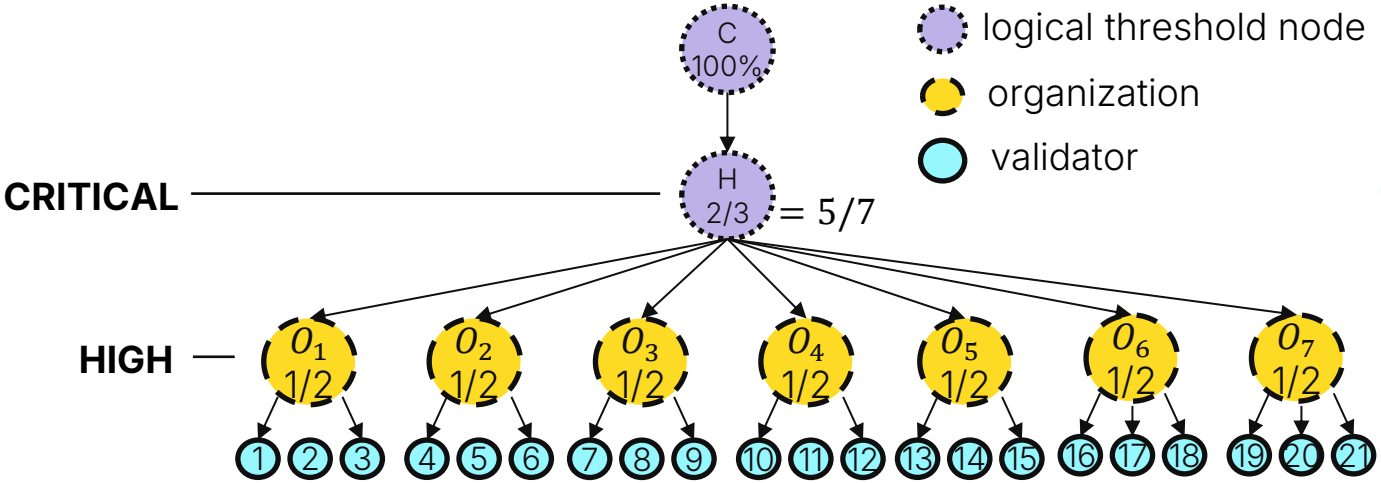
# Current top-tier configuration

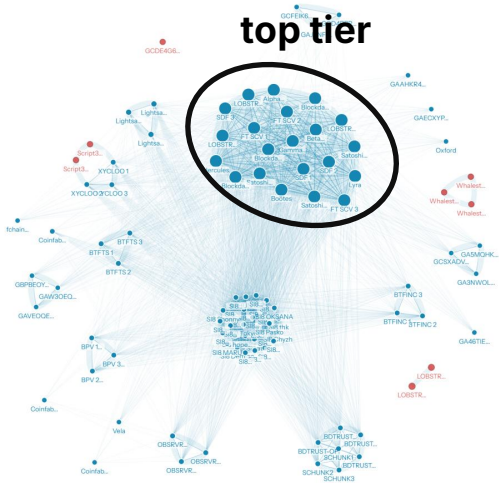



7 top-tier organizations
each setup as level HIGH
All have the same slices
⇒ quorum = slice

# Current top-tier configuration

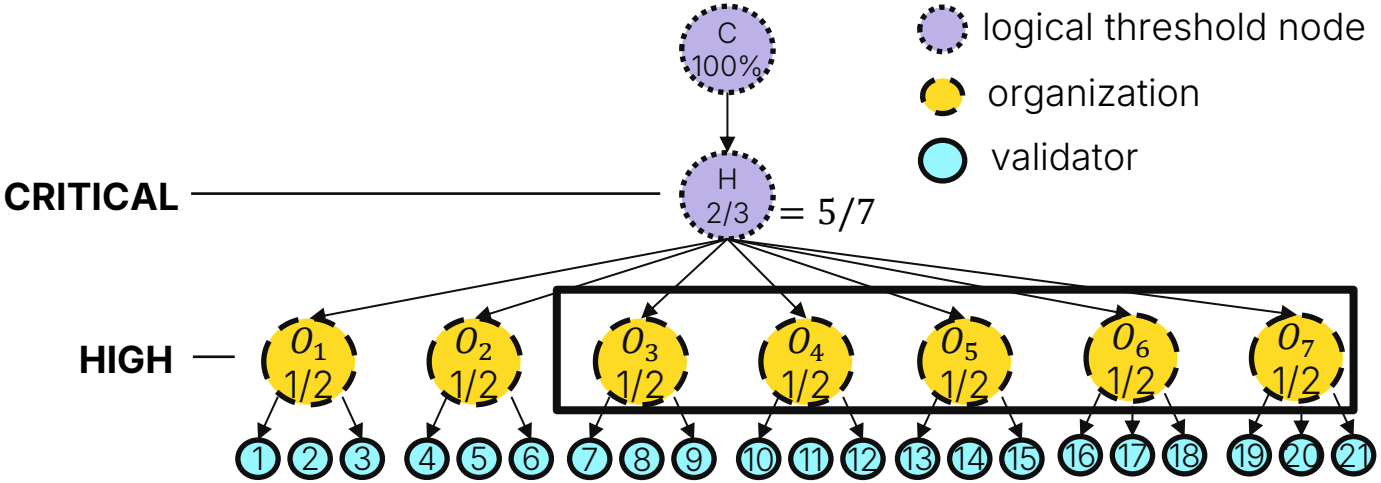


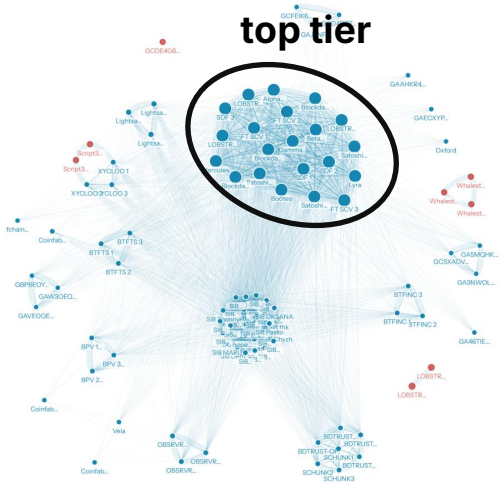




7 top-tier organizations
each setup as level HIGH
All have the same slices
⇒ quorum = slice

Minimal splitting set:

# Current top-tier configuration

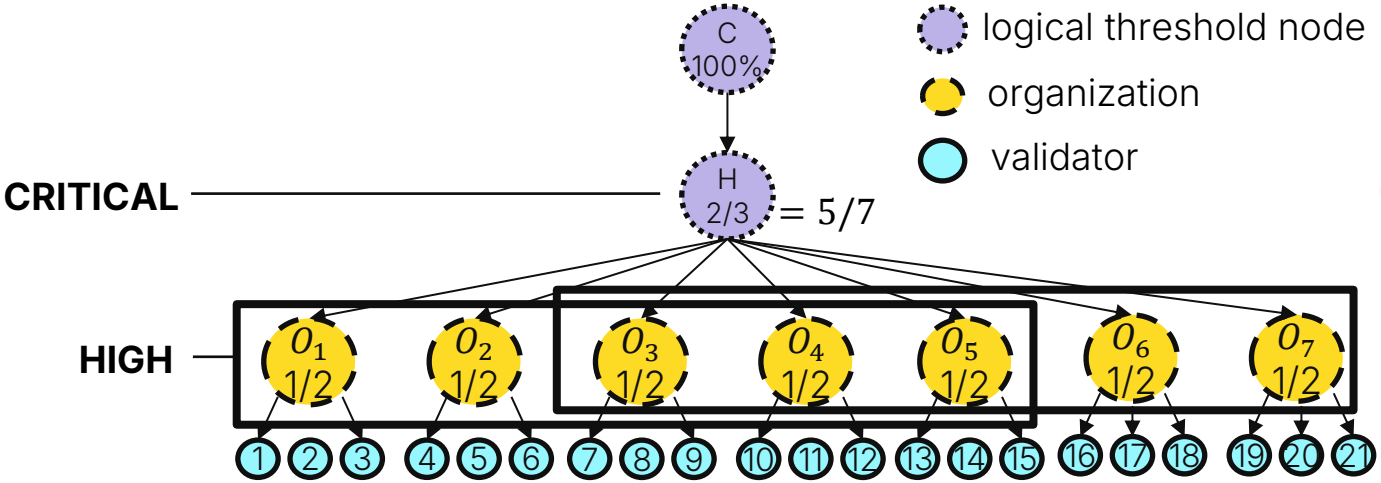


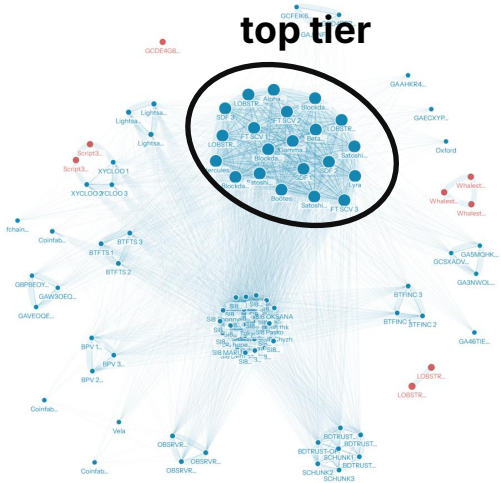




7 top-tier organizations
each setup as level HIGH
All have the same slices
⇒ quorum = slice

Minimal splitting set:

# Current top-tier configuration




7 top-tier organizations
each setup as level HIGH
All have the same slices
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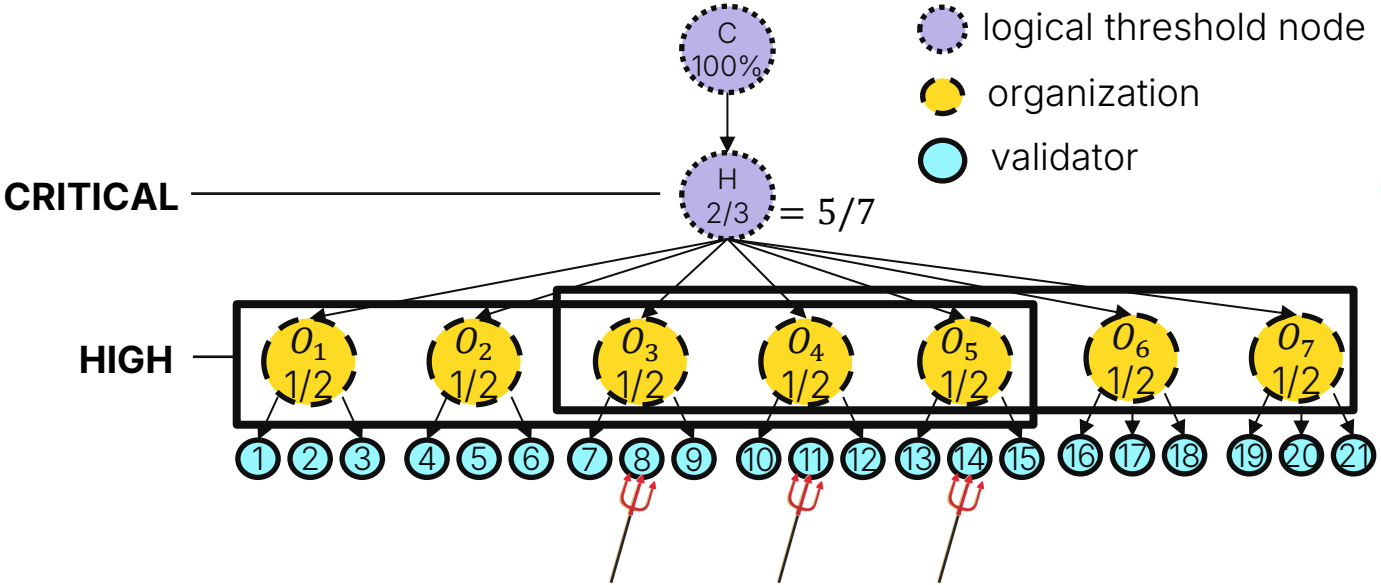
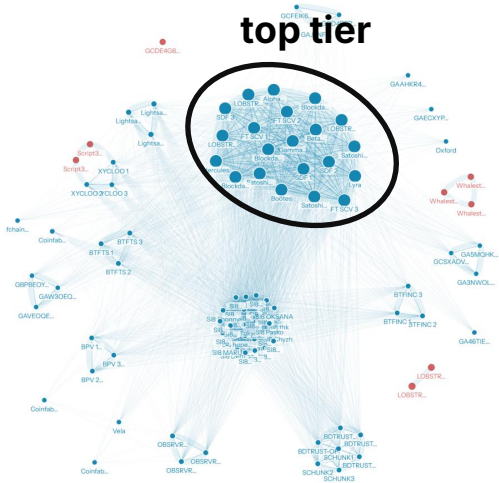
Minimal splitting set:

# Current top-tier configuration

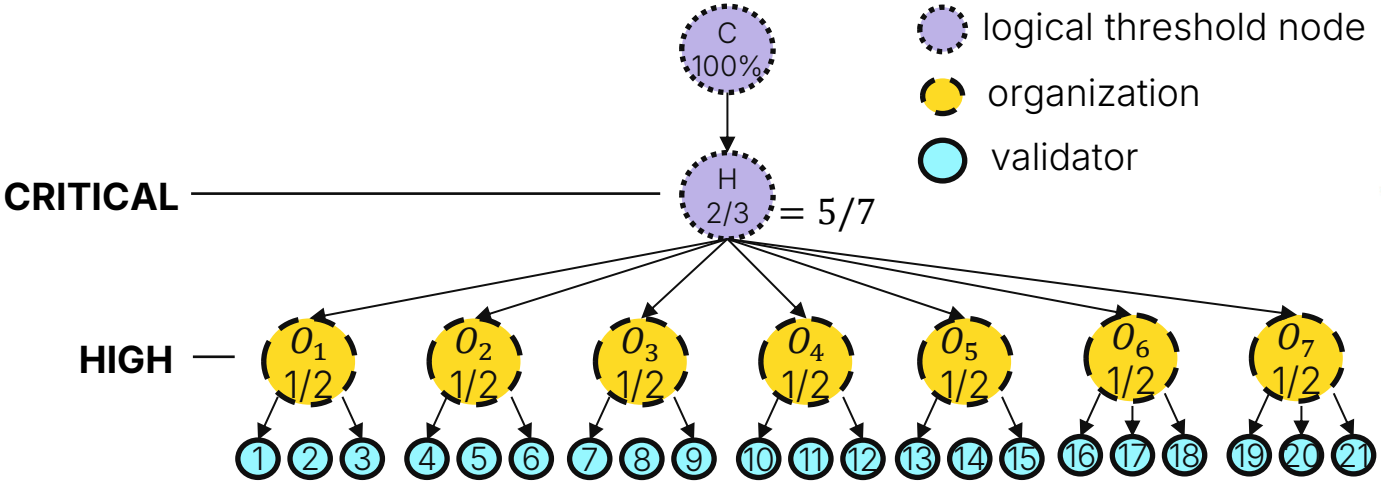


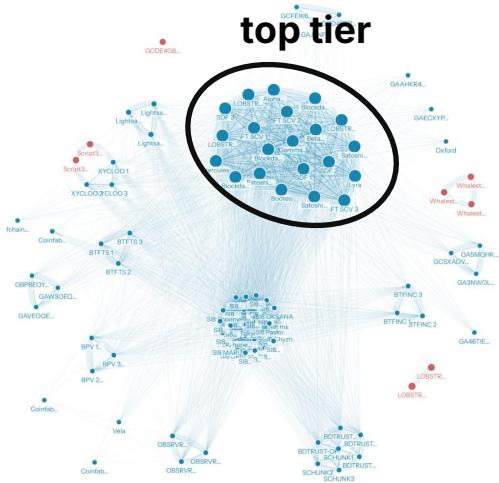




7 top-tier organizations
each setup as level HIGH
All have the same slices
⇒ quorum = slice

Minimal splitting set:
3 validators

# Current top-tier configuration

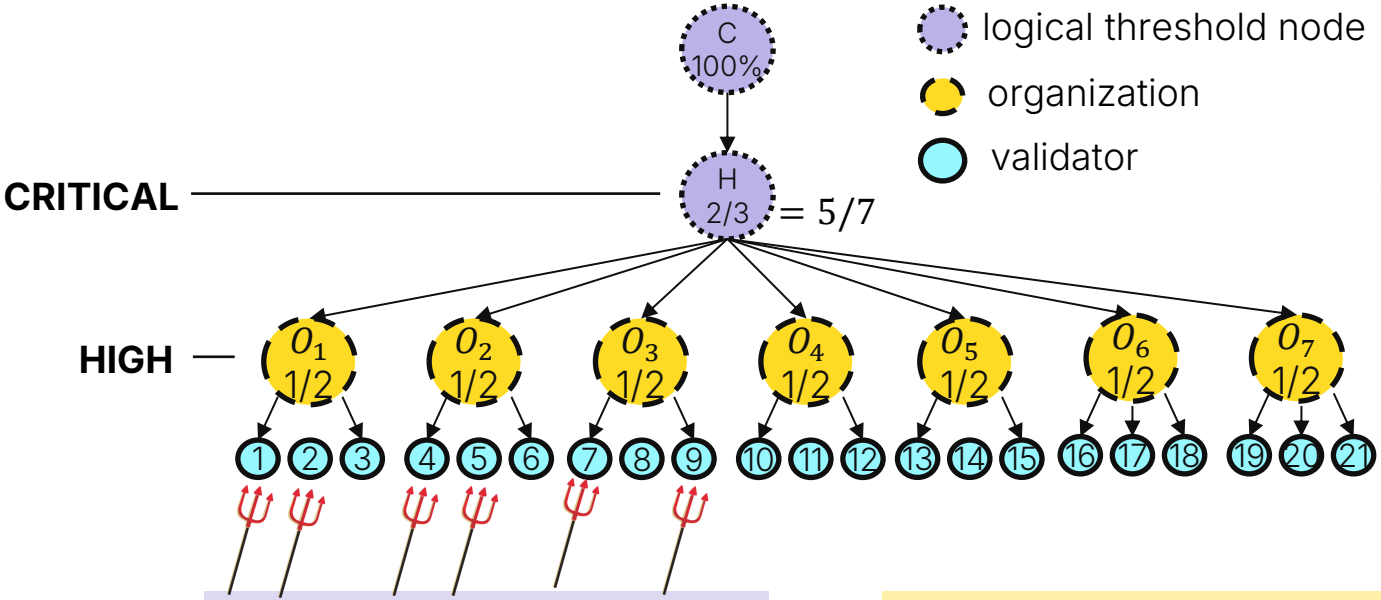


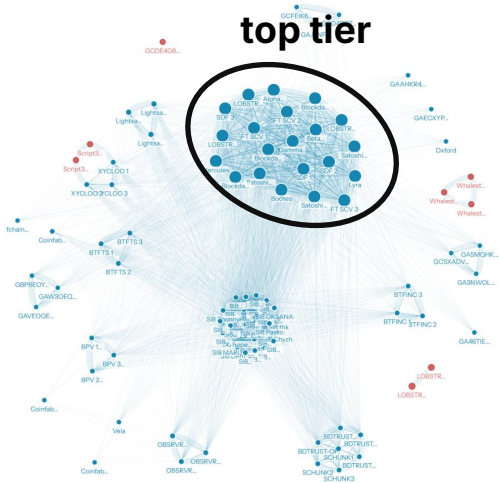




7 top-tier organizations
each setup as level HIGH
All have the same slices
⇒ quorum = slice

Minimal splitting set:
3 validators
minimal quorum-blocking set:

# Current top-tier configuration

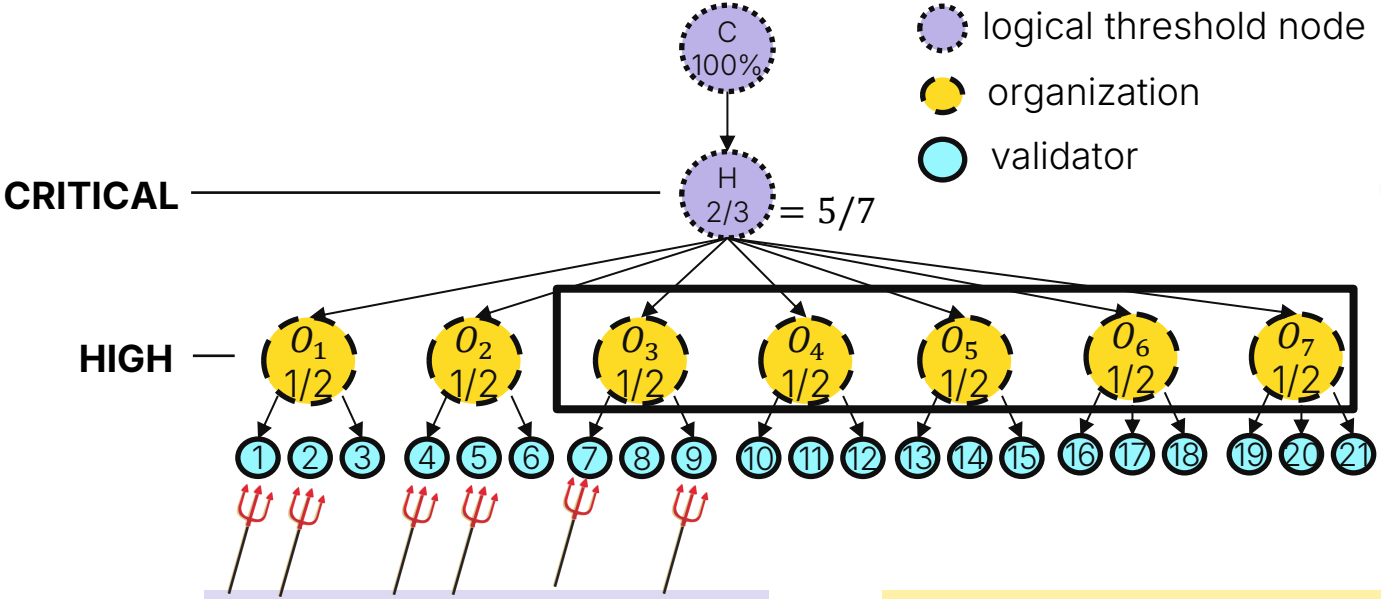


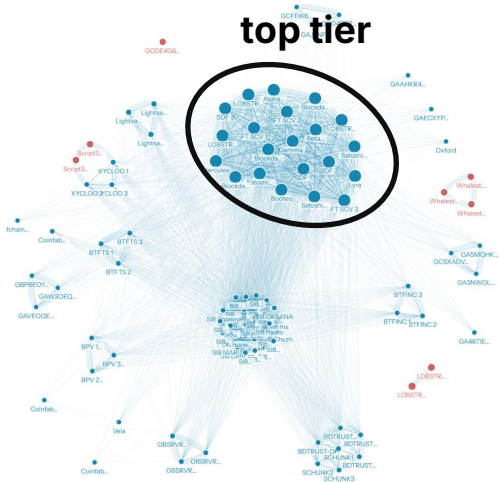




7 top-tier organizations
each setup as level HIGH
All have the same slices
⇒ quorum = slice

Minimal splitting set:
3 validators
minimal quorum-blocking set:
6 validators

# Current top-tier configuration

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Minimal splitting set:
3 validators
minimal quorum-blocking set:
6 validators

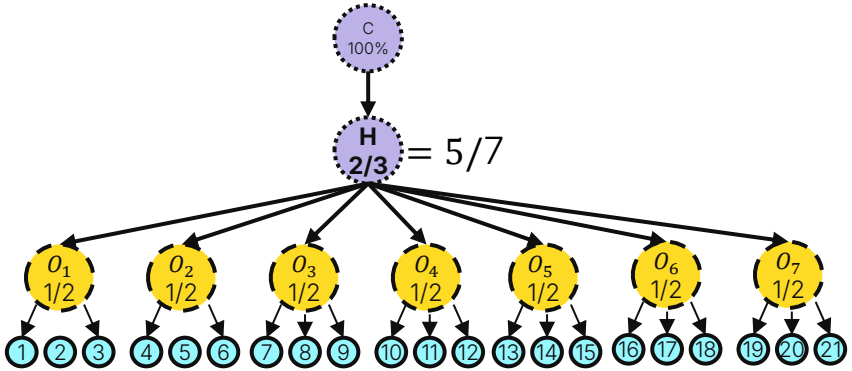
# Puzzle

logical threshold node

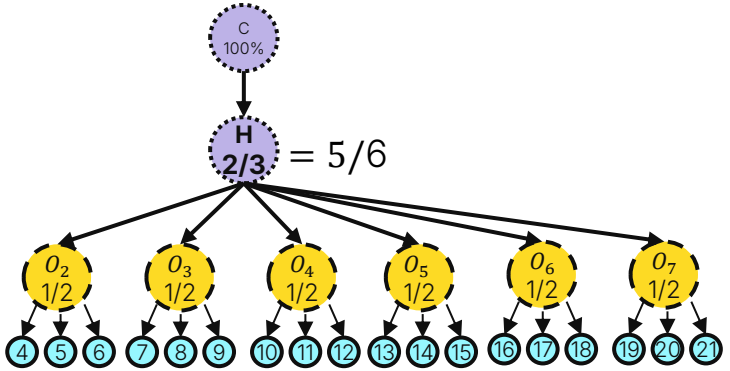
organization

validator

validators 1 to 20 use:




validators 21 uses:

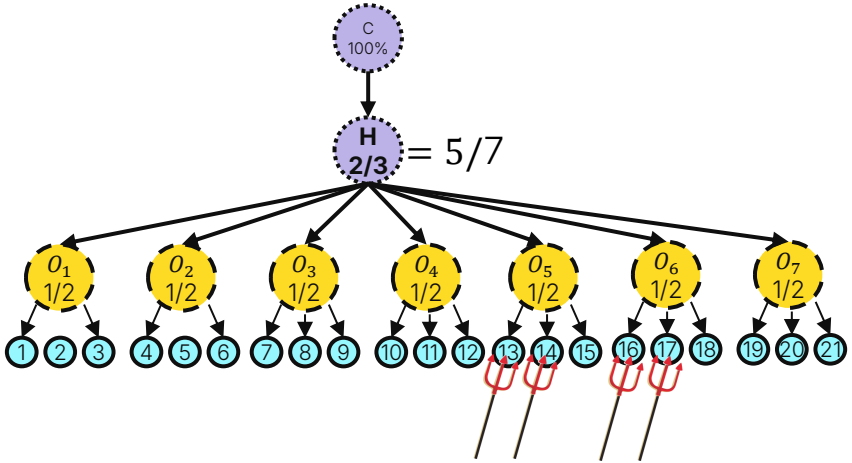



What is the size of a minimal blocking set?

# Puzzle

logical threshold node
organization
validator

validators 1 to 20 use:

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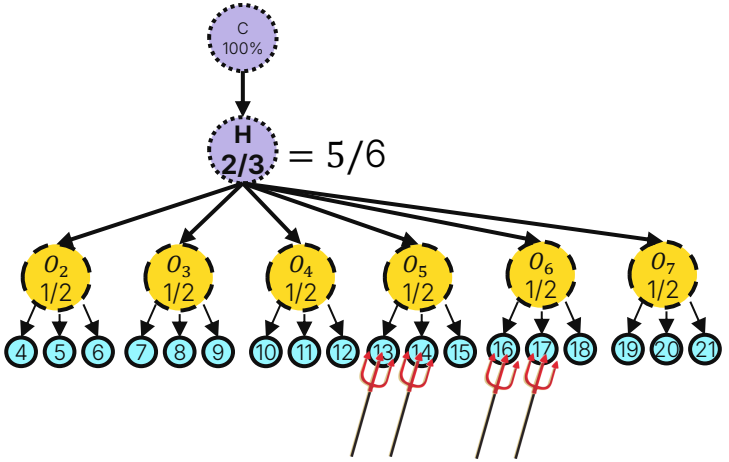


What is the size of a minimal blocking set?

# Puzzle

logical threshold node

organization

validator

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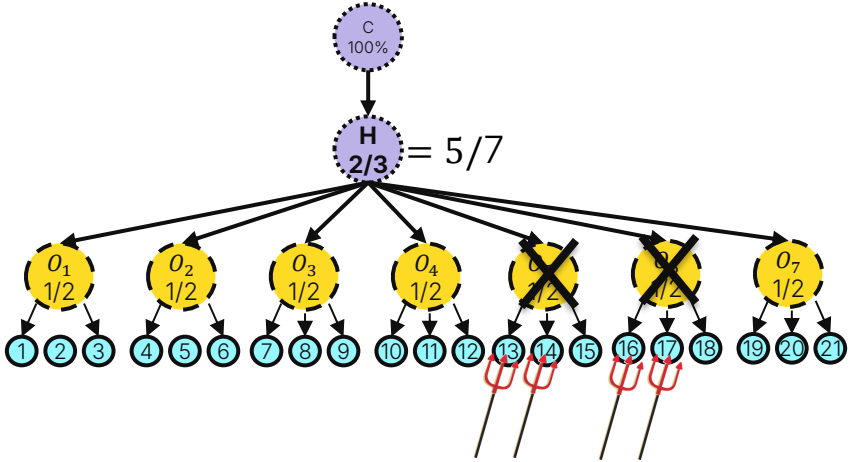


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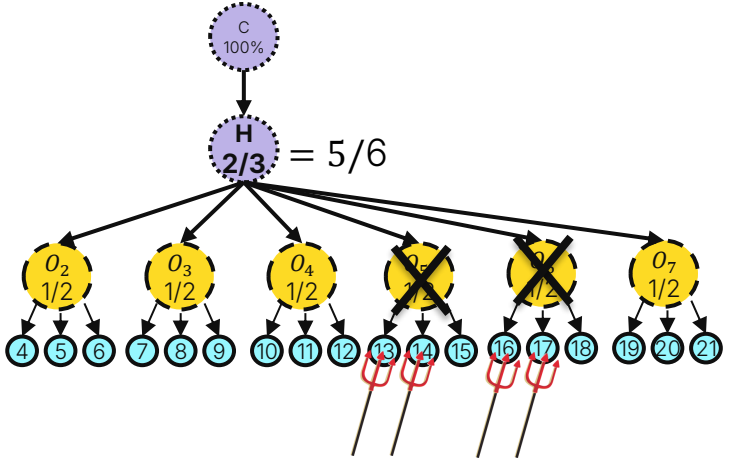


What is the size of a minimal blocking set?

# Puzzle

logical threshold node
organization
validator

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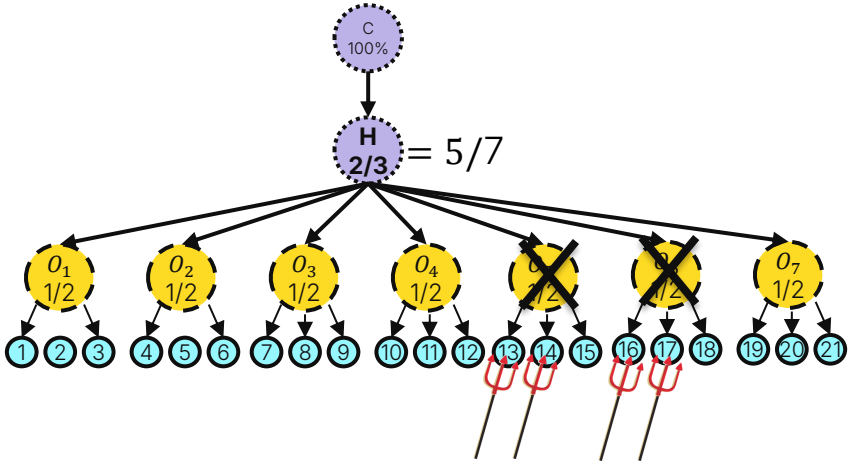


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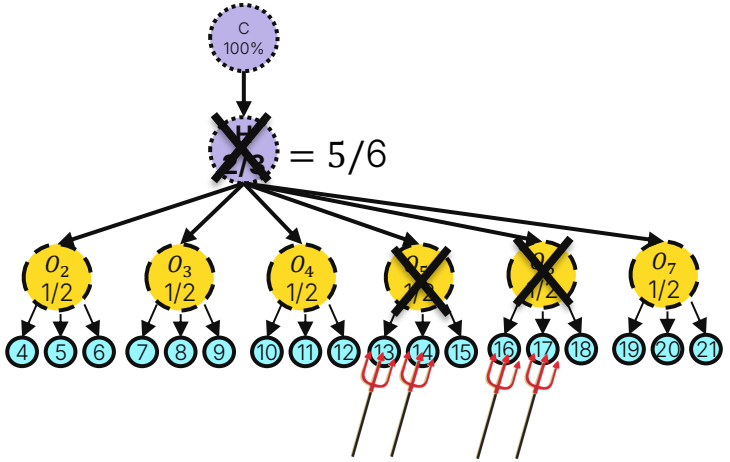


What is the size of a minimal blocking set?

# Puzzle

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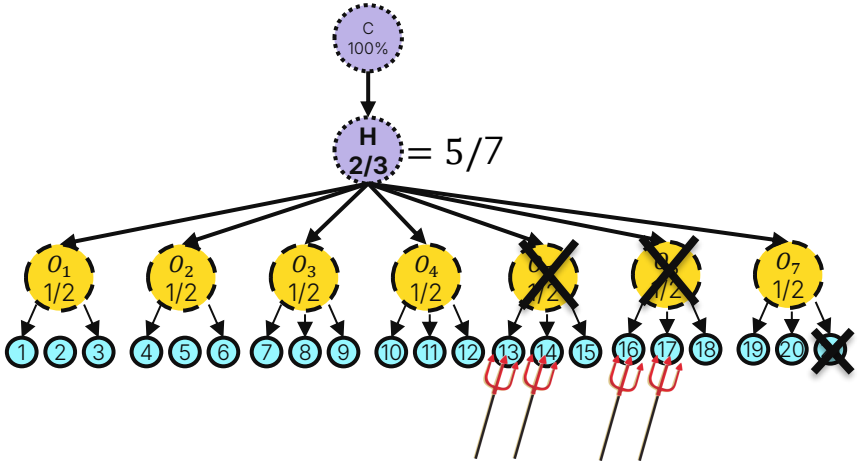
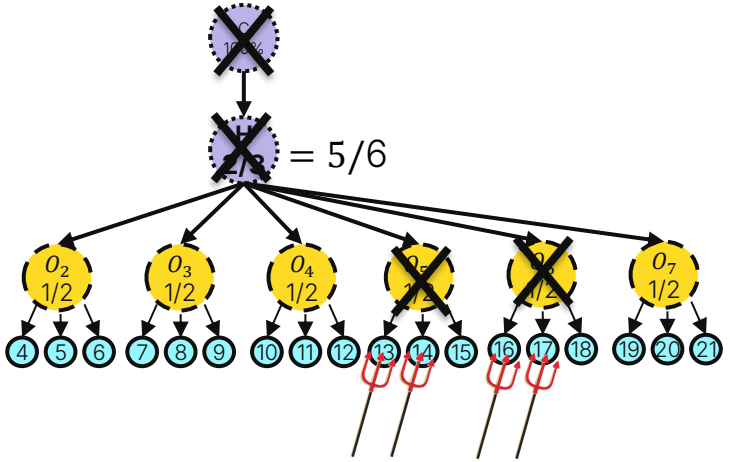



validators ~~21~~ uses:




What is the size of a minimal blocking set?

# Puzzle

logical threshold node
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validator

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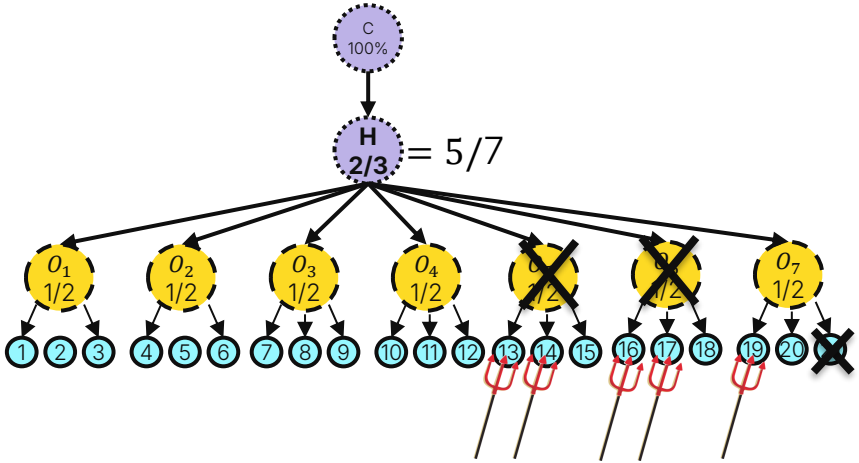
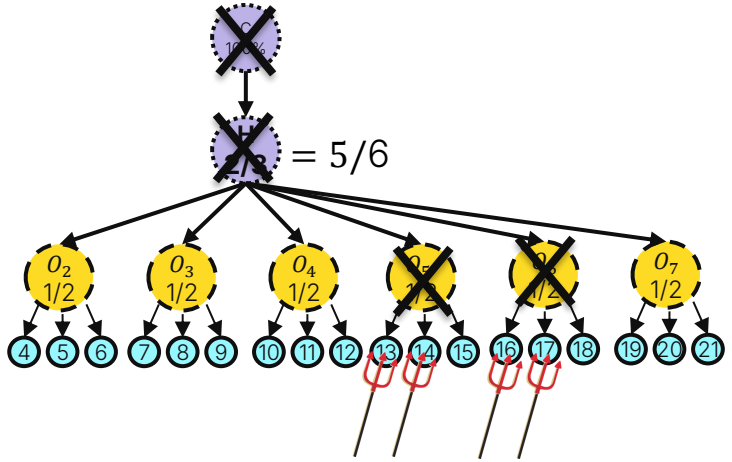
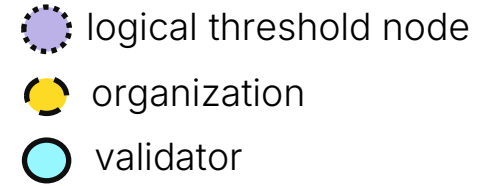



validators ~~21~~ uses:




What is the size of a minimal blocking set?

# Puzzle

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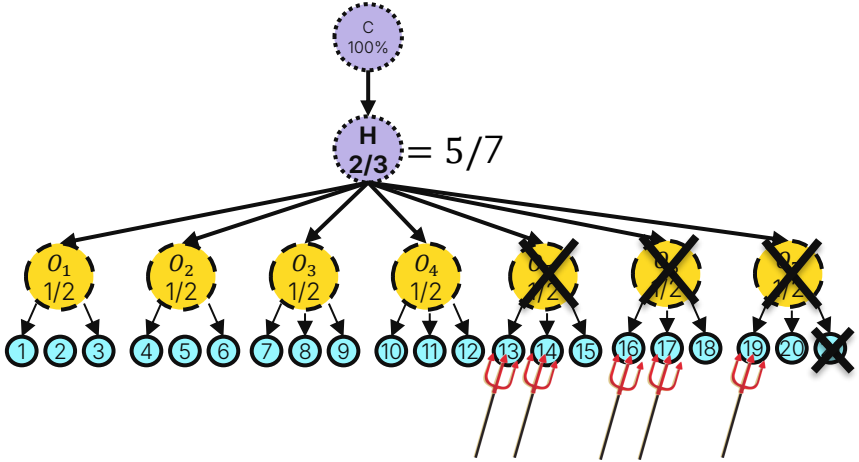


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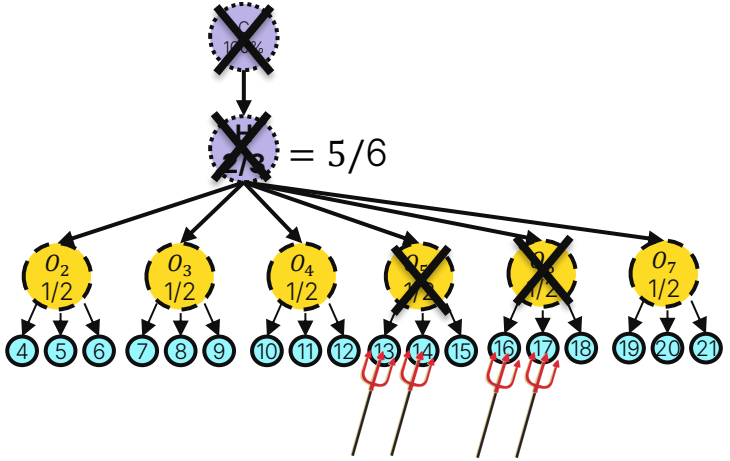


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# Puzzle

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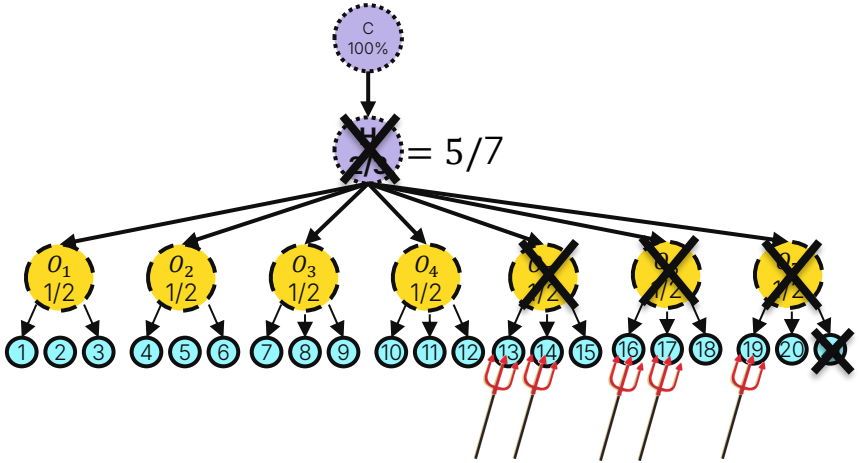


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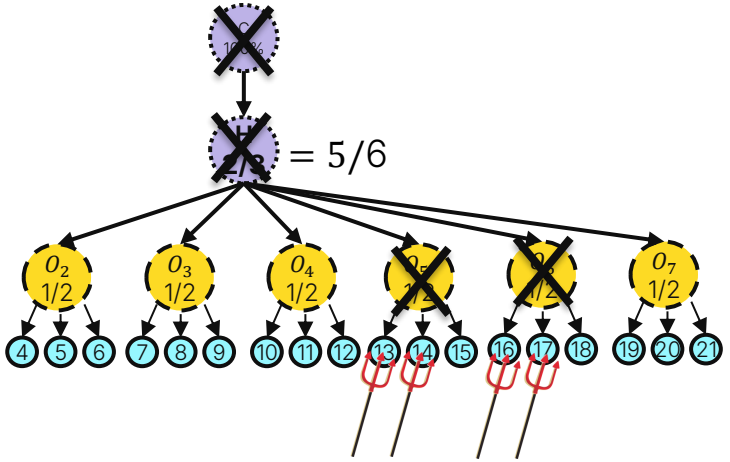


What is the size of a minimal blocking set?

# Puzzle

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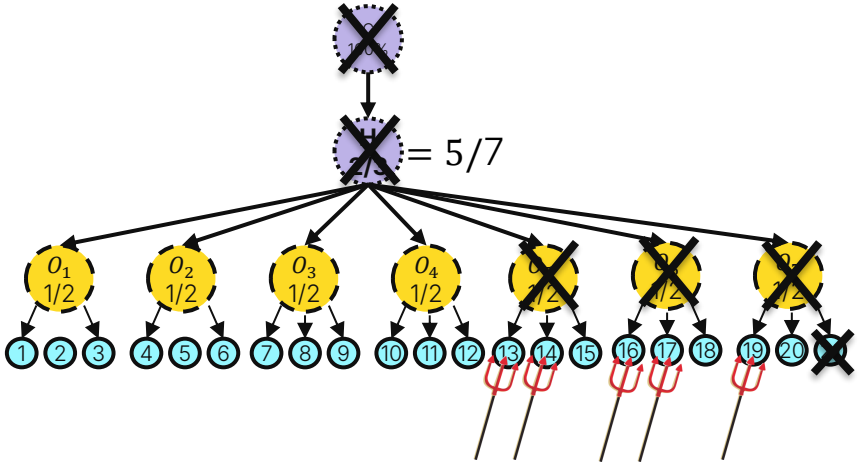


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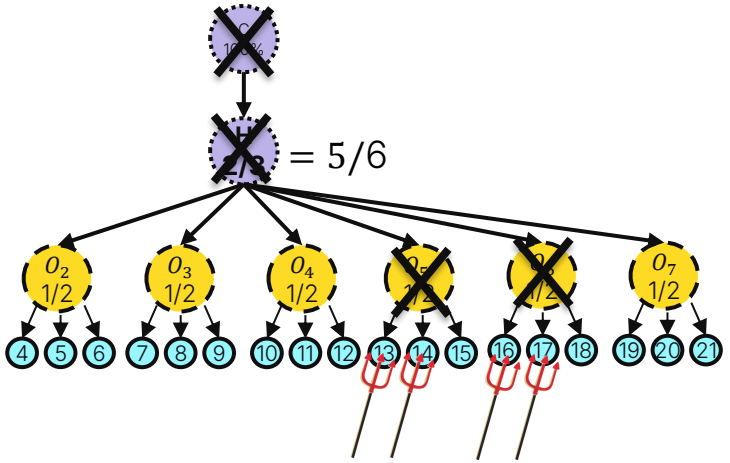


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# Puzzle

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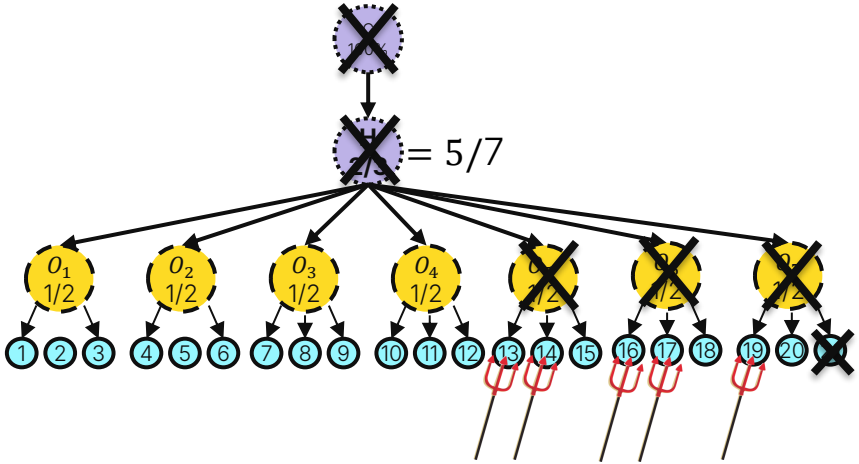


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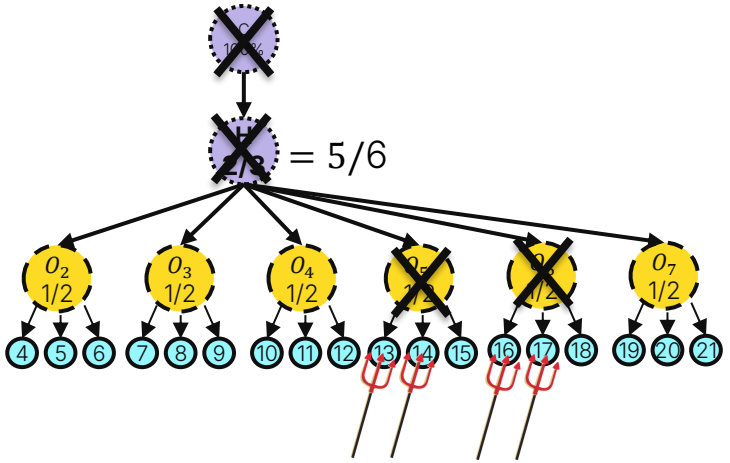


What is the size of a minimal blocking set?

5