Simplex Consensus
A Fast and Simple Consensus Protocol

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Cornell Tech

Joint work with Rafael Pass

Consensus Protocols in today's world

Algorand's Pure Proof of Stake Blockchain

Delivering security, scalability, decentralization and sustainability since 2019.

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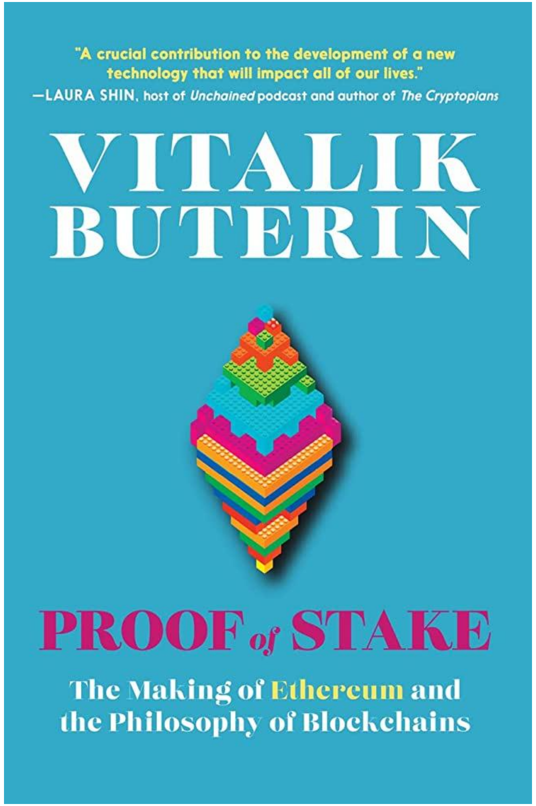
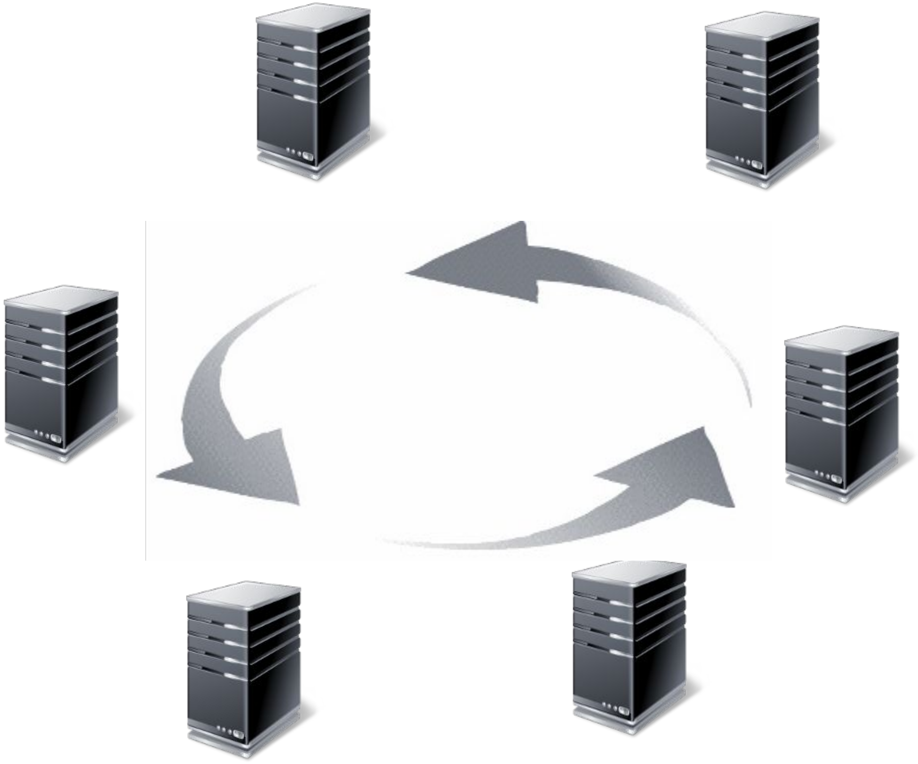


Consensus (a.k.a. state machine replication, public ledger)



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- **Liveness**

hold even when
some nodes corrupted
(e.g., assume ⅔ honest)

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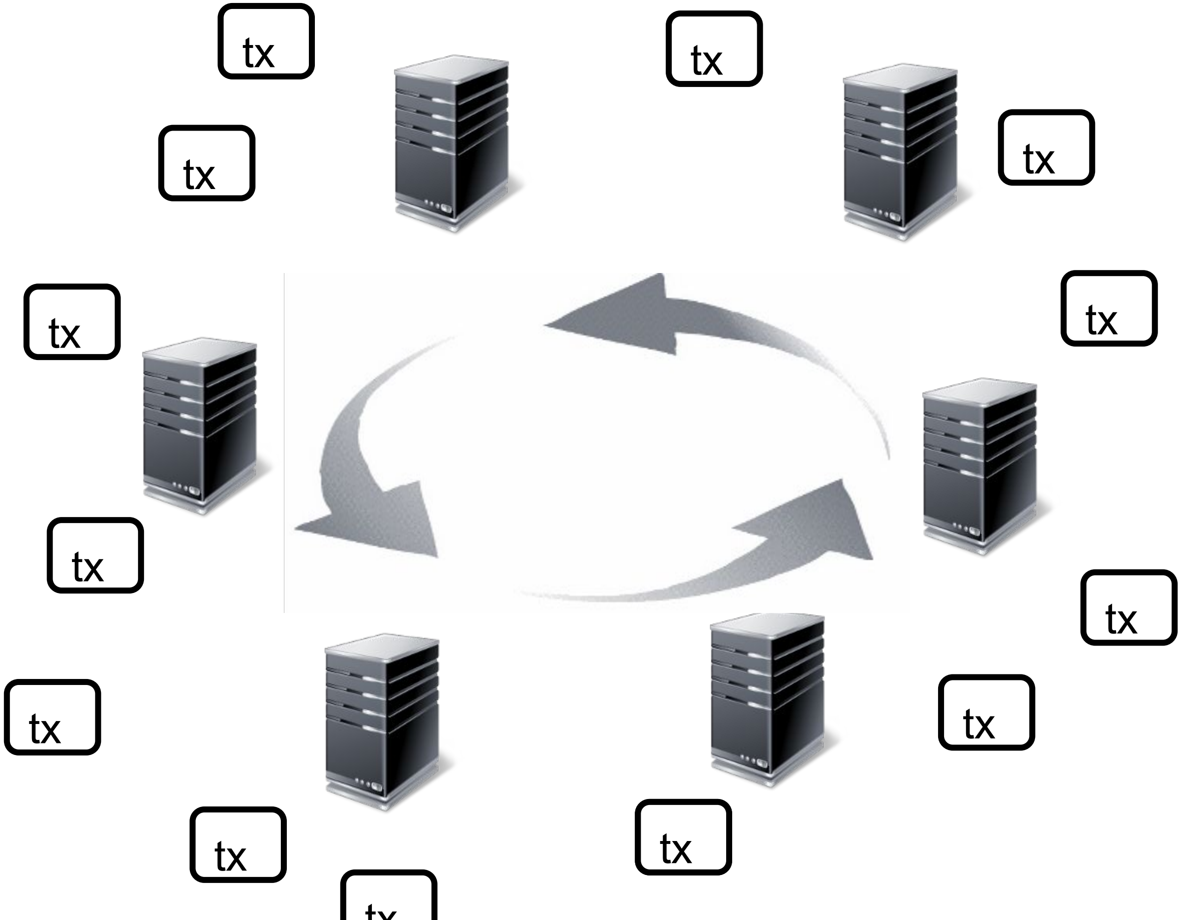

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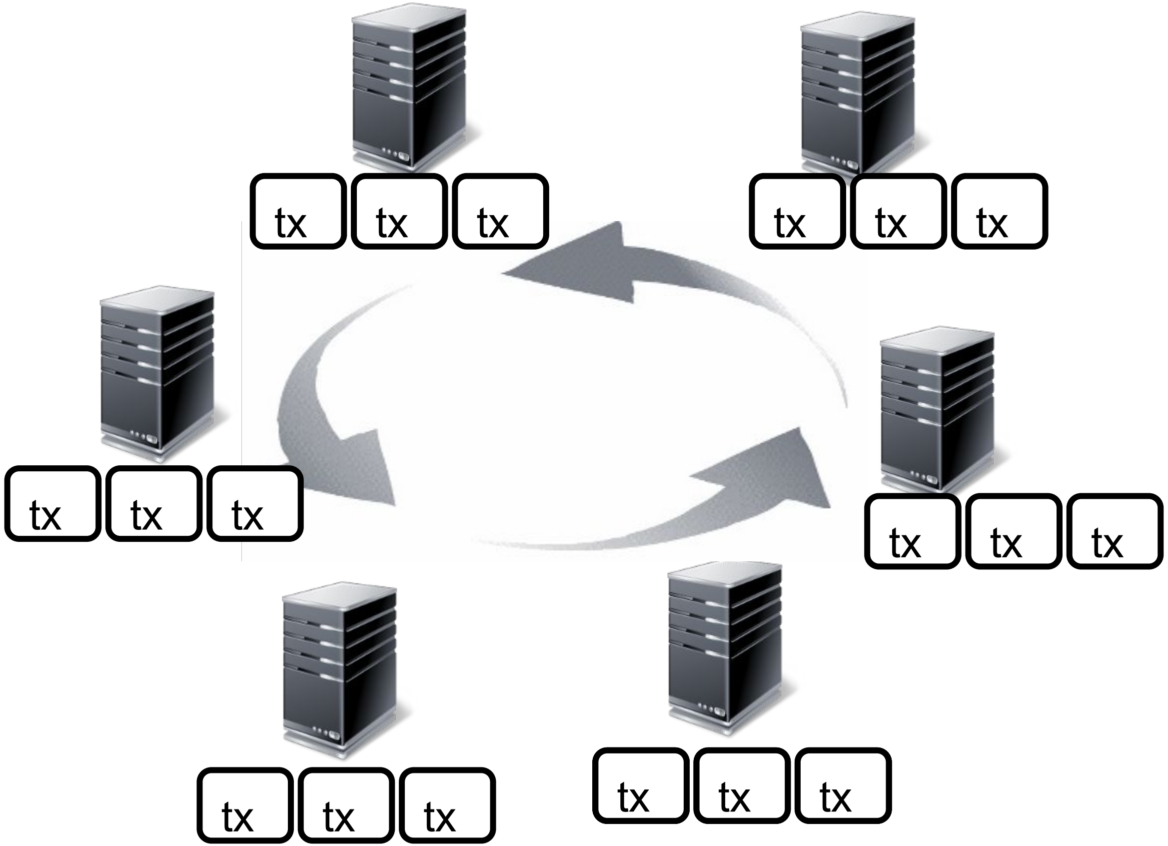

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New era, new requirements

- thousands of players
- malicious faults
- unreliable Internet
- fast transaction confirmation time
- **fairness**

Bitcoin and Proof-of-Work

- Amazing protocol, but sub-optimal "performance":
- E.g. **Bitcoin** has
  - Transaction confirmation time: ~60 minutes (6 blocks)
  - Block time: 10 min (7 transactions per second)
- Wastes electricity and computational resources.

> "And Riot Platforms' mine in **Rockdale, Texas**, uses about the same amount of electricity as the nearest 300,000 homes, making it the most power-intensive Bitcoin mining operation in America."

(source: New York Times)

Proof-of-Stake blockchains

- Can be much more performant than **Proof-of-Work** blockchains
- E.g. Ethereum
  - Transaction confirmation time: **15 mins**
  - Block time: **12 sec**
  - Throughput: **350 tps** (assuming block size of 4200 txs)
- E.g. Algorand
  - Transaction confirmation time: **4 sec**
  - Block time: **4 sec**
  - Throughput: **1050 tps** (assuming block size of 4200 txs)
- No computational waste
- **Two different philosophies**
  - Dynamic/sleepy participation [PS'18]: "people come and go"
  - **Partial synchrony**: security even under network partitions, faster.

(sources: ethereum.org, algorand.org)

(Partially-Synchronous) Proof-of-Stake blockchains

Uses **classical permissioned consensus protocols** under-the-hood

- In classical consensus, the set of ***n*** players is known ahead of time.
- Overall latency inherited from underlying consensus protocol.
- Require additional features for “fairness”: **random-leader consensus**

This talk: classical consensus protocols for the proof-of-stake setting

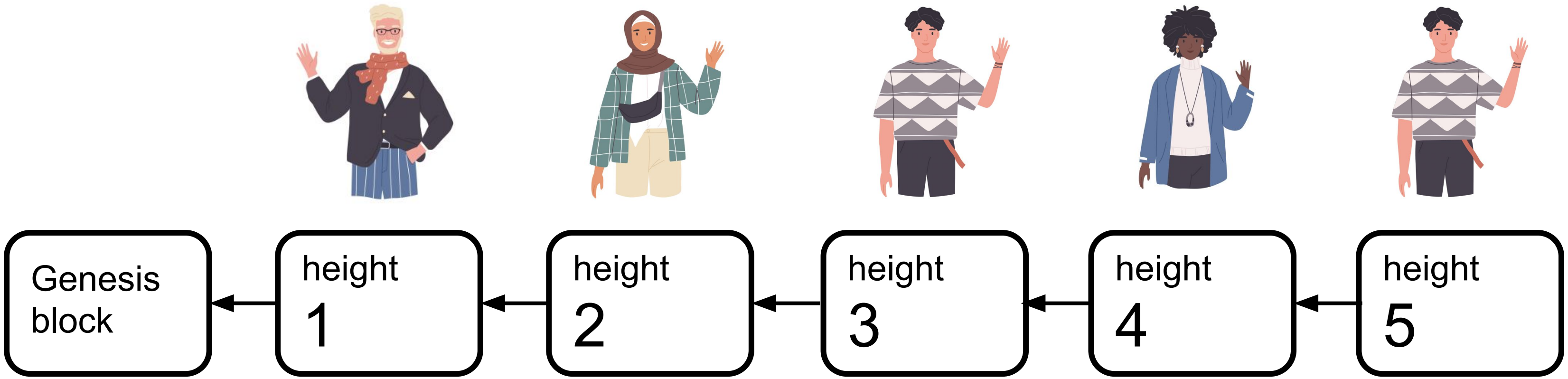
This talk:
Designing a simpler and faster random-leader consensus protocol

What do we look for in a consensus protocol?

1. **Fairness.** Each player should have a fair chance at proposing each block.

    Something like PBFT — where the same leader can propose every block for eternity — is not suitable for a blockchain application.

Random-leader consensus



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2. **Latency.** Specifically, must have fast *transaction confirmation time.*
   a. The *optimistic* case: when every player is honest.
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3. **Easy-to-understand.** Should be easy to understand *why* the protocol is secure.

Transaction confirmation time

Suppose a transaction **tx** is provided to the protocol by time ***t***. How long does it take for **tx** to be finalized?

- Optimistic Confirmation Time (no faults)
  - **Proposal Confirmation Time**: when a new block is proposed, how long does it take for it to get confirmed?
  - **Optimistic Block Time**: how long does a transaction need to wait before being included in a block proposal?

Transaction confirmation time

Suppose a transaction **tx** is provided to the protocol by time ***t***. How long does it take for **tx** to be finalized?

- Pessimistic Confirmation Time (allowing faults)
  - **Worst-case confirmation time.** How long does it take in the worst case to be finalized?
  - **Expected Liveness**: On average, how long does it take?
    (We assume that the transaction arrives at the beginning of the **i**th block proposal opportunity.)

Partial Synchrony

The network may be unreliable, and even occasionally partitioned in half.

Formally, there is a fixed unknown time **GST**, an unknown time bound $\boldsymbol{\delta}$, and a known time bound $\boldsymbol{\Delta > \delta}$ s.t.

- **Before GST**, messages take arbitrarily long to be delivered
- **After GST**, every message is delivered within **$\boldsymbol{\delta}$ seconds.**

Partial synchrony models a flaky Internet, or implementation bugs that cause players to drop messages.

State-of-the-art

Theoretical latency of partially-synchronous protocols that support random leaders

First “random-leader” partially synchronous

	Proposal Conf. Time	Optimistic Block Time	Pessimistic Liveness ($f = \lceil n/3 \rceil - 1$)
Algorand* [CGMV18]	**3δ**	3δ	$4\delta + 2\Delta$
ICC [CDH+22]	**3δ**	**2δ**	$5.5\delta + 1.5\Delta$
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Pipeline Fast-Hotstuff [JNFG20] Jolteon [GKKS+22]	5δ	**2δ**	$10.87\delta + 9.5\Delta$
Chained Hotstuff (v6) [YMR+19]	7δ	**2δ**	$19.31\delta + 12.18\Delta$
Streamlet [CS20a]	10Δ	2Δ	39.56Δ

*Base protocol without sortition.

Table 1: Latency of Popular Consensus Protocols (Random Leaders)

State-of-the-art

Theoretical latency of partially-synchronous protocols that support random leaders

These protocols pipeline their block proposals to achieve **2δ** block time

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However, they require multiple honest leaders in-a-row to confirm blocks, which hurts pessimistic liveness.

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Protocols that don't pipeline blocks usually sacrifice block time, but get good expected liveness

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Easiest protocol description [**C**S20]

This talk

A new consensus protocol, called **Simplex Consensus**

- Partial synchrony, **$f < n/3$** byzantine faults
- In our eyes, easiest security proofs!
- Can get communication efficiency using "sortition" [Algorand]

Thm: Assuming a (Bare) PKI, CRH, there exists a partially synchronous consensus protocol in the "random-leader model" with:

- Proposal confirmation time of **3δ**
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Essentially all prior work in this model has non-trivial liveness proof

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Comparisons

Theoretical latency of protocols that support random leaders

Simplex:
The best of both worlds

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Protocol Description

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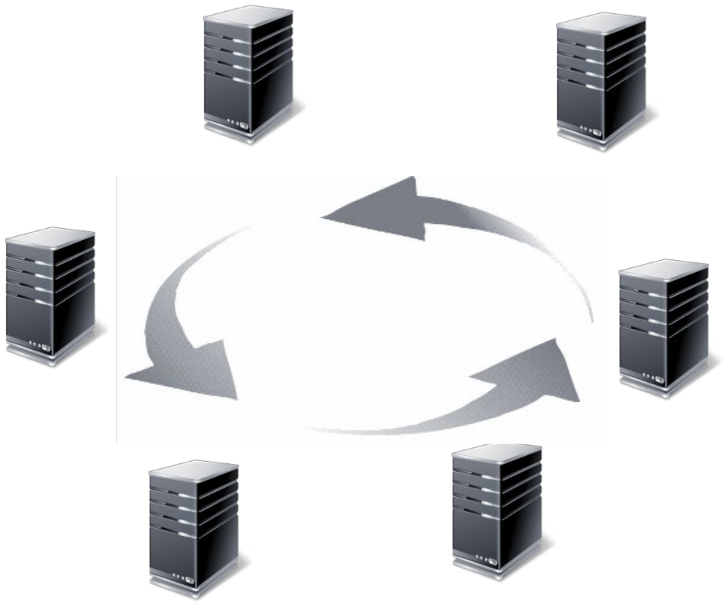
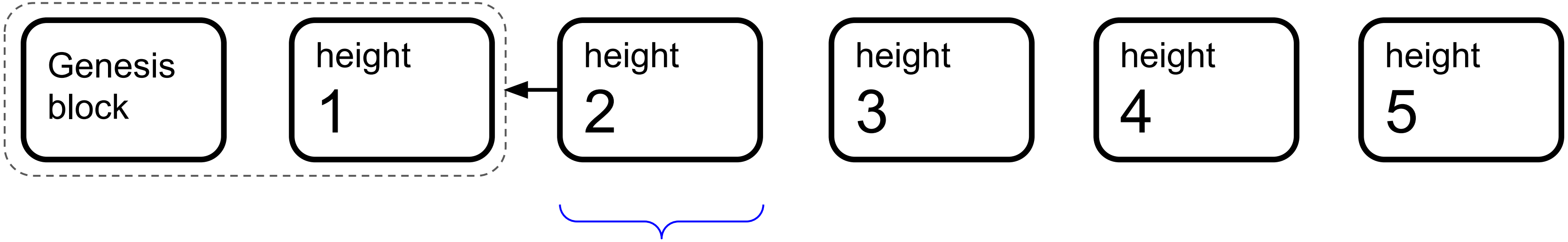


n players, f < n/3 malicious faults.
we know their public keys ahead of time (bare PKI)

Simplex Consensus

Key data structure: **blockchain**



each block of height **h** is a tuple of the form

$\mathbf{b_h}$ **= (h,** *hash of a parent chain*, **txs)**

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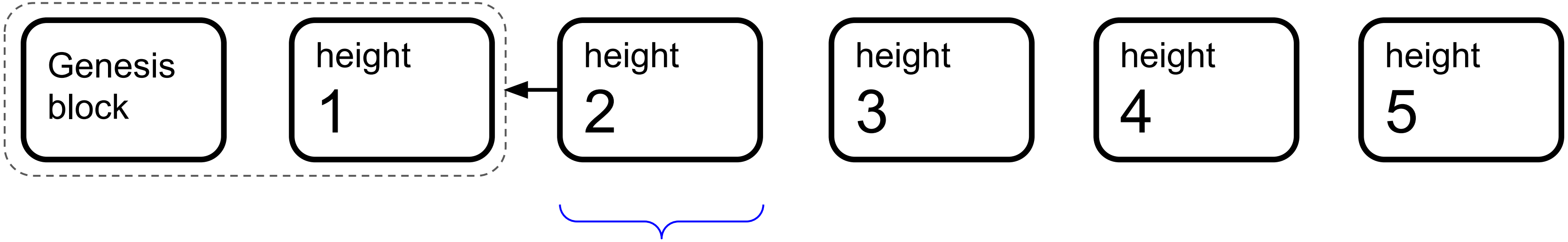

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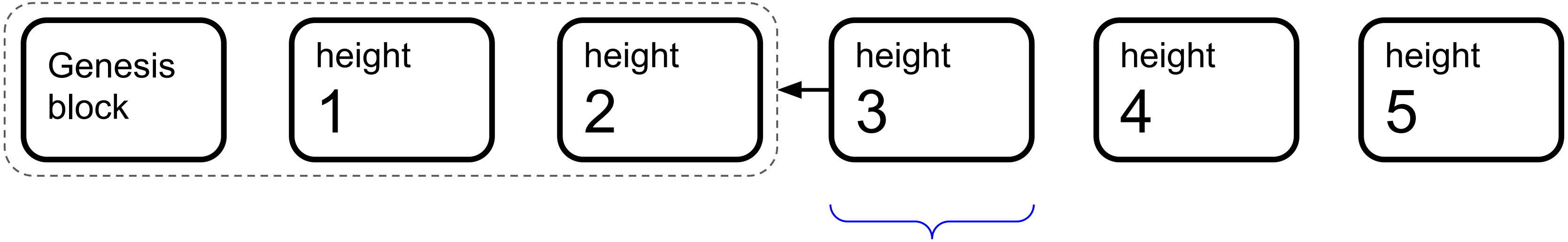

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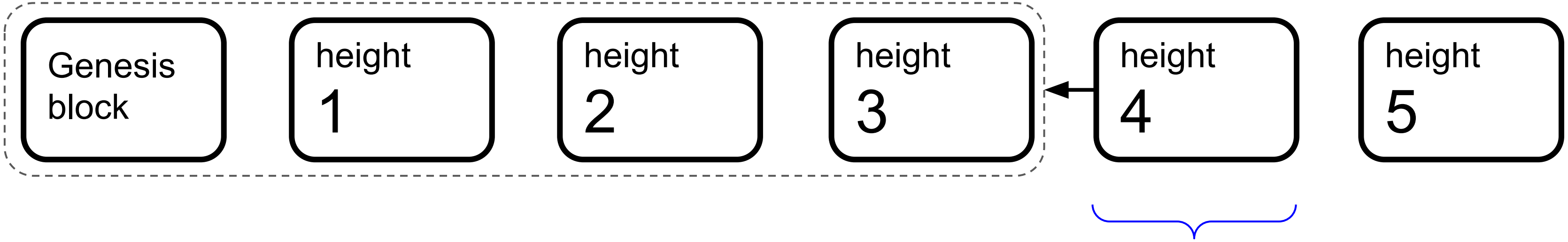

each block of height **h** is a tuple of the form

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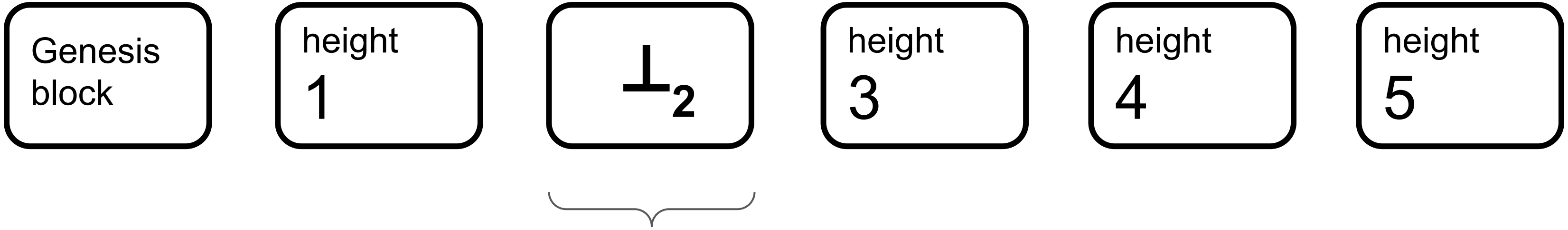
Dummy blocks

We also allow the blockchain to contain “**dummy blocks**”



a dummy block of height **h** is the tuple

$$\perp_h = (h, \perp, \perp)$$

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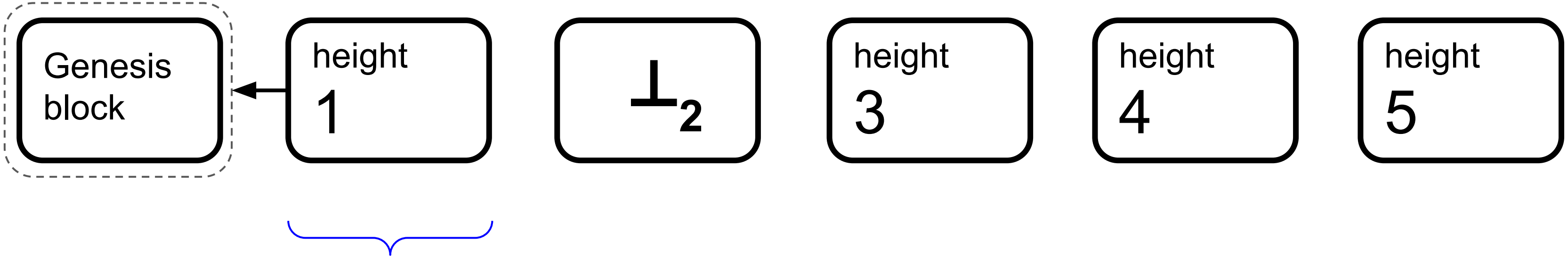

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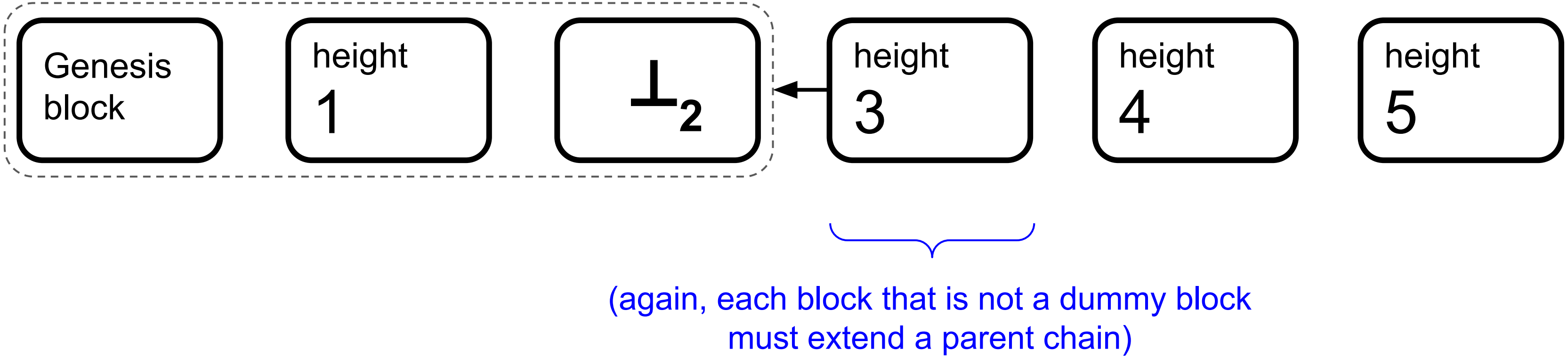

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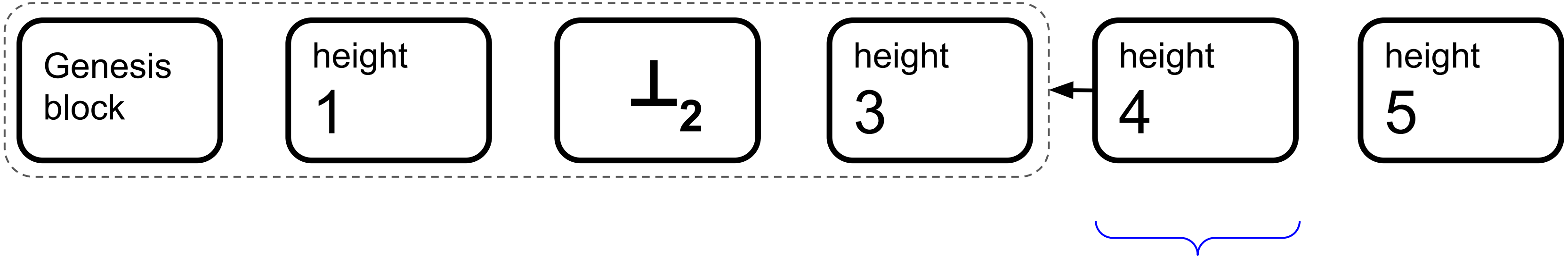

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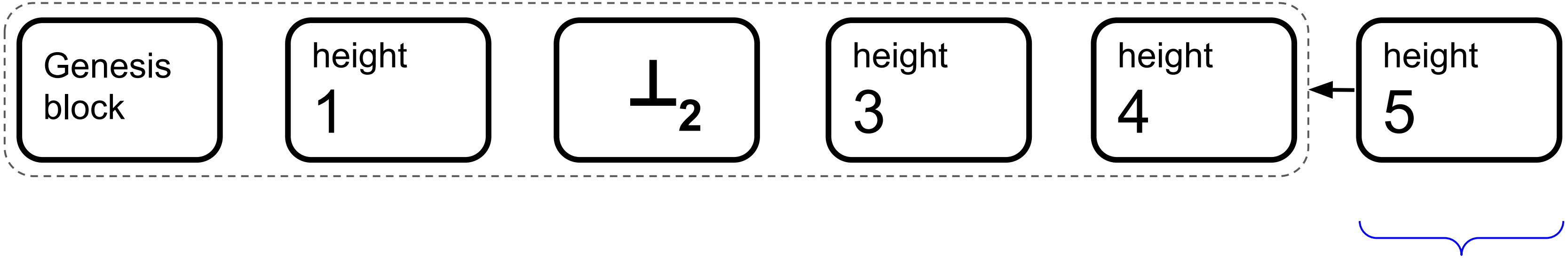

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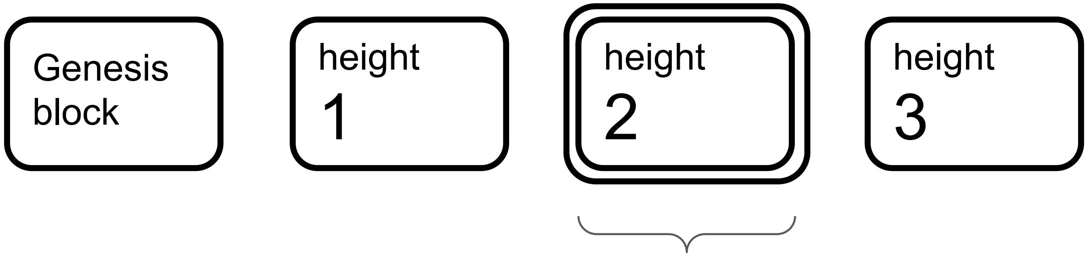
Notarized blocks

Key data structure: **notarized blocks**



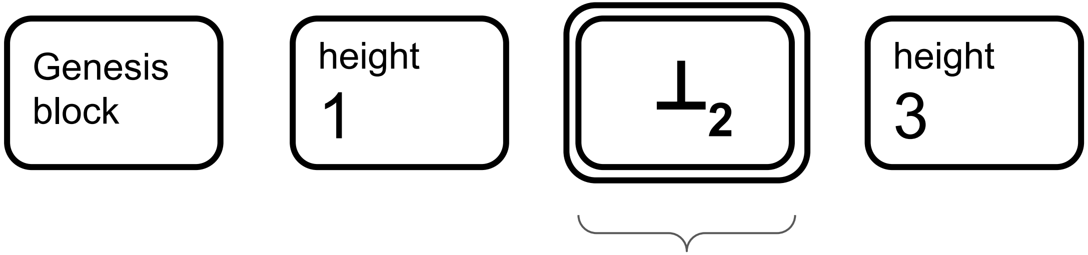
a block is notarized in my view if I've seen

> 2n/3 votes for it

a vote for **b** = a signed message "vote for **b**"

Notarized blocks

Dummy blocks can also be **notarized.**



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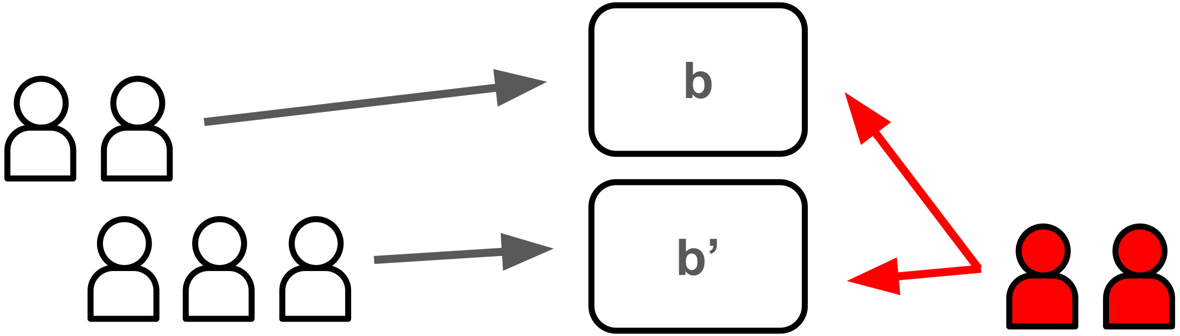
“Quorum intersection”

If honest players only vote for one of **b** or **b’**, then it cannot be that both **2n/3** players voted for **b**, and **2n/3** players voted for **b’**.



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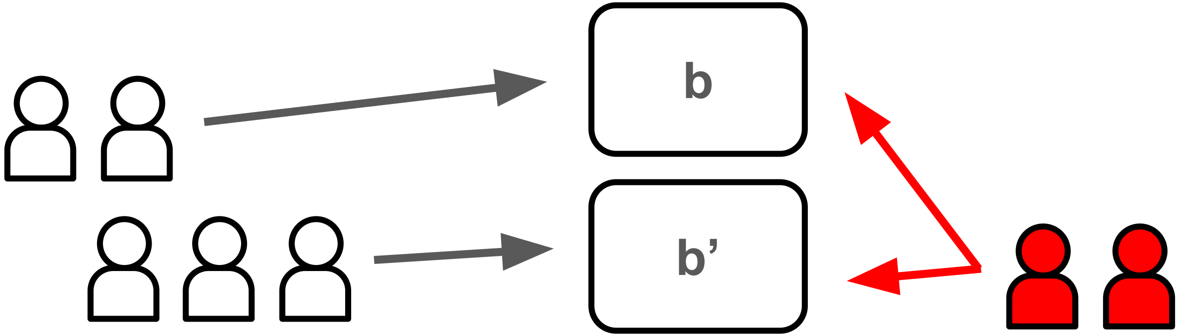

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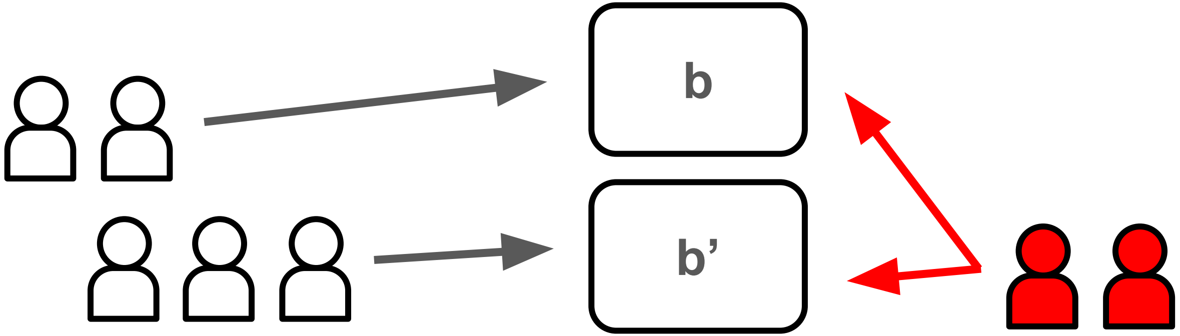

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n – f votes

n + f total votes
< 4n/3 since **f < n/3**

corrupt players can always vote for both

2f votes

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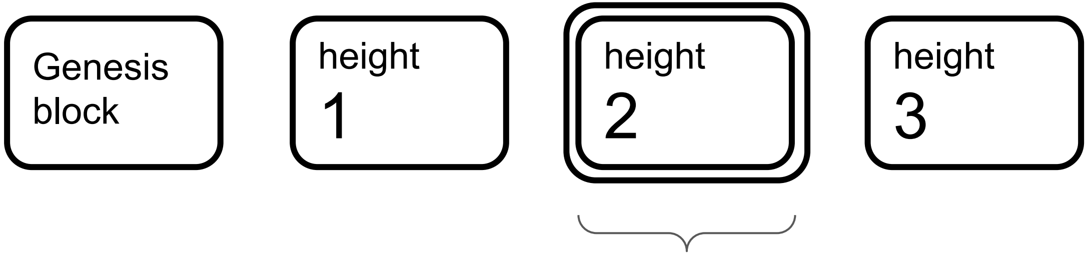
Key data structure: **notarized blocks**



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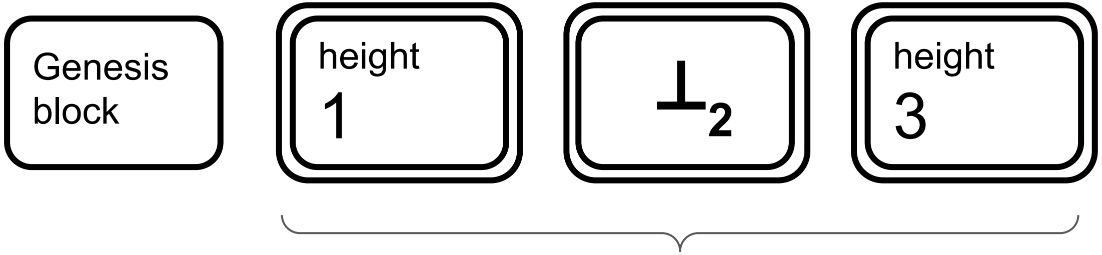
Notarized blockchains

Key data structure: **notarized blockchain**

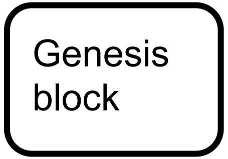


every block of the chain is notarized (except genesis)

The Simplex Consensus Protocol

Proceed in iterations **h = 1, 2, 3, …**

In each iteration **h**, collectively try to build a notarized block of height **h.**



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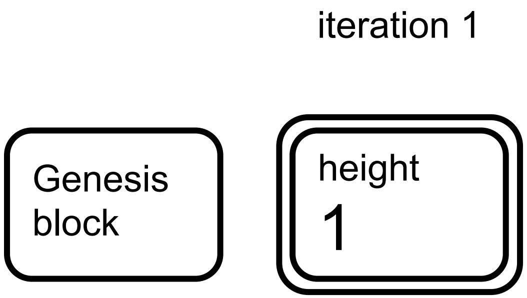

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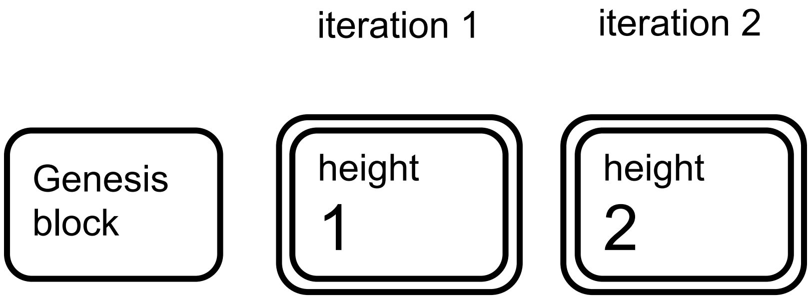
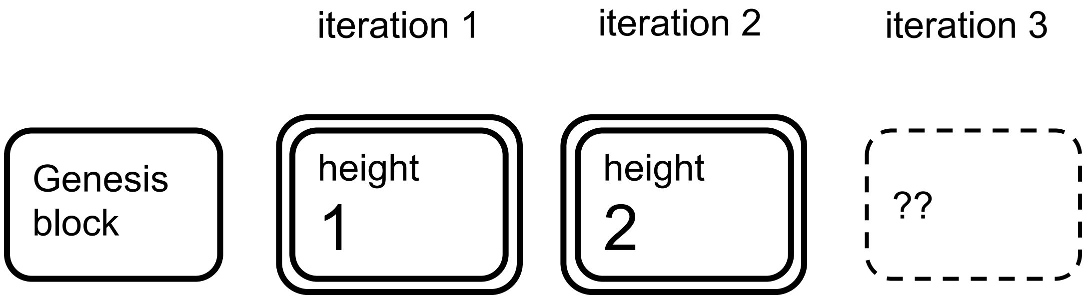


The Simplex Consensus Protocol

Proceed in iterations **h = 1, 2, 3, …**

In each iteration **h**, collectively try to build a notarized block of height **h.**



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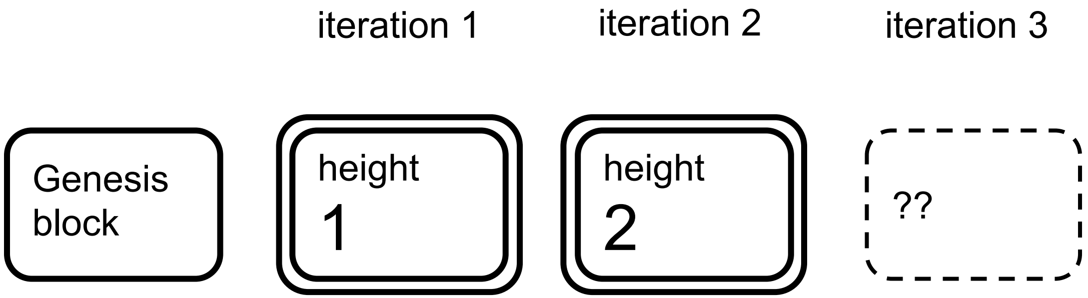
Proceed in iterations **h = 1, 2, 3, …**

Only move to the next iteration when I've seen a notarized blockchain of length **h**.

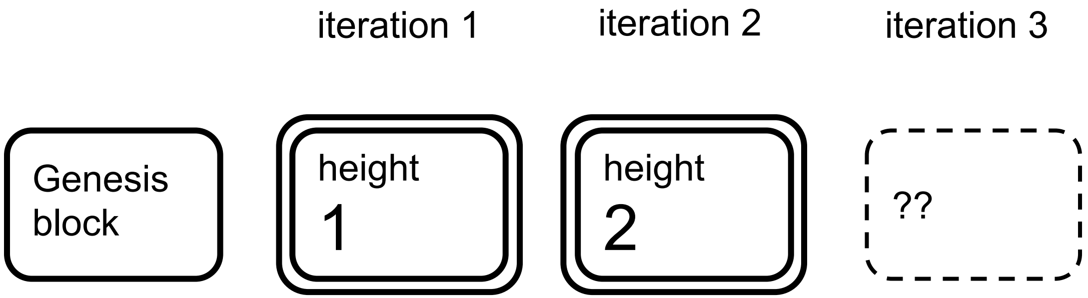


The Simplex Consensus Protocol

Proceed in iterations **h = 1, 2, 3, …**

Only move to the next iteration when I've seen a notarized blockchain of length **h**.

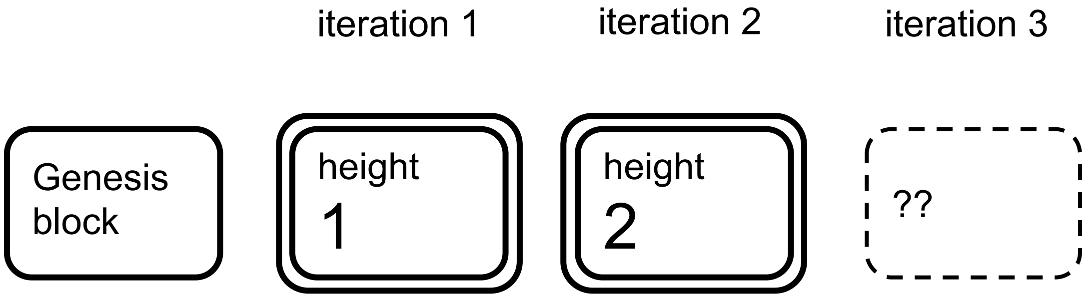
(Also, send this notarized blockchain to everyone else.)



Constructing notarized blocks

Each iteration has a leader player chosen randomly ahead of time.

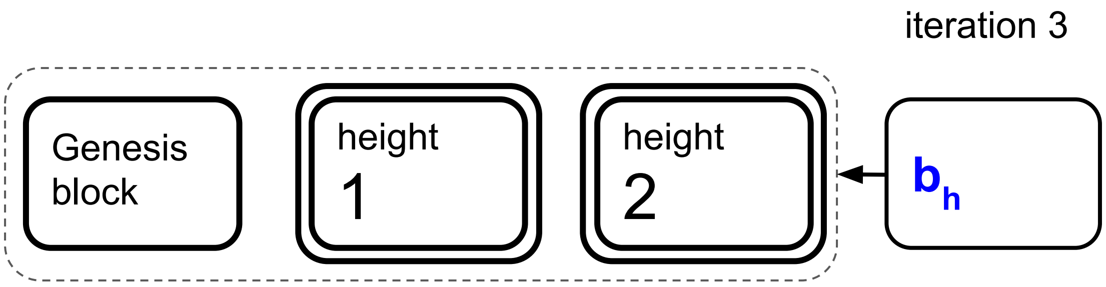
Specifically, the leader of iteration **h** = *H** **(h)** mod **n**, where *H** is a random oracle.



Constructing notarized blocks

Each player **i**, on entering iteration **h**

1. If **i** is the leader**, i** chooses notarized blockchain of length **h-1**, extends it with a new block $\mathbf{b_h}$ and sends everyone a signed message "**propose** $\mathbf{b_h}$".



Constructing notarized blocks

Should include all pending transactions.

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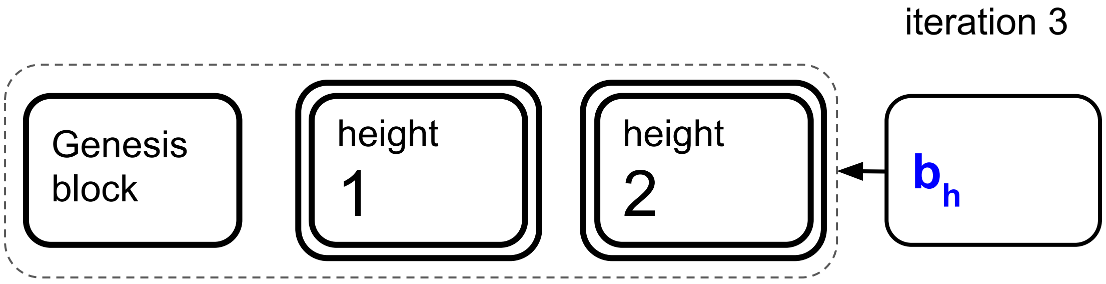

Constructing notarized blocks

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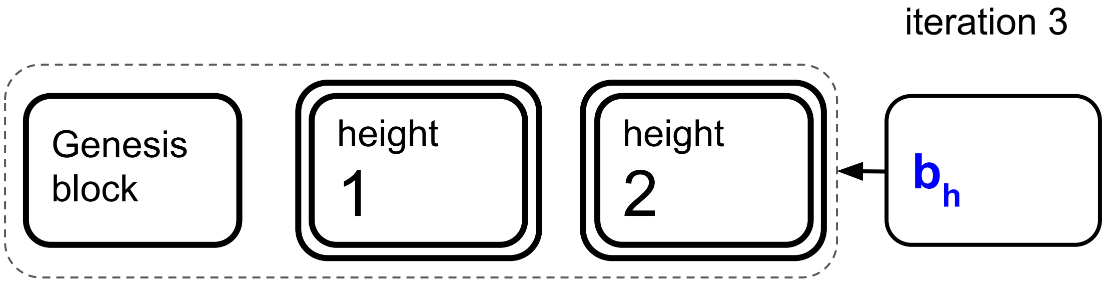

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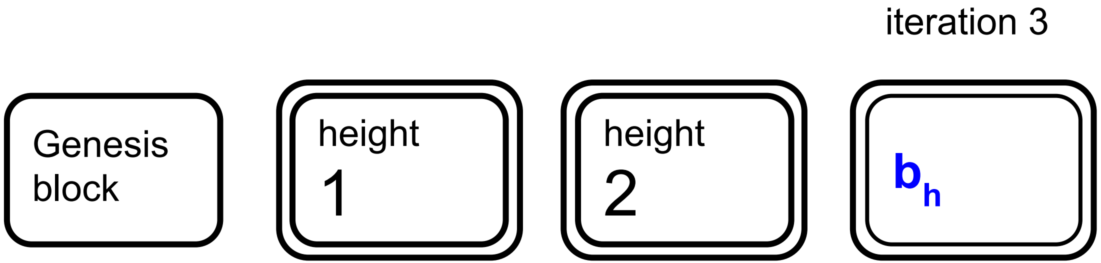

If the network is good and the leader is honest, the block proposal will get notarized!

Constructing notarized blocks

Each player **i**, on entering iteration **h**

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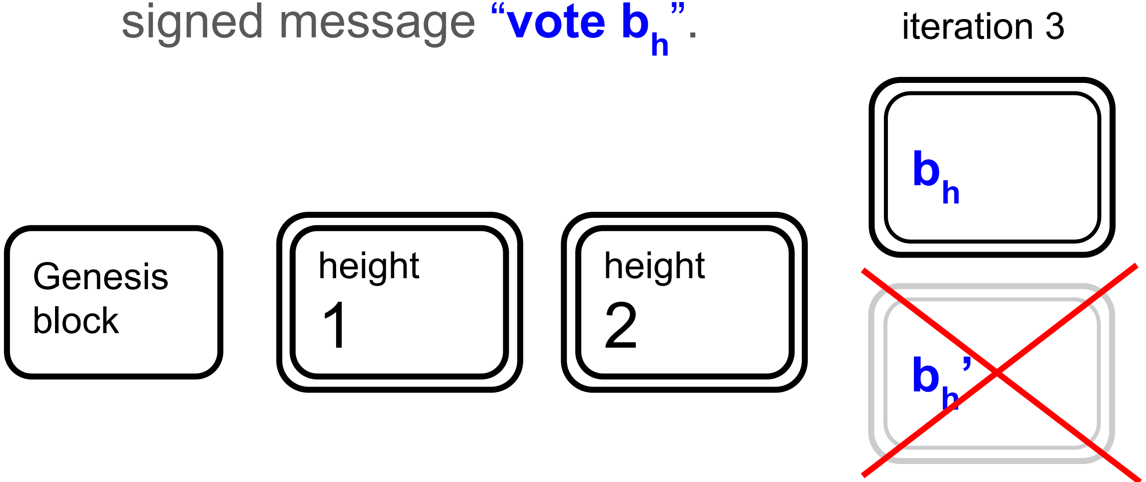
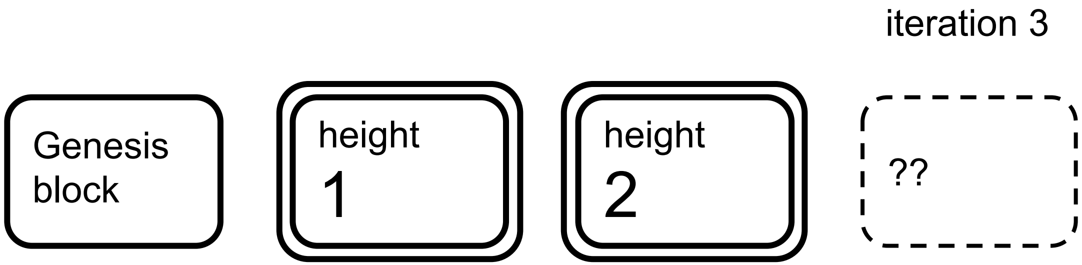


At most one block proposal from the leader can be notarized in honest view

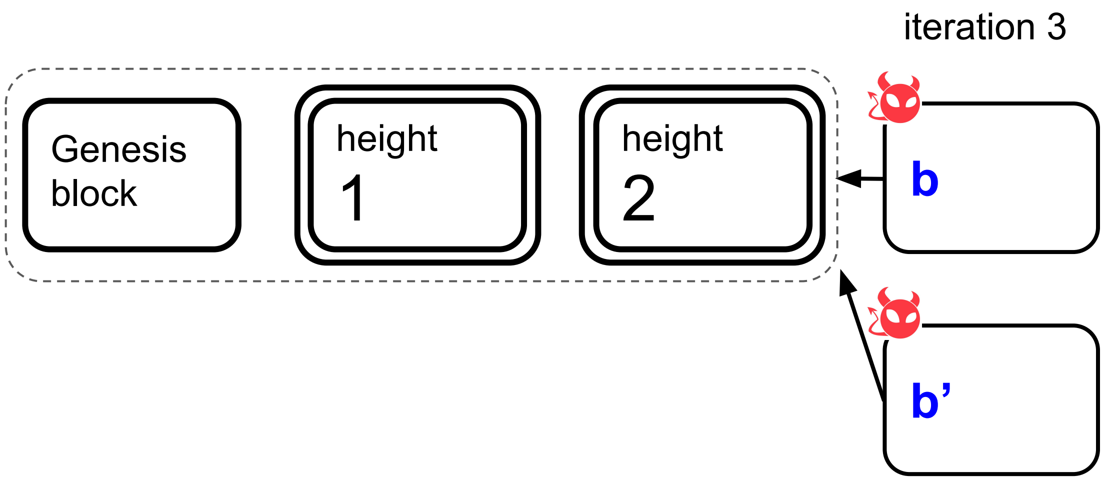
Handling faults

Scenario 1: if the network drops all messages, or leader crashed, maybe players never see a block proposal for that iteration…



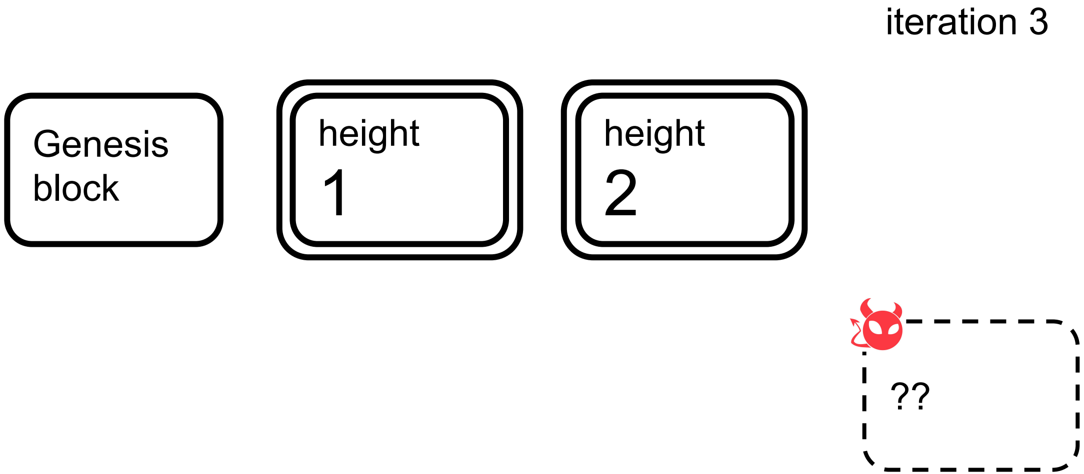
Handling faults

Scenario 2: a faulty leader sends different proposals to different players, and honest players split their vote, so no block proposal gets notarized...



Solution: dummy blocks.

If **3Δ time** has passed since player **i** has entered iteration **h**, and if **i** still has not entered iteration **h+1**, player **i** sends to everyone a signed message "**vote $\perp_h$**".



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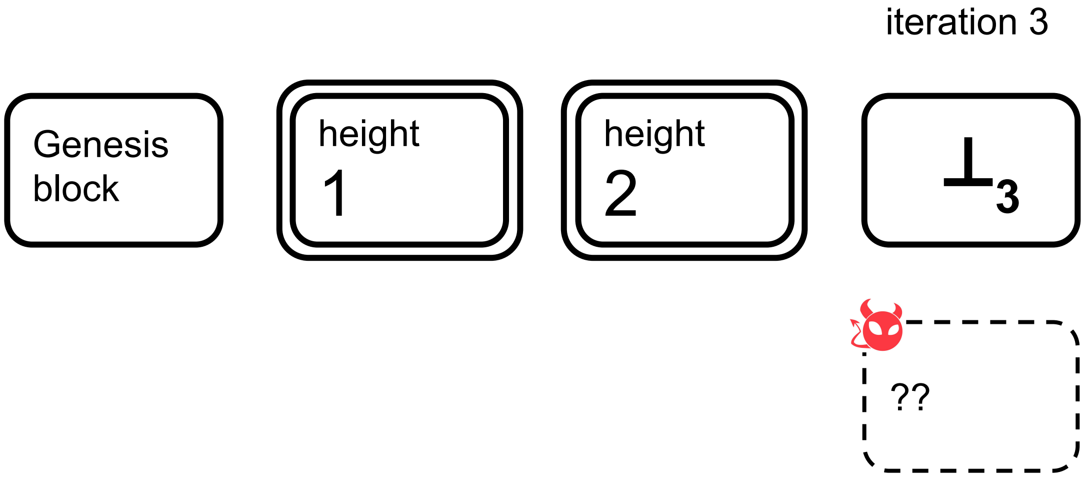

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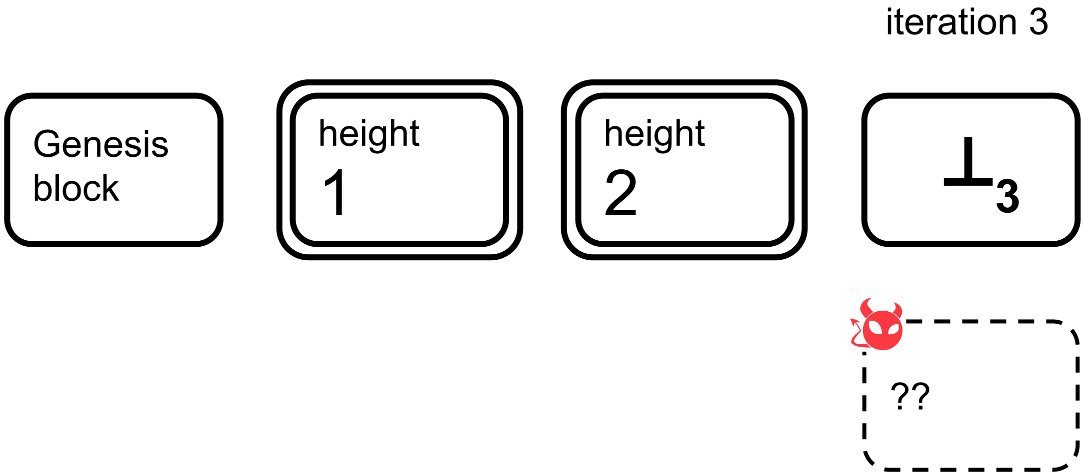

Recall: the dummy block of height **h** is the tuple **$\perp_h$ = (h, ⊥, ⊥)**

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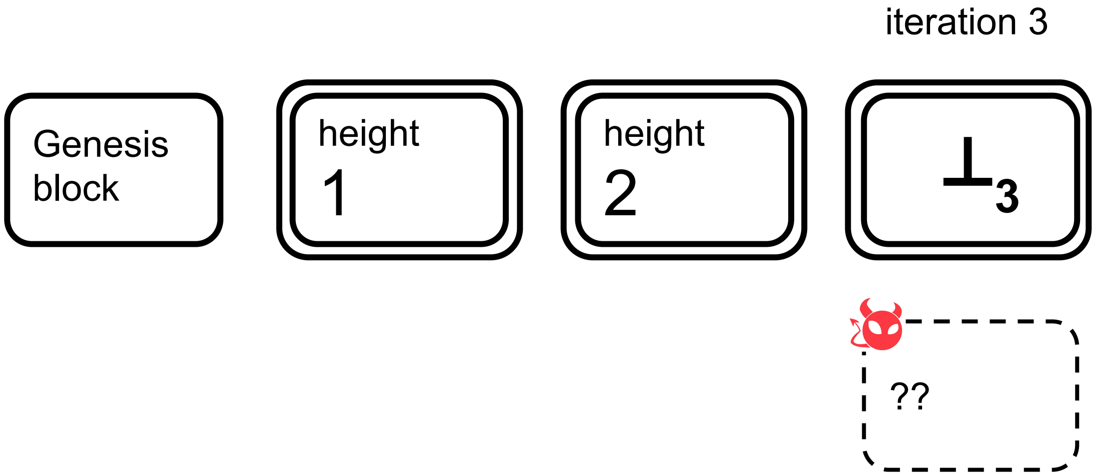

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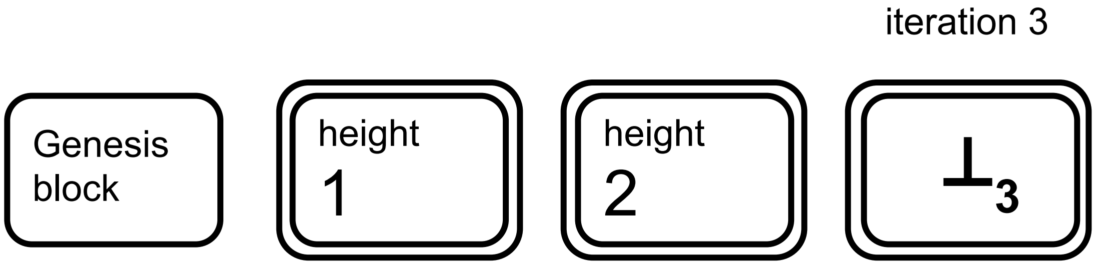

On seeing notarized dummy block,
can now move on to the next iteration!

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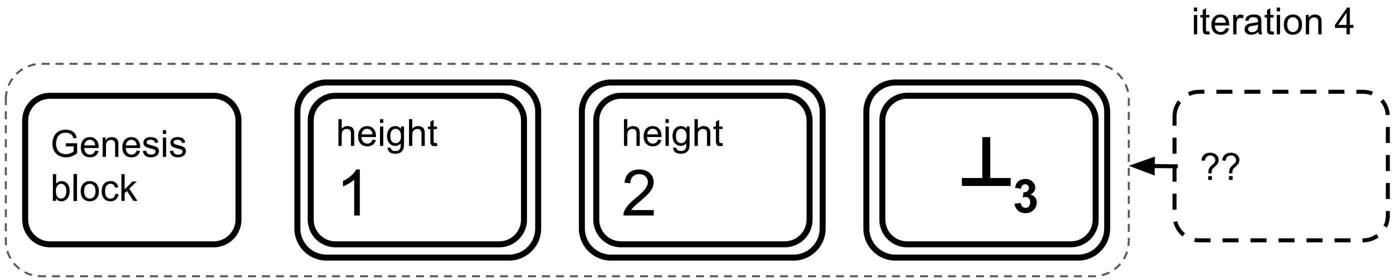

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Intuition: example of an honest view

If there are faults during iteration **h**, there may be ***both***

- a notarized block proposal (for **h**), and
- a notarized dummy block $\perp_h$

in the view of honest players.

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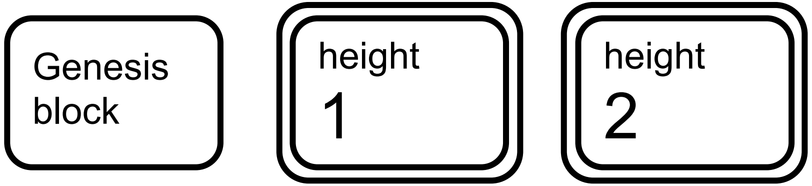
i.e. Alice sees a notarized block proposal for h=3



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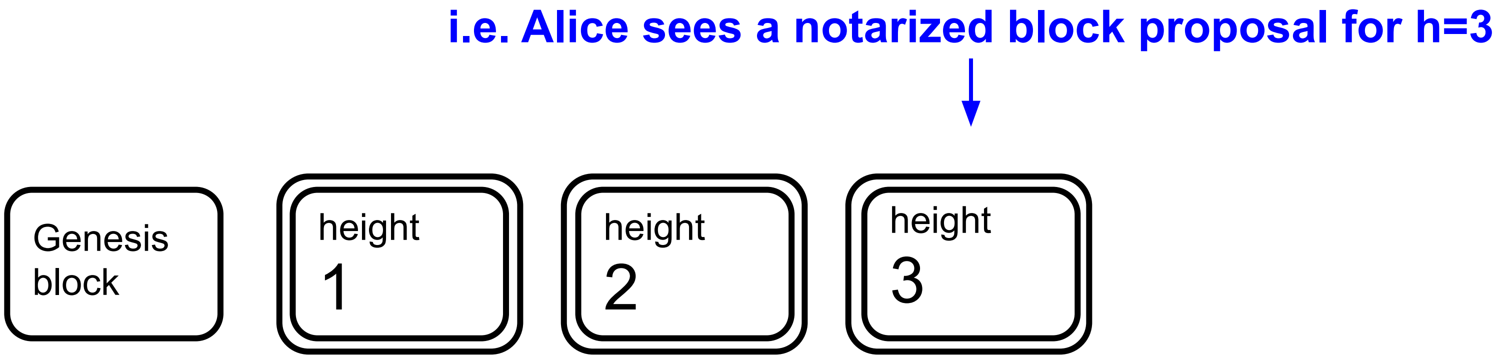

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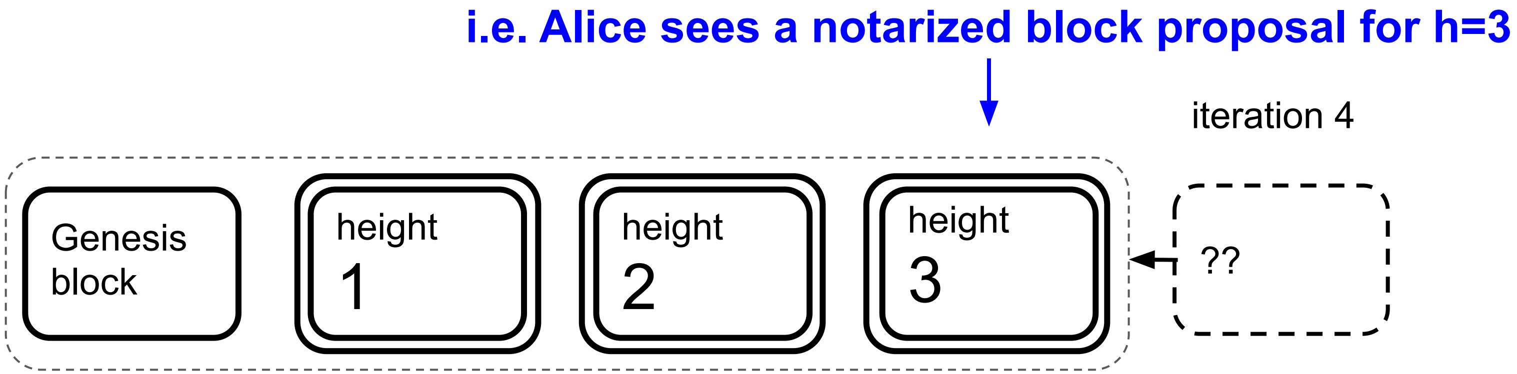

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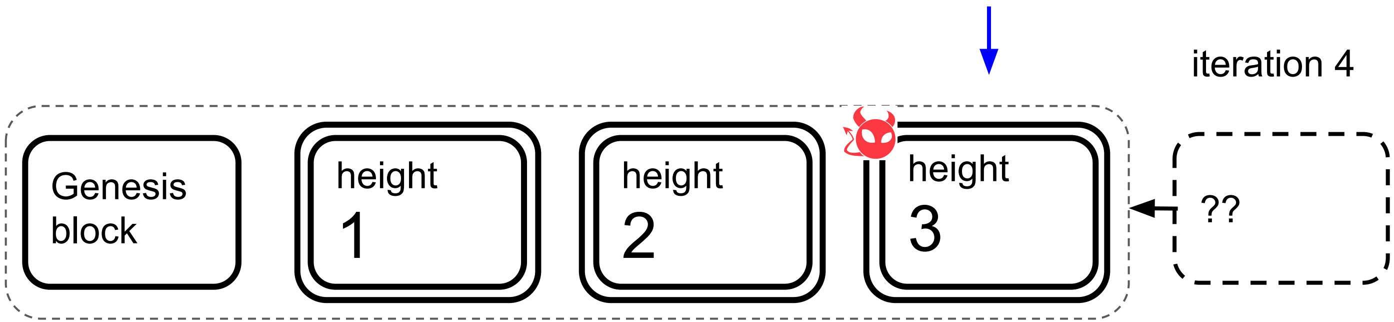

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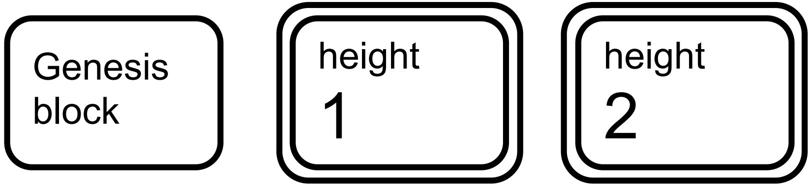
but everyone else times out
(and votes for $\perp_3$)



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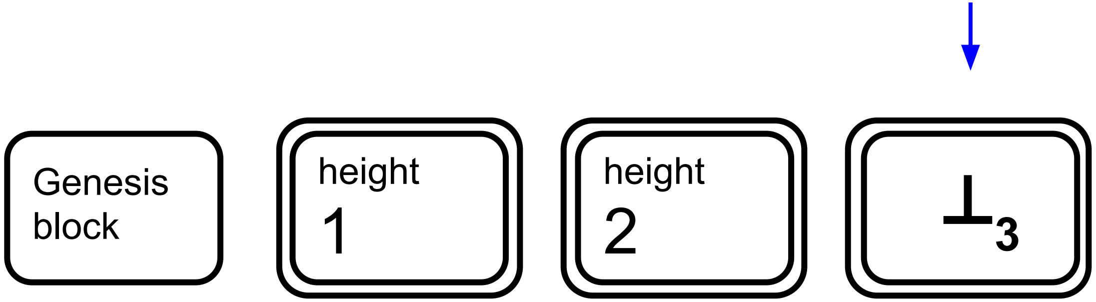
so Bob sees a notarized dummy block $\bot_3$



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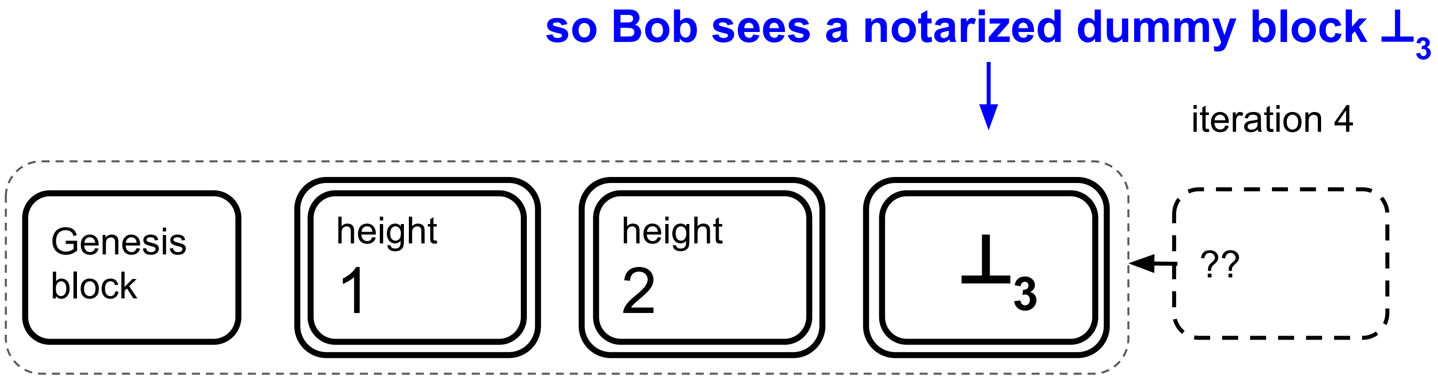

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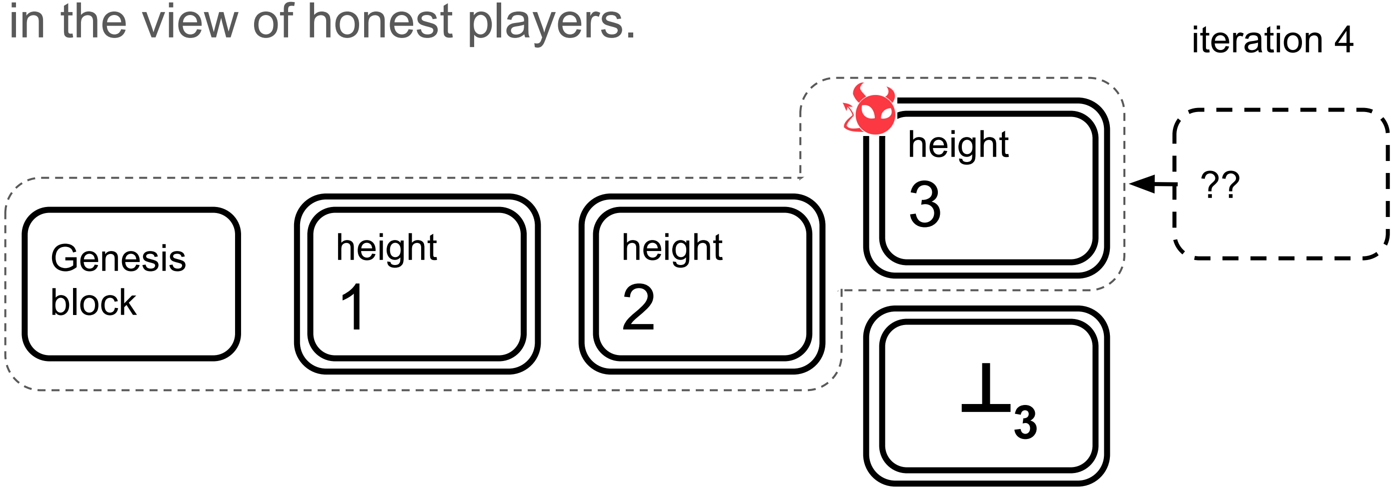

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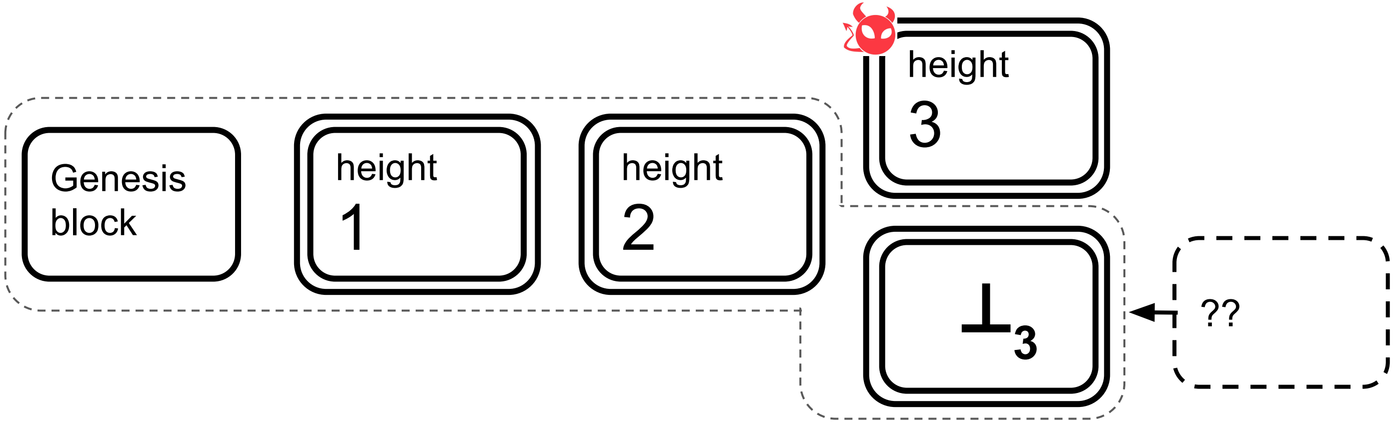

Finalizing blocks

When player **i** enters iteration **h+1**, if **i** did not time out and vote for the dummy block for **h**, player **i** sends everyone a signed "**finalize h**" message.

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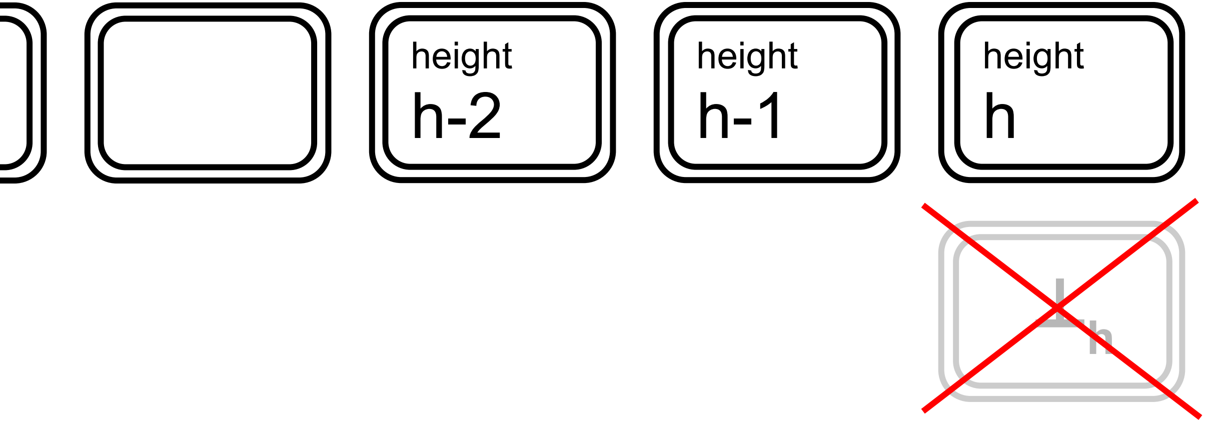

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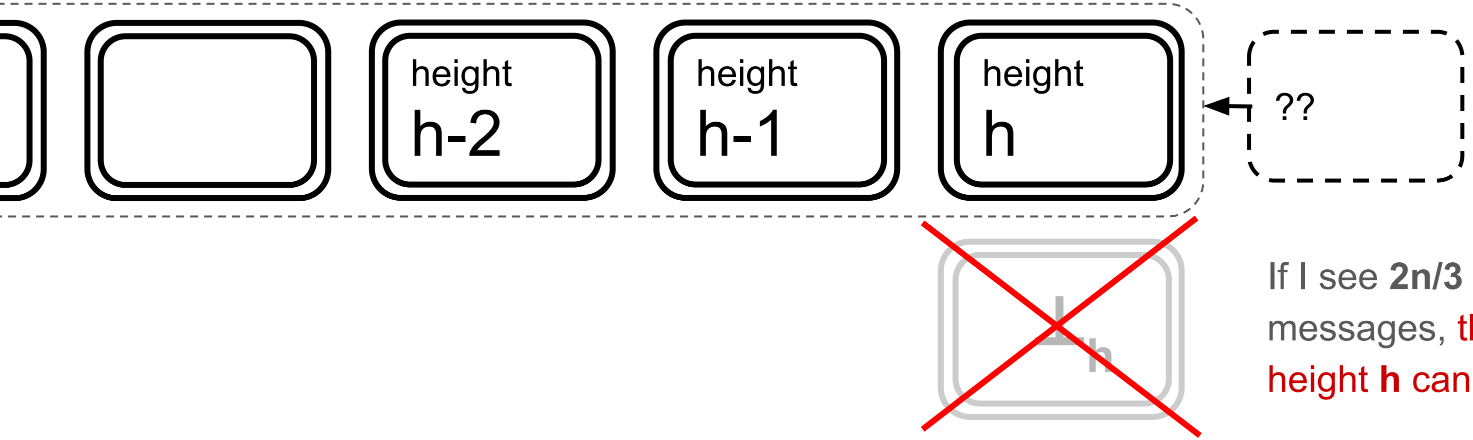


If I see **2n/3 “finalize h”** messages, the dummy block of height **h** cannot be notarized!

Protocol Summary

In each iteration **h = 1, 2, 3, …** each player does the following:

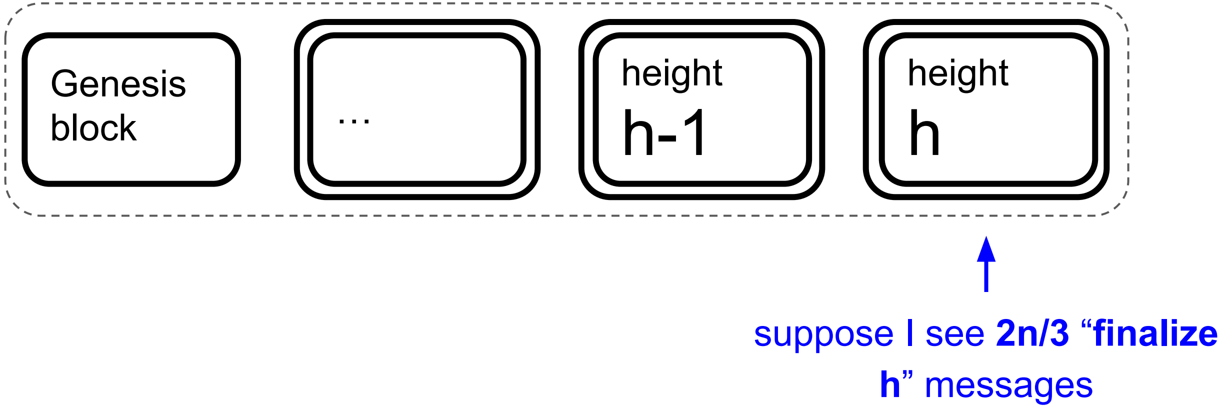
1. The leader proposes a new block of height **h** extending a notarized blockchain of length **h-1**.
2. On seeing the first valid block proposal **b** from the leader, send everyone "**vote b**".
3. (Timeout) After **3Δ time**, if we are still in iteration **h**, send everyone "**vote** $\bot_h$".
4. On seeing a notarized blockchain of length **h**, enter iteration **h+1**. If we did not previously timeout, send everyone "**finalize h**".

At any point, in any iteration

5. On seeing **2n/3 finalize** messages for any **h**, we can finalize any notarized blockchain of length **h**.

Consistency

Thm: Consider two finalized chains LOG, LOG' s.t |LOG| ≤|LOG'|.
Then, LOG ≤ LOG'

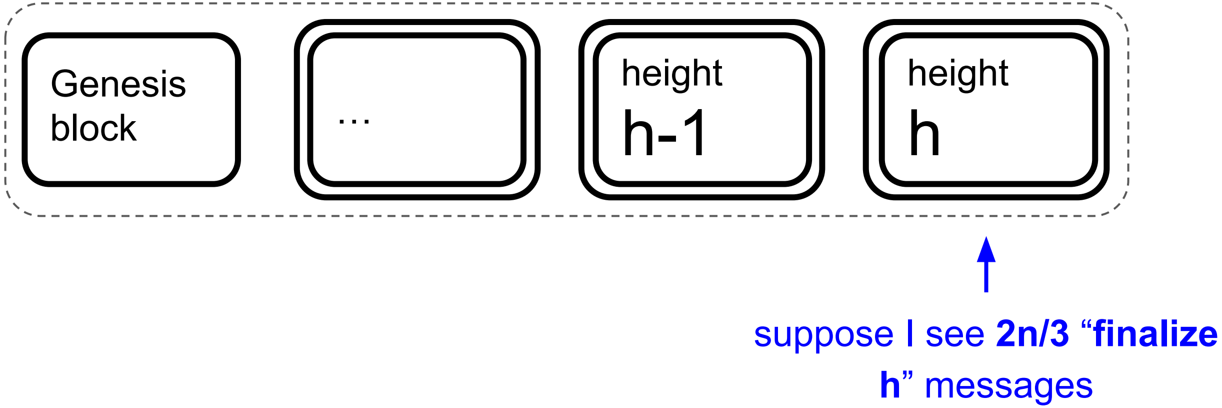


Proof: Consider the shorter one: LOG, let its length be **h**

Consistency

Since LOG is finalized, some honest player sees **2n/3** "**finalize h**" messages.

Claim: there can be only one notarized blockchain of length **h**, across all honest views



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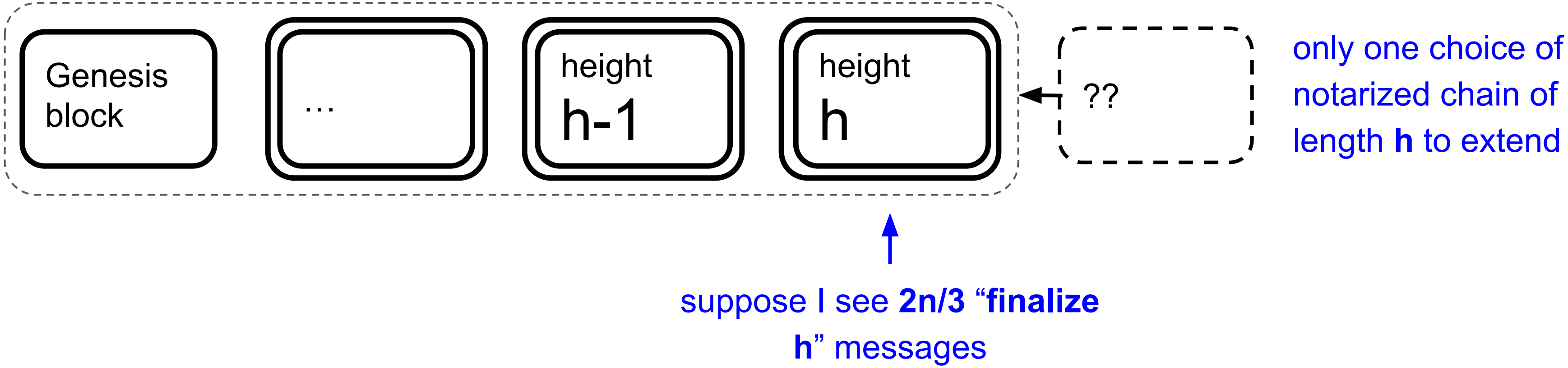
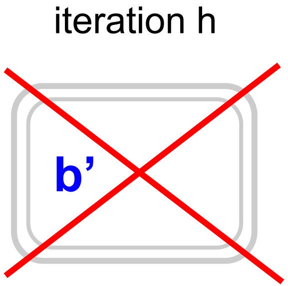
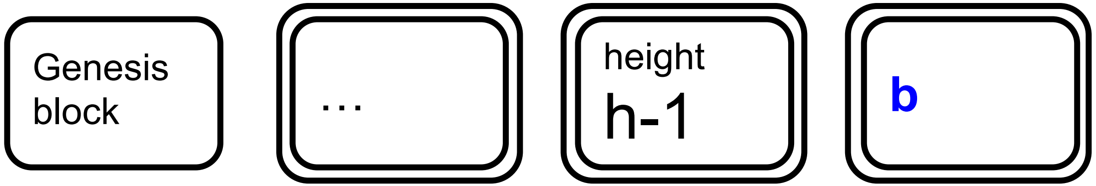


Consistency

Claim: At most one block proposal from the leader can be notarized in honest view



Proof: Each honest player votes for at most one proposal. Quorum intersection.



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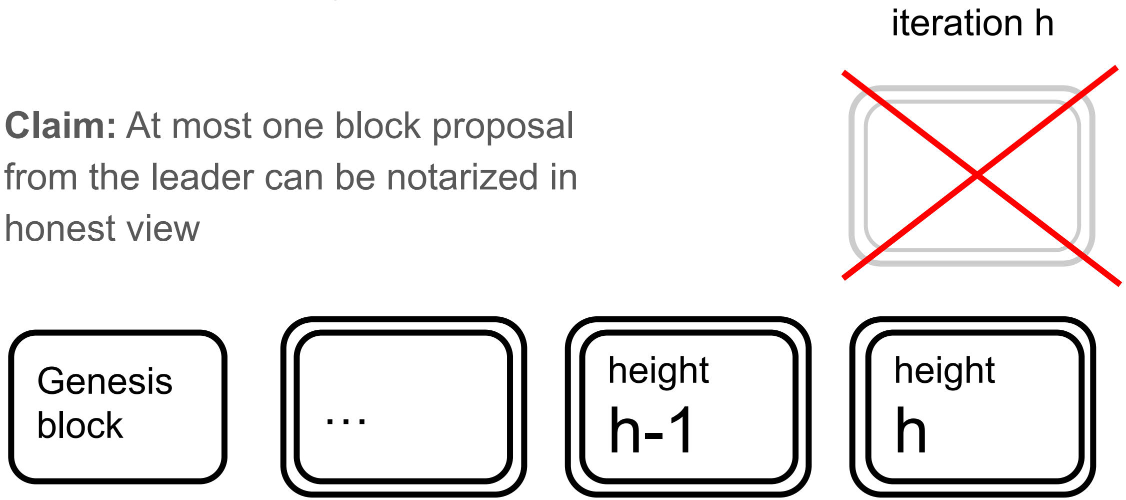

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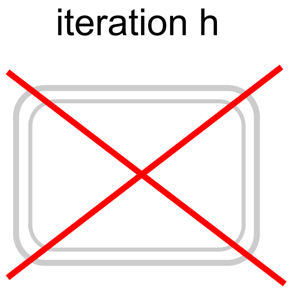

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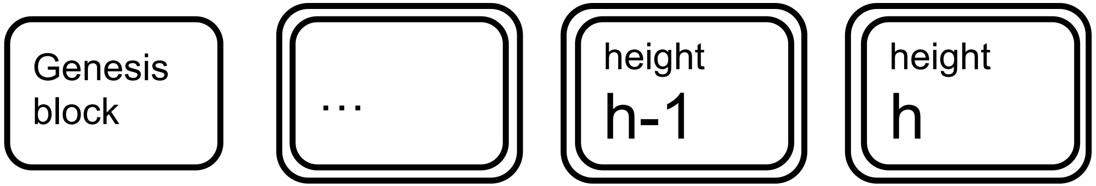

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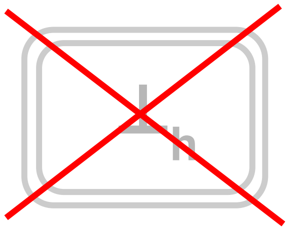

Proof: Each honest player either votes **finalize** or for $\perp_h$. Apply quorum intersection.

Consistency

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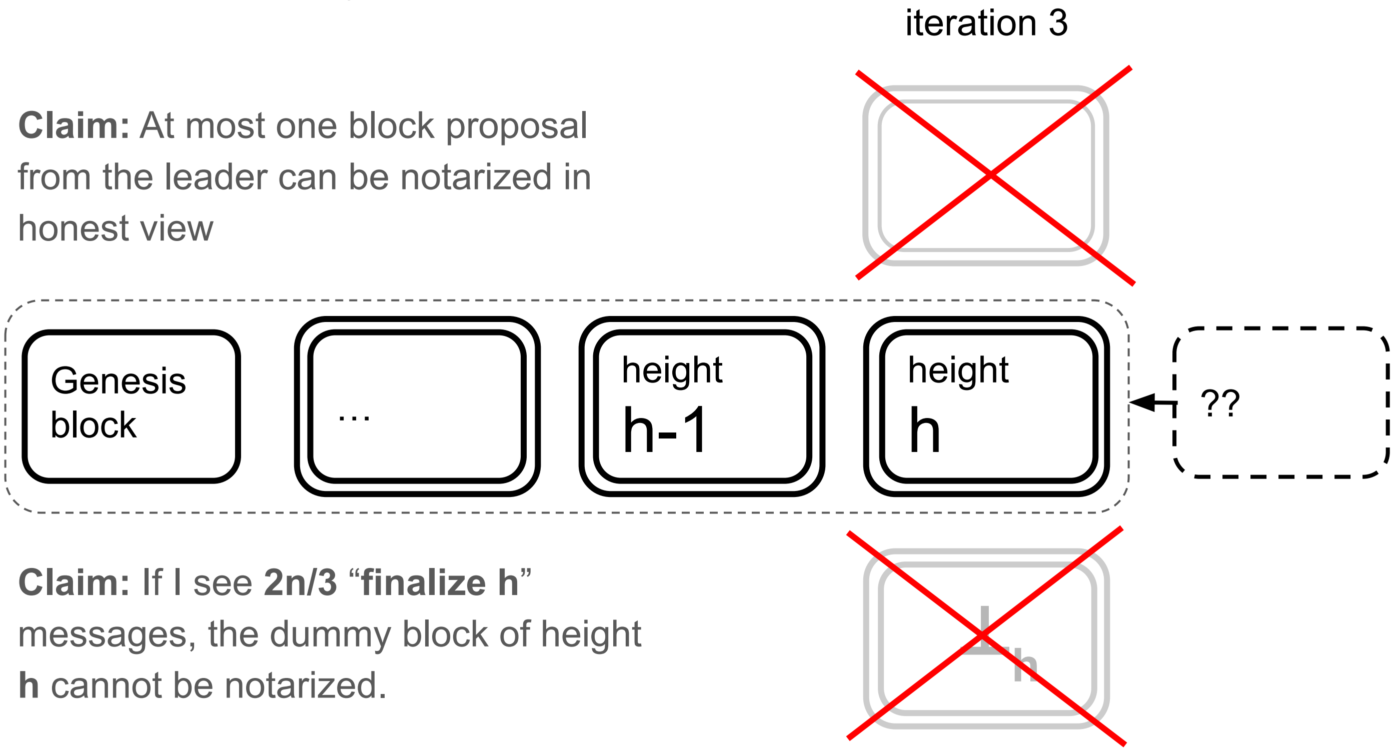
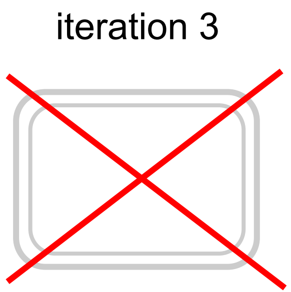


Claim: If I see **2n/3 "finalize h"** messages, the dummy block of height **h** cannot be notarized.

Thus, if someone sees **2n/3 "finalize h"** messages: only one choice of notarized chain of length **h** to extend

LOG ≤ LOG'

Consistency



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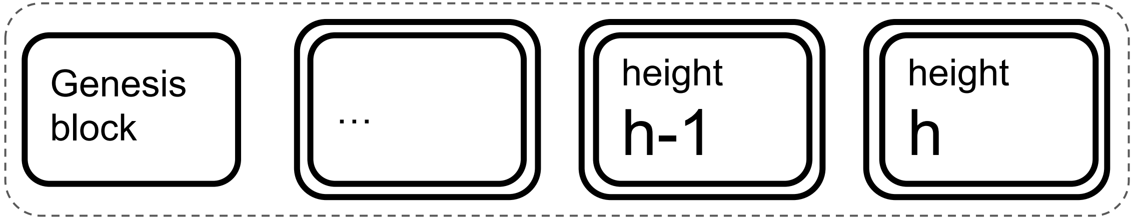
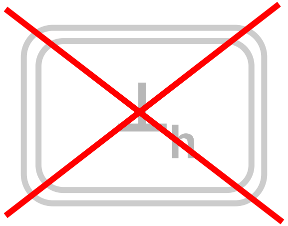


Safe to finalize the transactions in this notarized chain!



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Liveness

Claim: if the network is good (after GST), an honest leader can always get its block proposal notarized, and then finalized.

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Fact: if some honest player enters iteration h by time t, if $t > GST$, then every honest player enters iteration h by time $t + \delta$.

When an honest player enters an iteration h, it sends its notarized blockchain of length $h-1$ to everyone else.

Liveness

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Liveness

Subclaim 1: every honest node will see a notarization for some block of height h by time $t + 2\delta$.

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Every honest player enters iteration $\boldsymbol{h}$ and sees the proposal.

Either everyone sends "**vote** $\mathbf{b_h}$", or someone already entered iteration **h+1**.

Liveness

Subclaim 1: every honest node will see a notarization for some block of height ***h*** by time ***t* + 2*δ***.

time *t*

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time *t* + *δ*

Every honest player enters iteration ***h*** and sees the proposal.

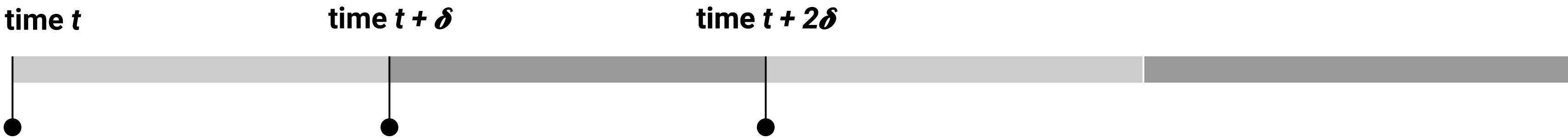
Either everyone sends "**vote** $\mathbf{b_h}$", or someone already entered iteration **h+1**.

time *t* + 2*δ*

Every honest player sees some notarized block of height ***h***.

Liveness

Subclaim 2: The dummy block of height ***h*** (denoted $\perp_h$) cannot be notarized in any honest view before time ***t + 2δ***.



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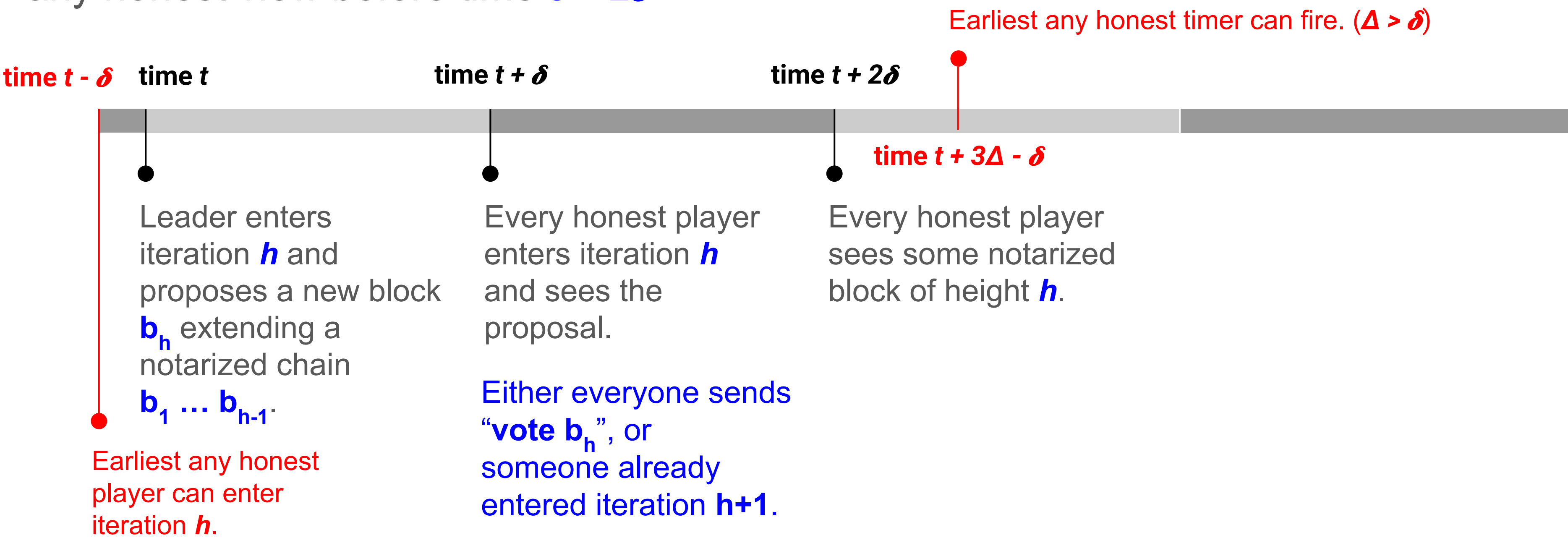
Every honest player sees some notarized block of height ***h***.

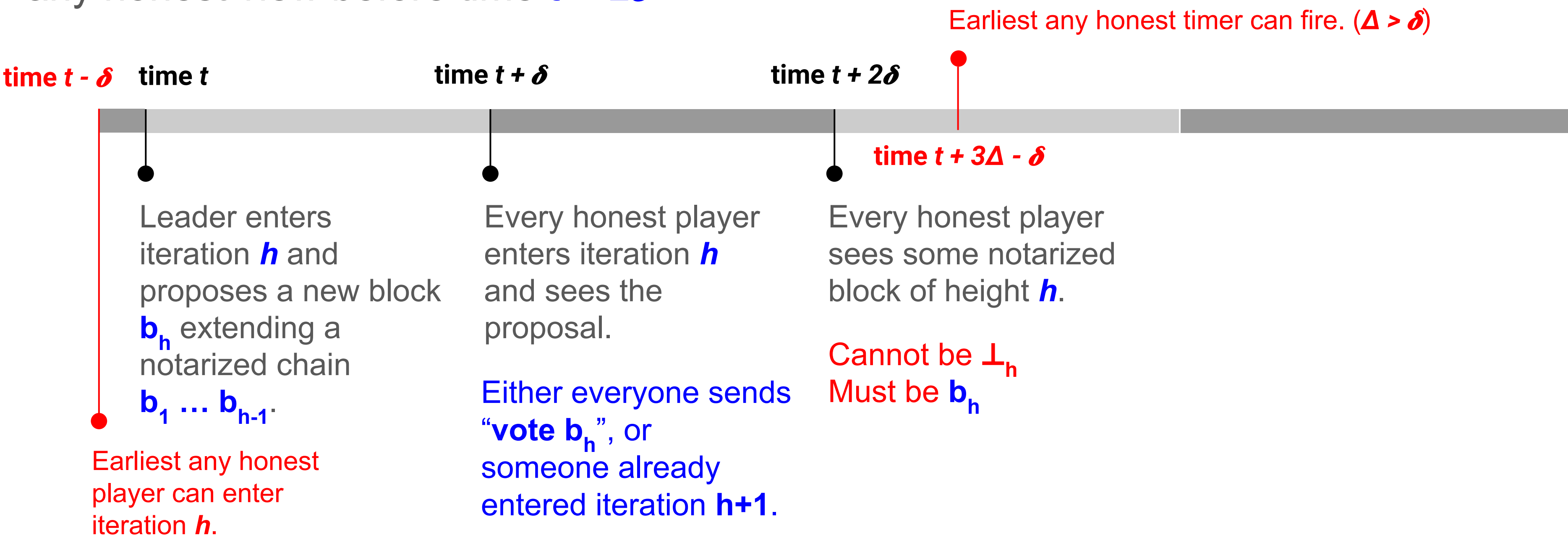
Liveness

Subclaim 2: The dummy block of height ***h*** (denoted $\perp_h$) cannot be notarized in any honest view before time $\boldsymbol{t + 2\delta}$.



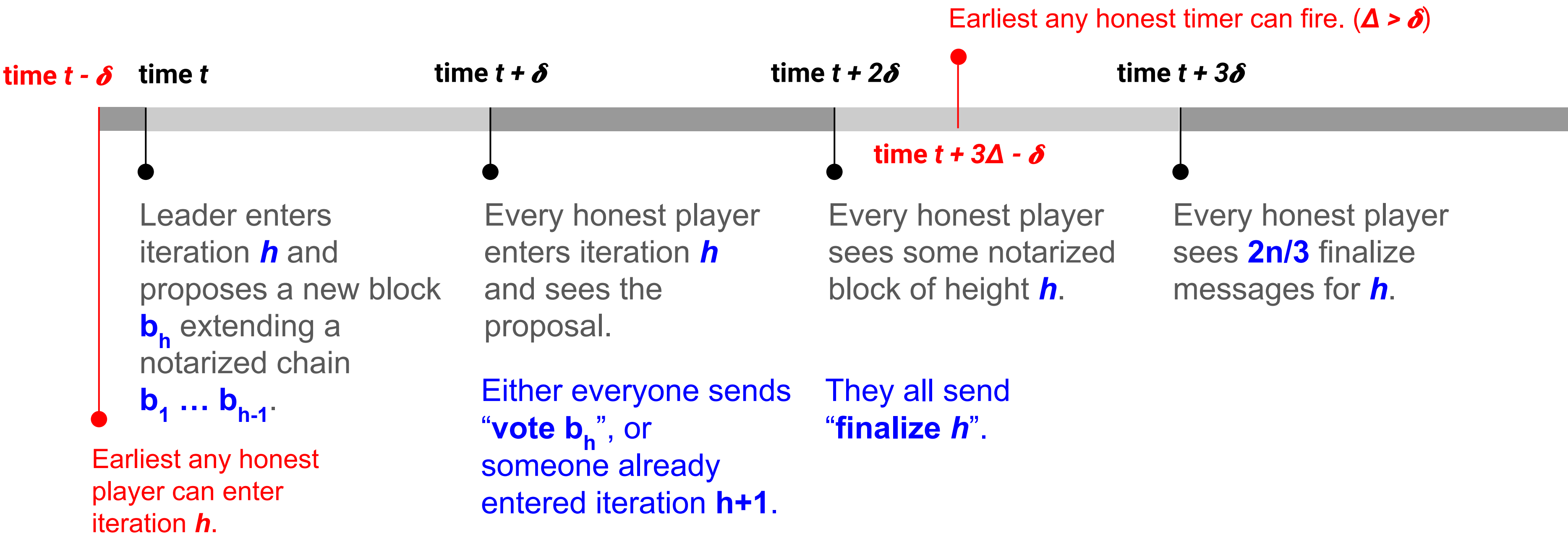
Liveness

Subclaim 2: The dummy block of height ***h*** (denoted $\bot_h$) cannot be notarized in any honest view before time $\boldsymbol{t + 2\delta}$.



Liveness

Thus, every honest player finalizes the leader's block proposal by time $t + 3\delta$.



Liveness for faulty leaders

Claim: if the network is good (after GST), **any** iteration will conclude after $\mathbf{3\Delta + \delta}$ time.

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Every honest player has entered iteration ***h***.

Either every honest timer for iteration ***h*** has fired, or some honest process entered iteration ***h+1*** already.

If timer fires, multicast "**vote $\bot_h$**".

Liveness for faulty leaders

Claim: if the network is good (after GST), **any** iteration will conclude after $3\Delta + \delta$ time.

time *t*

Every honest player has entered iteration ***h***.

time $t + 3\Delta$

Either every honest timer for iteration ***h*** has fired, or some honest process entered iteration ***h+1*** already.

If timer fires, multicast "**vote $\bot_h$**".

time $t + 3\Delta + \delta$

Every honest player enters iteration ***h+1***.

Expected Liveness

Claim: Suppose that every honest player sees TX before iteration ***h***. Suppose every honest player enters iteration **h** by time **t**. Then TX is in the output of every honest player by time $\mathbf{t + 3.5\delta + 1.5\Delta}$, in expectation.

Proof: In expectation, it takes 3/2 iterations to get an iteration with an honest leader. Thus, in expectation the number of iterations with faulty leaders is 1/2. Thus, the waiting time is at most

$$1/2 \cdot (3\Delta + \delta) + 3\delta$$
$$= 3.5\delta + 1.5\Delta$$

as desired.

In Conclusion

A new consensus protocol, called **Simplex Consensus**

- Partial synchrony, **$f < n/3$** byzantine faults
- In our eyes, easiest security proofs!
- Can get communication efficiency using “sortition” [Algorand]

Thm: Assuming a (Bare) PKI, CRH, there exists a partially synchronous consensus protocol in the “random-leader model” with:

- Proposal confirmation time of **3δ**
- Optimistic block time of **2δ**
- Expected pessimistic liveness of **$3.5\delta + 1.5\Delta$**
- Worst-case liveness of **$4\delta + \omega(\log \lambda) \cdot (3\Delta + \delta)$**

What Next?

Work on understandable, efficient permissioned consensus

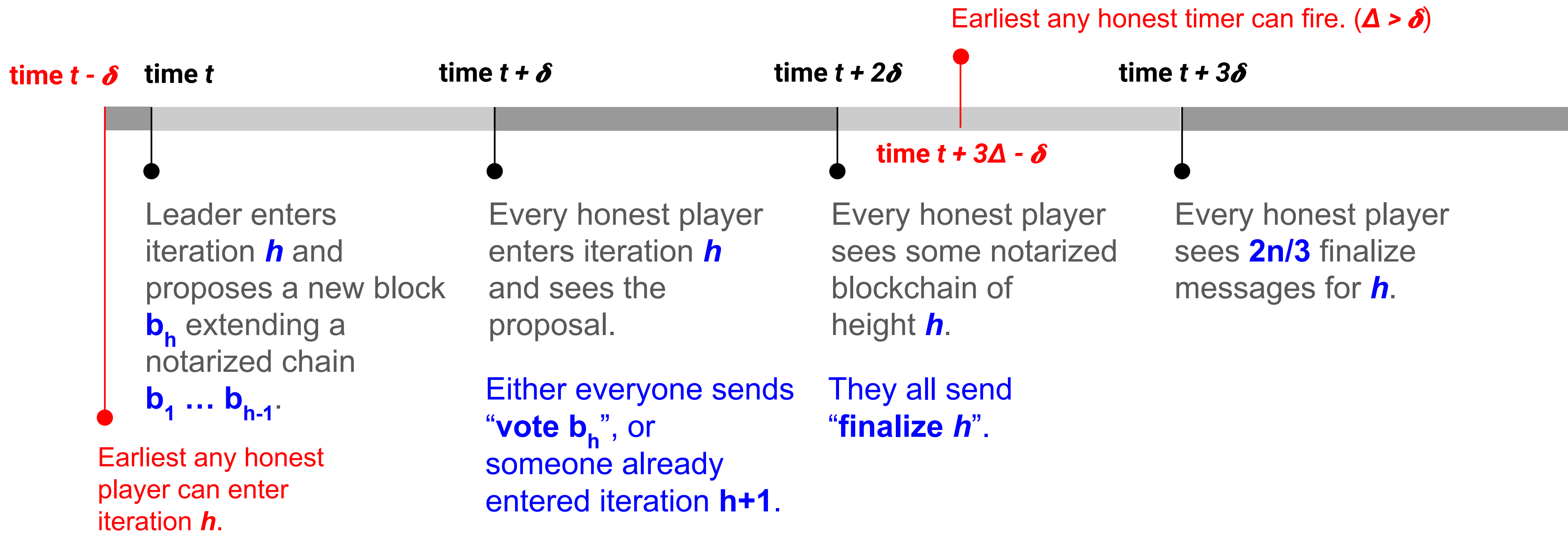
- Simplex [**C**P23], Streamlet [**C**S20]

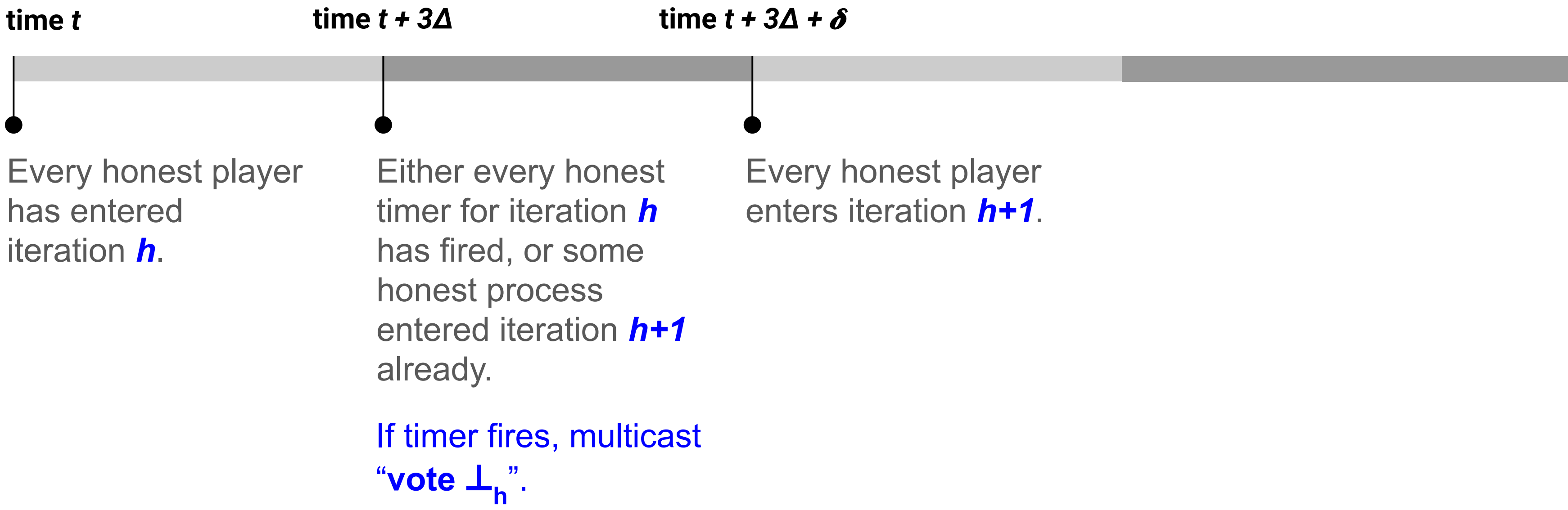
Work on formalizing execution environments of protocols in the presence of various adversaries:

- Universal Reductions [**C**FP22]
- Non-equivocation in Distributed Protocols [B**C**S22]

Next

- The permissionless setting, dynamic participation
- Decentralized exchanges


Earliest any honest timer can fire. ($\Delta > \delta$)
time $t - \delta$
time t
time $t + \delta$
time $t + 2\delta$
time $t + 3\delta$
time $t + 3\Delta - \delta$
Leader enters iteration h and proposes a new block b_h extending a notarized chain $b_1 \dots b_{h-1}$.
Earliest any honest player can enter iteration h.
Every honest player enters iteration h and sees the proposal.
Either everyone sends "vote b_h", or someone already entered iteration **h+1**.
Every honest player sees some notarized blockchain of height h.
They all send "**finalize** h".
Every honest player sees **2n/3** finalize messages for h.


time t
time $t + 3\Delta$
time $t + 3\Delta + \delta$
Every honest player has entered iteration ***h***.
Either every honest timer for iteration ***h*** has fired, or some honest process entered iteration ***h+1*** already.
If timer fires, multicast "**vote $\perp_h$**".
Every honest player enters iteration ***h+1***.