Simplex Consensus
A Fast and Simple Consensus Protocol

Benjamin Chan

Cornell Tech

Joint work with Rafael Pass

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A consensus protocol with the
easiest security proofs*
best latency
of all the protocols we've seen thus far.
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Goal: A practical protocol that is intuitive* enough to teach in class. (I will try to teach it now.)

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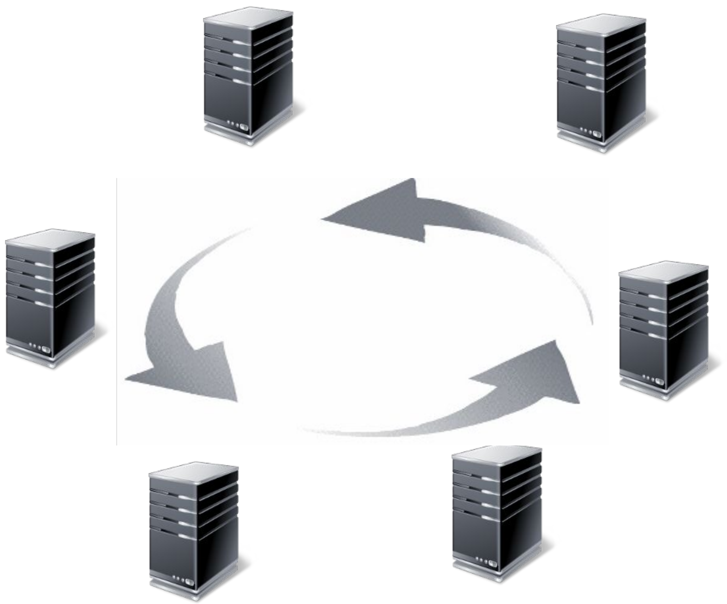
Our setting: the consensus problem



n players, **f < n/3** malicious faults, **partial synchronous** network.
know public keys ahead of time (bare PKI)

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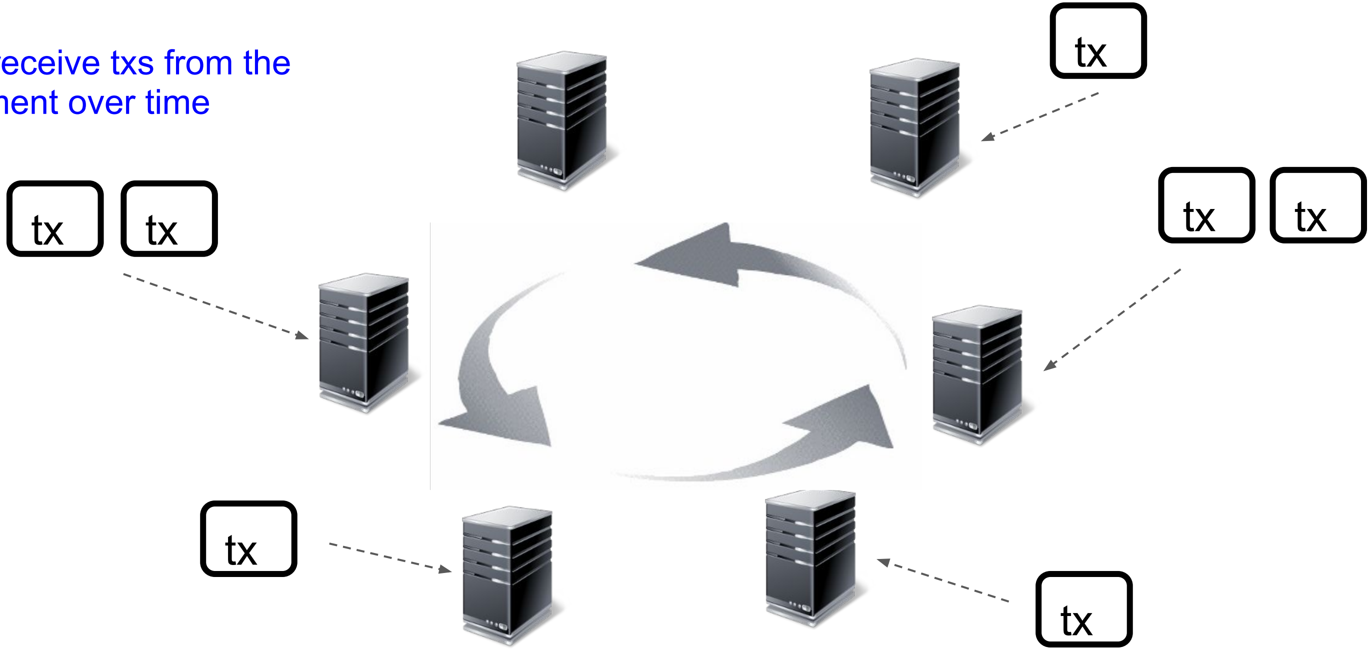

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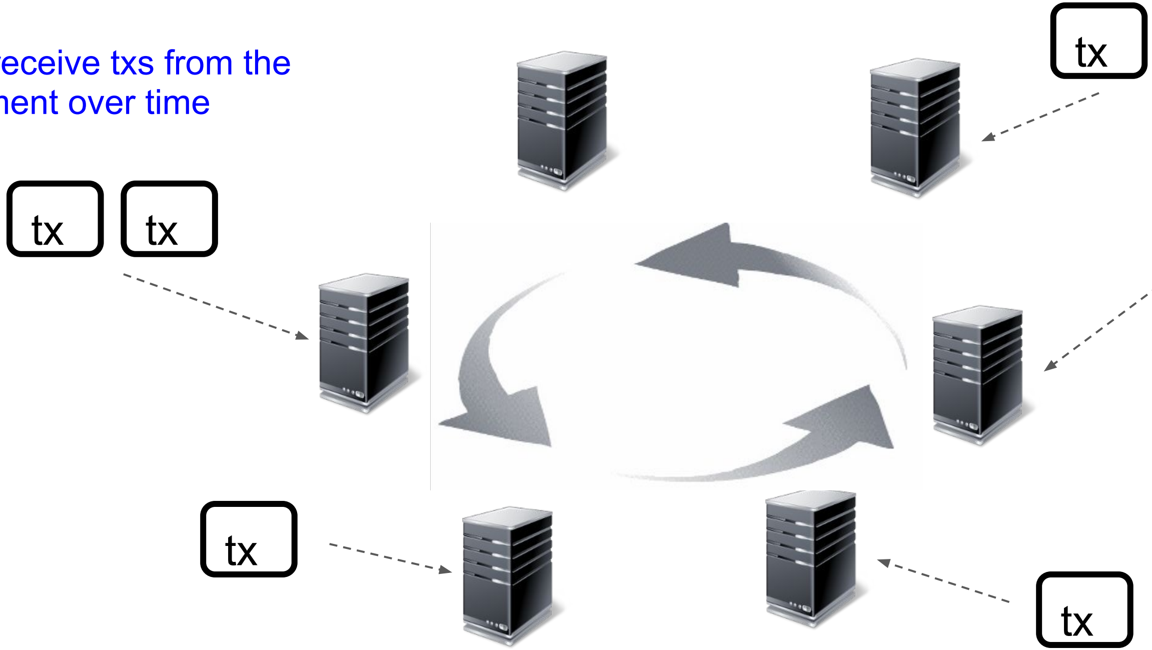

Different players may see different orders of txs!

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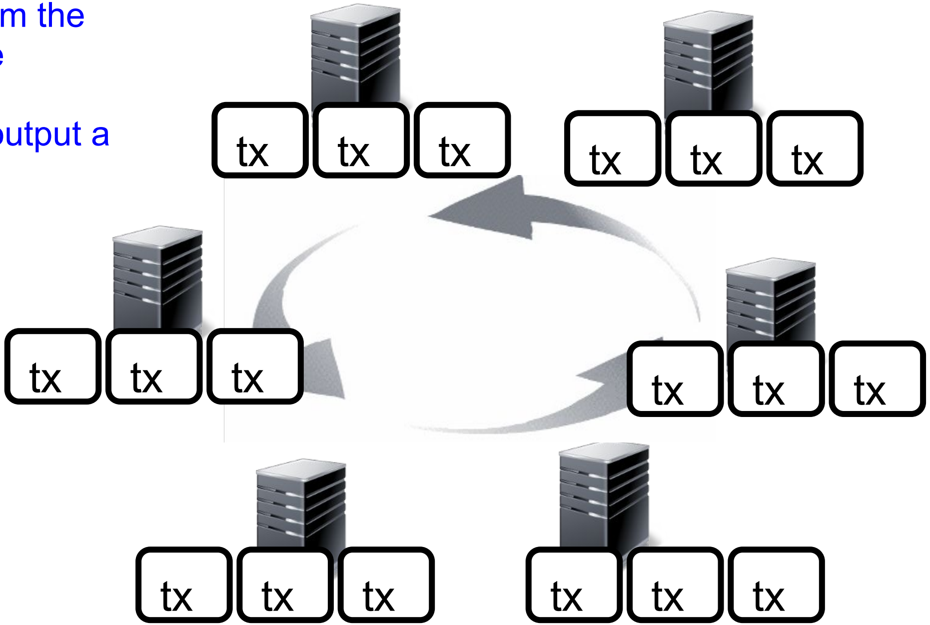
2. players continuously output a log of “finalized txs”



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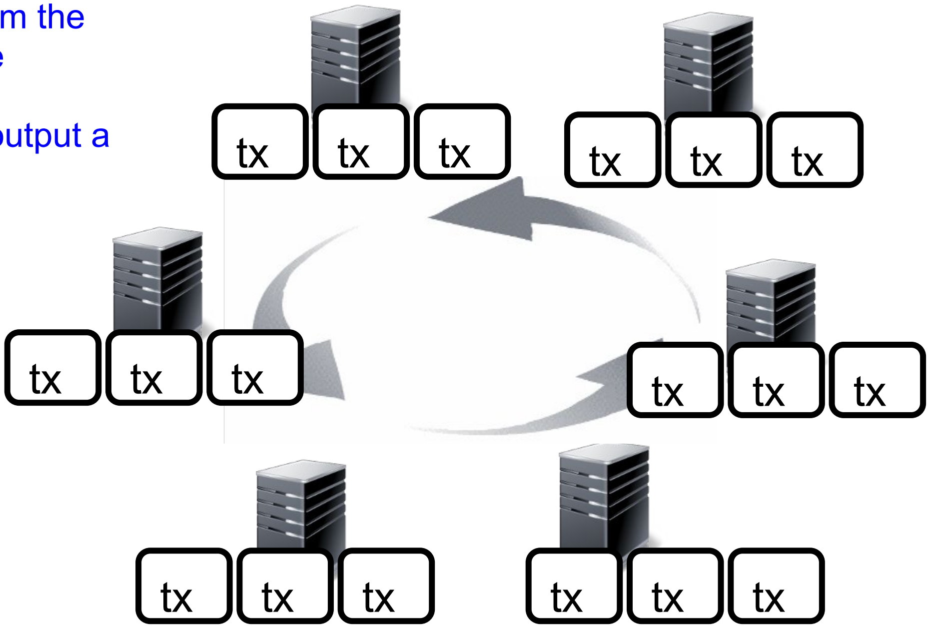

Consistency

(all players output the same ordering of finalized txs)

Liveness

(transactions eventually get finalized)

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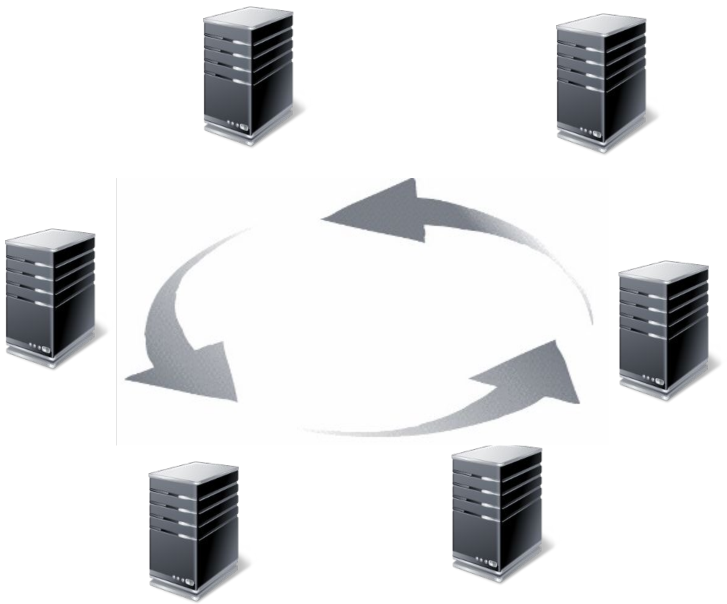

∃ unknown time **GST**, an unknown **δ**, and a known time bound **Δ > δ** s.t.

- **After GST**, every message is delivered within **δ seconds.**
- **Before GST,** no guarantee.

Models unreliable network [DSL88]

n players, **f < n/3** malicious faults, **partial synchronous** network.
know public keys ahead of time (bare PKI)

Our Work

Thm: Assuming a (Bare) PKI, CRH, there exists a partially synchronous "random-leader" consensus protocol for $f < n/3$ static corruptions, and:

- Optimistic confirmation time of $\boldsymbol{3\delta}$ (excluding block time)
- Optimistic block time of $\boldsymbol{2\delta}$
- Expected pessimistic confirmation time* of $\boldsymbol{3.5\delta + 1.5\Delta}$
- Worst-case confirmation time of $\boldsymbol{4\delta + \omega(\log \lambda) \cdot (3\Delta + \delta)}$
- Easiest security proofs (in our eyes)

δ: unknown, true message delay during periods of synchrony
Δ: known, public upper bound on δ

Get efficient communication via "sortition" [CM18]

Comparisons

Theoretical latency of protocols that support random leaders

	Proposal Conf. Time	Optimistic Block Time	Pessimistic Liveness ($f = \lceil n/3 \rceil - 1$)
Simplex	$\mathbf{3\delta}$	$\mathbf{2\delta}$	$\mathbf{3.5\delta + 1.5\Delta}$
Algorand* [CGMV18]	$\mathbf{3\delta}$	3δ	$4\delta + 2\Delta$
ICC [CDH+22]	$\mathbf{3\delta}$	$\mathbf{2\delta}$	$5.5\delta + 1.5\Delta$
PaLa [CPS18]	4δ	$\mathbf{2\delta}$	$6.25\delta + 9.25\Delta$
Pipeline Fast-Hotstuff [JNFG20] Jolteon [GKKS+22]	5δ	$\mathbf{2\delta}$	$10.87\delta + 9.5\Delta$
Chained Hotstuff (v6) [YMR+19]	7δ	$\mathbf{2\delta}$	$19.31\delta + 12.18\Delta$
Streamlet [CS20a]	10Δ	2Δ	39.56Δ

*Base protocol without sortition.

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

Comparisons

Theoretical latency of protocols that support random leaders

Fun note: all protocols differ only slightly in protocol description

	Proposal Conf. Time	Optimistic Block Time	Pessimistic Liveness ($f = \lceil n/3 \rceil - 1$)
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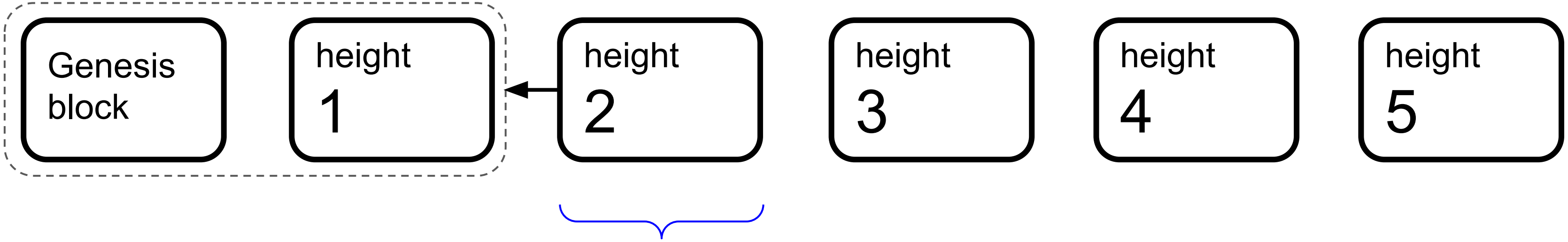
Protocol Description

Preliminaries

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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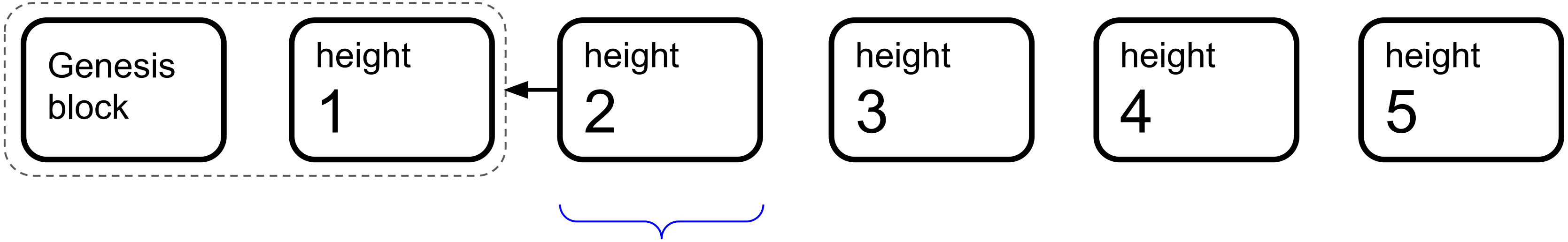

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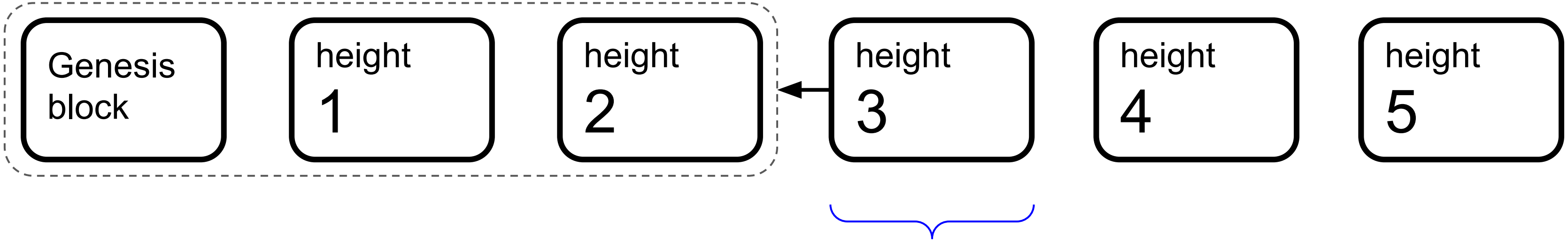

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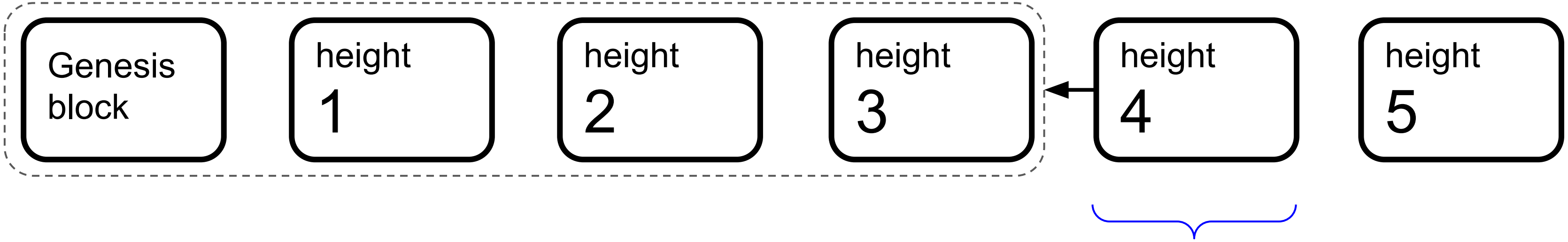

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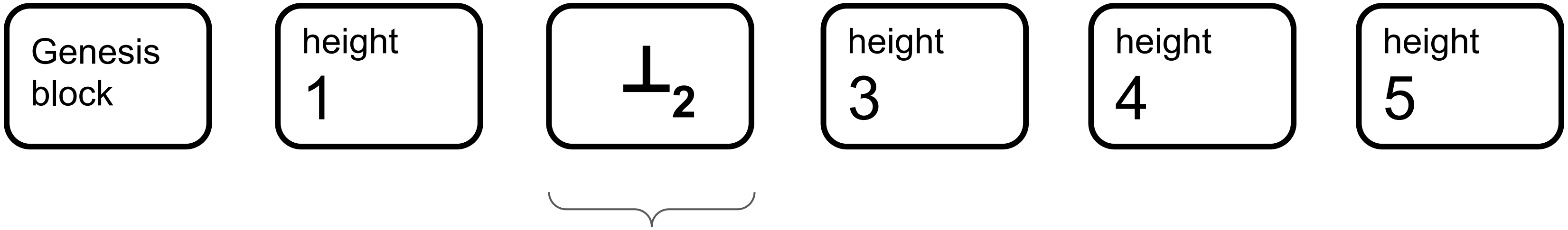
Preliminaries: dummy blocks

We also allow the blockchain to contain "**dummy blocks**"



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

$$\bot_h = (h, \bot, \bot)$$

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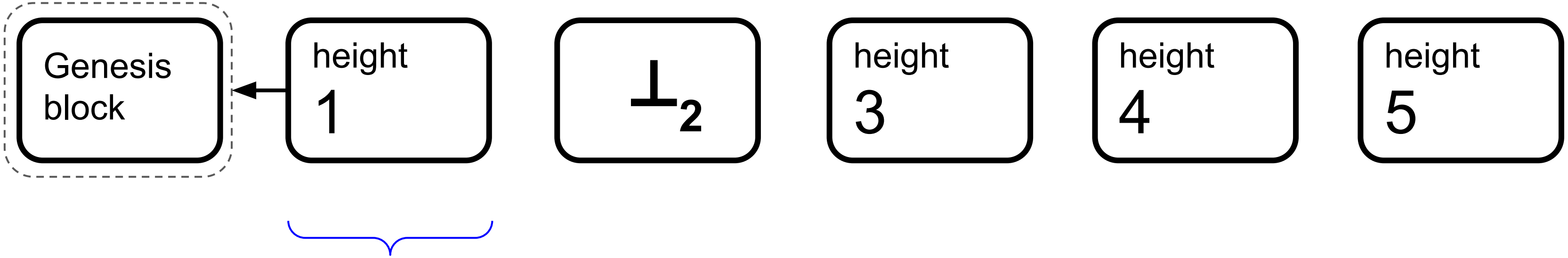

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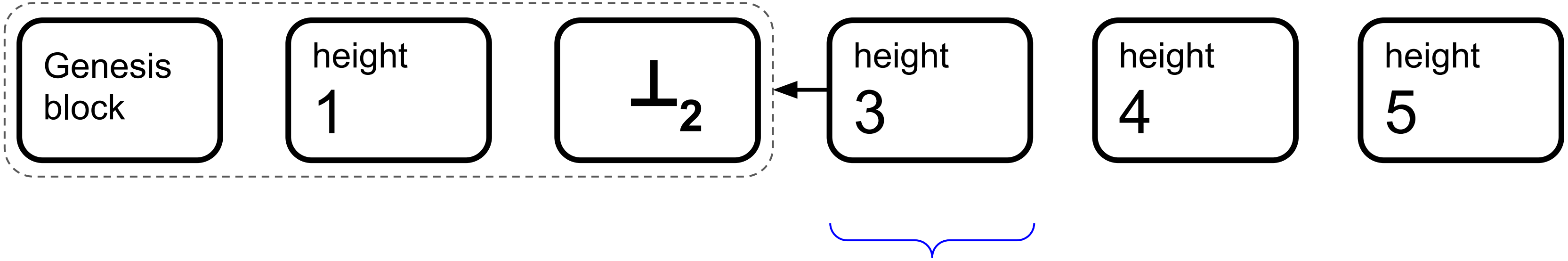

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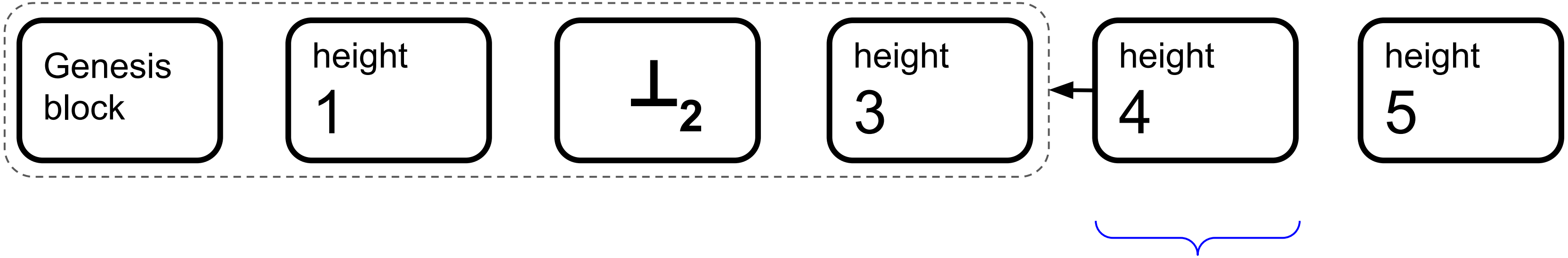

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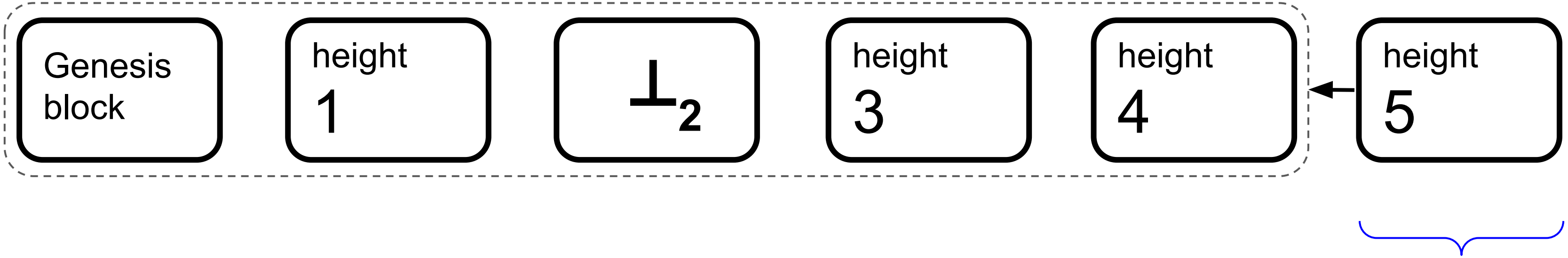

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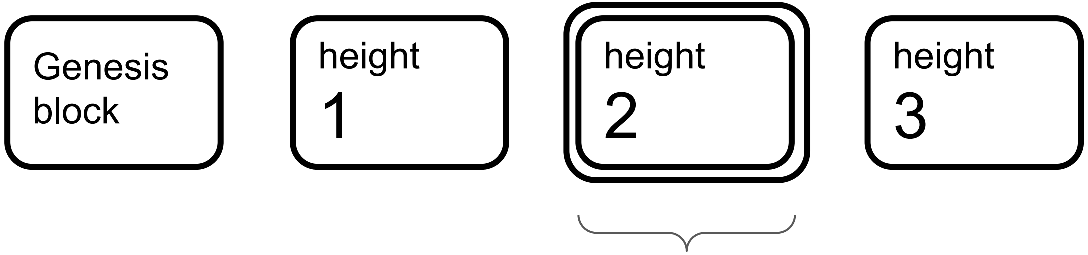
Preliminaries: voting for blocks

A player **i** votes for a block $\mathbf{b_h}$ by signing the message "**vote** $\mathbf{b_h}$"

Preliminaries: notarized blocks

Key data structure: **notarized blocks**



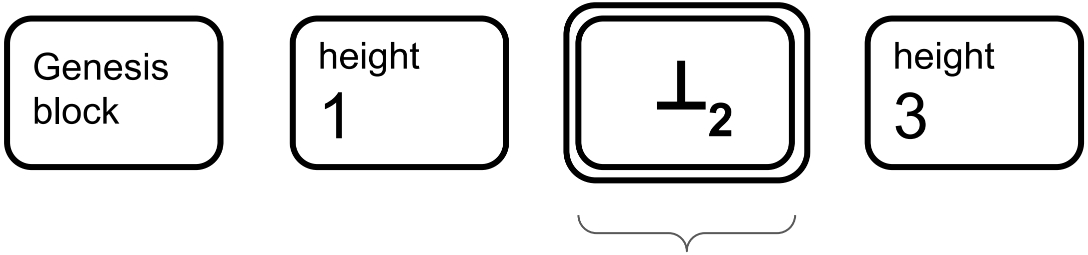
a block is notarized in my view if I've seen

> 2n/3 votes for it

(i.e. signatures from > 2n/3 different players)

Preliminaries: notarized blocks

Dummy blocks can also be **notarized.**



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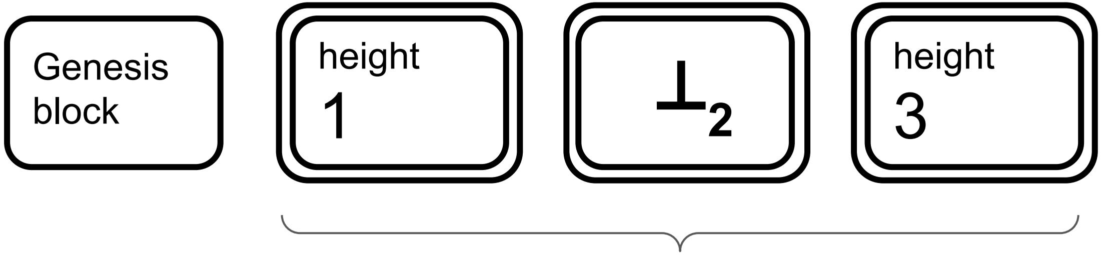
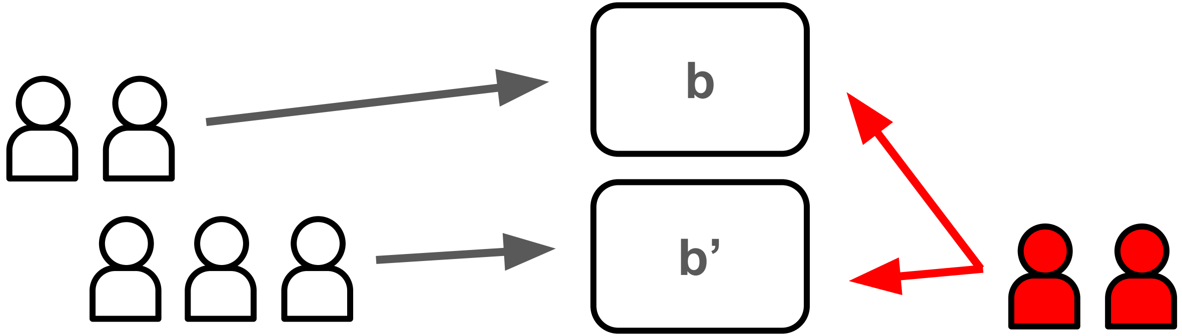


every block of the chain is notarized (except genesis)

Preliminaries: “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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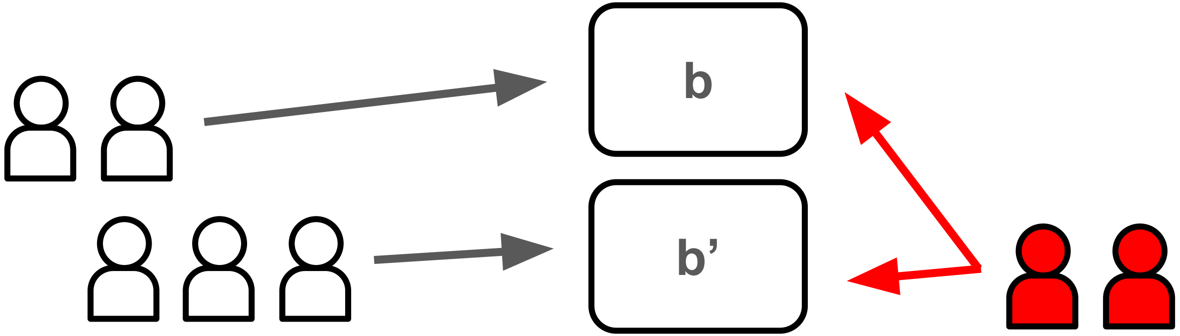

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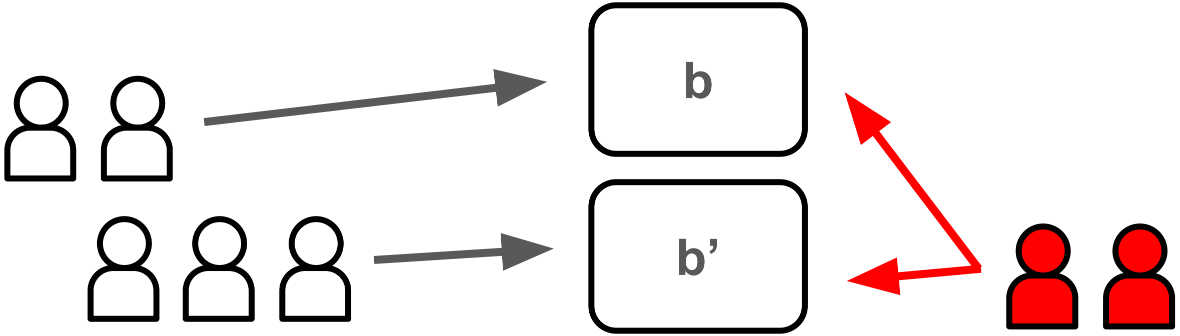

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n – f votes

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

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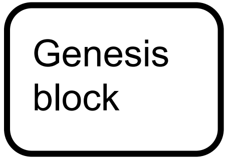
2f votes

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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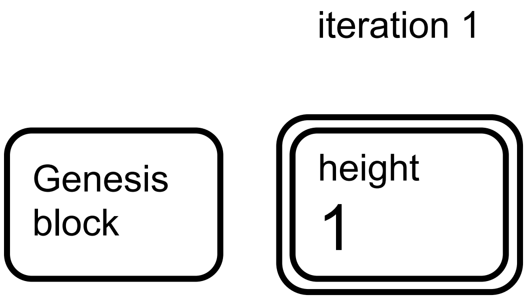

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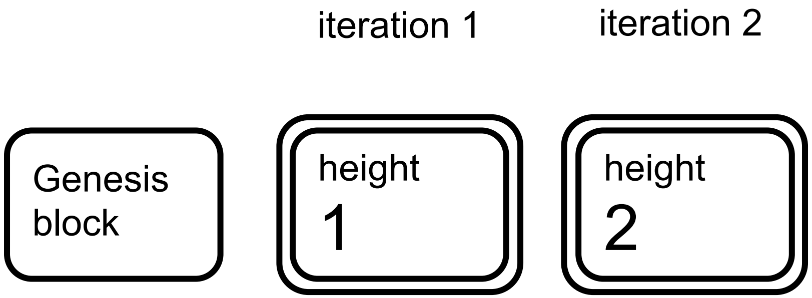

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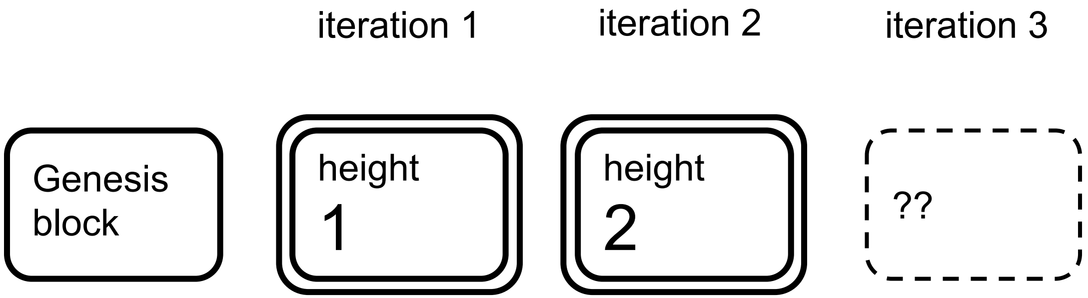

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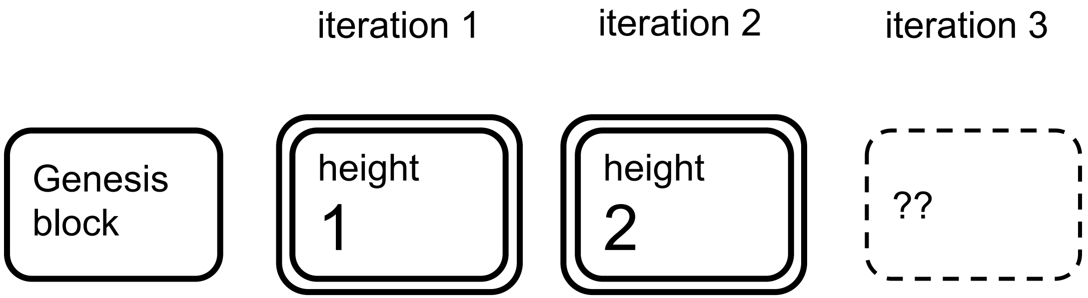
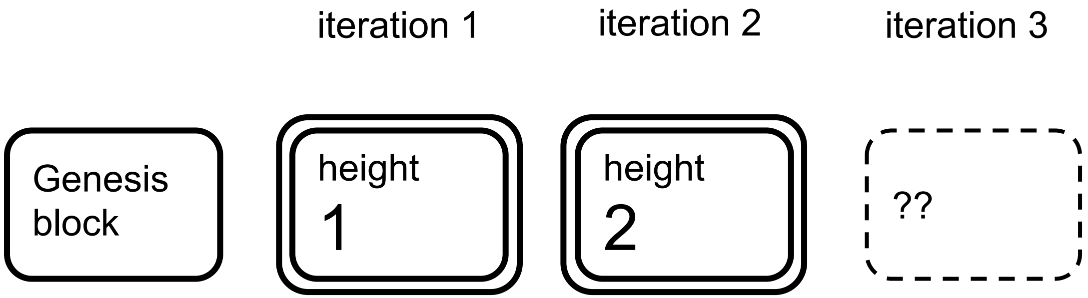


The Simplex Consensus Protocol

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

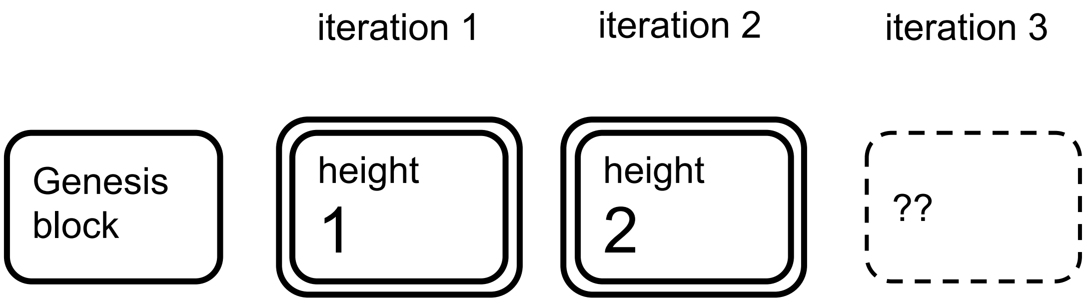
Move to the next iteration when I've seen a notarized blockchain of length **h** (and send this notarized blockchain to everyone else).



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**

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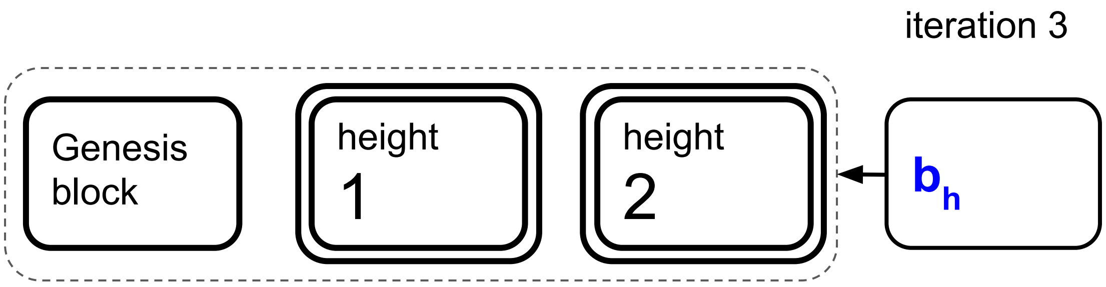

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Should include all pending transactions.

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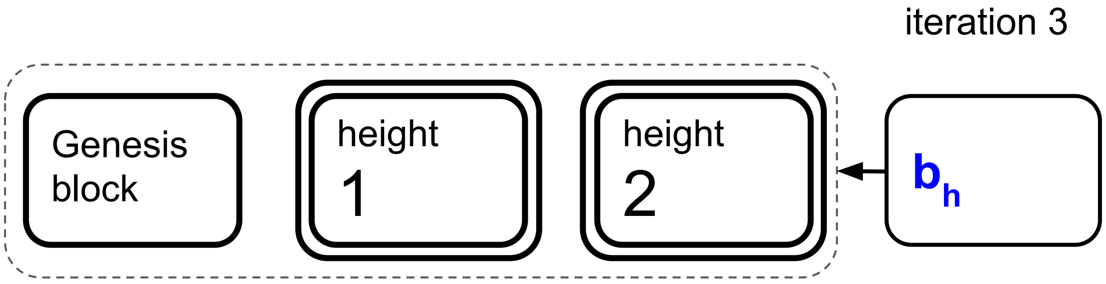

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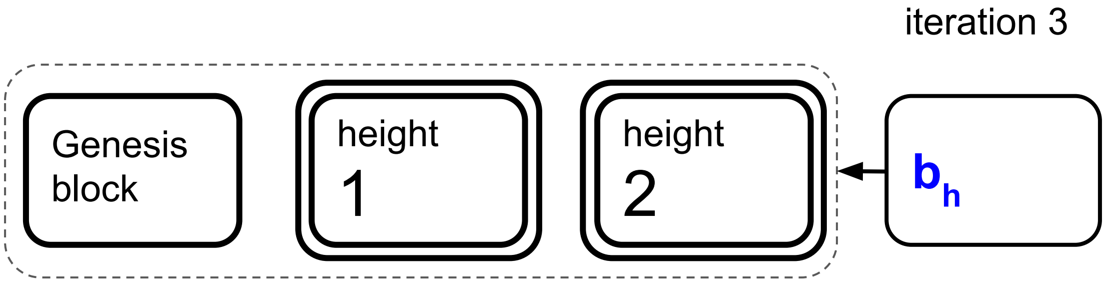

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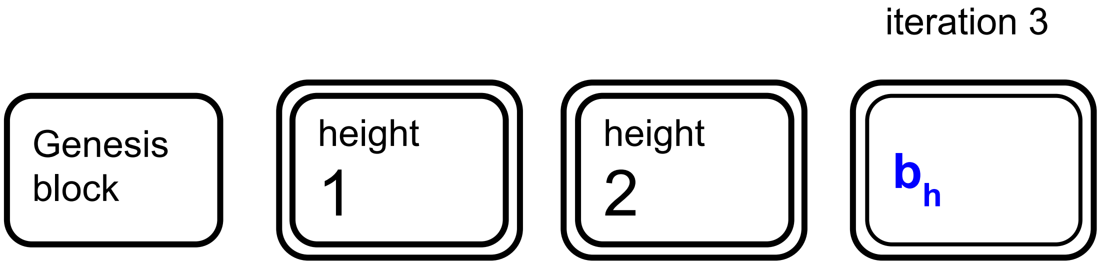

If the network is good and the leader is honest, the block proposal will get notarized!

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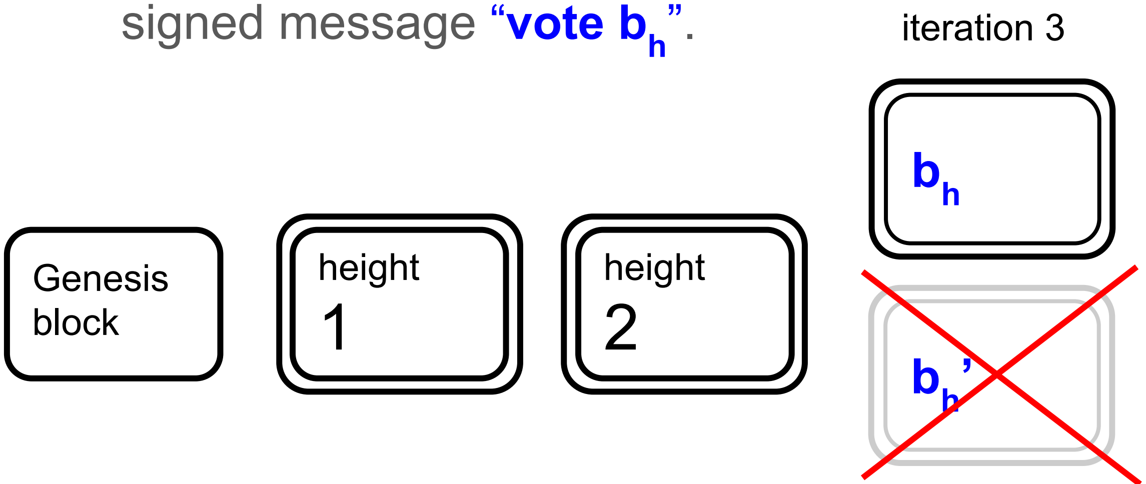
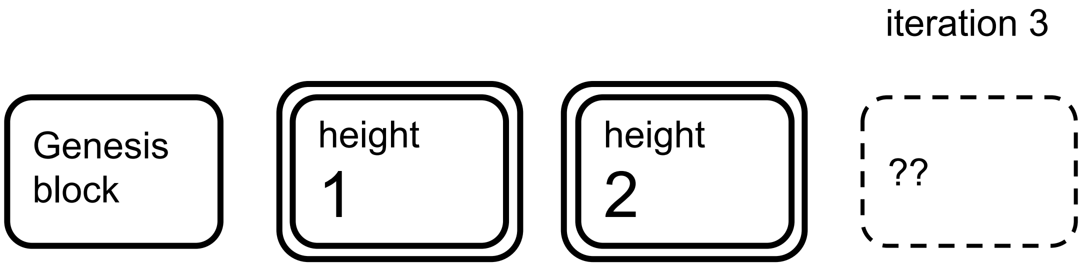


At most one block proposal from the leader can be notarized in honest view

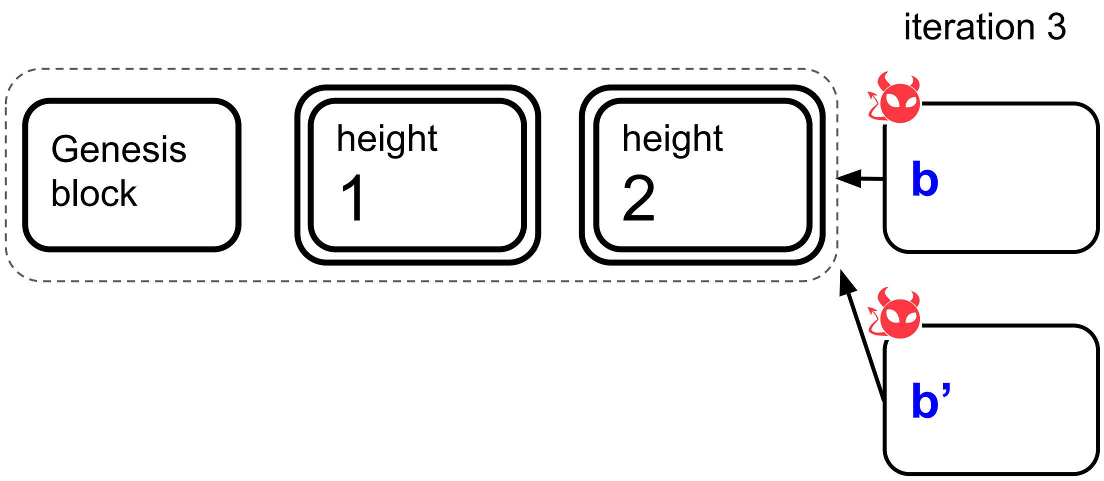
Handling faulty iterations

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



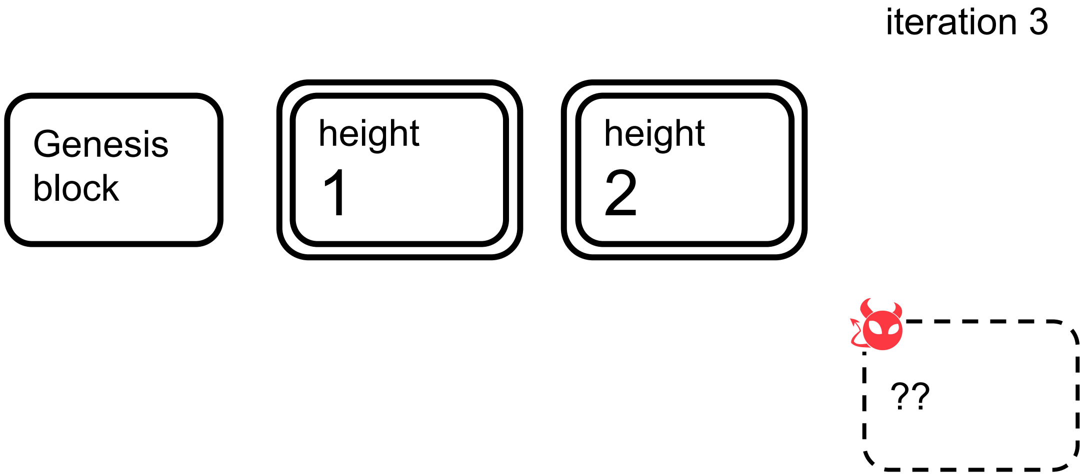
Handling faulty iterations

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 $\bot_h$**”.



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Recall: **Δ** is a public parameter that upper bounds message delay after GST.

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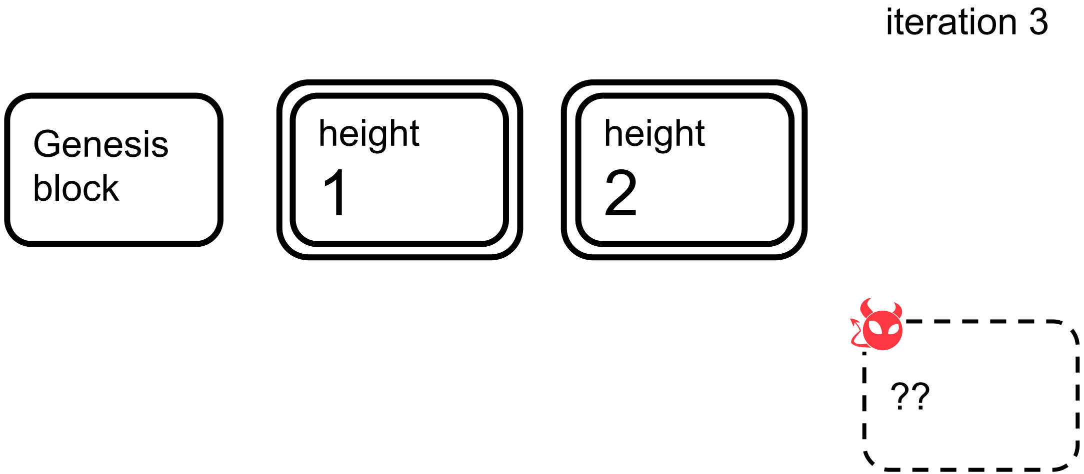

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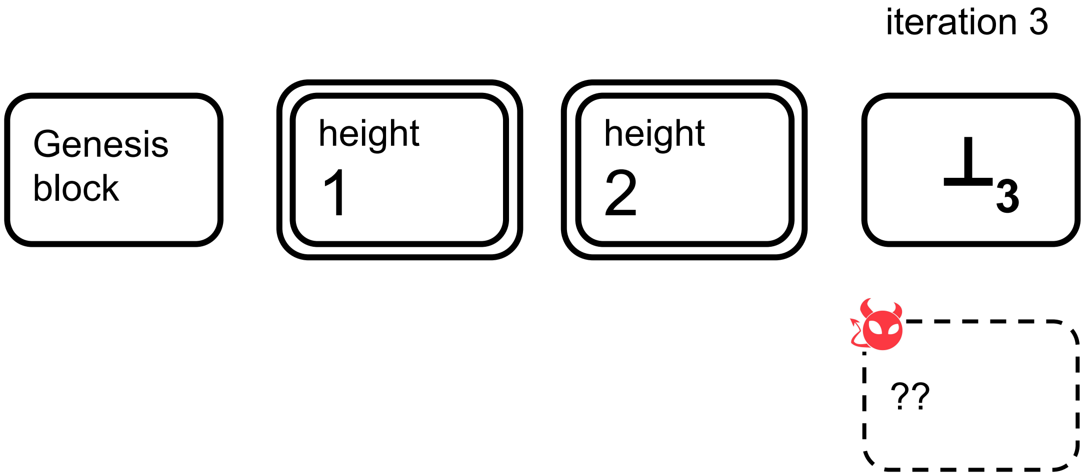

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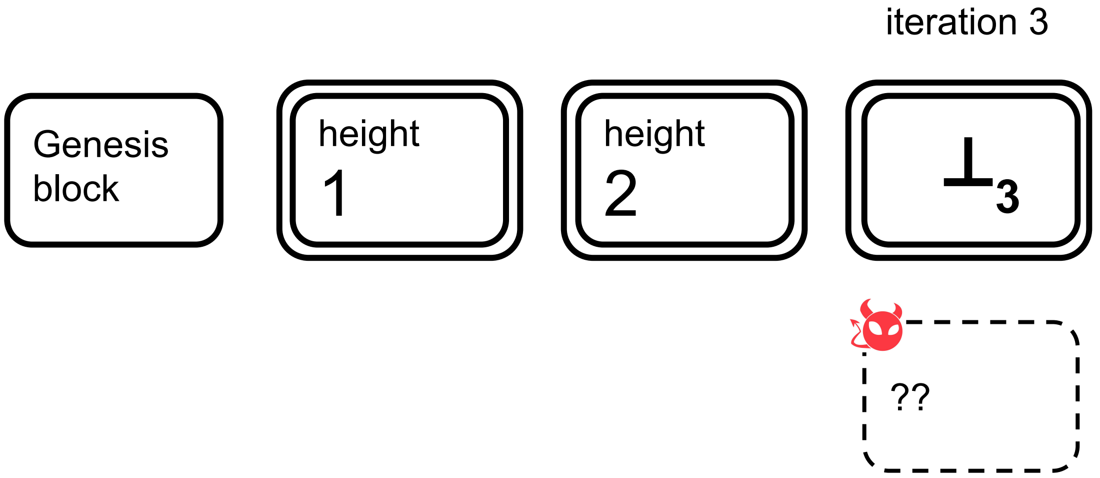

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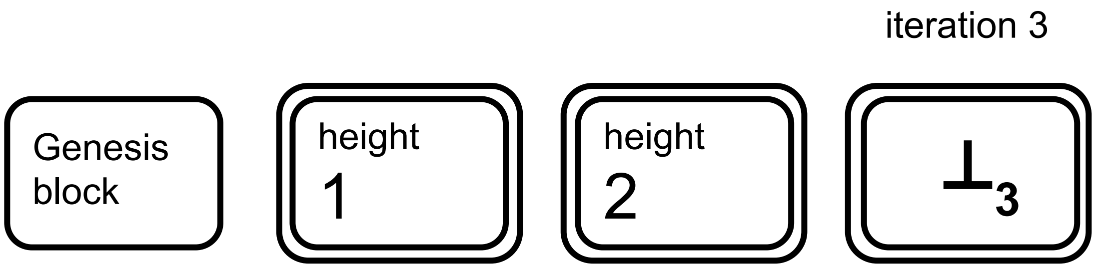

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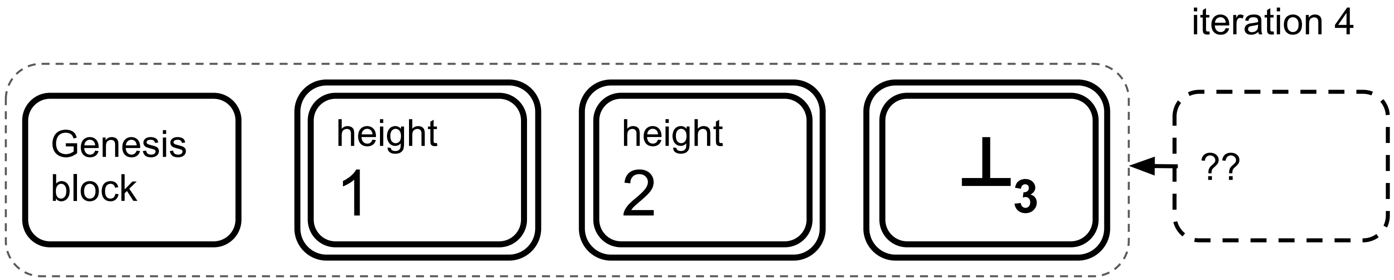

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Interlude…

Due to faults, there may be ***both***

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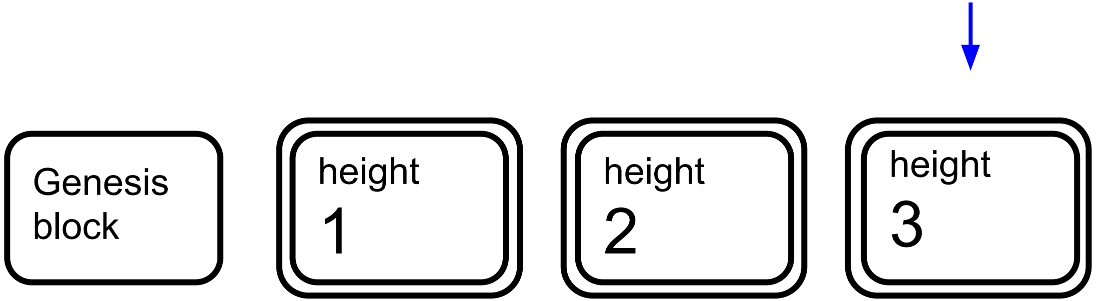

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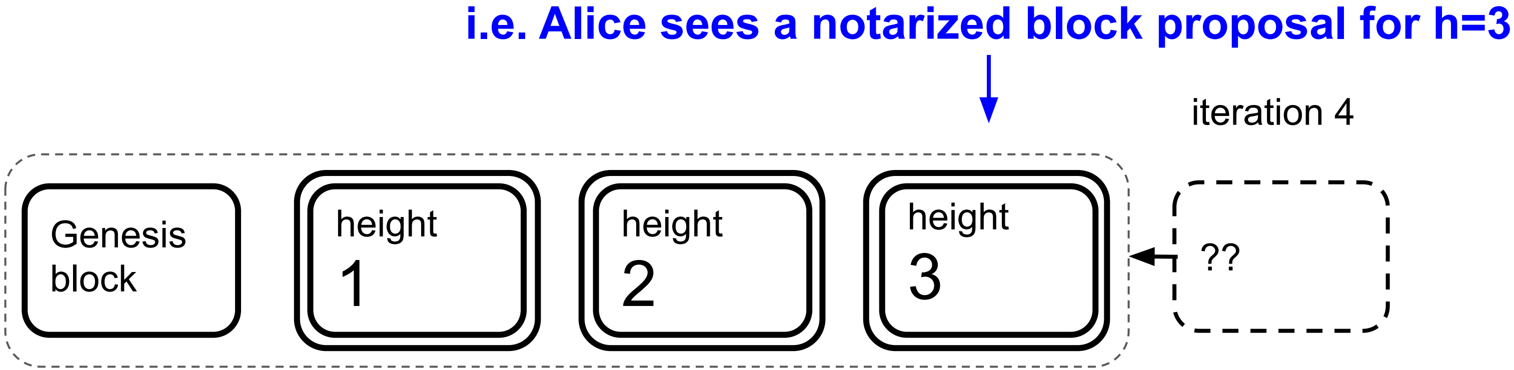

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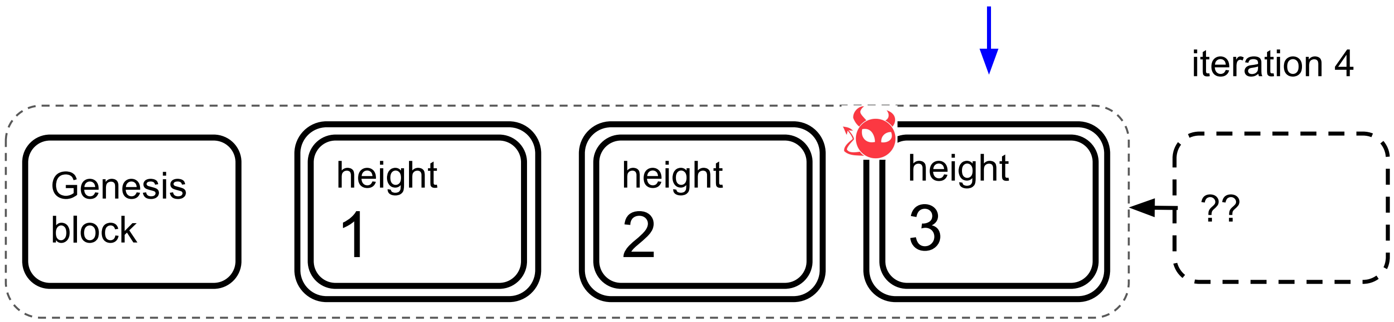

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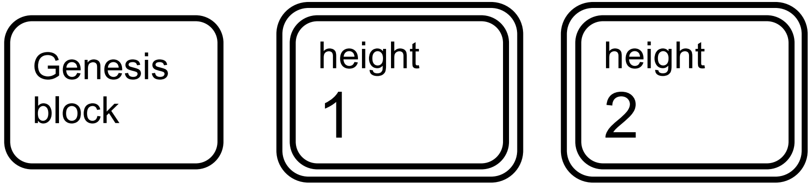

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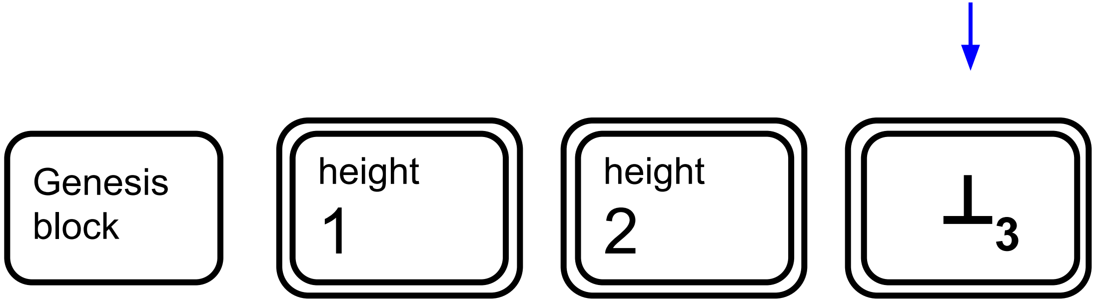

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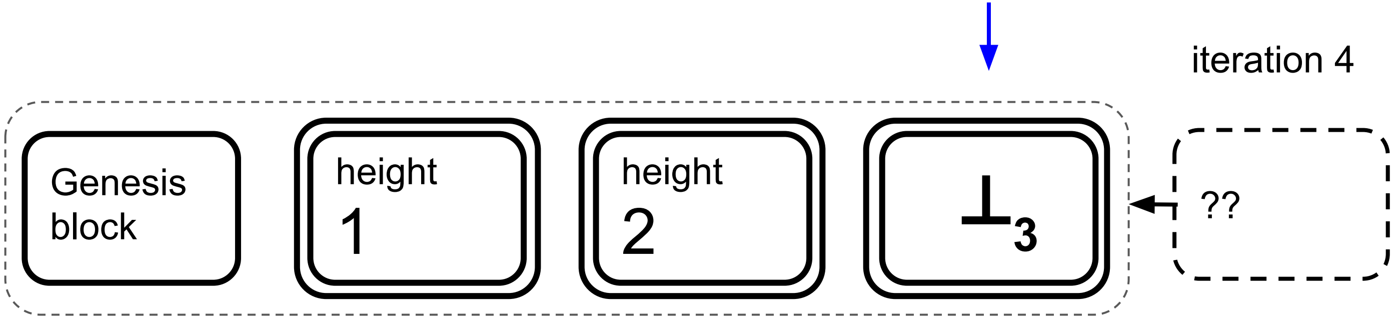

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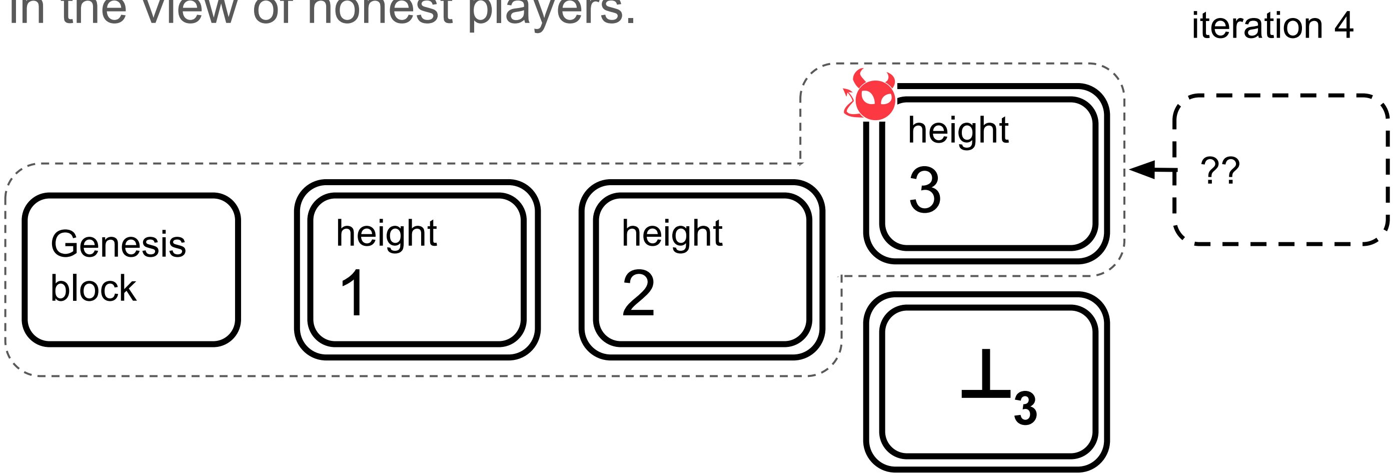

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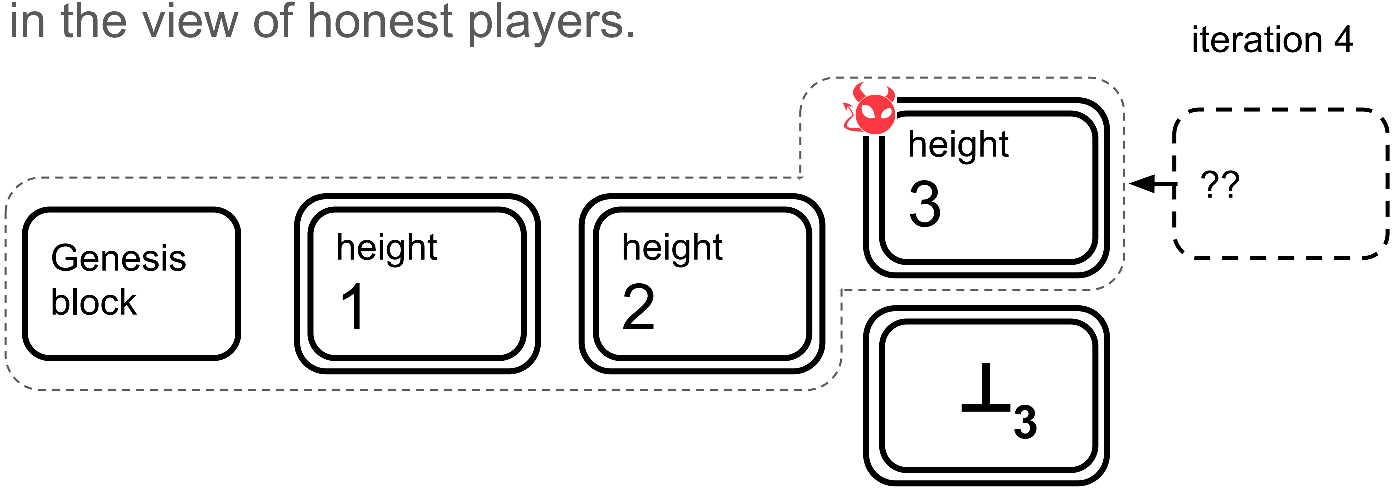
The next leader can extend either notarized chain



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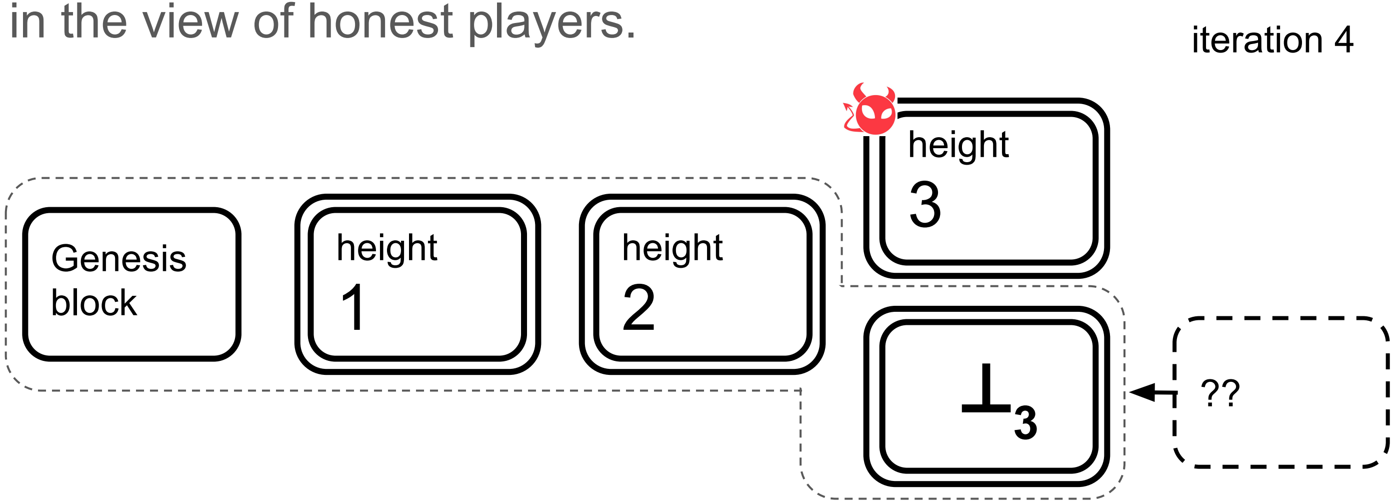

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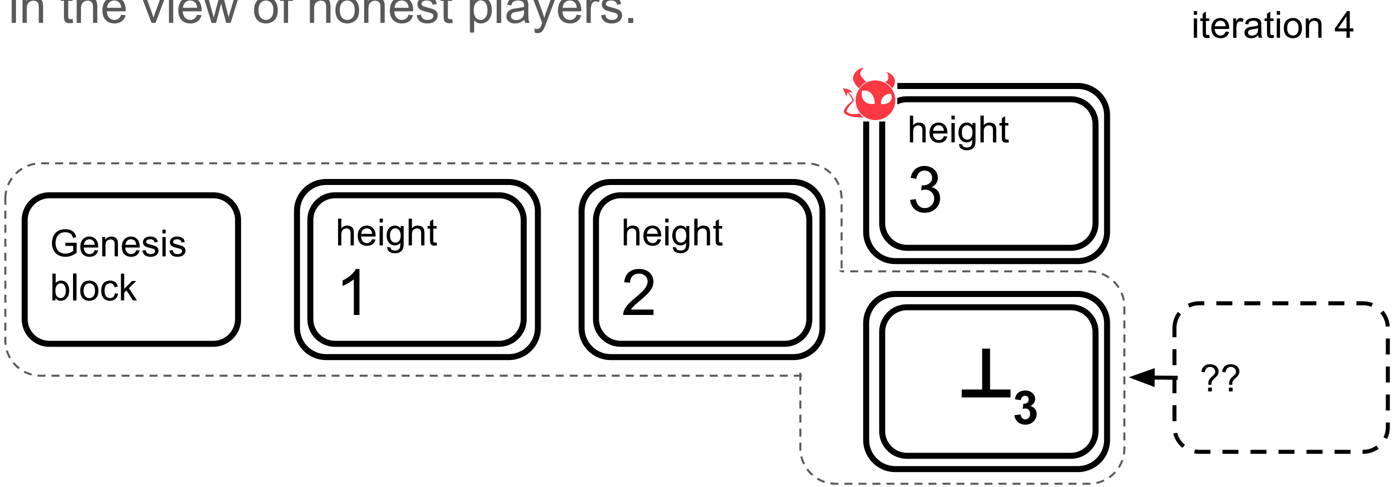
For agreement, need to decide on a single block at each height **h**



Finalizing blocks

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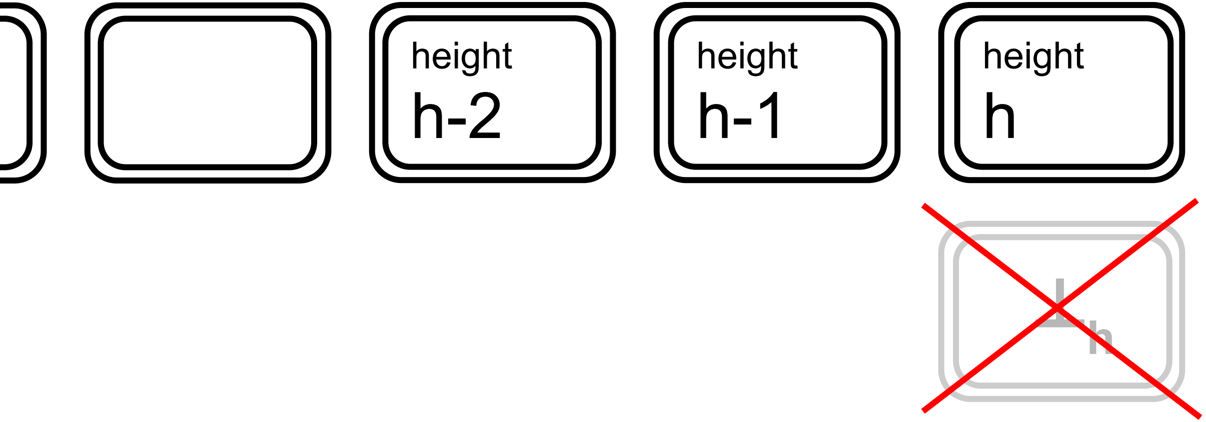

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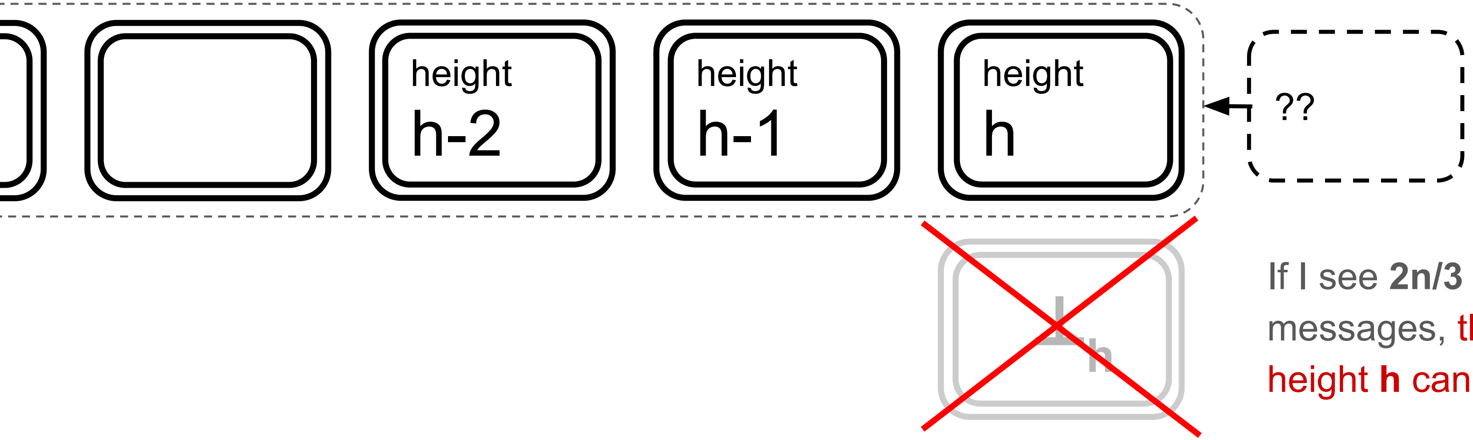

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Security Proofs

Consistency

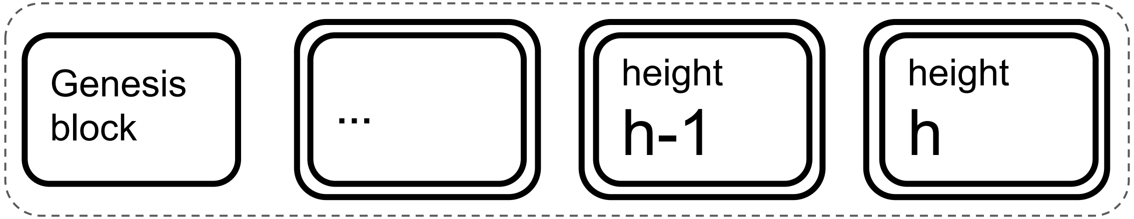
Thm: Let Alice and Bob be two honest players.

Suppose Alice outputs **LOG**, and Bob outputs **LOG'**, s.t **|LOG| ≤|LOG'|**.

Then, **LOG** is a prefix (or equal to) **LOG'**.

Consistency

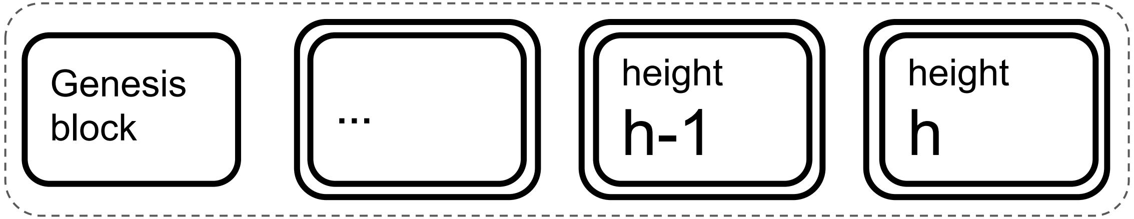
Proof: Consider Alice's chain **LOG**, which is the shorter one; let its length be **h**



Consistency

Since **LOG** is finalized by Alice, Alice 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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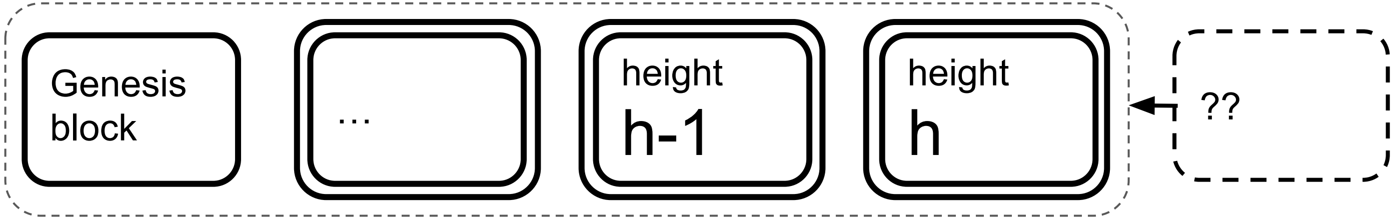
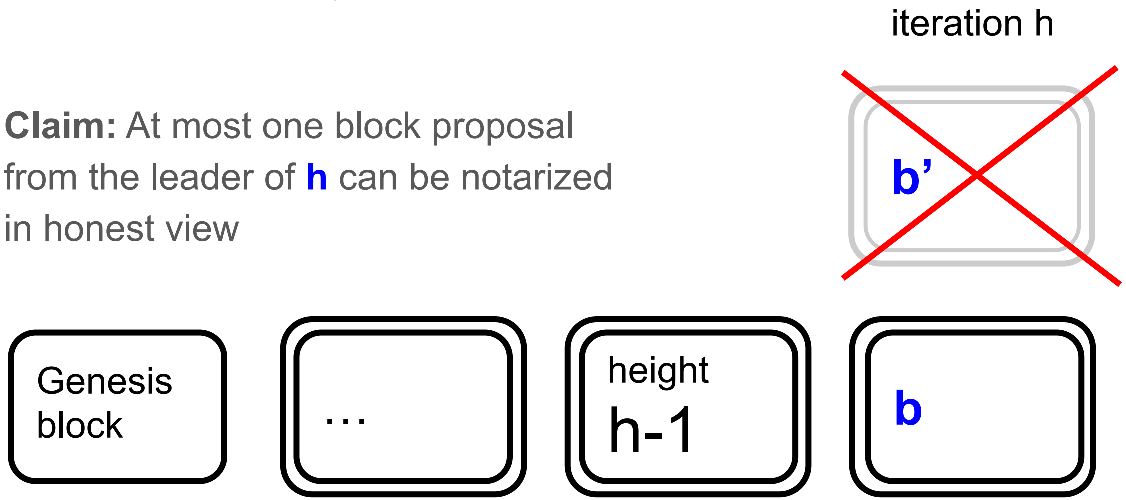


Thus Bob's chain must extend Alice's chain

Consistency

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

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



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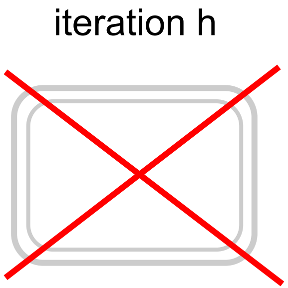

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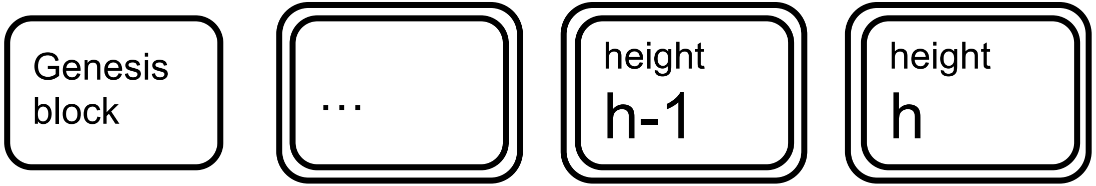

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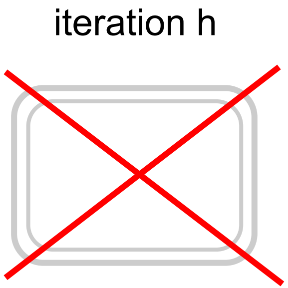

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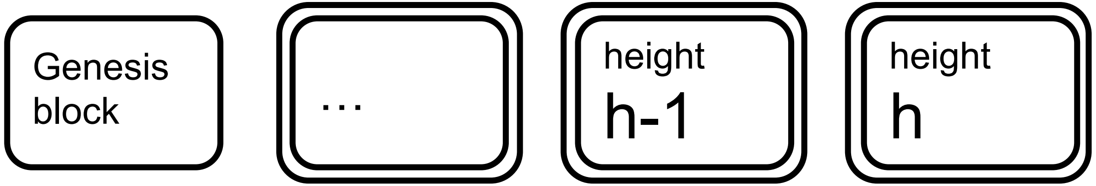
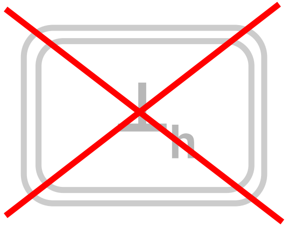


Claim: Since Alice saw **2n/3** **"finalize h"** messages, the dummy block of height **h** cannot be notarized in any honest view.



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

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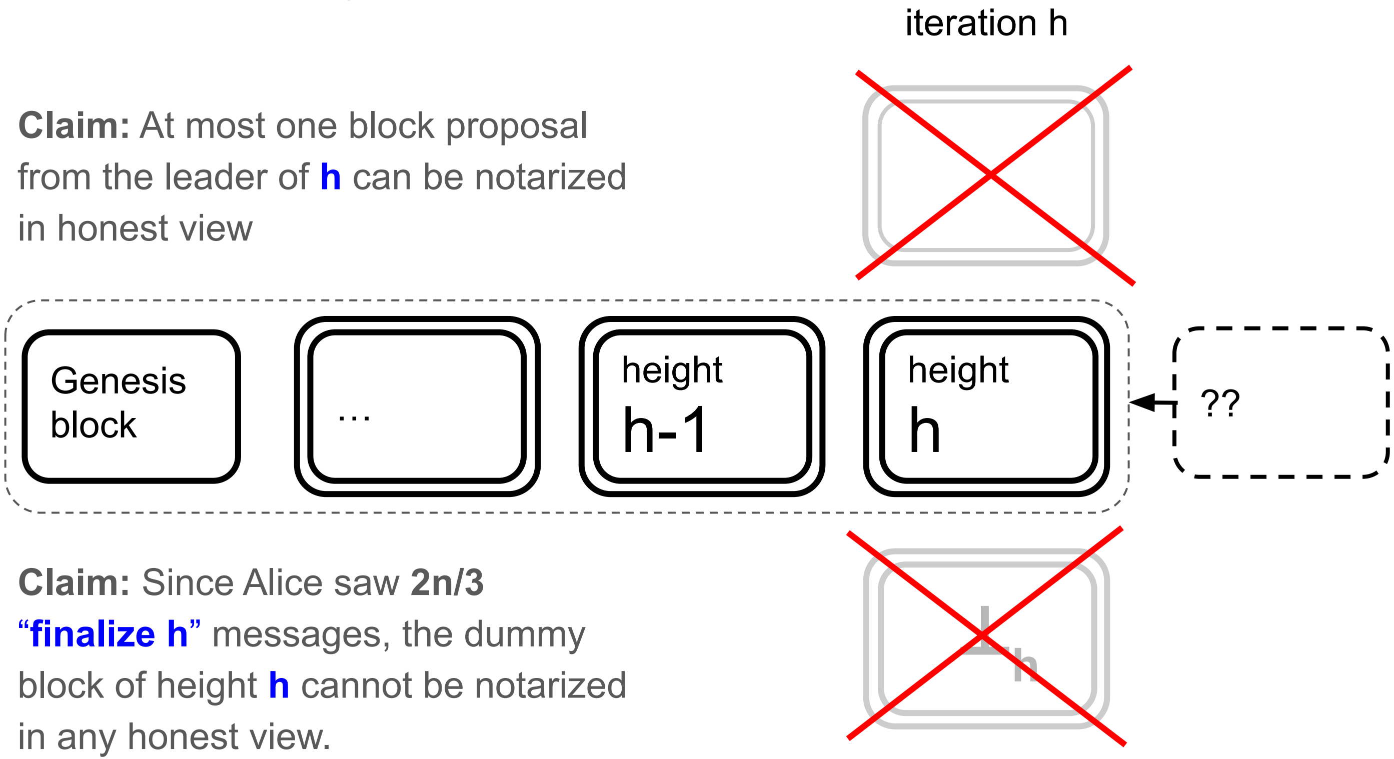

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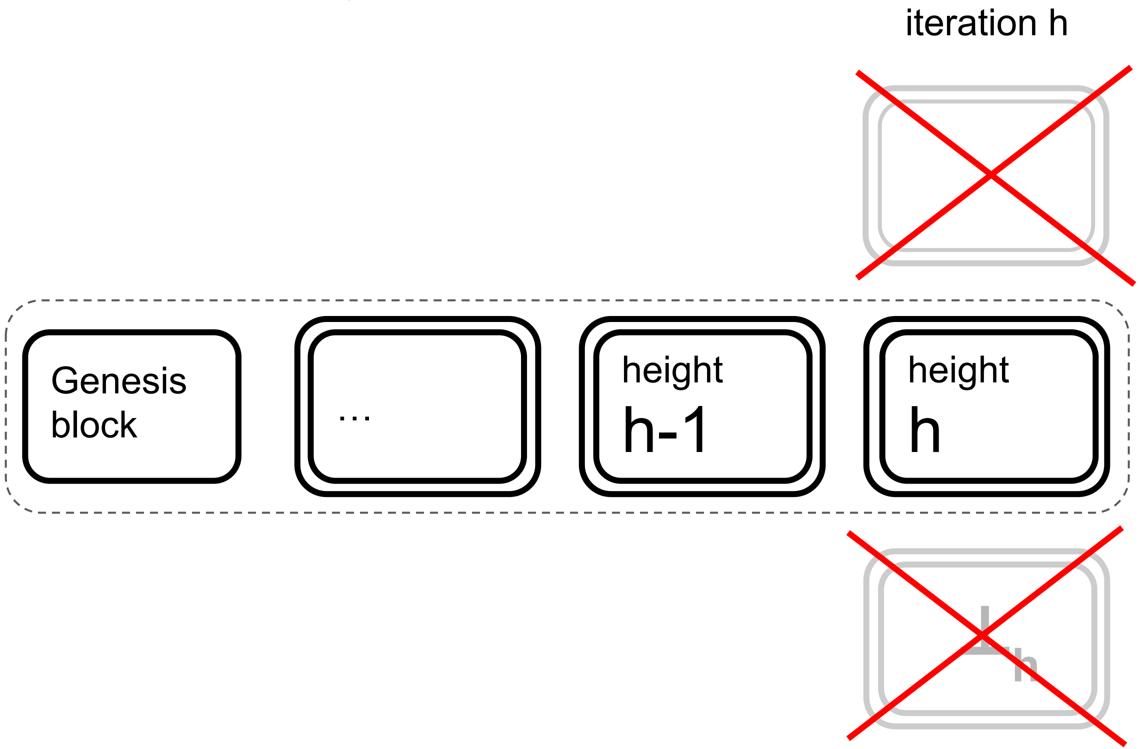

Safe to finalize the transactions in Alice's chain!

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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time *t*

Leader enters iteration ***h*** and proposes a new block $\mathbf{b_h}$ extending a notarized chain $\mathbf{b_1 \ldots b_{h-1}}$.

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

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Leader enters iteration h and proposes a new block b_h extending a notarized chain $b_1 \dots b_{h-1}$.

Every honest player enters iteration h and sees the proposal.

Either everyone sends "**vote** b_h", or someone already entered iteration **h+1**.

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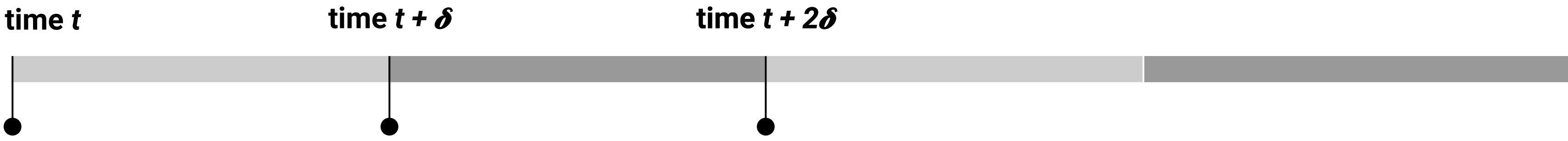
Subclaim 2: The dummy block of height ***h*** (denoted $\perp_h$) cannot be notarized in any honest view before time $\boldsymbol{t + 2\delta}$.



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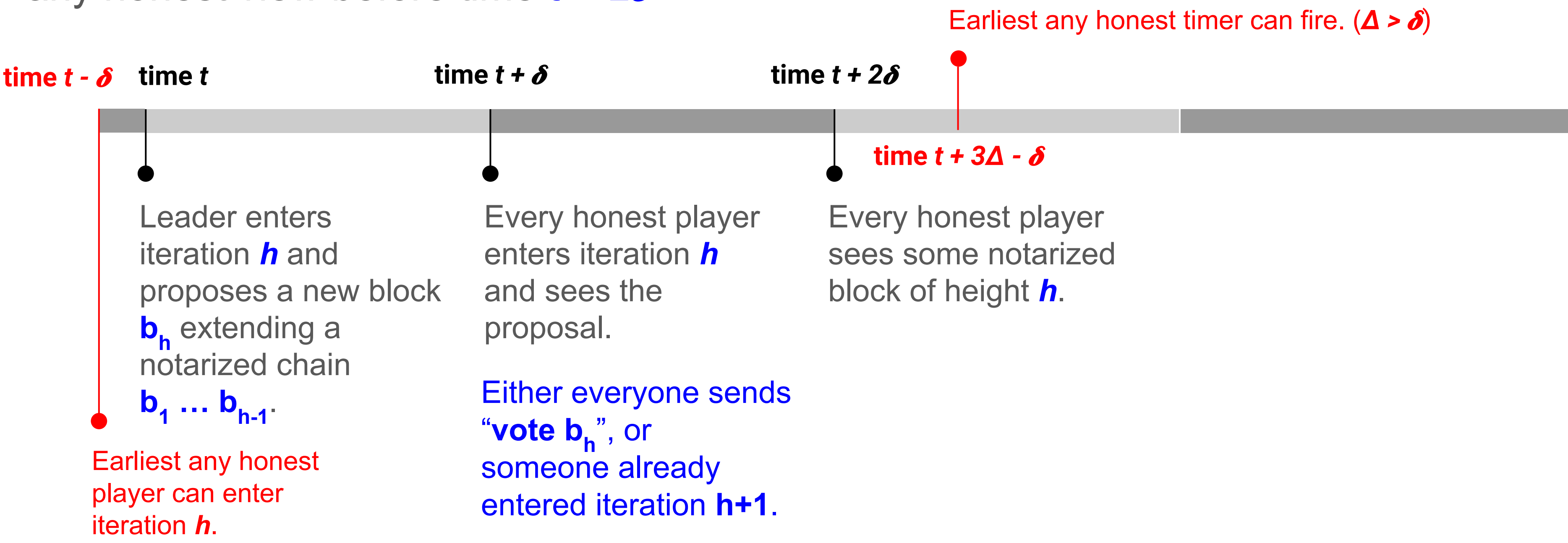

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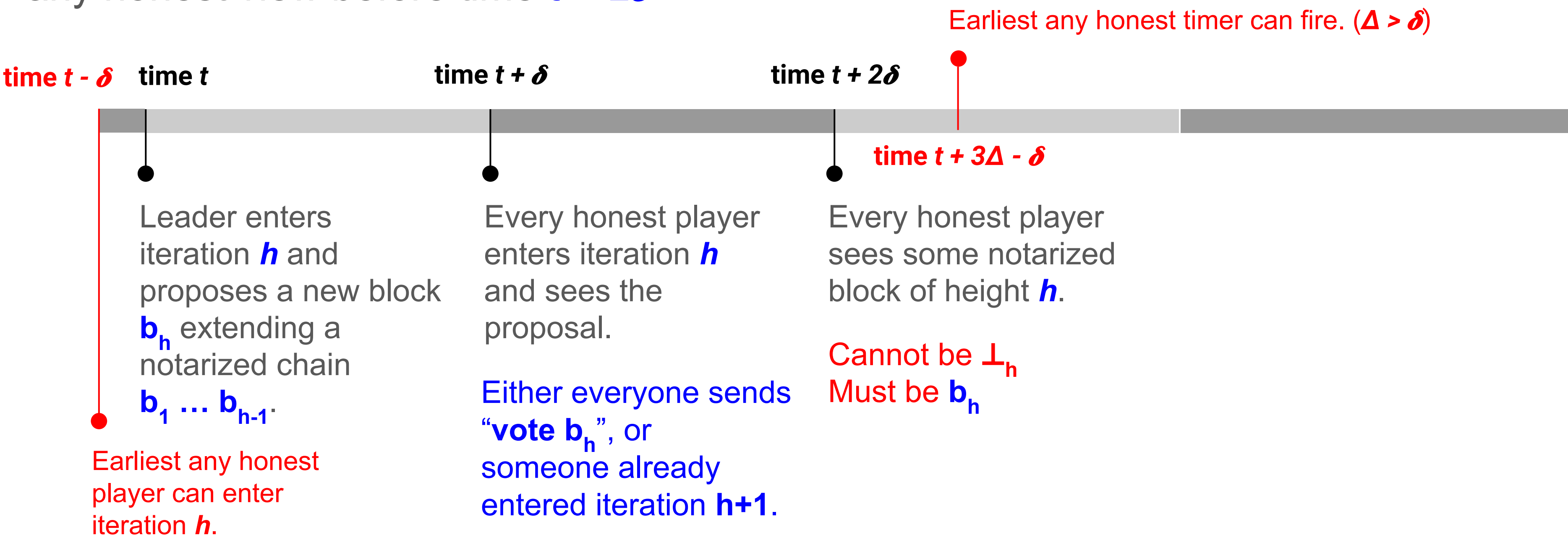
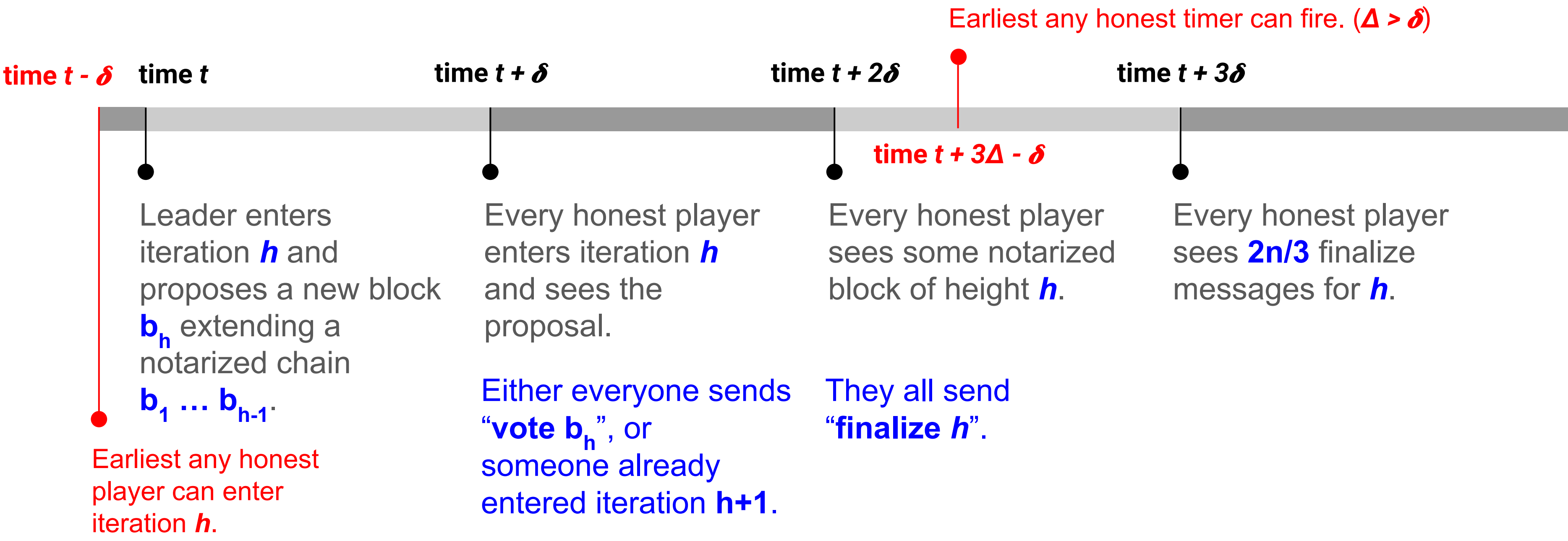


Liveness

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



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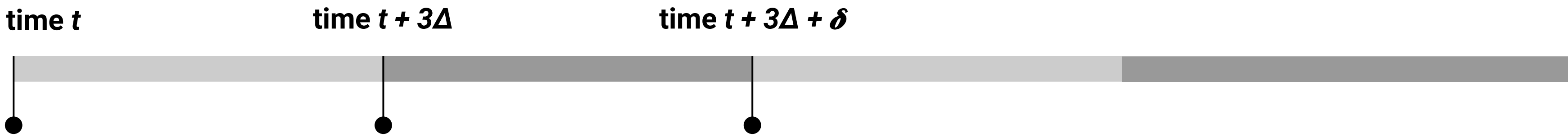

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Every honest player enters iteration ***h+1***.

In Conclusion

A new consensus protocol

- 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 **$4\delta + \omega(\log \lambda) \cdot (3\Delta + \delta)$**

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Thank you!

Appendix

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.

2. **Latency.** Specifically, must have fast *transaction confirmation time.*

    a. The *optimistic* case: when every player is honest.

    b. The *pessimistic* case: when some players are faulty.

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3. **Easy-to-understand.** Should be easy to understand *why* the protocol is secure.

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]	$\mathbf{3\delta}$	3δ	$4\delta + 2\Delta$
ICC [CDH+22]	$\mathbf{3\delta}$	$\mathbf{2\delta}$	$5.5\delta + 1.5\Delta$
PaLa [CPS18]	4δ	$\mathbf{2\delta}$	$6.25\delta + 9.25\Delta$
Pipeline Fast-Hotstuff [JNFG20] Jolteon [GKKS+22]	5δ	$\mathbf{2\delta}$	$10.87\delta + 9.5\Delta$
Chained Hotstuff (v6) [YMR+19]	7δ	$\mathbf{2\delta}$	$19.31\delta + 12.18\Delta$
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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State-of-the-art

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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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ICC [CDH+22]	$\mathbf{3\delta}$	$\mathbf{2\delta}$	$5.5\delta + 1.5\Delta$
PaLa [CPS18]	4δ	$\mathbf{2\delta}$	$6.25\delta + 9.25\Delta$
Pipeline Fast-Hotstuff [JNFG20] Jolteon [GKKS+22]	5δ	$\mathbf{2\delta}$	$10.87\delta + 9.5\Delta$
Chained Hotstuff (v6) [YMR+19]	7δ	$\mathbf{2\delta}$	$19.31\delta + 12.18\Delta$
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

	Proposal Conf. Time	Optimistic Block Time	Pessimistic Liveness ($f = \lceil n/3 \rceil - 1$)
Algorand* [CGMV18]	$\mathbf{3\delta}$	3δ	$4\delta + 2\Delta$
ICC [CDH+22]	$\mathbf{3\delta}$	$\mathbf{2\delta}$	$5.5\delta + 1.5\Delta$
PaLa [CPS18]	4δ	$\mathbf{2\delta}$	$6.25\delta + 9.25\Delta$
Pipeline Fast-Hotstuff [JNFG20] Jolteon [GKKS+22]	5δ	$\mathbf{2\delta}$	$10.87\delta + 9.5\Delta$
Chained Hotstuff (v6) [YMR+19]	7δ	$\mathbf{2\delta}$	$19.31\delta + 12.18\Delta$
Streamlet [CS20a]	10Δ	2Δ	39.56Δ

*Base protocol without sortition.

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

Easiest protocol description [CS20]

Comparisons

Theoretical latency of protocols that support random leaders

Simplex:
The best of both worlds

	Proposal Conf. Time	Optimistic Block Time	Pessimistic Liveness ($f = \lceil n/3 \rceil - 1$)
Simplex	$\mathbf{3\delta}$	$\mathbf{2\delta}$	$\mathbf{3.5\delta + 1.5\Delta}$
Algorand* [CGMV18]	$\mathbf{3\delta}$	3δ	$4\delta + 2\Delta$
ICC [CDH+22]	$\mathbf{3\delta}$	$\mathbf{2\delta}$	$5.5\delta + 1.5\Delta$
PaLa [CPS18]	4δ	$\mathbf{2\delta}$	$6.25\delta + 9.25\Delta$
Pipeline Fast-Hotstuff [JNFG20] Jolteon [GKKS+22]	5δ	$\mathbf{2\delta}$	$10.87\delta + 9.5\Delta$
Chained Hotstuff (v6) [YMR+19]	7δ	$\mathbf{2\delta}$	$19.31\delta + 12.18\Delta$
Streamlet [CS20a]	10Δ	2Δ	39.56Δ

*Base protocol without sortition.

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

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.)