Blockchains in the lens of BFT

Dahlia Malkhi
Diem Association and Novi

State-Machine-Replication (SMR)
with
Byzantine Fault Tolerance (BFT)

SIFT [1976]

A mission critical spacecraft control system is crafted with redundant sensors and compute units

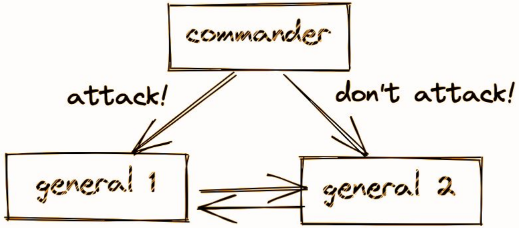
Sensors and compute units might fail arbitrarily

Control commands are exerted by consensus voting among units

State-Machine-Replication (SMR)
with
Byzantine Fault Tolerance

Byzantine Generals [LPS 1980]

Timeless foundations of concurrency and reliability
- consensus
- fault models
- solutions, impossibilities and lower bounds



State-Machine-Replication (SMR) with Byzantine Fault Tolerance

<u>SIFT [1976]</u>

A mission critical spacecraft control system is crafted with redundant sensors and compute units

Sensors and compute units might fail arbitrarily

Control commands are exerted by consensus voting among units

<u>Double Spend [2008]</u>

Money in its digital form requires keeping a ledger of transfers

This is easy to prevent if there is a trusted entity maintaining a centralized ledger

Users might try to duplicate coins or double-spend their balance

SMR forms agreement on a ledger among mistrusting parties

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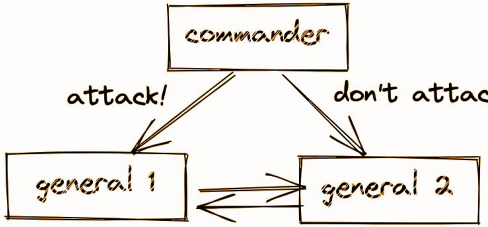
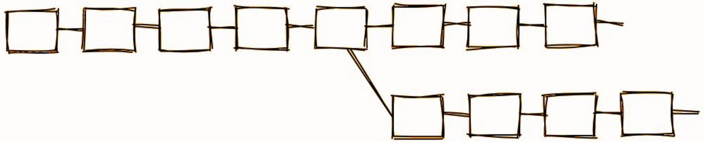


Nakamoto Consensus [N2008]

New settings and use-cases:
- scale
- geo distributed interconnect
- incentives



Outline

What are we trying to solve

Classical SMR results

Enter Partial Synchrony

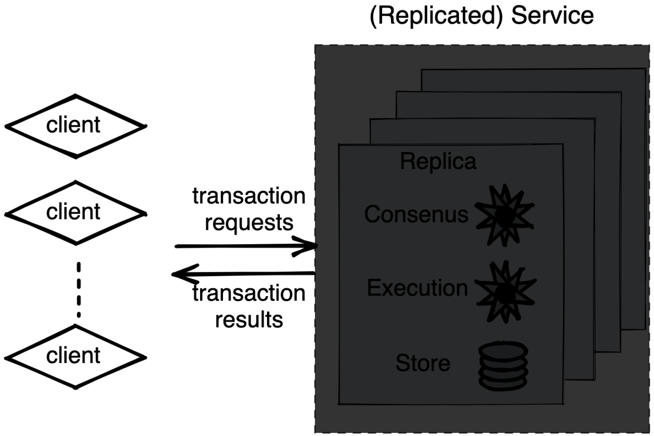
Bitcoin and Nakamoto Consensus

Scaling BFT

State-Machine-Replication (SMR) [L1978, S1990]

Untrusted/unreliable individual component, trusted/reliable service as whole

Core approach: A single server modeled as a **deterministic** state-machine, then replicated for fault tolerance



State-Machine-Replication (SMR) [L1978, S1990]

Untrusted/unreliable individual component, trusted/reliable service as whole

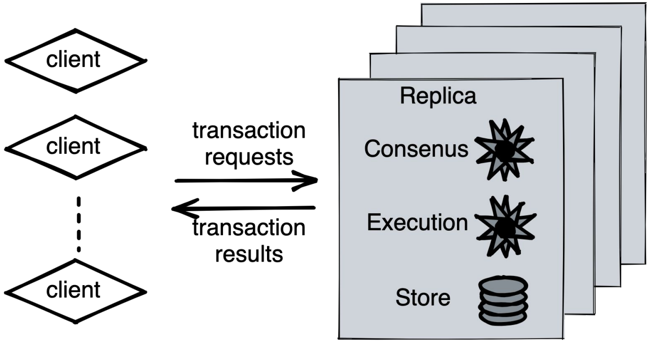
Core approach: A single server modeled as a **deterministic** state-machine, then replicated for fault tolerance

Linearizability [HW1990]: Correct execution modeled as a sequential state-machine, receive client requests, execute, store output, return response

Replicas have three key functions: Ordering, Execution, Store

Often, the same parties (**validators**, nodes, replicas, ..) provide all functions.

Authenticated store: succinct proofs of membership



SMR and Consensus

The main building block for SMR is **log replication**

It is reducible to a sequence of single-shot Consensus decisions

Much of the academic literature focuses on the Consensus problem, including important **impossibilities and lower bounds**

There are differences: receiving request from clients and sending output to them changes what is considered **valid** as output, and when is it **solvable**

SMR practical solution optimize a sequence of single-shot decisions with a (cheaper) **steady-state** leader regime and a (more complex) **view-change**

SMR Problem Model

Known set of N validators

Safety - validators store and execute the same log of transactions

Liveness - every client request is eventually executed by validators

(External) Validity - transactions are (signed) requests by clients

Fault Model

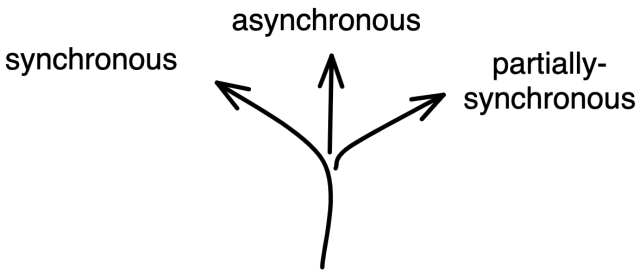
Communication model: modeled as an **adversary** that controls the network

Synchronous model – there is a known bound Δ on message transmission delays imposed by the adversary

Asynchronous model – the adversary can cause unbounded delays

Partial synchrony model – there is **Global Stabilization Time (GST)** after which there is a known bound Δ on message transmission delays imposed by the adversary

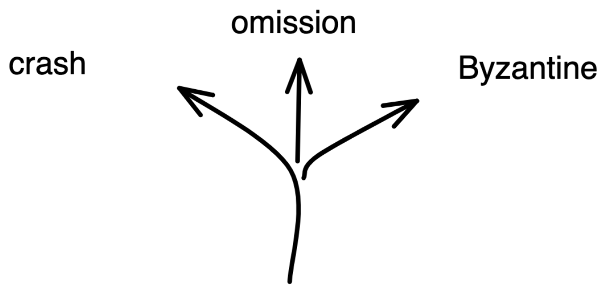
synchronous < partial synchrony < asynchronous



Fault Model

Decentralization, trust(less) systems and the Byzantine faults: modeled as an **adversary** that corrupts validators

- **Fraction of faults**: threshold, probabilistic, power, incentives
- **Failure modes**: crash, omission, Byzantine
- **Authentication**: confidential messages, signatures



crash < omission < Byzantine

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Which model should I use?

Under asynchrony:

- [FLP 1985] Liveness is not guaranteed against even a single failure, and a log replication algorithm must have (under network duress) non-terminating executions

Under partial synchrony:

- [Folklore] Under network transmission delays, Consensus requires $F < N/2$.
- [DLS 1988] Under network transmission delays, Byzantine Consensus requires $F < N/3$.

Under synchrony:

- [FLM 1985] If there is no public key setup, Byzantine Consensus requires $F < N/3$
- [Folklore] Under omissions faults, Consensus requires $F < N/2$
- [AT 1999] Consensus must have executions with $F+1$ rounds
- [DR 1982] Consensus must have executions with a quadratic number of messages.

	safety against asynch?	liveness against asynch?	progress during synch?
$f < n/3$	✓	✗	net speed
$n/3 \le f < n/2$	✗	✓	slow
$n/2 \le f$	✗	✗	✗

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Practical BFT Settings [LPS 1982, DLS 1988, L1989-1998, CL1999]

Partial synchrony model

$N = 3F+1$ permissioned/known validators

PKI enables validators to sign messages

Adversary controls up to F validators

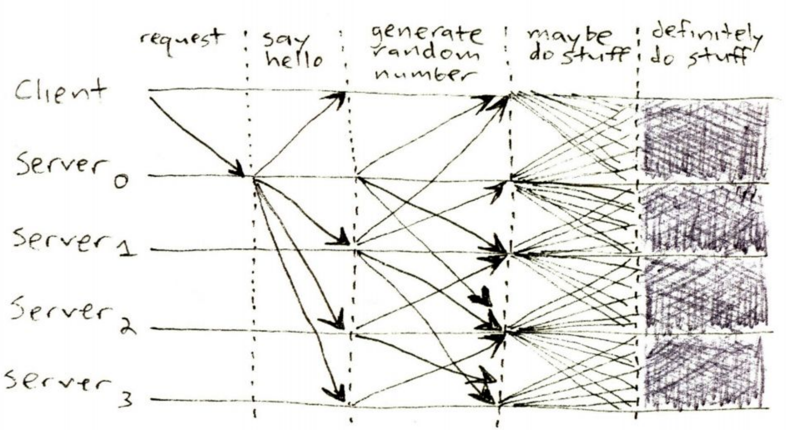
Focus on a single agreement decision

Classical BFT SMR

Super quadratic communication

Error-prone

Developer-unfriendly



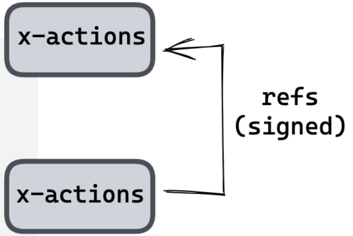
J. Mickens, 2013

BFT in the Lens of Blockchains

Simple and transparent

Blocks carry client-requests + signed-references (chaining)

Chain rules to participate and to commit finality



PBFT[CL1999] in the Lens of Blockchains

<u>Steady leader protocol:</u>

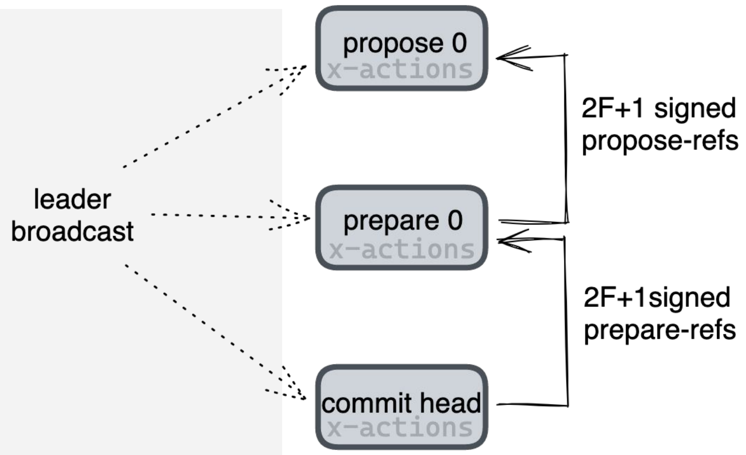
Broadcast blocks to validators
(e.g., via gossip)

First round: 2F+1 signed **proposal**-refs to prepare

Second round: 2F+1 signed **prepare**-refs to commit

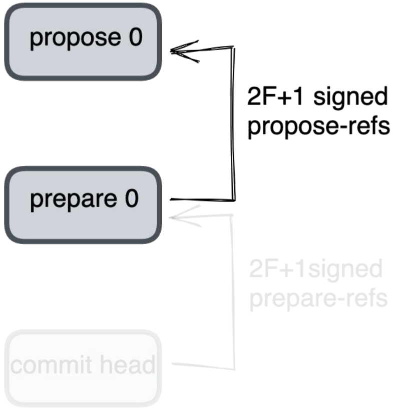
Only the **head** of chain committed

Omitted: chaining, pipelining



PBFT in the Lens of Blockchains

View-change protocol (by new leader):



PBFT in the Lens of Blockchains

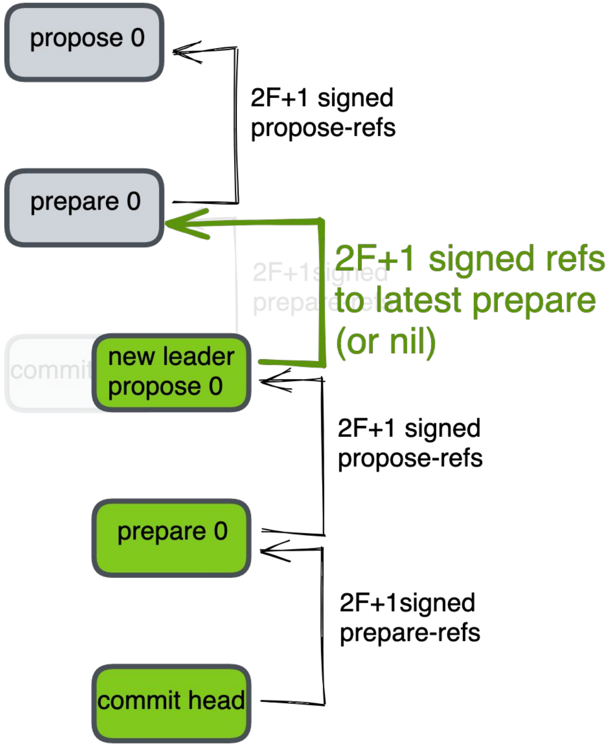
<u>View-change protocol (by new leader):</u>

Broadcast **justified** proposal carrying 2F+1 signed prepare-refs

Safety: a leader cannot hide a previous commit

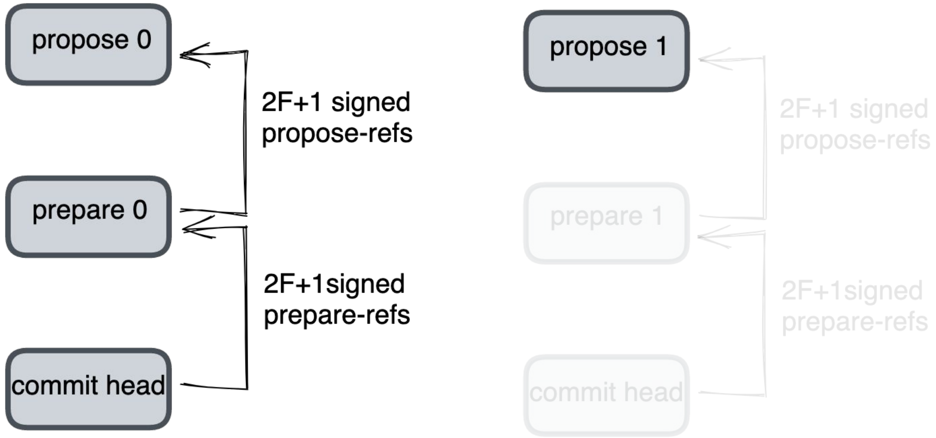
- F may be nil
- F may lie
- At least one must refer to prepare if it has been committed

Liveness: a leader can elicit 2F+1 latest-prepare refs



PBFT in the Lens of Blockchains

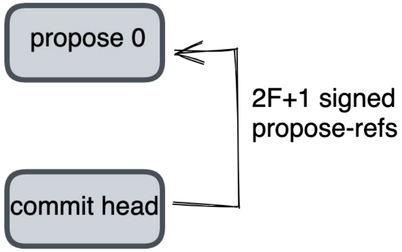
Why 2F+1?



PBFT in the Lens of Blockchains

Why two rounds?

Imagine a one-round protocol

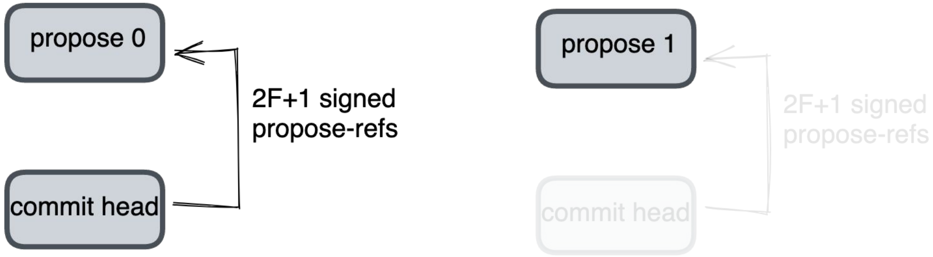


PBFT in the Lens of Blockchains

Why two rounds?

Imagine a one-round protocol

It can prevent equivocation by the first leader



BFT in the Lens of Blockchains

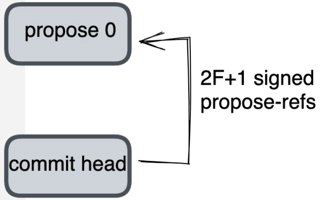
Why two rounds?

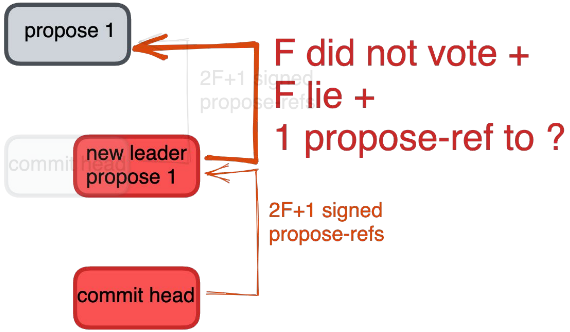
Imagine a one-round protocol

It can prevent equivocation by the first leader

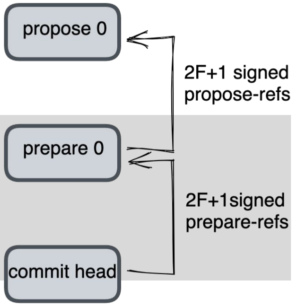
But it cannot convince a new leader of a commit outcome

Special case: Leader itself can commit after a single round [DLS1988]





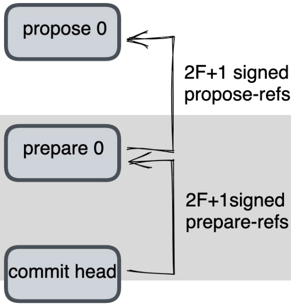
PBFT Complexity



How do we measure complexity?

Count cryptographic validations

PBFT Complexity



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Steady leader protocol:

Broadcast proposal to participants (e.g., via gossip)

- O(N) to validate leader proposal

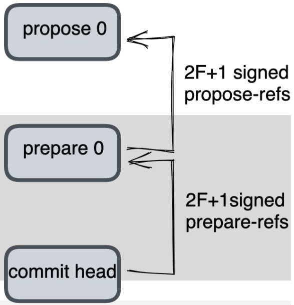
First round: 2F+1 signed proposal-refs to prepare

- O(N x N) to validate leader prepare carrying O(N) signatures on propose-refs

Second round: 2F+1 signed prepare-refs to commit

- same

PBFT Complexity



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View-change protocol (by new leader):

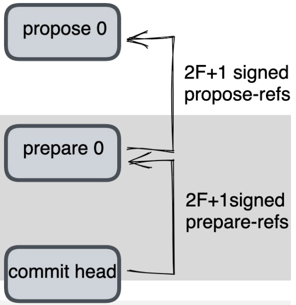
Broadcast **justified** proposal :
2F+1 signed prepare-refs (possibly different), each prepare contains 2F+1 signatures on propose-refs

- O(N x N^2) to validate leader proposal with:
  O(N) signatures on
  O(N) signed propose-refs

Cascading view-changes:

- O(N) x O(N^3)

Vote Aggregation [CKPS2001] and SBFT [GA+2019]



How do we measure complexity?

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Steady leader protocol:

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- O(N)/O(N) to validate leader proposal

First round: 2F+1 signed proposal-refs to prepare

- O(N x N)/O(N) to validate leader prepare carrying O(N)/O(1-aggregate) signatures on propose-refs

Second round: 2F+1 signed prepare-refs to commit

- same

View-change protocol (by new leader):

Broadcast **justified** proposal :
2F+1 signed prepare-refs (possibly different), each prepare contains 2F+1 signatures on propose-refs

- O(N x N^2)/O(NxN) to validate leader proposal with:
  O(N) (non-aggregate-able) signatures on
  O(N)/O(1-aggregate) signed propose-refs

Cascading view-changes:

- O(N) x O(N^3)/O(N) x O(N^2)

Practical BFT SMR for Partial Synchrony

	LPS 1982	DLS 1988	PBFT 1999
Safe against F < N/3 byz faults	👍	👍	👍
Safe against asynchrony	👎	👍	👍
Number of messages to consensus decision	poly	poly	quadratic*
Number of messages to rotate leader	poly	poly	quadratic
Network speed	N/A	👎	👍

*Can be linear with threshold-cryptography

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Bitcoin/Nakamoto Consensus [N2008]

NYTimes piece on Bitcoin [Andreesen, 2014]: "*Bitcoin is the first practical solution to a longstanding problem in computer science called the Byzantine Generals Problem.*"

Bitcoin/Nakamoto Consensus

Nakamoto Consensus (NC) is based on two mechanisms.

Proof-of-work
"*Pricing via Processing or Combatting Junk Mail*" [DN 1992]
This creates scarcity, a new coin can be minted every X time period

Hash chains
"*How to timestamp a Digital Document*" [HS92]
This creates an incentive for agreement, a coin has value only if it is part of the longest existing chain

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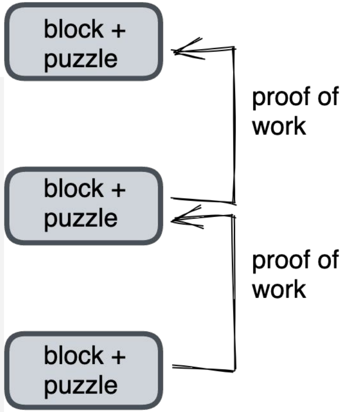
Putting them together

Puzzle solution must becomes part of the chain for mining/transfers to have effect



Bitcoin/Nakamoto Consensus

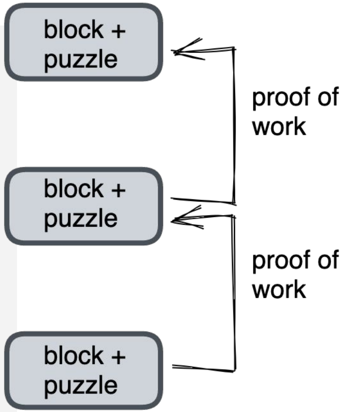
In order to participate in NC, a validator needs to mine blocks and append them to the chain.

NC is based on the following three rules:

1. **Longest fork wins**. A validator adopts the longest proof-of-work (PoW) chain to its knowledge (breaking ties arbitrarily) and attempts to mine a new block that extends this longest chain.

2. **Propagation**. Upon adopting a new longest chain, either through mining or by receiving from others, a validator broadcasts the newly acquired block(s);

3. **k-depth commit**. A validator commits a block if it is buried at least k blocks deep in the longest chain adopted by the validator. Here, k is a security parameter (6 is common in practice) that controls the probability of incorrect commit



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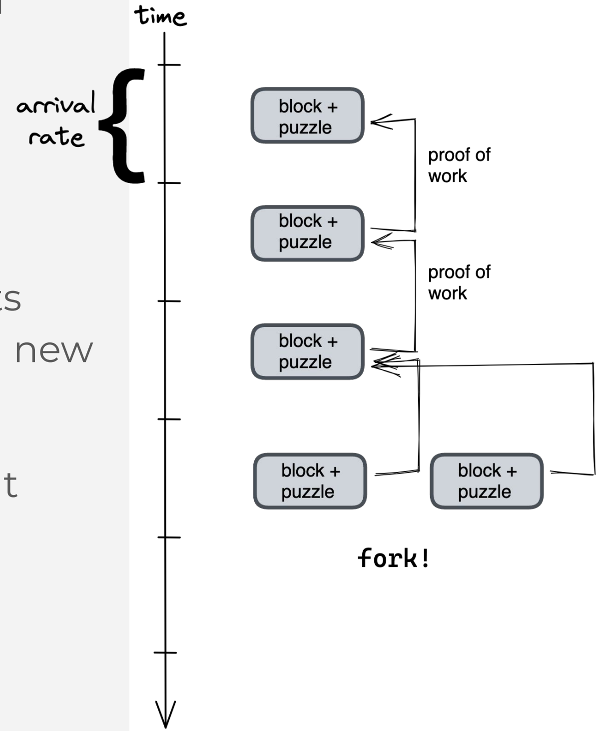

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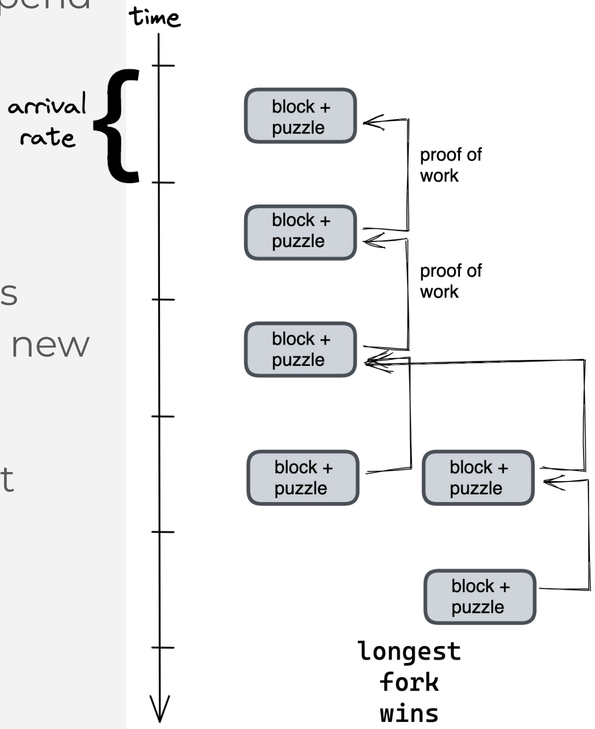


When is NC Safe?

[R2019, N2021]

NC In the Len of BFT

Imagine a round-based protocol among a set of N validators, with F Byzantine

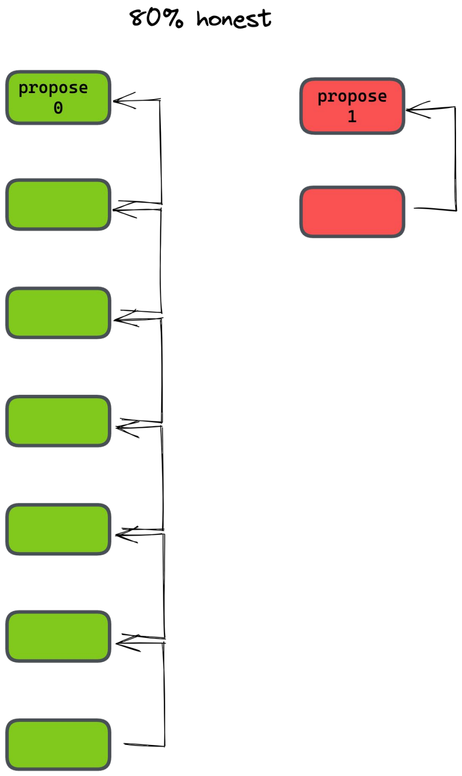
In each round, one validator selected uniformly at random to broadcast a proposal/vote

Honest validators extend the longest chain they know

Byzantine validators may extend any chain they choose

> The best attack strategy is to maintain their own chain k levels deeps and then expose it

If 49% are Byzantine then the bad chain will be longer than the good chain with probability exponentially small in k



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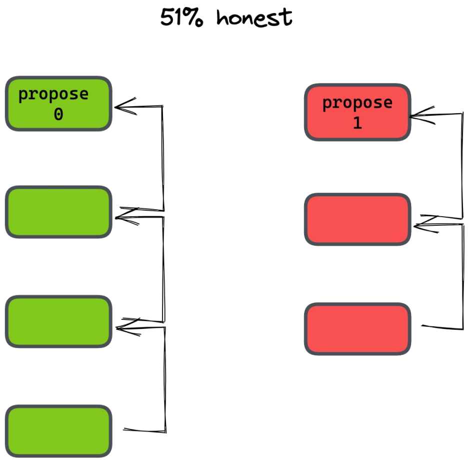


NC In the Len of BFT

In NC, there are no rounds and no known set of participants

Mining is modeled as a Possion process with expected interval *g*

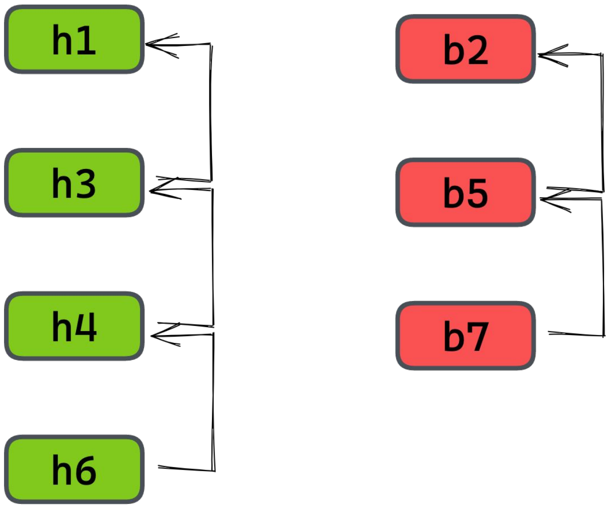
The adversary has power P < 50% to mine

We mark the arrivals of the process h1, b2, h3, h4, b5, h6, b7, ..

A proposal by a good validator takes less than Δ to propagate

since $g \gg \Delta$ we ignore the possibility of two honest arrivals within < Δ

A fork succeeds if there is a segment with more than k Byzantine arrivals and less than k honest arrivals



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*Can be linear with threshold-cryptography

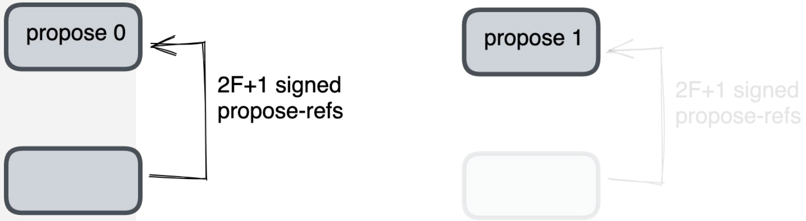
Practical BFT SMR for Partial Synchrony

	LPS 1982	DLS 1988	PBFT 1999	Casper 2017	HotStuff 2019
Safe against $f < n/3$ byz faults	👍	👍	👍	👍	👍
Safe against asynchrony	👎	👍	👍	?	👍
Number of messages to consensus decision	poly	poly	quadratic*	quadratic*	linear
Number of messages to rotate leader	poly	poly	quadratic	quadratic*	linear
Network speed	N/A	👎	👍	👎	👍

*Can be linear with threshold-cryptography

HotStuff [YM+ 2019]

Recall, one round prevents equivocation



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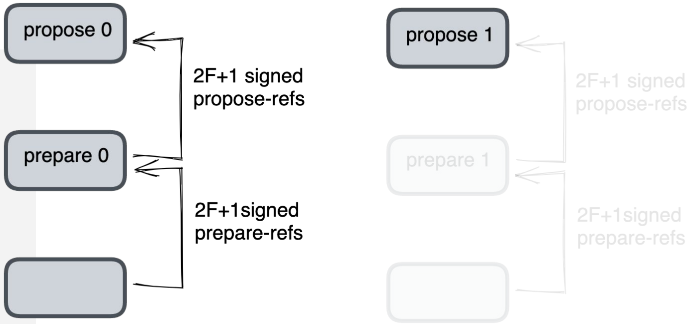
Recall, one round prevents equivocation

Two rounds guarantee there is at most one prepare per leader view



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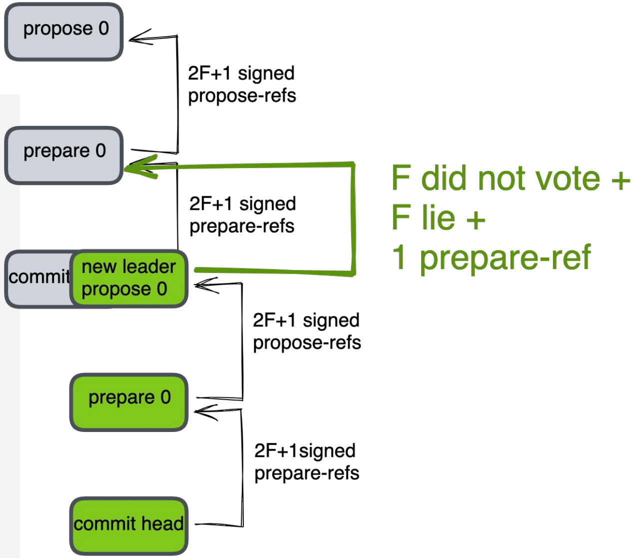

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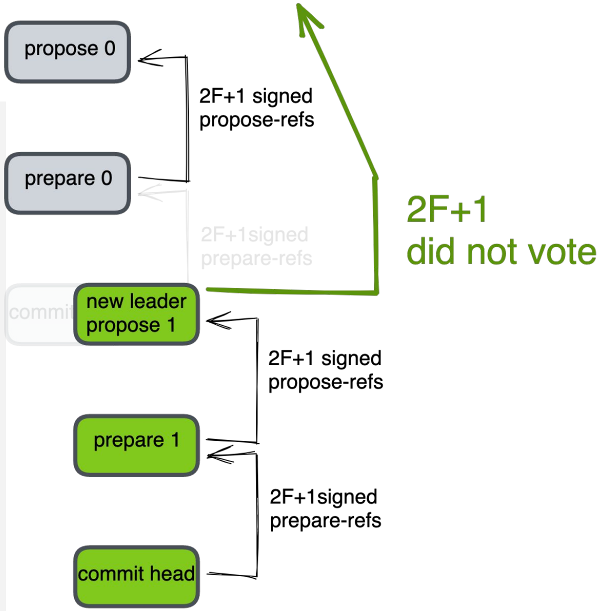
One round prevents equivocation

Two rounds guarantee there is at most one prepare per leader view

> If there was a commit, even a single validator can tell a new leader a prepare which might have committed and is safe to propose
>
> If there was **no** commit, a leader can **prove** by including 2F+1 attestations they did not vote prepare
>
> For liveness, even if a validator ref'ed a higher prepare, it must accept the leader's proposal because it carries a **proof**



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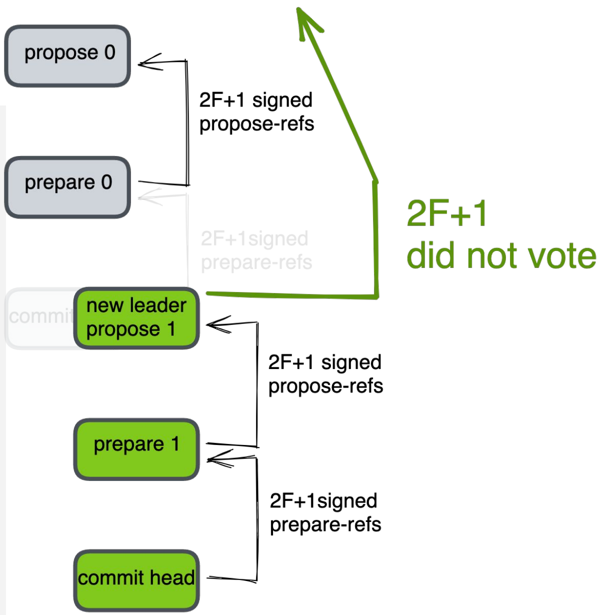
One round prevents equivocation

Two rounds guarantee there is at most one prepare per leader view

> If there was a commit, even a single validator can tell a new leader what might have committed and is safe to propose

What if the leader sends only one prepare? (subtle)

> If a validator has a **higher** prepare, it cannot trust the leader and abandon it
>
> Option-1 [Casper, VG 2016]: leader must wait Δ (maximal network delay)
>
> Option-2: Add a round



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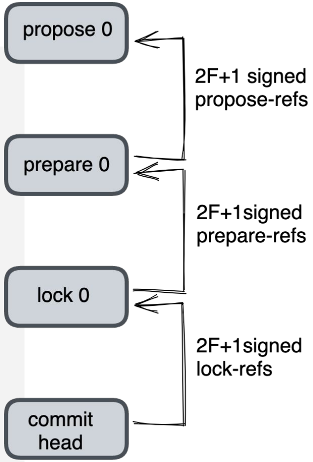
Two rounds guarantee there is at most one prepare per leader view

> If there was a ~~commit~~ lock, even a single validator can tell a new leader a prepare which might have ~~committed~~ locked and is safe to propose

Three rounds



HotStuff [YM+ 2019]

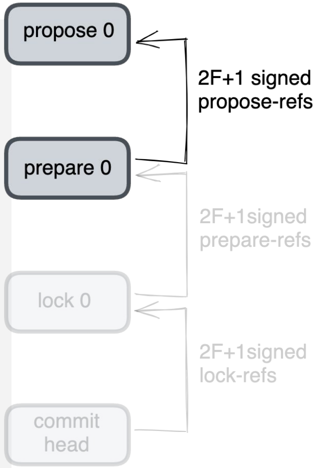
One round prevents equivocation

Two rounds guarantee there is at most one prepare per leader view

> If there was a commit, even a single validator can tell a new leader what might have committed and is safe to propose

Three rounds

> If a validator has a **higher** prepare, it **can** trust the leader and abandon it



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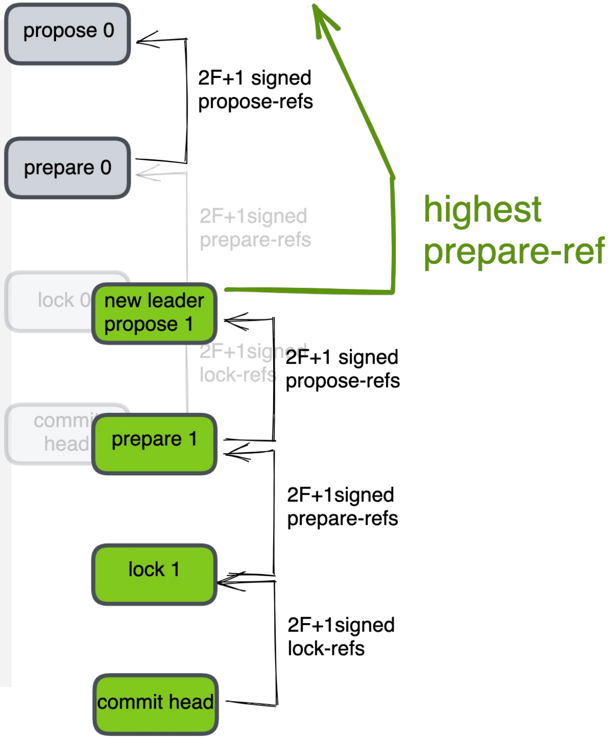

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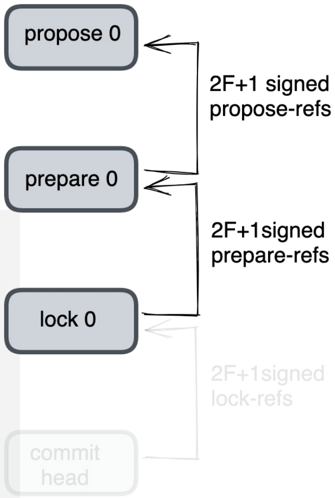
It works!

If a validator has a **higher** prepare, it **can** trust the leader and abandon it

If a validator has a higher **lock**, an honest leader cannot hide the highest prepare



HotStuff [YM+ 2019]

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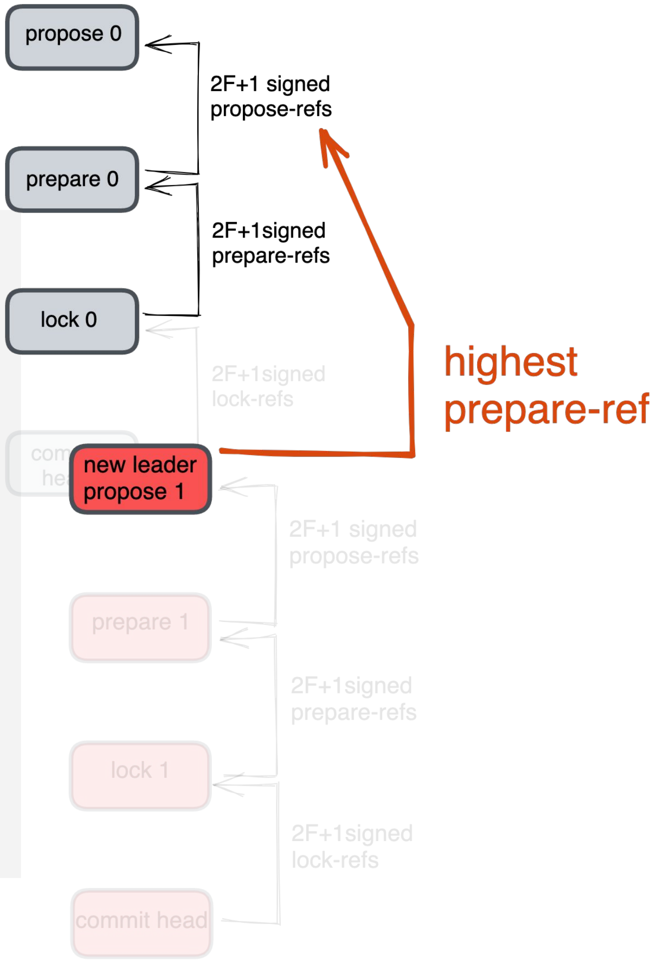

An evolution of BFT consensus protocols

	PBFT 1999	Casper 2017	HotStuff 2019
Safe against *f* < *n/3* byz faults	👍	👍	👍
Safe against asynchrony	👍	?	👍
Number of messages to consensus decision	quadratic*	quadratic*	linear
Number of messages to rotate leader	quadratic	quadratic*	linear
Network speed	👍	👎	👍

*Can be linear with threshold-cryptography

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Number of messages to rotate leader	quadratic	quadratic*	linear
Network speed	👍	👎	👍
Rounds to commit	2	2	3

*Can be linear with threshold-cryptography

An evolution of BFT consensus protocols

	PBFT 1999	Casper 2017	HotStuff 2019	DiemBFT 2021
Safe against *f* < *n/3* byz faults	👍	👍	👍	👍
Safe against asynchrony	👍	?	👍	👍
Number of messages to consensus decision	quadratic*	quadratic*	linear	linear
Number of messages to rotate leader	quadratic	quadratic*	linear	linear + ε
Network speed	👍	👎	👍	👍
Rounds to commit	2	2	3	2

*Can be linear with threshold-cryptography