Fault-Tolerant Distributed Transactions on Blockchain

Practical Byzantine Fault-Tolerant Consensus

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A Resilient Database Management System (RDBMS)

Client

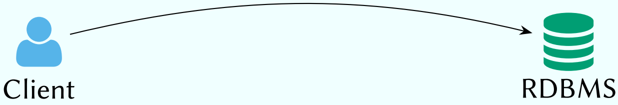
RDBMS

ParentOf	
Parent	Child
Alice	Carol
Bob	Carol
Carol	Dan
Carol	Eve
Dan	Faythe

The *RDBMS* should be resilient,
while serving as a *single coherent system* in a *transparent* way.

A Resilient Database Management System (RDBMS)

$\tau =$ "`SELECT Child`
`FROM ParentOf`
`WHERE parent = 'Carol';`"



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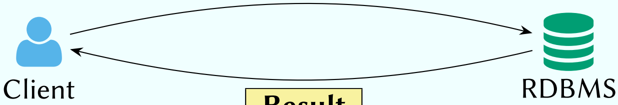

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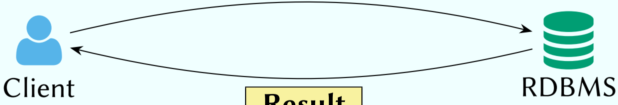

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Reminder: Deterministic execution

All replicas in the RDBMS must perform the same execution of every transaction. E.g.,

$$\tau = \text{“Remove a child of Carol from the ParentOf table,”}$$

should result in all replicas removing the same child!

A Resilient RDBMS: What Can Go Wrong?

We assume *malicious* participation!

Malicious replicas can …

- try to insert *forged* transactions into the RDBMS;
- try to prevent *some* clients from using the RDBMS;
- try to send *invalid results* to clients using the RDBMS;
- try to *interfere* with the working of other replicas of the RDBMS;
- try to *disrupt* the consensus used by the RDBMS.

A *Practical* Definition of Consensus for Client-Server Services

Each replica $\textsc{q} \in \mathfrak{R}$ maintains an append-only *ledger* $\mathcal{L}_{\textsc{q}}$
(representing a sequence of *client transactions*).
A *consensus protocol* operates in rounds $\rho = 0, 1, 2, 3, \dots$ that each satisfy:

Termination Eventually, each good replica $\textsc{r} \in \mathcal{G}$ will append a single client transaction τ to their ledger such that: after round ρ, we have $\mathcal{L}_{\textsc{r}}[\rho] = \tau$.

Non-divergence If good replicas $\textsc{r}_1, \textsc{r}_2 \in \mathcal{G}$ appended τ_1 and τ_2 to their ledger in round ρ, then $\tau_1 = \tau_2$.

Validity If good replica $\textsc{r} \in \mathcal{G}$ appended τ to its ledger, then τ is requested by some client.

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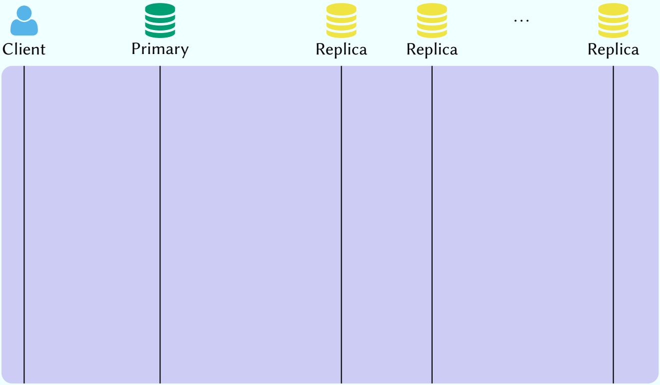
Service If a good client requests τ, then eventually a good replica will append τ to its ledger.

Primary-Backup Replication

Primary Coordinates consensus: propose the order of transactions to replicate.

Backup Accept proposals and verifies behavior of the primary.



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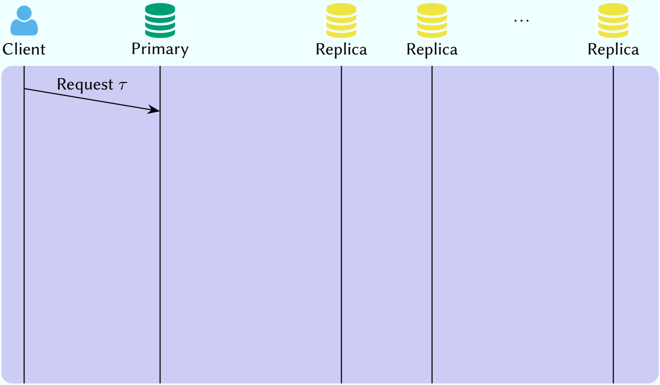

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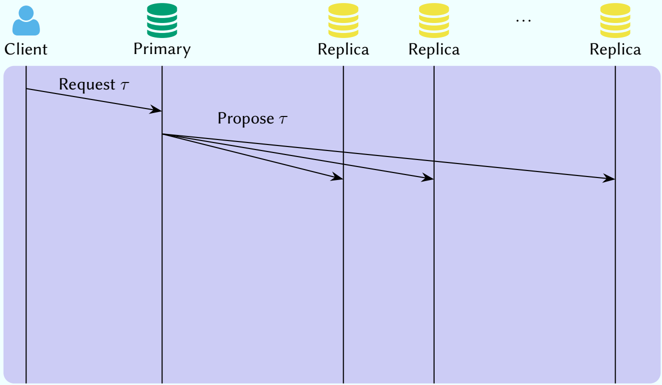

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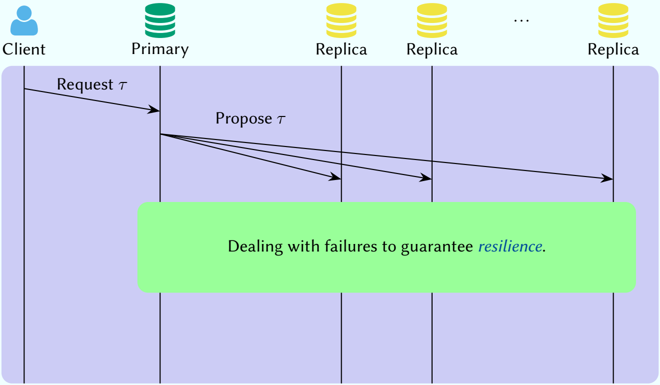

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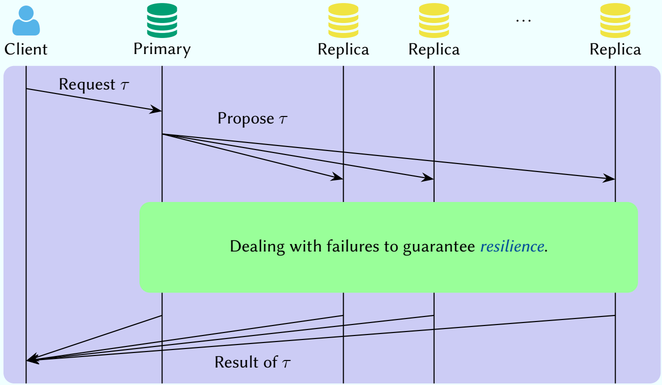

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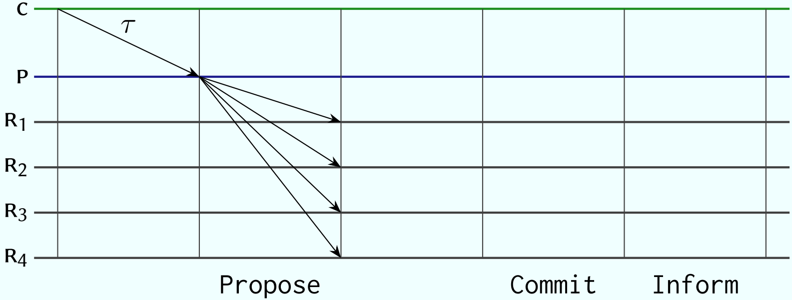

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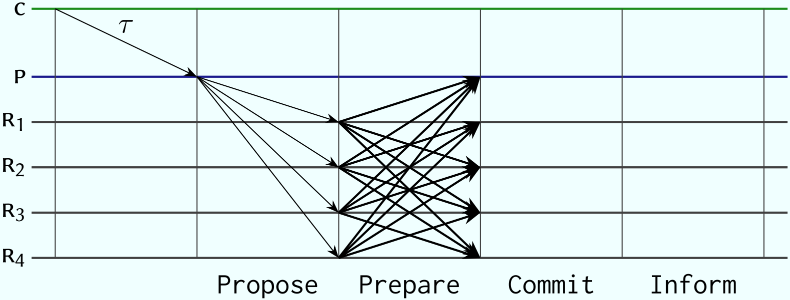

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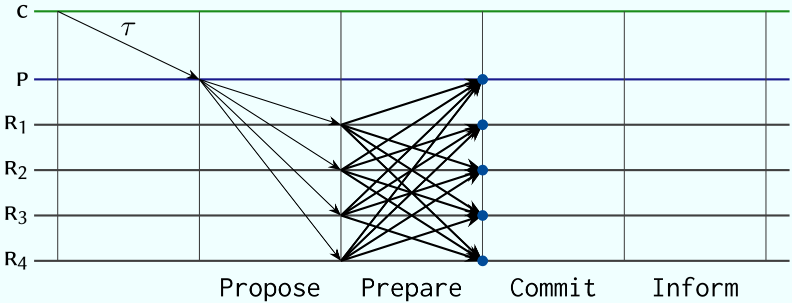

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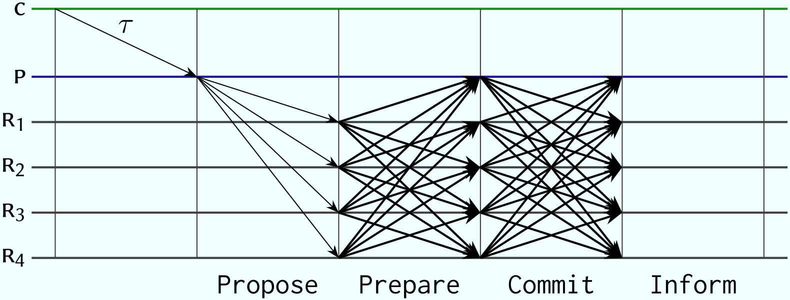

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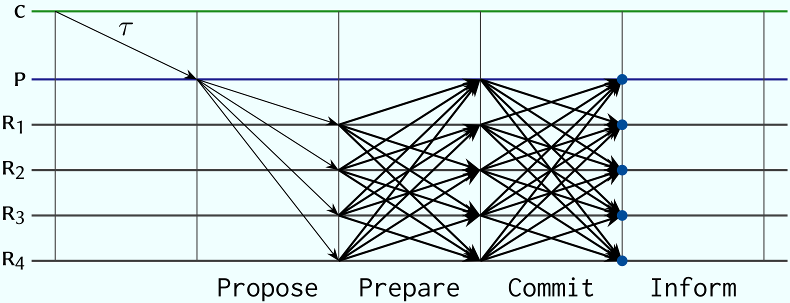

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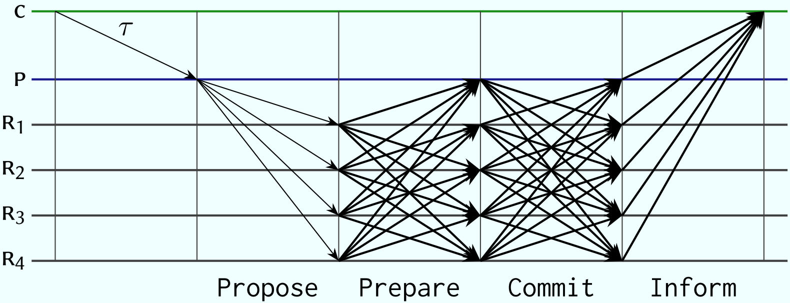

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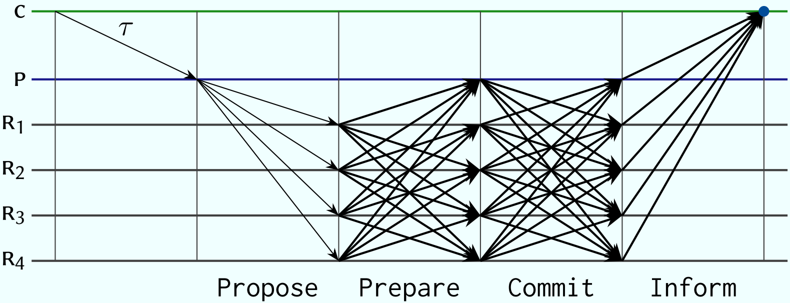

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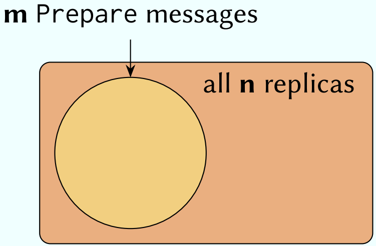

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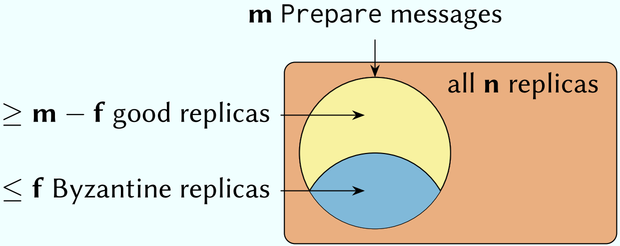

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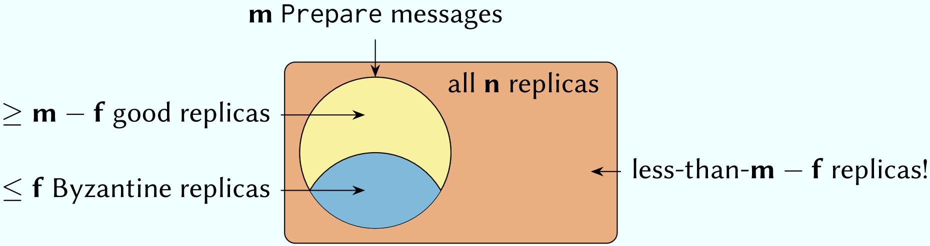

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Take maximum value for $\mathbf{m}$: $\mathbf{m} = \mathbf{nf} = \mathbf{n} - \mathbf{f}$. We must have:

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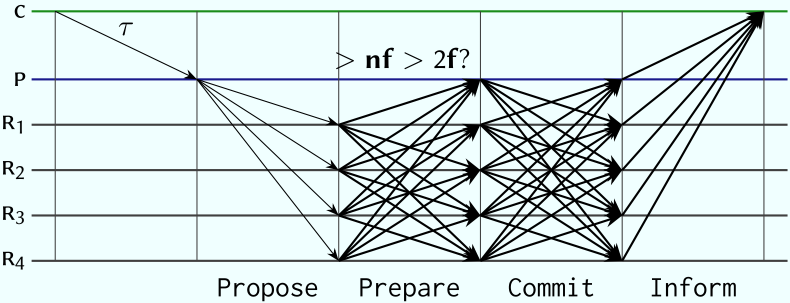

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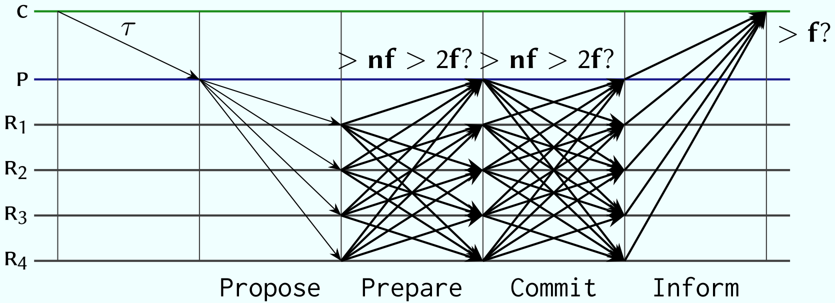

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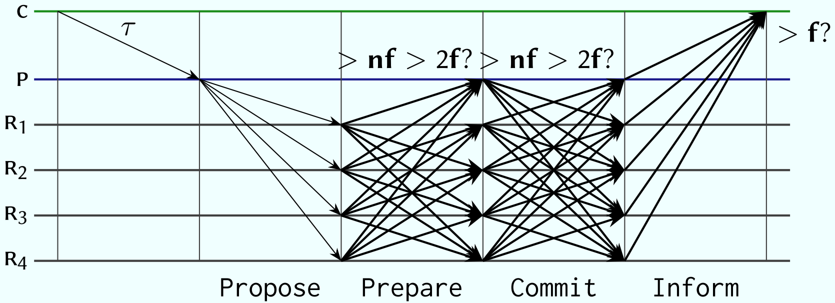
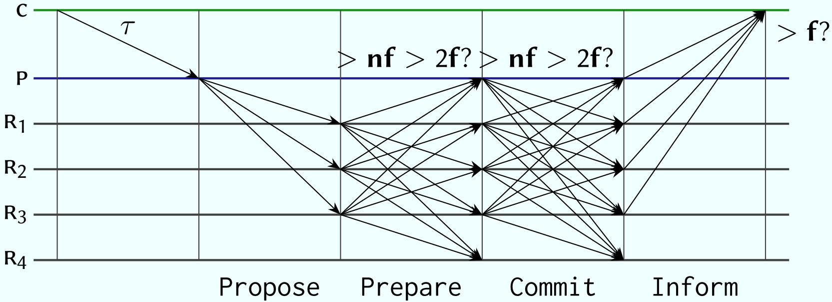


Theorem

If the primary is good and the network is reliable,
then all good replicas will commit and the client will observe outcome.

Recovering from Failure: Detecting Failures

Case 1: Primary failure, ignores replica R_4



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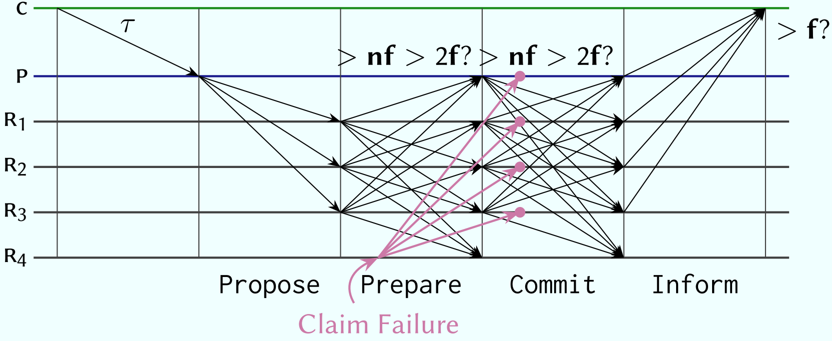

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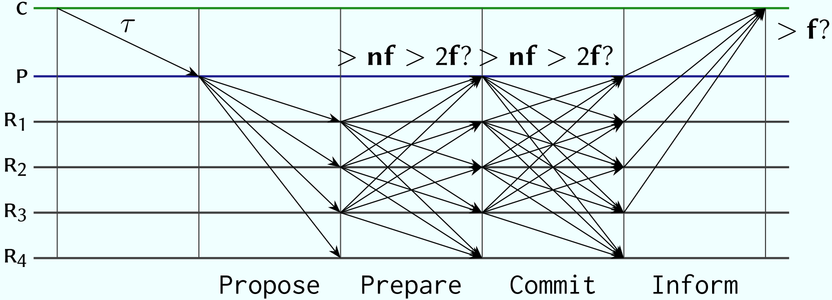

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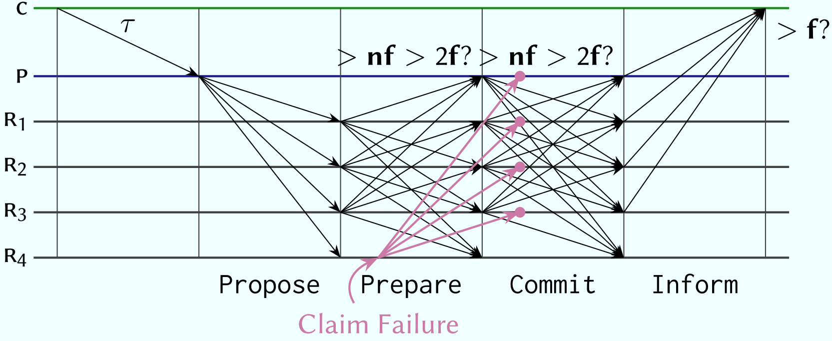
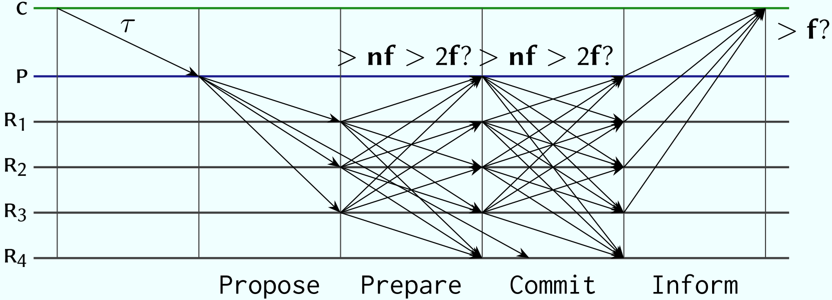


Recovering from Failure: Detecting Failures

Case 3: Message delays



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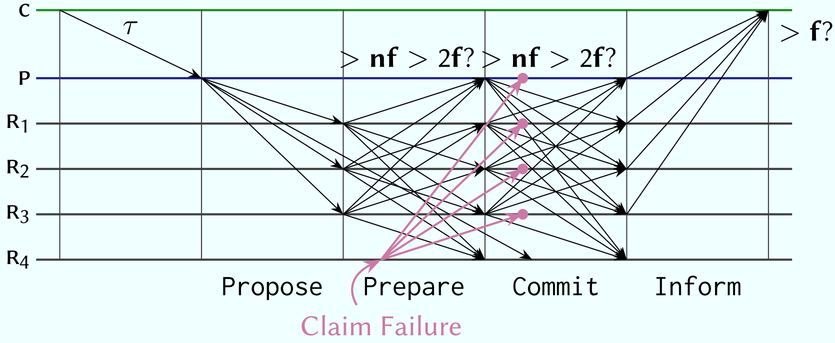

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What do replicas R_1, R_2, and R_3 see?

- They got `Proposal` and `Commit` messages from the primary.
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- They got a *failure claim* from R_4.

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Implications

- We cannot detect all failures.
- Byzantine replicas can lie about primary failure.
- Network failure can look like primary failure.

Recovery from Failure: Two Cases

We cannot detect all failures.

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We cannot detect all failures.

Assume (for now): No network failures

Upon a failure claim, we can distinguish two cases:

We cannot pinpoint a failure

"A few failure claims (at-most-**f**)"

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"A lot of failure claims (at-least-**f**)"

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- Use *checkpoints* to recover any backups.

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- *Sufficient* replicas fail to commit.
- The primary failed.
- Elect a new primary.
- Use *view-change* to recover failed state.

PBFT Operates in Views

In view v, the replica $\textsc{p}$ with $\mathrm{id}(\textsc{p}) = v \bmod \mathbf{n}$ is the primary.

- View v will perform consensus rounds until failure.
- If view v fails to perform rounds: we assume failure of $\textsc{p}$.
- Upon failure of $\textsc{p}$, we move to view $v + 1$.
- View $v + 1$ must recover *all* requests with possibly-observed outcomes.

PBFT Operates in Views

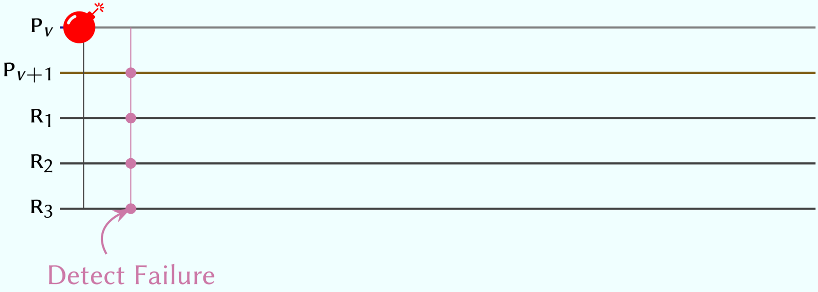
In view v, the replica $\textsc{p}$ with $\text{id}(\textsc{p}) = v \bmod \mathbf{n}$ is the primary.

- View v will perform consensus rounds until failure.
- If view v fails to perform rounds: we assume failure of $\textsc{p}$.
- Upon failure of $\textsc{p}$, we move to view $v + 1$.
- View $v + 1$ must recover *all* requests with possibly-observed outcomes.

The two phases of a view-change

- Phase 1: *Synchronize* failure detection.
- Phase 2: *New-View* proposal.

Recovery from Failure: *New-View* Proposal



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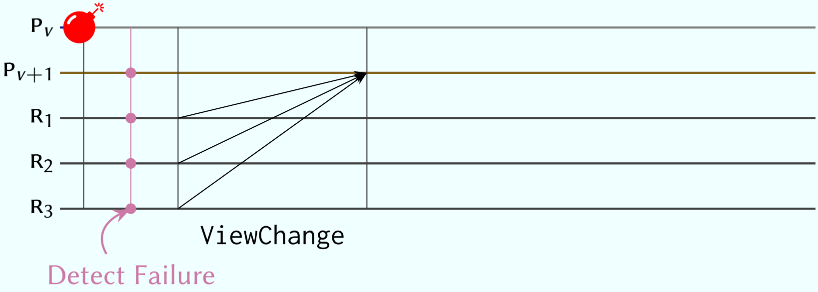

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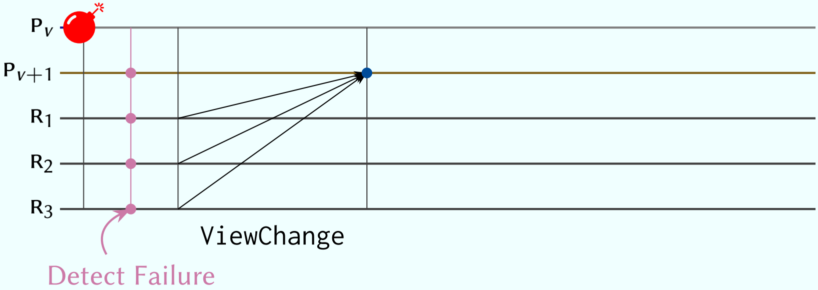

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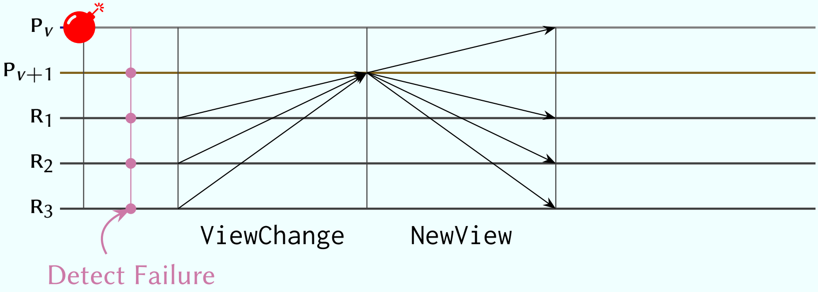

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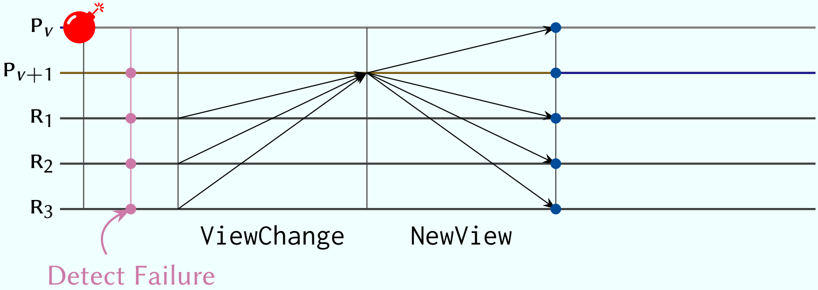

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- P_{v+1} proposes a NewView message with content N as the basis for recovery.
- Each replica updates their internal state in accordance with N.

Interpretation of a `NewView` Message

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Informal goal: "View $v + 1$ must recover *all* requests with possibly-observed outcomes".

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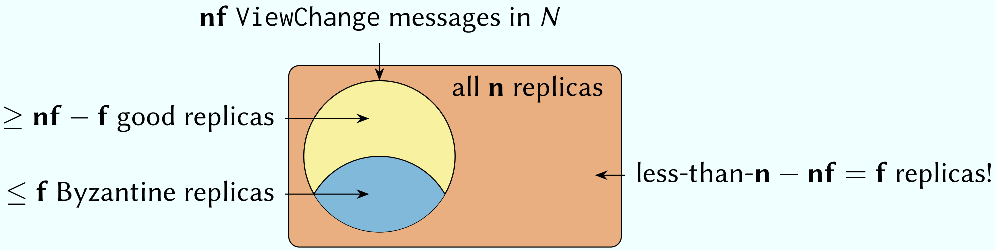

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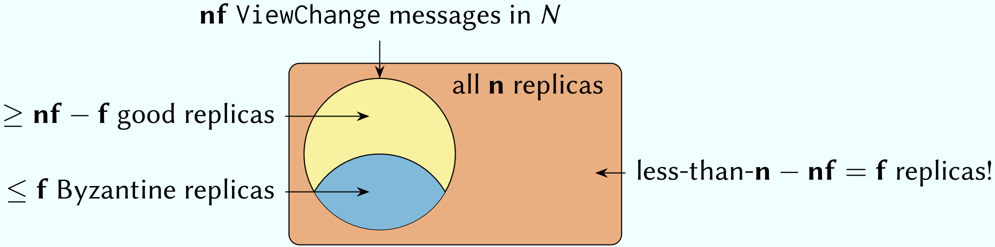

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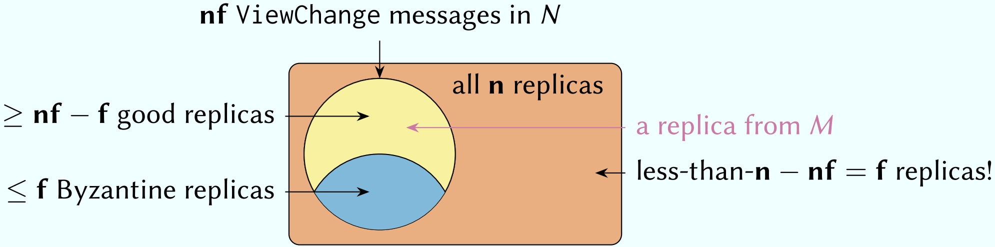

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Recover transactions τ for round ρ for which a prepare certificates was included in N for a view $w \leq v$ such that no *more recent* certificates for round ρ exists.

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Inductive case: $w < v$, $\mathbf{n} > 3\mathbf{f}$

Consider a view-change to view w', $w < w' < v$:

- View-change *fails*—View w' will not make new prepare certificates for any rounds.
- View-change *succeeds*—View w' can make new prepare certificates for any round ρ', but *only* if no transactions where recovered for round ρ'.

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Start of a new view

Consider a round ρ. If N contains

- no prepare certificates for ρ, then consider nothing proposed yet;
- a commit certificate for ρ, then consider round ρ committed;
- a prepare certificate for ρ, then repropose the certified transaction.

View-Changes and Authenticated Communication

We described a view-change protocol with *message forwarding*: digital signatures.

View-changes with authenticated communication only is possible, but more complex.

Recovery from Failure: Starting a View-Change

Consider a replica R

- When does R start participating in a view-change?

Recovery from Failure: Starting a View-Change

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- When can R expect any commit?
  - If R forwarded a client request to the current primary.
  - If R received a `Proposal` message or received $\mathbf{f} + 1$ `Prepare` or `Commit` messages.

Recovery from Failure: Out-of-Sync

What if …

- R_1 starts the view-change at $t_1 = 15$, with an expected duration of 4.
- R_2 starts the view-change at $t_2 = 20$, with an expected duration of 2.
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Replicas need to start view-change roughly at the same time.
Replicas must wait long enough for the new primary to be able to finish.

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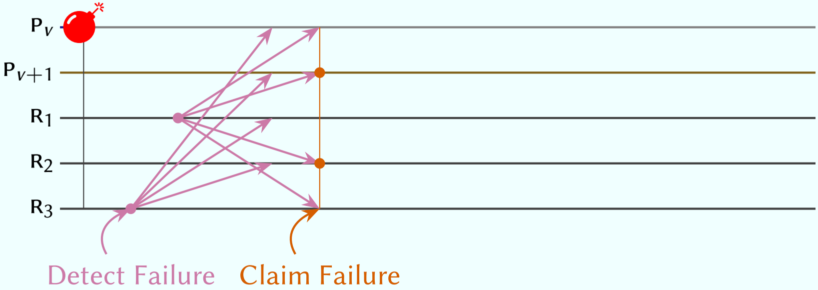

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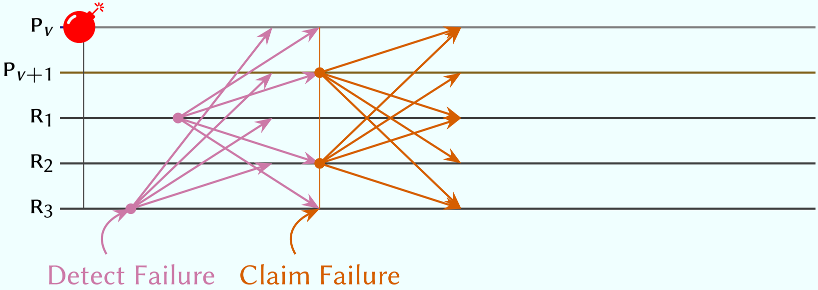

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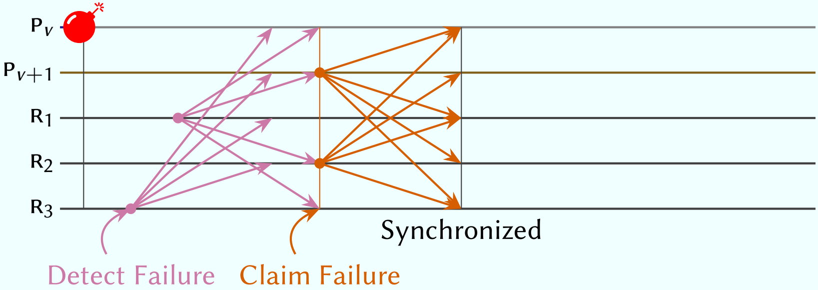

Recovery from Failure: Remaining Issues

- Dealing with failures when we cannot pinpoint a failure.
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- The unbounded number of rounds considered during view-changes:
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Solution: the *checkpoint* protocol

- After committing for all rounds up-to-ρ,
  replicas can broadcast a `Checkpoint` for round ρ.
- After receiving $\mathbf{f} + 1$ **matching** `Checkpoint` messages for round ρ:
  At-least one good replica committed in round $\rho \rightarrow$ Save to copy that commit decision!
- After receiving $\mathbf{n} - \mathbf{f}$ **matching** `Checkpoint` messages for round ρ:
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Use checkpoint certificates to reduce the size of `ViewChange` messages:
Only include the last checkpoint certificate and details on rounds *after* that checkpoint