Revisiting Fast Practical Byzantine Fault Tolerance: Thelma, Velma, and Zelma

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Abstract

In a previous note [1], we observed a safety violation in Zyzzyva [7, 9, 8] and a liveness violation in FaB [12, 13]. In this manuscript, we sketch fixes to both. The same view-change core is applied in the two schemes, and additionally, applied to combine them and create a single, enhanced scheme that has the benefits of both approaches.

1 Introduction

The crux of a view-change protocol is a mechanism that guarantees that a decision in a new view does not conflict with a decision that can ever be committed in any lower view. In [1], we exposed safety issues with the view-change mechanism of Zyzzyva [7, 9, 8], and liveness issues with that of FaB [12, 13].

In this manuscript, we sketch fixes for both. The principles we provide concentrate around a core view-change scheme that is applied in the two schemes.

The difficulty in protocols like FaB and Zyzzyva is that they combine a fast-track decision with a recovery-track. Therefore, a possible decision is tranfered across views in two ways, corresponding to the two tracks, and combining them requires care. Simply put, in our approach a replica accepts a leader proposal in a new view as *safe* only if it is compatible with a potential decision from the highest view-number of any lower view.

We first sketch in §2 a solution modeled after FaB, that we name Thelma, for a single-shot consensus. Borrowing from FaB, Thelma provides an optimistically fast BFT solution in a fault model parameterized by $n = 3f + 2t + 1$ with the following guarantees. It is fast during periods of synchrony, and in face of up to t non-leader failures. It is always safe against f Byzantine failures.

We proceed in §3 with a solution modeled after Zyzzyva, that we name Velma, for state-machine-replication. Borrowing from Zyzzyva, Velma provides an optimistically fast execution track in a fault model of $n = 3f + 1$ with the following guarantees. It reaches a commit decision on client requests in three-hops during periods of synchrony and of no failures. It is always safe against up to f Byzantine failures.

Both Thelma and Velma require replicas to maintain information from a constant-bounded number of previous views, and to send constant-bounded information in new-view messages. This improved on two previous solution frameworks that have optimistically tracks: Refined-Quorum-Systems [6], a fast single-shot Byzantine consensus, and Azyzzyva [2], a fast State-Machine-Replication. In both of these previous works, replicas maintain/send information from all past views.

Finally, we combine in §4 the benefits of the parameterized fault model $n = 3f + 2t + 1$ with full state-replication in a solution, that we name Zelma. In Zelma, a decision on a client request is committed in the fast track during periods of synchorny, when up to t non-leader replicas are faulty. Zelma provides safety at

all times against up to f Byzantine failures. It guarantess liveness during periods of synchrony with up to f failures.

In all three protocols, we shed light on correctness via a proof sketch. Formal algorithm descriptions and correctness proofs are deferred to a future manuscript.

1.1 Preliminaries

The focus of this work is providing state-machine-replication (SMR) for *n replicas*, f of which can be Byzantine faulty. An unbounded set of *clients* may form *requests* and submit them to replicas. We refer to members of the system, replicas or clients, as *nodes*. The communication among nodes is authenticated, reliable, but asynchronous; that is, we assume that a message sent from a correct node to another correct node is signed and eventually arrives.

At the core of SMR is a protocol for deciding on a growing log of operation requests by clients, satisfying the following properties:

Agreement If two correct replicas commit decisions at log position s, then the decisions are the same.

Validity If a correct replica commits a decision at some log position, then it was requested (and signed) by some client.

Liveness If some correct client submits a request, and the system is eventually partially-synchronous [5], then eventually the replicas commit some decision.

In the case of Thelma (as in FaB), we concentrate only on the core consensus problem for a single decision.

View Change

The solutions we discuss employ a classical framework that revolves around an explicit ranking among proposals via *view* numbers.

Replicas all start with an initial view, and progress from one view to the next. They accept requests and respond to messages only in their current view.

In each view there is a single designated *leader*. In a view, zero or more decisions may be reached. This strategy separates safety from liveness: It maintains safety even if the system exhibits arbitrary communication delays and again up to f Byzantine failures; it provides progress during periods of synchrony.

If a sufficient number of replicas suspect that the leader is faulty, then a view change occurs and a new leader is elected. The mechanism to trigger moving to a higher view is of no significance for safety, but it is crucial for liveness. On the one hand, replicas must not be stuck in a view without progress; on the other hand, they must not move to a higher view capriciously, preventing any view from making progress. Hence, a replica moves to a higher view if either a local timer expires, or if it receives new view suggestions from $f + 1$ replicas. Liveness relies on having a constant fraction of the views with a correct leader, whose communication with correct replicas is timely, thus preventing $f + 1$ replicas from expiring.

Dealing with leader replacement is the pinnacle of both safety and liveness. A core aspect in forming agreement against failures is the need for new leaders to safely adopt previous leader values. The reason is simple, it could be that a previous leader has committed a decision, so the only safe thing to do is adopt his value.

In the prevailing solutions for the benign settings (DLS [5], Paxos [10], VR [14], Raft [15]), leader replacement is done by reading from a view-change quorum of $n - f$ replicas, and choosing the value with the maximal view [1] number. Note that $n - f$ captures a requirement that the quorum intersects every leader-quorum in previous views (not only the most recent one). It is crucial to take into consideration how leader quorums of multiple previous views interplay. Choosing the value with the maximal view-number is crucial because there may be multiple conflicting values and choosing an arbitrarily value is not always a safe decision.

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[1]In DLS, the term *phase* is used, and in Paxos, *ballot*.

A similar paradigm holds in PBFT [3, 4]. The new leader needs to read from a *view-change quorum* of $n - f$ replicas and choose a value with the maximal view-number. Different from the benign case, in the Byzantine settings, uniqueness is achieved by using enlarged, Byzantine quorums [11]. Byzantine quorums guarantee intersection not just in any node but in a correct node.

In Byzantine settings, a correct node also needs to prove a decision value to a new leader. This is done in PBFT[2] by adding another phase before a decision. The first phase ensure uniqueness via *prepare* messages from $n - f$ nodes. In the second phase, nodes send a *commit-certificate* consisting of $n - f$ prepare messages. A decision can be reached when a *commit-quorum* of $n - f$ nodes have sent a commit-certificate.

The two-phase scheme guarantees the follows. If there is a decision, there exists a correct node in the intersection between a commit-quorum and a view-change quorum that passes a commit-certificate to the next view.

Indeed, a new leader chooses in PBFT a value whose commit-certificate, rather than a prepare, has the maximal view-number.

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[2]We refer here to the PBFT version with signed messages [3].

2   Thelma: Revisiting the FaB View-Change

2.1   A Skeletal Overview of PFaB

Martin and Alvisi introduce Fast Byzantine Consensus (FaB) in [12, 13], a family of protocols parameterized by various resilience assumptions. The papers use the Paxos terminology to model roles: *proposers*, *acceptors*, and *learners*. And it employs *proposal numbers* to enumerate proposals. We will adhere to the Zyzzyva (and PBFT) terminology, and translate those to *leaders*, *replicas*, and *view-numbers*.

FaB has two variants. The first FaB variant works with $n = 5f + 1$ replicas, trading fast termination by with reduced resilience. Here, we focus on the second variant, parameterized with $n = 3f + 2t + 1$, where $t \leq f$. We refer to it here as PFaB. It works in two tracks, a fast track and a recovery track.

The fast track protocol of PFaB is an easy two-step protocol. A leader pre-proposes a value to replicas, who each *accept* one value per view and respond with a *prepare* message. A decision is reached in PFaB when a *fast-quorum* of $n - t$ replicas accept the leader's proposal and send a prepare response for it.

The fast track is guaranteed to complete in periods of synchrony with a correct leader and up to t Byzantine replicas. However, parameterized FaB does not necessarily guarantee fast progress even in periods of synchrony, if the parameter t threshold of failures is exceeded. That is, although PFaB is always safe despite up to f Byzantine failures, it is not always fast.

If progress is stalled, PFaB allows progress via a recovery protocol, which is essentially PBFT (adapted to $n = 3f + 2t + 1$). The recovery track is guaranteed to complete during periods of synchrony if the number of actual Byzantine failures does not exceed f.

More precisely, in PFaB, the recovery track revolves around forming a commit-certificate called a *commit-proof*. When replicas accept a leader proposal, in addition to sending *prepare* messages (`ACCEPTED`) to the leader, replicas also send signed prepare messages to each other. We say that a replica has a commit-certificate for a value v if it receives in a view prepare messages for v from a *recovery-quorum* of $(n - f - t)$ replicas. Upon obtaining a commit-certificate, a replica sends it in a *commit* message (`COMMITPROOF`) to other replicas.

A decision is reached if either a fast-quorum of $n - t$ replicas send prepare messages (for the same value), or a recovery-quorum of $(n - f - t)$ replicas send commit messages (for the same value).

The core mechanism in PFaB for transferring safe values across views is a *progress certificate* containing new-view messages (`REP`) from a *progress-quorum* of $n - f$ replicas. A new-view message from a replica contains the new view's number, the last value it sent in a prepare message, and the last commit-certificate it sent in a commit message.

In PFaB, a progress-certificate for a specific new view is said to *vouch for* a value v if there does not exist a set of $f + t + 1$ new-view messages with an identical prepare value v' such that $v' \neq v$; and there does not exist any commit-certificate with value v' such that $v' \neq v$.

2.2   Thelma

We now outline a new view-change scheme within the above PFaB protocol framework. We will refer to the fixed protocol as Thelma.

In order to fix PFaB, each replica needs to maintain with the last prepare and commit messages it sent their original view numbers. When a replica copies its last prepare and commit messages into a new-view message, it needs to attach the original view numbers to them.

A decision is transferred across views via a progress-certificate as follows.

- A possible fast-track decision is transferred across views via a set of prepares intersecting a progress-quorum. Complicating matters, each prepare may be repeated in higher views, hence different prepares in the intersection may carry different view-numbers.

- A possible recovery track decision is transferred across views via a commit-certificate.

To combine possible decision values from both tracks, replicas need to choose the highest previous view in which a decision is possible. If both tracks appear possible for the same view-number, then a commit-certificate provides evidence against a potential fast-track decision in the same view.

More specifically, let P be a progress-certificate consisting of view-change messages from a progress-quorum of $n - f$ replicas.

In order to simplify processing P, we introduce several key notions.

fast-certificate(d): The highest view-number v such that $f + t + 1$ prepare messages in P contain the value d and a view-number at least v. If no such v exists, we set fast-certificate(d) to -1.

PFAST(d): If fast-certificate(d) has the highest view-number among fast-certificates in P, then PFAST(d) is true; otherwise, it is false.

PSLOW(d): If a commit-certificate for d exists in P and has the highest view-number among commit-certificates, then PSLOW(d) is true; otherwise, it is false.

We are now ready to determine when a value d is safe for a progress-certificate P:

1. PSLOW(d) holds, and for all d', fast-certificate(d') has view-number no higher than the commit-certificate for d, or

2. PFAST(d) holds, and for all d', a commit-certificate for d' if exists has view-number lower than fast-certificate(d), or

3. for no value d' does PSLOW(d') or PFAST(d') hold; hence, all values are safe.

2.3 Examples

To demonstrate Thelma's view-change, we revisit the "stuck" scenario in [1], as well as another scenario.

For these scenarios, we set $f = 1$, $t = 0$, $n = 3f + 2t + 1 = 4$. Denote the replicas by i_1, i_2, i_3, i_4, one of whom, say i_1, is Byzantine.

The first scenario goes through one view change.

View 1:

1. Leader i_1 (Byzantine) pre-proposes value d to i_2, i_3.

2. i_1, i_2, i_3 send prepare messages for d.

3. i_2 collects a view-1 commit-certificate for d and sends a commit message for d.

4. Meanwhile, the leader i_1 equivocates and pre-proposes d' to i_4.

View 2:

1. The new leader i_2 collects a progress-certificate consisting of new-view messages from a quorum of 3 replicas (including itself):

   - from i_1, the new-view message contains a prepare for d' from view 1, and no commit-certificate.
   - from i_2, the new-view message contains a prepare for d from view 1, and a view-1 commit-certificate for it.
   - from i_4, the new-view message contains a prepare for d', and no commit-certificate.

In this progress-certificate, PSLOW(d) holds, and no fast-certificate has a view-number higher than d's commit-certificate view-number (1). Therefore, it determines d as the only safe value to propose.

Indeed, notice that a decision on d is still possible in view 1: i_3 may send a commit message, and i_1 (Byzantine) may send a commit message even though it already moved to view 2.

The second scenario goes through two view changes.

View 1:

1. Leader i_1 (Byzantine) pre-proposes value d to i_2, i_3.

2. i_1, i_2, i_3 send prepare messages for d.

3. i_1 collects a commit-certificate for d (and stalls).

4. Meanwhile, the leader i_1 equivocates and pre-proposes d' to i_4.

View 2:

1. The new leader i_2 collects a progress-certificate consisting of new-view messages from a quorum of 3 replicas (including itself):

   - from i_1, a new-view message contains the prepare for d' from view 1, and no commit-certificate.
   - from i_2, a new-view message contains the prepare for d from view 1, and no commit-certificate.
   - from i_4, a new-view message contains the prepare for d', and no commit-certificate.

2. d' is a safe value for the progress-certificate since $\text{PFAST}(d')$ it true, and there are no commit-certificates. i_2 uses the progress-certificate to pre-propose d' to replicas as a safe value.

3. everyone sends prepare messages for d', and a client learns that d' is committed.

View 3:

1. The new leader i_3 collects a progress-certificate consisting of new-view messages from a quorum of 3 replicas:

   - from i_1, the new-view message hides the fact that it prepared a value in view 2, and contains a prepare for d from view 1, and a view-1 commit-certificate for it.
   - from i_3 and i_4, the new-view message contains a prepare for d' from view 2

In this progress-certificate, $\text{PFAST}(d')$ holds, and the highest commit-certificate has view-number 1 (for d). Therefore, it determines B as the only safe value to propose.

Note that this scenario demonstrates that a commit-certificate may not necessarily override a set of $f+1$ prepares, unless its view-number is at least that of the highest fast-certificate.

2.4   Correctness

Claim 1. *Let a value d (ever) become a committed decision in view v in the fast track. Then the progress-certificate for every higher view $v' > v$ determines d as the only safe value.*

Proof Sketch. Since d becomes a committed decision in view v in the fast track, there is a fast-quorum Q of $n - t$ replicas that send prepare messages for d in view v, before moving to any higher view.

By way of contradiction, let P' be the progress-certificate whose view-number $v' > v$ is the lowest, such that d is not the only safe value for P'. We are going to draw certain conclusions about PFAST and PSLOW for P' in order to arrive at a contradiction.

PFAST for P'. First, let us compute PFAST for P'.

Denote by Q' the progress-quorum of $n - f$ replicas whose new-view messages are included in P'. Q and Q' intersect in a set of at least $f + t + 1$ correct replicas. These replicas report the prepare messages they sent in a view v or higher (up to $v' - 1$). By assumption, these prepares all contain the value d. Hence, fast-certificate(d) is at least v in P'.

By assumption, no value $d' \neq d$ is safe to propose in a view higher than v and less than v'. Hence, the number of replicas with prepare messages in P' for any value $d' \neq d$ with view v or higher is at most $f + t$. Specifically, in view v, there may be at most t correct replicas outside Q that have prepares for d'. Additionally, there may be f Byzantine replicas with prepares for d' with arbitrary view numbers. In total, there are not enough prepares for fast-certificate(d') to be v or higher.

We conclude that PFAST(d) is true, and for every other d', PFAST(d') is false.

PSLOW for P'. We now compute PSLOW for P'. Once again, we already showed that the number of replicas with prepare messages for any value $d' \neq d$ whose view is v or higher is at most $f + t$. In total, there are not enough prepares for a commit-certificate on d' to have view v or higher.

Therefore, either PSLOW(d') is false, or its commit-certificate has view-number lower than v.

Putting the constraints on PFAST and PSLOW for P' together, we conclude that d is the only safe value for P', and we arrive at a contradiction. $\qquad\square$

Claim 2. *Let a value d (ever) become a committed decision in view v in the recovery track. Then the progress-certificate for every higher view $v' > v$ determines d as the safe value.*

Proof Sketch. Since d becomes a committed decision in view v in the slow track, there is a recovery-quorum Q of $n - f - t$ replicas that send commit messages for d in view v, before moving to any higher view.

By way of contradiction, let P' be the progress-certificate whose view-number $v' > v$ is the lowest, such that d is not the (only) safe value for P'. We are going to draw certain conclusions about PFAST and PSLOW for P' in order to arrive at a contradiction.

PFAST for P'. First, let us compute PFAST for P'.

Denote by Q' the progress-quorum of $n - f$ replicas whose new-view messages are included in P'.

By assumption, no value $d' \neq d$ is safe to propose in a view higher than v and less than v'. However, there may be f Byzantine replicas in Q' with prepares for d' with arbitrary view numbers. There may be additionally up to $f + t$ correct replicas outside Q that have prepares for d' in view v. Therefore, fast-certificate(d'), if non-negative, can be at most v. We conclude that either PFAST(d') is false, or fast-certificate(d') has view number at most v, or both.

PSLOW for P'. We now compute PSLOW for P'. We already showed that the number of replicas with prepare messages in view v or higher for any value $d' \neq d$ is at most $2f + t$. In total, there are not enough prepares for a commit-certificate on d' to have a view number v or higher.

On the other hand, Q and Q' intersect in a set of at least $t + 1$ correct replicas. These replicas report the commit message they sent in view v or higher (up to $v' - 1$). By assumption, these commits all contain the value d. Hence, PSLOW(d) holds, and for no other d' is PSLOW(d') true.

Putting the constraints on PFAST and PSLOW for P' together, we conclude that d is the only safe value for P', and we again arrive at a contradiction. $\qquad\square$

Claim 3. *Every progress certificate determine some safe value.*

Proof Sketch. Since the rules for determining the safe value for a certificate are all positive, i.e., no values are explicitly ruled out by a certificate, there is always a possible safe value for every progress certificate. $\quad\square$

3 Velma: Revisiting the Zyzzyva View-Change

3.1 A Skeletal Overview of Zyzzyva

Zyzzyva [7, 9, 8] is a full State-Machine-Replication (SMR) protocol that has two commit paths. A two-phase path that resembles PBFT and a fast path.

The fast path does not have commit messages, and replicas speculatively execute requests and optimistically return *prepare* results directly to clients. A client learns a commit decision in the fast path by seeing $3f + 1$ prepare messages. The optimistic mode is coupled with a recovery mode that guarantees progress in face of failures. The recovery mode intertwines a two-phase $(2f + 1)$-quorum exchange into the protocol. In the two-phase recovery mode, replicas proceed to speculatively execute commands as well. In both modes, replicas may need to roll back speculative executions if in the end they conflict with committed decisions.

In Zyzzyva, a possible decision value is transferred across views in two possible ways, corresponding to the two decision tracks of the protocol (fast and two-phase): In the fast track, a possible decision value manifests itself as $f+1$ prepare messages. In the two-phase track, it manifests itself as a commit-certificate. Combining the two, Zyzzyva prefers a commit-certificate over $f + 1$ prepares; and among two commit-certificates, it prefers the one with the longer request-log.

We proceed with a skeletal description of the Zyzzyva sub-protocols, a fast-track sub-protocol, a two-phase sub-protocol, and a view-change sub-protocol. Our description omits details regarding checkpoint management, and many other optimizations, which are not crucial for correctness considerations, and are described in the original papers.

Messages. All messages in the protocol are signed and may be forwarded carrying the original sender's signature. The protocol makes use of the following interactions.

Client-request: A *client-request* (REQUEST) from a client to the leader contains some operation o, whose semantics are completely opaque for the purpose of this discussion.

Ordering-request: A leader's *pre-prepare* message is called an *ordering-request* (ORDER-REQ), and contains a leader's log of client requests $OR_n = (o_1, ..., o_n)$. (In practice, the leader sends only the last request and a hash of the history of prior operations; a node can request the leader to re-send any missing operations.)

Ordering-response: When a replica *accepts* a valid pre-prepare request, it speculatively executes it and sends the result in a *prepare* message called an *ordering-response* (SPEC-RESPONSE).

Commit-request: A *commit-request* (COMMIT) from the client to the replicas includes a *commit-certificate* CC, a set of $2f + 1$ signed replica responses (SPEC-RESPONSE) to an (identical) ordering-request OR_n.

Commit-response: When a replica obtains a valid commit-certificate CC for OR_n, it responds to client requests in OR_n with a *commit* message called a *commit-response* (LOCAL-COMMIT).

View-change: A *view-change* (VIEW-CHANGE) message from a replica to the leader of a new view captures the replica's *local state*.

New-view: A *new-view* (NEW-VIEW) message from the leader of a new view contains a set P of view-change messages the leader collected, which serves as a *leader-proof*. It includes an ordering-request for a *leader-log* $G_n = (o_1, ..., o_n)$.

The fast-track sub-protocol. Zyzzyva contains a fast-track protocol in which a client learns the result of a request in only three message latencies, and only a linear number of crypto operations. It works as follows.

A client sends a request o to the current leader. The current leader extends its local log with the request o to OR_n, and sends a pre-prepare (ordering-request) carrying OR_n. We did not say how a leader's local log is initialized. Below we discuss the protocol for a leader to pick an initial log when starting a new view.

A replica *accepts* a pre-prepare from the leader of the current view if it has valid format, and it extends any previous pre-prepare from this leader. Upon accepting a pre-prepare, a replica extends its local log to OR_n It speculatively executes it, and sends the result directly to the client in a *prepare* message.

A decision is reached on OR_n in view v in the fast track when $3f+1$ distinct replicas have sent a prepare message for it.

The two-phase sub-protocol. If progress is stalled, then a client waits to collect a *commit-certificate*, a set of $2f+1$ prepare responses for OR_n. Then the client sends a commit-request carrying the commit-certificate to the replicas. A replica responds to a valid commit-request with a *commit* message.

A decision is reached on OR_n in view v in the two-phase track when $2f+1$ distinct replica have sent a commit message for it.

The view-change protocol. The core mechanism in Zyzzyva for transferring safe values across views is for a new Zyzzyva leader to collect a set P of view-change messages from a quorum of $2f+1$ replicas. Each replica sends a view-change message containing the replica's *local state*: Its local request-log, and the commit-certificate with the highest view number it responded to with a commit message, if any.

The leader processes the set P as follows.

1. Initially, it sets a *leader-log* G to an empty log.

2. If any view-change message contains a valid commit-certificate, then it selects the one with the longest request-log OR_n and copies OR_n to G.

3. If $f+1$ view-change messages contain the same request-log OR'_m, then it extends the tail of G with requests from OR'_m. (If there are two OR'_m logs satisfying this, one is selected arbitrarily.)

4. Finally, it pads G with null request entries up to the length of the longest log of any valid prepare.

The leader sends a new-view message to all the replica. The message includes the new view number $v+1$, the set P of view-change messages the leader collected as a *leader-proof* for view $(v+1)$, and the *leader-log* G. A replica accepts a new-view message if it is valid, and *adopts* the leader log. It may need to roll back speculatively executed requests, and process new ones.

3.2 Velma

We now outline a new view-change scheme within the above Zyzzyva protocol framework. We will refer to the fixed protocol as Velma.

In order to fix Zyzzyva, we change the method for the leader and for replicas to select safe leader-logs during a view-change. Let P be a set of view-change messages from a view-change quorum of $2f+1$ replicas.

In order to simplify processing P, we introduce several key notions. These are similar, but not identical to those introduced in Thelma, because in Velma we need to determine safety of request-logs, rather than of a single value.

extends: An *extends* relation between two request-logs O_1, O_2, denoted $O_1 \sqsubseteq O_2$, indicates that O_1 is a prefix (not necessarily strict) of O_2. If $O_1 \not\sqsubseteq O_2$ and $O_2 \not\sqsubseteq O_1$ then they are *conflicting*.

fast-certificate(O): The highest view-number v such that $f+1$ prepare messages in P contain a log that extends O and a view-number at least v.

To explain this notion, recall that a fast-track decision on a log O in some view v intersects a view-change quorum in $f+1$ correct replicas. However, since a committed decision may be repeatedly proposed,

and possibly extended, in higher views, each of these $f + 1$ replicas sends a new-view message with a prepare containing a log that may extend O, and may have a view-number v or higher.

If no such view-number exists, we set fast-certificate(O) to -1.

slow-certificate(O): The highest view-number v for which a commit-certificate exists for O.

If no such view-number exists, we set slow-certificate(O) to -1.

PFAST(O): If fast-certificate(O) has the highest view-number among fast-certificates in P, and there is no O' extending O (i.e. $O \sqsubset O'$) with the same fast-certificate, then PFAST(O) is true; otherwise, it is false.

PSLOW(O): If slow-certificate(O) has the highest view-number among slow-certificates, and there is no O' extending O (i.e. $O \sqsubset O'$) with the same slow-certificate, then PSLOW(O) is true; otherwise it is false.

We are now ready to determine when a log O is safe for a progress-certificate P:

1. PSLOW(O) holds, and for all O', fast-certificate(O') is lower than slow-certificate(O), or

2. PFAST(O) holds, and for all O', slow-certificate(O') is lower than fast-certificate(O), or

3. PSLOW(O) holds, and for every O' whose fast-certificate(O') has the same view-number as slow-certificate(O), we have $O' \sqsubseteq O$, or

4. PFAST(O) holds, and for every O' whose fast-certificate(O') has the same view-number as slow-certificate(O), we have $O' \sqsubseteq O$, or

5. for no value d' does PSLOW(d) or PFAST(d) hold; hence, all values are safe.

3.3   Examples

To demonstrate Velma's view-change, we revisit the two safety-violation scenarios in [1].

Our first scenario requires four replicas i_1, i_2, i_3, i_4, of which one, i_1, is Byzantine. It proceeds in 3 views, and arrives at a conflicting decision on the first log position.

View 1: Creating a commit-certificate for (a).

1. Leader i_1 sends pre-prepare with log (a) to replicas i_2 and i_3.

2. Leader i_1 (Byzantine) equivocates and sends pre-prepare with log (b) to replica i_4.

3. Replicas i_2, i_3 speculatively execute a, obtain a speculative result and send it in a prepare message to a client.

4. The client collects a commit-certificate *cert* of view-1 prepares from i_1, i_2, i_3 for the log (a) and sends it to i_1.

View 2: Deciding (b).

1. The new leader i_2 collects view-change messages from a quorum of 3 (including itself) as follow:

   - Replica i_2 sends its view-1 prepare for log (a).
   - Replica i_4 sends its view-1 prepare for log (b):
   - Replica i_1 (which is Byzantine) joins i_4 and sends a view-1 prepare for log (b).

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Based on these view-change messages, PFAST is $(1, (b))$ and PSLOW is $(-1, \perp)$. Hence, (b) is the only safe choice.

i_2 sends a new-view message consisting of the log (b), using the set of view-change messages as proof that this is a safe value.

2. Every replica zeros its log (undoing a, if needed), speculatively execute b, and sends a view-2 prepare for log (b).

3. A client collects speculative-responses from all replicas, and b becomes successfully committed at log position 1.

View 3: Choosing the right commit-certificate.

1. The new leader i_3 collects view-change messages from a quorum of s as follow:

   - Replica i_1, which is Byzantine, hides the value it prepared in view 2, and sends a view-1 commit-certificate $cert$ (see above) for (a).
   - Replicas i_3 and i_4 send their view-2 prepares for log (b).

   Based on these view-change messages, PFAST is $(2, (b))$, PSLOW is $(1, (a))$, and (b) is the only safe choice.

The second scenario is also rather short, uses four replicas, and two view changes.

View 1: Creating a commit-certificate for (a_1, a_2).

1. Leader i_1 sends pre-prepare with log (a_1, a_2) to replicas i_2 and i_3.

2. Leader i_1 (Byzantine) equivocates and sends pre-prepare with log (b_1, b_2) to replica i_4.

3. Replicas i_2, i_3 speculatively execute a_1 followed by a_2, obtain a speculative result and send it in a prepare message to a client.

4. The client collects a commit-certificate $cert_1$ of view-1 prepares from i_1, i_2, i_3 for the log (a_1, a_2) and sends it to i_3.

View 2: Deciding (b_1).

1. The new leader i_2 collects view-change messages from a quorum of 3 (including itself) as follow:

   - Replica i_2 sends its view-1 prepare for log (a_1, a_2).
   - Replica i_4 sends its view-1 prepare for log (b_1, b_2).
   - Replica i_1 (which is Byzantine) joins i_4 and sends a view-1 prepapre for log (b_1, b_2).

   Based on these view-change messages, PFAST is $(1, (b_1, b_2))$i, and PSLOW is $(-1, \perp)$. Hence, (b_1, b_2) is the only safe choice.

   i_2 sends a new-view message consisting of the log (b_1, b_2), using the set of view-change messages as proof that this is a safe value.

2. Every replica zeros its log (undoing a_1, a_2, if needed). It first proceeds to speculatively execute b_1, and sends a view-2 prepare for log (b_1).

3. A client collects a commit-certificate $cert_2$ of view-1 prepares from i_1, i_2, i_4 and send it to replicas i_1, i_2, and i_4. They respond with a commit message for log (b_1).

4. The client collects commit messages and b_1 becomes successfully committed at log position **1**.

View 3: Choosing the right commit-certificate.

1. The new leader i_3 collects view-change messages from a quorum of s as follow:

   - Replica i_3 sends commit-certificate $cert_1$ (see above) for (a_1, a_2).
   - Replica i_4 sends commit-certificate $cert_2$ (see above) for (b_1), and its local log (b_1, b_2).
   - Replica i_1 (Byzantine) can join either one, or even send an view-change message with an empty log.

   Based on these view-change messages, PFAST is $(2, (b_1))$, and PSLOW has view-number at most 2. Therefore, (b_1) is the only safe choice for log position 1.

3.4 Correctness

The correctness argument for Velma are similar in essence to Thelma. However, care must be taken to preserve consistency across a sequence of consensus decisions, rather than one. And each decision must wait for execution results of a log of requests, rather than commit to an individual proposal value.

Claim 4. *Let a request-log OR_n (ever) become a committed decision in view v in the fast track. If a leader-proof of a higher view $v' > v$ determines OR as a safe leader-log, then $OR_n \sqsubseteq OR$.*

Proof Sketch. Since OR_n becomes a committed decision in view v in the fast track, there is a fast-quorum Q of n replicas that send prepare messages for OR_n in view v, before moving to any higher view.

By way of contradiction, let P' be the leader-proof whose view-number $v' > v$ is the lowest, and OR' a safe leader-log of P' conflicting with OR_n. We are going to draw certain conclusions about PFAST and PSLOW for P' in order to arrive at a contradiction.

PFAST for P'. First, let us compute PFAST for P'.

Denote by Q' the view-change quorum of $2f + 1$ replicas whose new-view messages are included in P'. Q and Q' intersect in a set of at least $f + 1$ correct replicas. These replicas report the prepare messages they sent in a view v or higher (up to $v' - 1$). By assumption, these prepares do not conflict with OR_n. Hence, fast-certificate(OR_n) is at least v in P'.

By assumption, OR' is not safe to propose in a view higher than v and less than v'. Hence, the number of replicas with prepare messages in P' for OR' is at most f.

In total, there are not enough prepares for fast-certificate(OR') to be v or higher. We conclude that PFAST(OR') is false for every OR' conflicting with OR_n, and PFAST(OR'_n) is true for some some OR'_n extending OR_n.

PSLOW for P'. We now compute PSLOW for P'. We already showed that the number of prepares for OR' with view-number v or higher is at most f. Therefore, there are not enough prepares for a commit-certificate on OR' to have view v or higher.

Therefore, either PSLOW(OR') is false, or its commit-certificate has view-number lower than v.

Putting the constraints on PFAST and PSLOW for P' together, we conclude that every safe leader-log for P' extends OR_n, and we arrive at a contradiction. $\square$

Claim 5. *Let a request-log OR_n (ever) become a committed decision in view v in the two-phase track. If a leader-proof of a higher view $v' > v$ determines OR as a safe leader-log, then $OR_n \sqsubseteq OR$.*

Proof Sketch. Since OR_n becomes a committed decision in view v in the slow track, there is a two-phase quorum Q of $2f + 1$ replicas that send commit messages for OR_n in view v, before moving to any higher view.

By way of contradiction, let P' be the leader-proof whose view-number $v' > v$ is the lowest, and OR' a safe leader-log of P' conflicting with OR_n. We are going to draw certain conclusions about PFAST and PSLOW for P' in order to arrive at a contradiction.

PFAST for P'.   First, let us compute PFAST for P'.

Denote by Q' the view-change quorum of $2f+1$ replicas whose new-view messages are included in P'. By assumption, the only prepare messages in P' whose view is higher than v and have OR' are faulty. Hence, there are at most f of them. In view v, there may be additionally up to f correct replicas outside Q that have prepares for OR'. Therefore in total, fast-certificate(OR') in P' is at most v. We conclude that either PFAST(OR') is false, or fast-certificate(OR') has view-number at most v, or both.

PSLOW for P'.   We now compute PSLOW for P'.

We already showed that the number of prepare messages in P' whose view is v or higher and have OR' is at most $2f$. In total, there are not enough prepares for a commit-certificate on OR' to have a view number v or higher.

On the other hand, Q and Q' intersect in at least one correct replica. This replica reports the commit message it sent in view v or higher (up to $v'-1$). By assumption, these commits all extend the value OR_n. Hence, PSLOW(OR') is false, and PSLOW(OR'_n) is true for some OR'_n extending OR_n.

Putting the constraints on PFAST and PSLOW for P' together, we conclude that every safe leader-log for P' extends OR_n, and we again arrive at a contradiction.   □

Claim 6. *Every leader-proof determines some safe value.*

Proof Sketch. Since the rules for determining the safe value for a proof are all positive, i.e., no values are explicitly ruled out by it, there is always a possible safe leader-log for every leader-proof.   □

4 Zelma: Putting Fab and Zyzzyva View-Change Together

Having fixed the view-change in Zyzzyva allows us to combine the mechanism for optimistic (fast track) execution with the parameterized $n = 3f + 2t + 1$ failure model of FaB. We name the combined solution Zelma.

In Zelma, a fast-quorum consists of $n - t$ replicas. The fast track allows a leader to extend the current log with a new client request. The client can commit a decision by seeing $n - t$ prepare messages. The optimistic mode is guaranteed to complete in periods of synchrony with a correct leader and up to t Byzantine replicas.

A two-phase quorum consists of $n - f - t$ replicas. It is essentially PBFT adapted to the parameterized fault model. More specifically, a client collects a commit-certificate consisting of signed prepares from a quorum of $n - f - t$ replicas. It forwards the certificate to the replicas. A decision is reached when a quorum of $n - f - t$ replicas received the commit-certificate.

The two-phase track is guaranteed to complete is periods of synchrony with a correct leader, up to f Byzantine replicas and additionally up to t slow replicas.

Zelma maintains safety at all times against up to f Byzantine failures.

If progress is stalled, Zelma provides eventual progress via a view-change protocol. A view-change quorum consists of $n - f$ replicas.

In Zelma, a possible decision value is transferred across views in two possible ways, corresponding to the two decision tracks of the protocol (fast and two-phase):

In the fast track, a possible decision value manifests itself as $f + t + 1$ prepare messages. These prepares may potentially have different view numbers and request-logs, but they all contain the committed decision as prefix. A fast-certificate records the $(f + t + 1)$-highest view-number among all the prepares for the same request-log prefix.

In the two-phase track, a decision manifests itself as a commit-certificate with $2f + t + 1$ identical prepares.

Combining the two, Zelma picks the highest view with either a commit-certificate or a fast-certificate. This becomes the initial leader-log for a new-view. If the highest commit-certificate and fast-certificate have equal view-numbers, then the initial leader-log is a concatenation of the commit-certificate log, with any remaining entries from the fast-certificate log.

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