Revisiting Fast Practical Byzantine Fault Tolerance

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Abstract

In this note, we observe a safety violation in Zyzzyva [7, 9, 8] and a liveness violation in FaB [14, 15]. To demonstrate these issues, we require relatively simple scenarios, involving only four replicas, and one or two view changes. In all of them, the problem is manifested already in the first log slot.

1 Introduction

A landmark solution in achieving replication with Byzantine fault tolerance has been the Practical Byzantine Fault Tolerance (PBFT) work by Castro and Liskov [3, 4]. Since the PBFT publication, there has been a stream of works aiming to improve the efficiency of PBFT protocols. One strand of these works revolves around *optimism* [10, 14, 15, 7, 9, 8, 5, 2]. In this strand, the focus is on providing a *fast* common case (i.e., when there are no link or server failures). In other cases, optimistic solutions fall back to some backup implementation with strong progress guarantees.

In this note, we observe that several key works in the "optimistic strand" do not deal with optimism correctly. In particular, we first present in §2 safety violations in Zyzzyva [7, 9, 8]. We then demonstrate in §3 how being "overly safe" gets FaB [14, 15] stuck. To demonstrate these issues, we require relatively simple scenarios, involving only four replicas, and one or two view changes. In all of them, the problem is manifested already in the first log slot.

We also briefly observe below that in other fast Byzantine replication solutions, an optimistic track is not fully intertwined with a regular protocol, hence they are *less fast*.

It therefore appears that the challenge posed in [12] of providing *Byzantine Fast Paxos* is left open:

> "Fast Paxos can also be generalized to a Fast Byzantine Paxos algorithm that requires only two message delays between proposal and learning in the absence of collisions. (However, a single malicious proposer can by itself create a collision.)" [12]

That is, none of the fast Byzantine agreement works we are aware of provides a solution that simultaneously addresses (i) optimal step-complexity, (ii) optimal resilience, (iii) safety against failures of less than a third of the system, and (iv) progress during periods of partial synchrony.

Our team has worked out a full solution, and will publish a follow up to this report in the near future.

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 [6], then eventually the replicas commit some 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 [6], Paxos [11], VR [16], Raft [17]), leader replacement is done by reading from a 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.

A similar paradigm holds in PBFT [3, 4]. The new leader needs to read from a 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 [13]. 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.

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

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

A decision can be reached when $n - f$ nodes have sent a commit-certificate. The two-phase scheme guarantees that if there is a decision, there is a correct node that passes a commit-certificate to the next view.

Sacrificing Resilience

The extra PBFT phase may be avoided by somewhat sacrificing resilience and using $n = 5f + 1$, as in FaB [14, 15], Zyzzyva5 [7], and Q/U [1]. Here, the intersection between a potential decision quorum and a view-change quorum has $2f + 1$ correct nodes, enough to provide both uniqueness and transfer of value.

Kursawe's Solution

Addressing a much more limited scope, Kursawe provided in 2002 a simple black box technique to transform any Asynchronous Byzantine Agreement (ABA) protocol (with a sufficiently strong validity property) into a consensus protocol that has an optimistic fast path [10]. It works as follows.

There are two possible commit tracks, and they may be combined (some nodes commit in the fast, some not). In the fast track, a node decides if all nodes prepare an identical value. In the fall-back track, any Byzantine agreement protocol is invoked, where nodes use their prepare values as initial inputs. The only requirement from the agreement protocol is that it satisfies the following validity property:

Byzantine validity: If all correct nodes start with the same input v, then the decision must be v.

This succinct solution framework is (almost trivially) correct. However, the recovery stage does not utilize the prepare steps which were already performed in the fast track. Hence, whereas the fast track is fast, the fall-back track is not optimal.

Additionally, as we already noted, it addresses a problem of a much more limited scope: It solves only a single-shot consensus; it does not address state replication (execution) at all.

FaB

FaB [14, 15] extends Kursawe's solution in several ways. First, the prepare messages from the fast track are input to the recovery phase, thus reducing the number of steps in recovery mode. In this way, the FaB recovery mode has the same overall cost as standard PBFT. Second, FaB extends the treatment to a parameterized failure model of $n = 3f + 2t + 1$. Thus, by appropriately increasing the system size, fast termination is achieved despite up to t non-leader Byzantine failures, whereas safety is guaranteed against f.

To achieve these enhancements, FaB cannot employ a Byzantine agreement protocol for recovery as a "black-box". Unfortunately, opening the recovery agreement protocol and incorporating the consensus steps into the FaB framework resulted in the omission we surface here (see §3).

Zyzzyva

Zyzzyva borrows from FaB the method for efficiently intertwining the optimistic fast track with the recovery track. It enhances the approach in a number of dimensions. Zyzzyva provides a state replication protocol, whereas FaB is a single shot consensus solution. Zyzzyva employs speculation in the execution of state updates, allowing a high throughput pipeline of state-machine replication, which is out of the FaB scope. Finally, a new leader in Zyzzyva cannot get "stuck" choosing a safe value as in FaB (§3). Unfortunately, the view-change protocol in Zyzzyva fails to provide safety against a faulty leader, as described in §2.

Upright

The Zyzzyva view-change protocol has been employed in UpRight [5], which also incorporates the parameterized failure model of $n = 3f + 2t + 1$ from FaB. The goal of UpRight is to build an engineering-strength BFT engine. The UpRight paper does not provide a full description of the algorithm, and rather indicates that it adopts these two previous solutions.

The Next 700 BFT Protocols

In *The Next 700 BFT Protocols*, Aublin et al. [2] provide a principled approach to view-change in BFT protocols. Their approach switches not only leaders, but also entire regimes, in order to respond to adaptive system conditions. One node of the 700 BFT protocol family is AZyzzyva, a protocol that combines the speculative (fast) path of Zyzzyva in a protocol called Zlight with a recovery protocol, e.g., PBFT. If Zlight fails to make progress, it switches to a new view that executes PBFT for a fixed number k of log slots. In this sense, AZyzzyva falls back to the approach of Kursawe [10], while extending it to a pipeline of state-machine commands and implementing a replicated state-machine. Indeed, Azyzzyva is simple and principled, and it is not vulnerable to the safety violations of Zyzzyva exposed here (§2). At the same time, the Azyzzyva recovery path requires more steps than the two-phase protocol of Zyzzyva. Additionally, Azyzzyva requires to wait for a commit decision (of k slots) to switch back from PBFT to Zlight.

2 Revisiting the Zyzzyva View-Change

2.1 Introduction

The Zyzzyva [7, 9, 8] has two commit paths. A two-phase path that resembles PBFT and a fast path.

The fast path does not have commit messages, and a client commits a decision by seeing $3f+1$ prepare messages[3]. The optimistic mode is coupled with a recovery mode that guarantees progress in face of failures. The recovery mode intertwines the PBFT two-phase steps into the protocol.

Quoting from [8], "Fast agreement and speculative execution have profound effects on Zyzzyvas view change subprotocol."

Indeed, 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 (as in PBFT). 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.

Here we show that either one of these rules may lead to violating safety.

The omissions are quite subtle, because unless a leader equivocates, a commit-certificate will not conflict with fast-paths of higher views.

Likewise, unless a leader equivocates, the log can only grow from one view to the next. Hence, in benign executions, higher views have longer (or at least non-decreasing[4]) sequence of commands, and the notions of highest view and longest request-log will be the same.

Nevertheless, we show that both these strategies do not provide safety, and permit the scenarios we surface here, where Zyzzyva breaks safety.

2.2 A Skeletal Overview of Zyzzyva

We start with an overview of Zyzzyva. Our description is merely skeletal, and glosses over many engineering details: We assume that all messages are signed and are forwarded carrying their signatures; we neglect the mechanism for checkpoint and space reclamation; and we do not optimize for messages sizes and crypto operations. These details and optimizations are covered in the Zyzzyva paper, and are omitted here for brevity and clarity.

As in the original paper, we break the Zyzzyva agreement protocol into three sub-protocols, a fast-track sub-protocol, a two-phase sub-protocol, and a view-change sub-protocol.

Messages. Since we mostly adopt the notation and terminology from PBFT, we start with a quick reference guide, mapping Zyzzyva's message types to PBFT's.

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).

[3] Note that, the terms *prepare* and *commit* are taken from PBFT; In Zyzzyva, the leader proposal message is called `ORDER-REQ` and the acknowledgements by replicas which are akin to prepare messages are called `SPEC-RESPONSE`.

[4] it seems that another, minor omission in the Zyzzyva protocol is that it does not explicitly indicate how to break ties in case of two maximal commit-certificates, of same length

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 new-view proof. It includes a new ordering request $G_n = (o_1, ..., o_n)$.

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 base 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 proof for new-view $(v+1)$, and a request-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.

2.3 Breaking Safety: First Scenario

We now proceed to demonstrate that the view-change mechanism in Zyzzyva does not guarantee safety. The overview of Zyzzyva we provided above should suffice to understand the scenarios below; for precise detail and notation of the Zyzzyva protocol, the reader is referred to [9].

Our first scenario demonstrates that the criterion for combining fast-track decision with two-phase decision may lead to a safety violation. In particular, prioritizing commit-certificate over $f + 1$ prepares, as done in Zyzzyva, is not always correct.

Our 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. Two clients c_1, c_2 provide a leader i_1 of view 1 with well-formed requests (`REQUEST`) a and b, respectively.
2. In view 1, the leader i_1 sends to replicas i_2 and i_3 a pre-prepare (`ORDER-REQ`) for a.
3. The leader i_1 (Byzantine) equivocates and sends replica i_4 a conflicting pre-prepare for b.
4. Replicas i_2 and i_3 accept the leader's well-formed pre-prepare, and speculatively execute a. They obtain a speculative result and send it in a prepare response (`SPEC-RESPONSE`) to c_1.
5. Client c_1 collects prepares from i_1, i_2 and i_3 for the request-log (a). These responses constitute a commit-certificate, denoted *cert*.

   Then the client expires waiting for additional responses. It sends a commit-request (`COMMIT`) for (a) that includes the commit-certificate *cert*. The commit-request reaches only i_1.

View 2: Deciding (b)**.**

1. All further messages are delayed, forcing the system to go through a view change.
2. In view 2, the leader i_2 collects view-change messages (`VIEW-CHANGE`) from itself, from i_1 and from i_4 as follow:

   - Replica i_2 sends its local log (a).
   - Replica i_4 sends its local log (b):
   - Replica i_1 (which is Byzantine) joins i_4 and sends a request-log (b).

   Based on these view-change messages, i_2 constructs a new request-log G consisting of (b), and sends it in a new-view message (`NEW-VIEW`) to replicas.
3. Every replica accepts the leader i_2 well-formed new-view message. Upon accepting it, each replica zeros its local log (undoing a, if needed). All replicas adopt the leader request-log (b) and speculatively execute b. They obtain a speculative result and send it in a response (`SPEC-RESPONSE`) to c_2.
4. The client c_2 of b collects speculative-responses from all replicas, and b **becomes successfully committed at log position** 1**.**

View 3: Choosing the wrong commit-certificate.

1. All further messages are delayed, forcing the system to go through a view change.
2. In view 3, the leader i_3 collects view-change messages (`VIEW-CHANGE`) from itself, from i_1 and from i_4 as follow:

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

Based on these view-change messages, i_3 chooses *cert*, the commit-certificate, and adopts it. It constructs a new request-log G consisting of requests (a), and sends it in a new-view message (`NEW-VIEW`) to replicas.

3. Each replica accepts the leader i_3 well-formed new-view message. Upon accepting it, replicas **zero their local logs, undoing b as needed.** Then they speculatively execute a, send the result, and a **becomes successfully committed at log position 1.**

2.4 Breaking Safety: Second Scenario

The second scenario demonstrates that the criterion for combining two-phase decisions from different views may lead to a safety violation. In particular, prioritizing the longest commit-certificate, as done in Zyzzyva, is not always correct.

Our second scenario again 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. In order to construct commit-certificates of different lengths, it utilizes four operation requests, a_1 by client c_1, a_2 by c_2, b_1 by c_3, and b_2 by c_4.

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

1. Four clients c_1, ..., c_4 provide a leader i_1 of view 1 with well-formed requests (`REQUEST`) for a_1, a_2, b_1, and b_2, respectively.
2. In view 1, the leader i_1 sends to replicas i_2 and i_3 two pre-prepare messages (`ORDER-REQ`). The first one is for a_1 at log position 1. The second one is for a_2 at log position 2, succeeding a_1.
3. The leader i_1 (Byzantine) equivocates and sends replica i_4 two conflicting pre-prepare requests. The first one is for b_1 at log position 1. The second one is for b_2 at log position 2 succeeding b_1.
4. Replicas i_2 and i_3 accept the relevant leader's well-formed pre-prepares, and speculatively execute a_1 followed by a_2. They obtain speculative results and send each result in a corresponding prepare response (`SPEC-RESPONSE`) to its requesting client.
5. The client c_2 of a_2 collects prepares from i_1, i_2 and i_3 for the request-log (a_1, a_2). These responses constitute a commit-certificate, denoted $cert_1$.

   Then the client expires waiting for additional responses. It sends a commit-request (`COMMIT`) for (a_1, a_2) that includes the commit-certificate $cert_1$. The commit-request reaches only i_3.

View 2: Deciding (b_1).

1. All further messages are delayed, forcing the system to go through a view change.
2. In view 2, the leader i_2 collects view-change messages (`VIEW-CHANGE`) from itself, from i_1 and from i_4 as follow:
   - Replica i_2 sends its local log (a_1, a_2).
   - Replica i_4 sends its local log (b_1, b_2).
   - Replica i_1 (which is Byzantine) joins i_4 and sends a request-log (b_1, b_2).

Based on these view-change messages, i_2 constructs a new request-log G consisting of (b_1, b_2), and sends it in a new-view message (NEW-VIEW) to replicas.

3. Each replica among i_1, i_2 and i_4 accepts the leader i_2 well-formed new-view message. Upon accepting it, replica i zeros its local log (undoing a_1, a_2 as needed), and adopts the leader request-log (b_1, b_2). It first proceeds to speculatively execute b_1, obtains a speculative result, and sends it in in a response (SPEC-RESPONSE) to c_3.

4. The client c_3 of b_1 collects speculative-responses from i_1, i_2 and i_4 for the request-log (b_1). These responses constitute a commit-certificate, denoted $cert_2$.

   Then the client expires waiting for additional responses. It sends a commit-request (COMMIT) for (b_1) that includes the commit-certificate $cert_2$.

5. Upon receiving the well-formed commit-request, replicas i_1, i_2, and i_4 respond to client c_3 with a commit message (LOCAL-COMMIT).

6. The client collects these commit messages and **$\mathbf{b_1}$ becomes successfully committed at log position 1**.

View 3: Choosing the wrong, maximal commit-certificate.

1. All further messages are delayed, forcing the system to go through a view change.

2. In view 3, the leader i_3 collects view-change messages (VIEW-CHANGE) from itself, from i_1 and from i_4 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, i_3 chooses $cert_1$, the commit-certificate with the longest request-log, and adopts it. It constructs a new request-log G consisting of (a_1, a_2), and sends it in a new-view message (NEW-VIEW) to replicas.

3. Each replica accepts the leader i_3 well-formed new-view message. Upon accepting it, replicas **zero their local logs, undoing $\mathbf{b_1}$ as needed.** Then they speculatively execute a_1, send the result, and **$\mathbf{a_1}$ becomes successfully committed at log position 1.**

3 Revisiting the FaB View-Change

3.1 Introduction

The Zyzzyva protocol borrows from an earlier work called FaB (Fast Byzantine Consensus) [14, 15]. FaB introduces a family of Asynchronous Byzantine Agreement (ABA) solutions exhibiting reduced latency when the system is behaving synchronously. In particular, it constructs a parameterized variant for $n \geq 3f+2t+1$, where $t \leq f$, that has optimal synchronous latency when no more than t non-leader members fail. Putting $t = 0$, we obtain a similar setting to Zyzzyva, and the guarantee of a fast execution in fail-free runs. In this paper for simplicity we focus on the case where n is minimal for a given f and t (so $n = 3f + 2t + 1$).

Briefly, the core mechanism for transferring safe values across views revolves around a "progress certificate". The certificate consists of signed new-view messages from a quorum of $n - f$ replicas to the leader of a new view. A new-view message from a replica contains the last pre-proposed message accepted by this replica, and the last commit-certificate it received. A progress certificate is said to "vouch for" a value v if it is safe for the leader of the new view to pre-propose v.

As we describe below, there is a bug in Parameterized FaB such that the progress certificate may vouch for no value at all, resulting in the protocol getting stuck.

Zyzzyva borrows from FaB the idea of an optimistic fast track, and enhances the approach in a number of dimensions. Zyzzyva provides a state replication protocol, whereas FaB is a single shot consensus solution. Zyzzyva employs speculation in the execution of state updates, allowing a high throughput pipeline of state-machine replication, which is out of the FaB scope. Finally, Zyzzyva includes view-numbers in the view-change protocol, which prevent the "stuck" situation in FaB that we expose here.

3.2 A Skeletal Overview of the FaB Protocol Family

Martin and Alvisi introduce Fast Byzantine Consensus (FaB) in [14, 15], 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, among which leaders are chosen to drive agreement in views. We will refer to this variant as FaB5. The second one is parameterized with $n = 3f + 2t + 1$, and we refer to it as PFaB.

$5f + 1$ FaB. The basic FaB5 protocol 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 FaB5 when $4f + 1$ replicas send a prepare response for it. During periods of synchrony, FaB5 is guaranteed to complete through these two easy steps, despite up to f arbitrary (Byzantine) non-leader failures.

If progress is stalled, replicas elect a new leader and move to a new view. The core mechanism in FaB5 for transferring safe values across views is a *progress certificate*. A progress-certificate consists of signed new-view messages (REP) from a quorum of $4f + 1$ replicas to the leader of a new view. A new-view message from a replica contains the value in a prepare message sent by this replica.

A progress-certificate is said to *vouch for* a value v if there does not exist a set of $2f + 1$ new-view messages with some identical accepted value v', where $v' \neq v$.

Intuitively, the reason FaB5 is safe is because if a decision is reached in a view, then $3f+1$ correct replicas prepared it. If the next view is activated, then in every progress-certificate quorum, $2f + 1$ of the quorum will prevent vouching for any conflicting proposal. Hence, no correct replica will ever override an accepted value.

The reason FaB5 is live is because there cannot be two sets of $2f+1$ vouching against each other's value. Hence, there always exists a safe value to propose.

Parameterized FaB. The second FaB variant is called Parameterized FaB (PFaB for short). PFaB borrow the idea of an optimistic fast execution track from a long line of works on early-stopping consensus, and in particular, from the optimistic asynchronous Byzantine agreement protocol of Kursawe in [10].

PFaB is parameterized with $n = 3f + 2t + 1$, where $t \leq f$. It works in two tracks, a fast track and a recovery track. The fast track is the same as FaB5, allowing a decision in two steps if $n - t$ replicas accept a leader proposal. The fast track is guaranteed to complete in periods of synchrony with a correct leader and up to t Byzantine replicas.

Different from FaB5, 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. The fast track is guaranteed to complete during periods of synchrony in two steps only if the number of actual Byzantine failures does not exceed t.

If progress is stalled, PFaB allows progress via a recovery protocol, which is essentially PBFT (adapted to $n = 3f + 2t + 1$).

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. When a replica receives in a view $(n-f-t)$ prepare messages for the same value, it forms a commit-certificate, and sends it in a *commit* message (`COMMITPROOF`) to other replicas.

A decision is reached if either $n-t$ prepare messages are sent (for the same value), or $(n-f-t)$ commit messages are sent (for the same value).

As in Fab5, the core mechanism in PFaB for transferring safe values across views is a progress certificate containing new-view messages (`REP`) from a quorum of $n - f$ replicas. Differently, in PFaB, a new-view message from a replica contains both 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 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 $v' \neq v$.

3.3 Getting Stuck

In this section, we demonstrate that a progress-certificate may contain $f + t + 1$ new-view messages with some prepare value, and a commit-certificate with a different value. This causes PFaB to get stuck because there is no value vouched-for by the certificate, hence new leaders cannot make any valid proposal.

For a scenario, 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 scenario goes through one view change.

View 1:

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

2. i_1, i_2, and i_3 accept the proposal and send prepare (`ACCEPTED`) messages. Their prepare messages reach only i_2, and i_2 forms a commit-certificate (`COMMITPROOF`) for the value A.

3. Meanwhile, the leader i_1 equivocates and pre-proposes B to i_4.

4. All further prepare messages other than those sent to i_1 are delayed. The delay triggers a view change.

View 2:

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

    - from i_1, the new-view message contains the value B, and no commit-certificate.

- from i_2, the new-view message contains the value A, and a commit-certificate for it.
- from i_4, the new-view message contains the value B, and no commit-certificate.

Now we are stuck. This progress certificate contains 2 messages (from i_1,i_4) with prepare value B. Hence, the certificate does not vouch for A. At the same time, it contains a commit-certificate (from i_2) with value A. Hence, it does not vouch for B either.

The PFaB paper includes an argument that all process certificates vouch for at least one value (Lemma 7), but unfortunately it has a mistake.

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