Chapter 18

Authenticated Agreement

Byzantine nodes are able to lie about their inputs as well as received messages. Can we detect certain lies and limit the power of byzantine nodes? Possibly, the authenticity of messages may be validated using signatures?

18.1 Agreement with Authentication

Definition 18.1 (Signature). If a node never signs a message, then no correct node ever accepts that message. We denote a message \( \text{msg}(x) \) signed by node \( u \) with \( \text{msg}(x)_u \).

Algorithm 71 Byzantine Agreement using Authentication

Code for primary \( p \):
1: if input is 1 then
2: broadcast \( \text{value}(1)_p \)
3: decide 1 and terminate
4: else
5: decide 0 and terminate
6: end if

Code for all other nodes \( v \):
7: for all rounds \( i \in 1, \ldots, f + 1 \) do
8: \( S \) is the set of accepted messages \( \text{msg}(1)_v \).
9: if \( |S| \geq i \) and \( \text{value}(1)_p \in S \) then
10: broadcast \( S \cup \{\text{value}(1)_v\} \)
11: decide 1 and terminate
12: end if
13: end for
14: decide 0 and terminate

Theorem 18.2. Algorithm 71 can tolerate \( f < n \) byzantine failures while terminating in \( f + 1 \) rounds.

Proof. Assuming that the primary \( p \) is not byzantine and its input is 1, then \( p \) broadcasts \( \text{value}(1)_p \) in the first round, which will trigger all correct nodes to decide for 1. If \( p \)'s input is 0, there is no signed message \( \text{value}(1)_p \), and no node can decide for 1.

If primary \( p \) is byzantine, we need all correct nodes to decide for the same value for the algorithm to be correct. Let us assume that \( p \) convinces a correct node \( v \) that its value is 1 in round \( i \) with \( i < f + 1 \). We know that \( v \) received \( i \) signed messages for value 1. Then, \( v \) will broadcast \( i + 1 \) signed messages for value 1, which will trigger all correct nodes to also decide for 1. If \( p \) tries to convince some node \( v \) late (in round \( i = f + 1 \)), \( v \) must receive \( f + 1 \) signed messages. Since at most \( f \) nodes are byzantine, at least one correct node \( u \) signed a message \( \text{msg}(1)_u \) in some round \( i < f + 1 \), which puts us back to the previous case.

Remarks:

- The algorithm only takes \( f + 1 \) rounds, which is optimal as described in Theorem 17.18.
- Using signatures, Algorithm 71 solves consensus for any number of failures! Does this contradict Theorem 17.11? Recall that in the proof of Theorem 17.11 we assumed that a byzantine node can distribute contradictory information about its own input. If messages are signed, correct nodes can detect such behavior – a node \( u \) signing two contradicting messages proves to all nodes that node \( u \) is byzantine.
- Does Algorithm 71 satisfy any of the validity conditions introduced in Section 17.1? No! A byzantine primary can dictate the decision.
value. Can we modify the algorithm such that the correct-input validity condition is satisfied? Yes! We can run the algorithm in parallel for \(2f+1\) primary nodes. Either 0 or 1 will occur at least \(f+1\) times, which means that one correct process had to have this value in the first place. In this case, we can only handle \(f \leq \frac{1}{2}\) byzantine nodes.

- In reality, a primary will usually be correct. If so, Algorithm 71 only needs two rounds! Can we make it work with arbitrary inputs? Also, relying on synchrony limits the practicality of the protocol. What if messages can be lost or the system is asynchronous?

- Zyzzyva uses authenticated messages to achieve state replication, as in Definition 15.6. It is designed to run fast when nodes run correctly, and it will slow down to fix failures.

## 18.2 Zyzzyva

**Definition 18.3 (View).** A view \(V\) describes the current state of a replicated system, enumerating the \(3f+1\) replicas. The view \(V\) also marks one of the replicas as the primary \(p\).

**Definition 18.4 (Command).** If a client wants to update (or read) data, it sends a suitable command \(c\) in a Request message to the primary \(p\). Apart from the command \(c\) itself, the Request message also includes a timestamp \(t\). The client signs the message to guarantee authenticity.

**Definition 18.5 (History).** The history \(h\) is a sequence of commands \(c_1, c_2, \ldots\) in the order they are executed by Zyzzyva. We denote the history up to \(c_k\) with \(h_k\).

**Remarks:**

- In Zyzzyva, the primary \(p\) is used to order commands submitted by clients to create a history \(h\).

- Apart from the globally accepted history, node \(u\) may also have a local history, which we denote as \(h^u\) or \(h^u_u\).

**Definition 18.6 (Complete command).** If a command completes, it will remain in its place in the history \(h\) even in the presence of failures.

**Remarks:**

- As long as clients wait for the completion of their commands, clients can treat Zyzzyva like one single computer even if there are up to \(f\) failures.

### In the Absence of Failures

**Algorithm 72 Zyzzyva: No failures**

1. At time \(t\) client \(u\) wants to execute command \(c\)
2. Client \(u\) sends request \(R = \text{Request}(c, t_u)\) to primary \(p\)
3. Primary \(p\) appends \(c\) to its local history, i.e., \(h^p = (h^p, c)\)
4. Primary \(p\) sends \(\text{OrderedRequest}(h^p, c, R)\) to all replicas
5. Each replica \(r\) appends command \(c\) to local history \(h^r = (h^r, c)\) and checks whether \(h^r = h^p\)
6. Each replica \(r\) runs command \(c_r\) and obtains result \(u\)
7. Each replica \(r\) sends \(\text{Response}(a, R)\) to client \(u\)
8. Client \(u\) collects the set \(S\) of received \(\text{Response}(a, R)\) messages
9. Client \(u\) checks if all histories \(h^r\) are consistent
10. if \(|S| = 3f + 1\) then
11. Client \(u\) considers command \(c\) to be complete
12. end if

**Remarks:**

- Since the client receives \(3f+1\) consistent responses, all correct replicas have to be in the same state.

- Only three communication rounds are required for the command \(c\) to complete.

- Note that replicas have no idea which commands are considered complete by clients! How can we make sure that commands that are considered complete by a client are actually executed? We will see in Theorem 18.15.

- Commands received from clients should be ordered according to timestamps to preserve the causal order of commands.

- There is a lot of optimization potential. For example, including the entire command history in most messages introduces prohibitively large overhead. Rather, old parts of the history that are agreed upon can be truncated. Also, sending a hash value of the remainder of the history is enough to check its consistency across replicas.

- What if a client does not receive \(3f+1\) \(\text{Response}(a, R)\) messages? A byzantine replica may omit sending anything at all! In practice, clients set a timeout for the collection of \(\text{Response}\) messages. Does this mean that Zyzzyva only works in the synchronous model? Yes and no. We will discuss this in Lemma 18.18 and Lemma 18.19.
Byzantine Replicas

Algorithm 73 Zyzzyva: Byzantine Replicas (append to Algorithm 72)

1: if $2f + 1 \leq |S| < 3f + 1$ then
2: Client $u$ sends $\text{Commit}(S)$, to all replicas
3: Each replica $r$ replies with a $\text{LocalCommit}(S)$, message to $u$
4: Client $u$ collects at least $2f + 1 \text{LocalCommit}(S)$, messages and considers $c$ to be complete
5: end if

Remarks:
- If replicas fail, a client $u$ may receive less than $3f + 1$ consistent responses from the replicas. Client $u$ can only assume command $c$ to be complete if all correct replicas $r$ eventually append command $c$ to their local history $h_r$.

Definition 18.7 (Commit Certificate). A commit certificate $S$ contains $2f + 1$ consistent and signed $\text{Response}(a, \text{OK})$, messages from $2f + 1$ different replicas $r$.

Remarks:
- The set $S$ is a commit certificate which proves the execution of the command on $2f + 1$ replicas, of which at least $f + 1$ are correct. This commit certificate $S$ must be acknowledged by $2f + 1$ replicas before the client considers the command to be complete.
- Why do clients have to distribute this commit certificate to $2f + 1$ replicas? We will discuss this in Theorem 18.13.
- What if $|S| < 2f + 1$, or what if the client receives $2f + 1$ messages but some have inconsistent histories? Since at most $f$ replicas are Byzantine, the primary itself must be Byzantine! Can we resolve this?

Byzantine Primary

Definition 18.8 (Proof of Misbehavior). Proof of misbehavior of some node can be established by a set of contradicting signed messages.

Remarks:
- For example, if a client $u$ receives two $\text{Response}(a, \text{OK})$, messages that contain inconsistent $\text{OK}$ messages signed by the primary, client $u$ can proof that the primary misbehaved. Client $u$ broadcasts this proof of misbehavior to all replicas $r$ which initiate a view change by broadcasting a $\text{IHatePrimary}$, message to all replicas.

Byzantine Replicas

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2f + 1 replicas that responded to c, with a Response(a,OR), message. Because there are only 3f + 1 replicas, there is at least one correct replica that sent a Response(a,OR), message for both c$_i$ and c$_j$. A correct replica only sends one Response(a,OR), message for each sequence number, hence the two commands must have different sequence numbers.

Lemma 18.11. Let c$_i$ and c$_j$ be two complete commands with sequence numbers i < j. The history h$_i$ is a prefix of h$_j$.

Proof. As in the proof of Lemma 18.10, there has to be at least one correct replica that sent a Response(a,OR), message for both c$_i$ and c$_j$. A correct replica r that sent a Response(a,OR), message for c$_i$ will only accept c$_j$ if the history for c$_j$ provided by the primary is consistent with the local history of replica r, including c$_i$.

Remarks:

• A byzantine primary can cause the system to never complete any command. Either by never sending any messages or by inconsistently ordering client requests. In this case, replicas have to replace the primary.

View Changes

Definition 18.12 (View Change). In Zyzzyva, a view change is used to replace a byzantine primary with another (hopefully correct) replica. View changes are initiated by replicas sending IHatePrimary, to all other replicas. This only happens if a replica obtains a valid proof of misbehavior from a client or after a replica fails to obtain an OR message from the primary in Algorithm 74.

Remarks:

• How can we safely decide to initiate a view change, i.e. demote a byzantine primary? Note that byzantine nodes should not be able to trigger a view change!

Algorithm 75 Zyzzyva: View Change Agreement

1. All replicas continuously collect the set H of IHatePrimary, messages
2. if a replica r received |H| > f messages or a valid ViewChange message then
3. Replica r broadcasts ViewChange([H'; h', S$_i$]);
4. Replica r stops participating in the current view
5. Replica r switches to the next primary “p = p + 1”
6. end if

Algorithm 76 Zyzzyva: View Change Execution

1. The new primary p collects the set C of ViewChange([H'; h', S$_j$]), messages
2. if new primary p collected |C| ≥ 2f + 1 messages then
3. New primary p sends NewView(C)$_p$, to all replicas
4. end if
5. if a replica r received NewView(C)$_p$, message then
6. Replica r recovers new history h$_{new}$ as shown in Algorithm 77
7. Replica r broadcasts ViewConfirm(h$_{new}$), message to all replicas
8. end if
9. if a replica r received 2f + 1 ViewConfirm(h$_{new}$), messages then
10. Replica r accepts h' = h$_{new}$ as the history of the new view
11. Replica r starts participating in the new view
12. end if

Remarks:

• Analogously to Lemma 18.11, commit certificates are ordered. For two commit certificates S$_i$ and S$_j$ with sequence numbers i < j, the history h$_i$ certified by S$_i$ is a prefix of the history h$_j$ certified by S$_j$.

• Zyzzyva collects the most recent commit certificate and the local history of 2f + 1 replicas. This information is distributed to all replicas, and used to recover the history for the new view h$_{new}$.

• If a replica does not receive the NewView(C)$_p$ or the ViewConfirm(h$_{new}$), message in time, it triggers another view change by broadcasting IHatePrimary, to all other replicas.
18.2. ZYZZYVA

How is the history recovered exactly? It seems that the set of histories included in \( C \) can be messy. How can we be sure that complete commands are not reordered or dropped?

- Can we be sure that all commands that completed at a correct client are carried over into the new view?

Lemma 18.13. The globally most recent commit certificate \( S_i \) is included in \( C \).

Proof. Any two sets of \( 2f+1 \) replicas share at least one correct replica. Hence, at least one correct replica which acknowledged the most recent commit certificate \( S_i \) also sent a LocalCommit\((S_i)\), message that is in \( C \).

Lemma 18.14. Any command and its history that completes after \( S_i \) has to be reported in \( C \) at least \( f+1 \) times.

Proof. A command \( c \) can only complete in Algorithm 72 after \( S_i \). Hence, \( 3f + 1 \) replicas sent a Response\( (a, 0, b) \), message for \( c \). \( C \) includes the local histories of \( 2f + 1 \) replicas of which at most \( f \) are byzantine. As a result, \( c \) and its history is consistently found in at least \( f + 1 \) local histories in \( C \).

Lemma 18.15. If a command \( c \) is considered complete by a client, command \( c \) remains in its place in the history during view changes.

Proof. We have shown in Lemma 18.13 that the most recent commit certificate is contained in \( C \), and hence any command that terminated in Algorithm 73 is included in the new history after a view change. Every command that completed before the last commit certificate \( S_i \) is included in the history as a result. Commands that completed in Algorithm 72 after the last commit certificate are supported by at least \( f + 1 \) correct replicas as shown in Lemma 18.14. Such commands are added to the new history as described in Algorithm 77. Algorithm 77 adds commands sequentially until the histories become inconsistent. Hence, complete commands are not lost or reordered during a view change.

Theorem 18.16. Zyzzyva is safe even during view changes.

Proof. Complete commands are not reordered within a view as described in Lemma 18.11. Also, no complete command is lost or reordered during a view change as shown in Lemma 18.15. Hence, Zyzzyva is safe.

Remarks:

- Zyzzyva correctly handles complete commands even in the presence of failures. We also want Zyzzyva to make progress, i.e., commands issued by correct clients should complete eventually.

- If the network is broken or introduces arbitrarily large delays, commands may never complete.

- Can we be sure commands complete in periods in which delays are bounded?

Definition 18.17 (Liveness). We call a system live if every command eventually completes.
Lemma 18.18. Zyzzyva is live during periods of synchrony if the primary is correct and a command is requested by a correct client.

Proof. The client receives a Response-messages from all correct replicas. If it receives \( 3f + 1 \) messages, the command completes immediately in Algorithm 72. If the client receives fewer than \( 3f + 1 \) messages, it will at least receive \( 2f + 1 \), since there are at most \( f \) correct commands. All correct replicas will answer the client’s Commit message with a correct LocalCommit message after which the command completes in Algorithm 74.

Lemma 18.19. If, during a period of synchrony, a request does not complete in Algorithm 72 or Algorithm 73, a view change occurs.

Proof. If a command does not complete for a sufficiently long time, the client will resend the \( \text{Request}(c,t) \) message to all replicas. After that, if a replica’s ConfirmRequest message is not answered in time by the primary, it broadcasts an IHatePrimary message. If a correct replica gathers \( f + 1 \) IHatePrimary messages, the view change is initiated. If no correct replica collects more than \( f \) IHatePrimary messages, at least one correct replica received a valid OrderedRequest message from the primary which it forwards to all other replicas. In that case, the client is guaranteed to receive at least \( 2f + 1 \) Response messages from the correct replicas and can complete the command by assembling a commit certificate.

Remarks:

- If the newly elected primary is byzantine, the view change may never terminate. However, we can detect if the new primary does not assemble \( C \) correctly as all contained messages are signed. If the primary refuses to assemble \( C \), replicas initiate another view change after a timeout.

Chapter Notes

Algorithm 71 was introduced by Dolev et al. [DFF+82] in 1982. Byzantine fault tolerant state machine replication (BFT) is a problem that gave rise to many different protocols. Castro and Liskov [MC99] introduced Practical Byzantine Fault Tolerance (PBFT) protocol in 1999 and applications like Farsite [AEMGG05] followed. This triggered the development of systems like Q/U [AEMGG05] and HQ [CML+06], which are quorum-based protocols. Zyzzyva [KAD+07] improved on performance especially in the case of no failures while Aardvark [CWA09] improves performance in the presence of failures. Guerraoui at al. [GKV10] developed a modular system which allows to more easily develop BFT protocols that match specific applications in terms of robustness or best case performance.

Bibliography