Ark: A Real-World Consensus Implementation

Zardosht Kasheff
zardosht@tokutek.com

Leif Walsh
leif@tokutek.com

Abstract

Ark is an implementation of a consensus algorithm similar to Paxos[7] and Raft[11], designed as an improvement over the existing consensus algorithm used by MongoDB® and TokuMX™.

Ark was designed from first principles, improving on the election algorithm used by TokuMX, to fix deficiencies in MongoDB’s consensus algorithms that can cause data loss. It ultimately has many similarities with Raft, but diverges in a few ways, mainly to support other features like chained replication and unacknowledged writes.

1 Introduction

Databases with built-in replication are ubiquitous. A short, non-exhaustive list of such databases and database-like technologies is Cassandra, Couchbase, CouchDB, FoundationDB, Kafka, Microsoft SQL Server, MongoDB, Oracle SQL, PostgreSQL, RabbitMQ, Redis, Riak, Zookeeper. Since in many use cases, replicas are treated as insurance against hardware and software faults, replication must provide strong, clear, and correct guarantees to the application layer. As such, there is a great deal of interest recently in understanding how these technologies work in theory and in practice.

MongoDB is a NoSQL DBMS with built-in leader/follower asynchronous replication. MongoDB’s Write Concern API[10] allows clients to choose from a spectrum of write consistency ranging from entirely unsafe (“unacknowledged”) through fully consistent (“majority”).

TokuMX[1] is a fork of MongoDB with a range of improvements centered on a different storage engine based on Fractal Tree indexes® [1].

MongoDB is known to have problems with its replication algorithm[6]. In short, the semantics offered by the Write Concern API are not reliably delivered in the face of network failures, which has contributed to a widespread sense of distrust in MongoDB.

In TokuMX, we have changed the replication election protocol to deliver the semantics of the Write Concern API in a provably correct way. In particular, this means that for clients using the “majority” Write Concern, TokuMX is a proper “CP” system, in the sense of Brewer’s so-called “CAP Theorem”[2].

As Ark is primarily a modification of the existing MongoDB consensus algorithm, it’s important to start with an understanding of that. In Section 2 we explain the goals and relevant aspects of the existing replication algorithm in MongoDB 2.6 and TokuMX 1.5. In Section 3 we detail how the current replication algorithm fails to deliver on the CP promise of the “majority” Write Concern, and causes two other related problems.

We describe our changes to the replication algorithm in Section 4, turning it into a new algorithm called Ark, and in Section 5 we draw parallels to the Raft paper and its safety and liveness proofs. We discuss specific implementation choices and tradeoffs in Section 7.

2 MongoDB replication

In MongoDB/TokuMX, the purpose of replication is to have multiple machines, or replicas, store the exact same data. This is leader/follower replication, as opposed to multi-master, which means that there should be a totally ordered sequence of client operations that is identical on every replica in the set. It is asynchronous, which means that followers pull updates from the leader and announce their synced position in the operation history, rather than the leader pushing changes to followers and waiting synchronously for them to respond.

A “replica set” is composed of a leader (“primary”) and a set of followers (“secondaries”). Replication’s main goals are to synchronize the data on each mem-
ber of the set (“replica”), to provide an API for clients to understand how much their updates have been replicated through the set, and to automatically fail over to a new primary if the primary crashes or is disconnected from the set.

2.1 Synchronization

Synchronization within the replica set is accomplished as follows:

One replica in the set is designated as primary, or the leader. The primary is the only replica that accepts updates from clients. All other replicas in the set are secondaries, or followers.

Details of each client update are written to the “oplog”, a totally ordered sequence of operations (similar to the binary log in MySQL, can also be thought of as the replication log). Entries in the oplog have a position associated with them, that defines the order of updates. Secondaries maintain an identical copy of the oplog, and apply modifications in the order they appear in the oplog.

Secondaries cannot be modified by users. The job of a secondary is to constantly pull data from the primary’s oplog, save it in its own oplog, and apply the operations to its copies of the user data collections. A secondary may serve some client reads from its data collections, or simply be available to be elected to primary if failover is necessary.

An important point here: the secondary does not have to be pulling data directly from the primary. Any secondary is allowed to pull data from any other replica in the replica set, as long as the other replica’s position is ahead of the secondary’s position.

Every two seconds, all replicas exchange information with each other, in what is called “heartbeats”. This information can be arbitrary. The two most important pieces of information exchanged in the current algorithm are the replica’s current oplog position and the fact that a replica is still up and responding. One thing that causes a replica to decide it is time to try to fail over to a new primary is the failure to receive a heartbeat from the current primary.

2.2 Write Concern

The purpose of “majority” Write Concern is to make the replica set fully consistent. Since a node can only be elected primary by a majority (see Section 2.3), if each update is only considered finished once acknowledged by a majority, any successful election must include a replica which was aware of the acknowledged update, and it will be that replica’s responsibility to ensure that the update persists.

Clients can use “majority” Write Concern on every update, which guarantees that the update will be persisted even if failover happens immediately after the update succeeds and reports majority acknowledgement.

Note that false negatives can still occur in this asynchronous model: an update may be replicated to a majority of replicas and be safe, but the acknowledgement might fail to return to the client. In Ark, just as in Raft, we consider this an acceptable failure mode. Applications that require stronger guarantees than this should use a system that implements a distributed atomic commit protocol like 2PC [5, 8], for example, Apache Zookeeper. Note that the “clients” in the Raft paper are similar to the database engine in TokuMX with Ark. In TokuMX, entries are committed to the oplog in the same transaction as they are applied to collections (the state machine in Raft), so the false negatives here do not result in multiple delivery of oplog messages, rather our false negative is at the higher database API layer.

We consider “majority” Write Concern to be the most interesting use case to support, since any weaker Write Concern expresses the client’s willingness to suffer data loss in some scenarios. The primary goal of Ark is to provide correct “majority” Write Concern, but we have also made some choices that make it more suitable for weaker consistency choices that are useful in some deployments.

2.3 Failover

Failover is the mechanism by which the replica set attempts to ensure that there is always exactly one primary available to serve client updates. If the primary crashes, is partitioned away from the majority of replicas by a network failure, or is otherwise unresponsive, the replica set attempts to select another replica to step up as primary.

A replica is deemed unreachable if a heartbeat request fails. At a high level, if the primary becomes unreachable by other replicas of the replica set, the other replicas will try to hold an “election”, a process by which they elect a new primary to start accepting
user updates. A majority (\(\lfloor n/2 \rfloor + 1\)) of replicas in the replica set are required to elect a new primary.

Note that the election process and the data synchronization process (the threads on a secondary responsible for picking a replica to copy data from) are fairly independent. There is a little synchronization used to determine oplog position, but that is it. Its possible for a secondary to be replicating oplog data from a replica that the majority component of replicas thinks is unreachable.

An important component of failover is rollback. Consider the following scenario:

- Replica A (the primary) receives an update, which it applies and logs. A network partition isolates A, a failover happens, and new primary, B, is elected before that update is replicated.
- B does not have the oplog entry for this update. In fact, by electing B, all of the replicas that elected B agreed that the oplog does not contain this update.
- At some point, when A gets reconnected to the set, it will see that the current primary B does not have this update in its oplog, and will “rollback”, or undo, the update. This is similar to the way a leader in Raft forces its followers to replace log entries that differ from its own.

For simplicity, assume all operations that appear in the oplog can be reversed.

So, in summary, there are three important concepts there:

1. Data synchronization.
2. Write acknowledgement.
3. Elections/failover and rollback.

The property we wish to have is the following. If a client successfully gets an acknowledgement for “majority” Write Concern for some update, then the user knows that the update is guaranteed to be in the replica set going forward, and will not be rolled back.

2.4 TokuMX differences

The replication concepts in TokuMX 1.5 are largely the same as in MongoDB 2.6. However, there are a few minor differences that are worth mentioning before we continue.

2.4.1 GTID

MongoDB’s oplog entries are ordered by a data type called \(\text{OpTime}\), which is the concatenation of a 32-bit timestamp with second resolution, and a 32-bit counter that is incremented with each operation, and reset to 1 each time the timestamp increases.

To support better concurrency, and in anticipation of some of the changes described in this report, TokuMX has always used a different data type to order oplog entries, called the \(\text{GTID}\). This is a pair of 64-bit integers, \(\langle \text{term}, \text{opid} \rangle\), where the \(\text{opid}\) is incremented each time an operation commits on the primary, and the \(\text{term}\) is incremented each time a new primary is elected, and at this point the \(\text{opid}\) is reset to 0. The \(\text{GTID}\) is compared lexicographically, so \(\langle 3, 100 \rangle < \langle 3, 101 \rangle < \langle 4, 0 \rangle\).

2.4.2 Idempotency

MongoDB’s oplog entries are required to be idempotent. This permits the oplog application to support at-least-once delivery, but limits the range of operations that can be expressed in the oplog.

TokuMX’s oplog entries are not required to be idempotent, therefore the oplog entries must be applied exactly once on secondaries. Given that the secondaries are already designed to store exact copies of the oplog, this is simple to implement by just locally noting which entries have and have not been applied. This is functionally equivalent to the suggestion in Raft that clients assign serial numbers to commands, and have the state machine avoid re-executing commands.

This removal of the idempotency restriction is to implement other optimizations in the application of oplog entries, and is mostly inconsequential to the problem of consensus. The point of consensus in the replication system is to copy the oplog perfectly, and application is effectively orthogonal.

2.5 Failover details

TokuMX’s current election/failover protocol, inherited from MongoDB, is as follows. Suppose there is a network partition such that the primary A is disconnected from the replica set. There are two independent things that must happen:

1. Another replica B notices that it cannot reach A, looks at what it knows of the state of the replica set (via heartbeat messages it has received), and decides “I think I’ll make a good primary”. B
then proceeds to elect itself as the set’s new primary.

2. Independently, A notices that it cannot reach a majority of the set, and decides to transition from primary \(\rightarrow\) secondary. The consequence of this is that A will stop accepting update operations from clients, because it is no longer convinced that a majority of replicas will acknowledge those updates.

Once B decides to elect itself, it does so with the following procedure:

- B broadcasts a message to all other replicas asking “should I try to elect myself?”. This is known as a speculative election (this is for heuristic purposes). With the replies, B learns:
  - Whether anyone would veto the election. If so, B does not try to elect itself.
  - Whether any replica has an oplog that is ahead of B’s oplog. If so, B does not try to elect itself.
  - If B is at the same oplog position as another potential primary. If so, it will sleep for a random period of time between 50 and 1050ms, and then try the election protocol again. The next time it tries, it will remember that it just slept and not sleep again.

- If all of the respondents say “yes”, then it proceeds with the authoritative election. B broadcasts a message that states “I wish to elect myself as primary”.

The protocol has begun. When each replica gets this message, it does the following:

- If there is a reason to veto, then it replies “veto” (e.g. B’s understanding of the set membership is stale, or another primary exists).
  A “veto” vote is functionally equivalent to “no”, in fact the election protocol works properly if “veto” is interpreted as “no”, but “veto” is an optimization replicas can use when they have concrete evidence that the election should not succeed.

- If the replica participating in the election has voted “yes” for anyone in the last 30 seconds (in an authoritative election; votes cast in a speculative election are not considered), then vote “no”. A replica may vote “yes” (in an authoritative election) only once every 30 seconds.

- Otherwise, vote “yes”. The replica doesn’t bother looking at the oplog’s position before voting yes. This last fact is strange, but true, which Zardosht pointed out in [https://groups.google.com/forum/?hl=en-US&fromgroups#!topic/mongodb-dev/lH3hs8h7NrE](https://groups.google.com/forum/?hl=en-US&fromgroups#!topic/mongodb-dev/lH3hs8h7NrE)

- If a majority reply to B saying “yes”, and no replica responds “veto”, then B declares itself as primary and begins accepting client updates.

If at any point, a primary notices that another primary exists, it blindly steps down. The hope is to have another election resolve the dual primary issue. If A and B are both primary, when they exchange heartbeats, they will step down.

3 Problems

Briefly, TokuMX and MongoDB currently have the following problem: a user may successfully get an acknowledgement for “majority” Write Concern for some update, and that update may not survive. Despite the fact that the update was acknowledged by a majority of replicas, the update may later roll back.

At a high level, there are three problems with the election protocol, and they are all loosely related:

1. Updates that succeed with “majority” Write Concern may roll back. Otherwise known as “data loss”. This is the big problem mentioned above.

2. Multiple primaries don’t resolve themselves in an intelligent way.

3. Letting a replica vote once every 30 seconds can lead to some long failover times if elections make it to the second phase and fail.

Now let’s dig into each of these problems a bit more.

**Problem 3.1** Write Concern of “majority” may not prevent the rollback of updates.
Before discussing the problems with this protocol, let’s first say what is not a problem: having A accept updates (temporarily) after becoming disconnected is not a problem. When A reconnects with the replica set, these additional updates will be rolled back. But this is okay, as long as we haven’t yet guaranteed to any clients that those updates are safe.

Instead, the problem with this protocol is the following: updates may get an acknowledgement of “majority” Write Concern (which does mean they’re safe), and still be rolled back.

Consider the following scenario:

- A network partition happens such that A is disconnected from the replica set.
- The rest of the set elects B as primary, but A has yet to transition to secondary (because that process is independent of the rest of the replica set’s election, in fact A may not yet know it has been disconnected).
- A then reconnects with the replica set, thinking it is still primary.
- Now we have two primaries, A and B. Also, recall that all other replicas in the set may be syncing the oplog from any other replica. They may all be replicating off A or B.
- This is the big problem. An update may replicate off of A or B, and get acknowledged by a majority of the replica set.
- At best, A and B realize they are both primary, step down, and allow an election to take place.

In Problem 3.2 we state why it can be worse.

Now we have a problem. Either A or B can win the new election, and the loser may have some update that was acknowledged by a majority of the replica set. This update will then be rolled back, violating the “majority” Write Concern contract with the client.

The fundamental flaw in the current replication algorithm that leads to this behavior is that secondaries blindly acknowledge any update that they can copy, regardless of whether the update may later rollback. If a secondary acknowledges an update from A after having voted B as primary, there is something wrong. The secondary should know that A’s new updates may be rolled back and therefore must not be acknowledged.

Problem 3.2 Multiple primaries don’t resolve themselves deterministically.

This is related to the first problem. We want multiple primaries to resolve themselves in a predictable way because we want to be able to predict which updates will survive and which will be rolled back.

Right now, if two primaries exist, and are made aware of each other via heartbeats, then they step down and let another election take care of the problem. This is problematic for the following reasons:

1. It requires two primaries seeing each other to resolve the issue. In the right kind of network partition, this may take an indefinitely long time. See [https://jira.mongodb.org/browse/SERVER-9848](https://jira.mongodb.org/browse/SERVER-9848).
2. If one primary gets a heartbeat message before it can send one to the other, that one primary will step down and the other will not. This makes “which primary wins” essentially arbitrary. Having any decision here be arbitrary is bad, because it makes the future unpredictable.

Problem 3.3 Elections may take a long time because a member can vote “yes” at most once every 30 seconds.

MongoDB’s election protocol requires that a member may not vote “yes” in more than one election in any 30-second period. We think this is because the order of oplog entries is primarily determined by the timestamp on the primary where they are created, so if successful elections happen too frequently, updates to successive legitimate primaries may end up getting reordered in the oplog as a result of clock skew. This would mean that, logically at least, there would have been multiple concurrent primaries, and the MongoDB replication system is not equipped to properly resolve this situation. Limiting elections to succeed at most once every 30 seconds means that if the maximum clock skew among replicas is less than 30 seconds, the order of updates done by a single client will not be changed too much by elections. Updates from one primary may be interspersed with the successive primary’s updates, but not with the one after that.

However, this 30 second threshold can be problematic in practice, especially if an election fails: this necessarily makes the set unavailable for at least 30 seconds, maybe more if successive elections fail.

Part of the problem in this case is that the candidate does not do a good job of using the first phase of
the election process to determine whether the second phase will succeed. That is bad, because a failed second phase can really elongate the downtime during a failover. Basically, if the first phase can determine that the second phase will be unsuccessful, it should do so. Currently, MongoDB and TokuMX have the following two issues:

1. [https://jira.mongodb.org/browse/SERVER-14382](https://jira.mongodb.org/browse/SERVER-14382) If a member will vote “no” in the second phase because it has voted “yes” for someone else in the last 30 seconds, it should notify the candidate of this in the first phase.

2. [https://jira.mongodb.org/browse/SERVER-14531](https://jira.mongodb.org/browse/SERVER-14531) If the candidate gets responses from less than a majority of replicas during the first phase, it should not proceed onto the second (authoritative) phase.

4. Ark Design

At a high level, we want the solution we employ to have the following characteristics:

- Any update that succeeds with majority Write Concern cannot be rolled back during a failover. (Problem 3.1)
- Multiple primaries should resolve themselves in a predictable way. (Problem 3.2)
- Failover times should be faster. We want to get rid of this 30 second timer between elections. (Problem 3.3)

We’ll start by restricting ourselves to the TokuMX replication algorithm, namely that oplog entries are identified by and ordered according to the GTID, as defined in Section 2.4.1 to be \( \langle \text{term}, \text{opid} \rangle \).

The key difference between Ark and the standard MongoDB replication algorithm is the term part of a GTID. This will be used to demarcate elections and to provide an association between election terms and client update operations. This association is critical for ensuring that updates with “majority” Write Concern cannot be rolled back.

Below, we will consider an election in a replica set led by a primary \( A \). In the voting protocol, another replica \( B \) tries to elect itself the new primary.

4.1 Election changes

The first protocol change is to associate the term in the oplog’s GTID with elections. Each authoritative election is identified with an electionTermId. Every replica in the set considers electionTermId to be a strictly monotonically increasing sequence.

**Definition 4.1** (electionTermId) Each authoritative election is identified by an electionTermId that is selected by the candidate \( B \).

If elected, this replica must use the electionTermId from its successful election as the term part of the GTIDs it creates for new oplog entries during its tenure.

The second protocol change is that each replica maintains a local value maxVotedTermId, which is always greater than or equal to the term in any GTID in its oplog.

**Definition 4.2** (maxVotedTermId) A replica’s maxVotedTermId is the maximum electionTermId for any election in which it voted “yes”.

A replica’s maxVotedTermId will be used to decide which updates to acknowledge and which elections to participate in.

During normal operation, this will be identical to the term part of the GTID for elements being added to the oplog by the current primary.

4.1.1 Term ID maintenance

These two values are propagated and maintained through a few different mechanisms:

- In speculative elections, when a replica votes “yes”, “no”, or “veto”, it includes its maxVotedTermId along with its ballot.

In the speculative election, the candidate learns about each other responding replica’s maxVotedTermId. If the candidate decides to proceed with an authoritative election, it specifies

\[
\text{electionTermId} = \max_{\text{ballots}} \text{maxVotedTermId} + 1
\]

and sends this electionTermId along with its authoritative election request to all voters.

- In authoritative elections, when a replica votes “yes” in an election, it updates
its maxVotedTermId to the election’s electionTermId.

Note that this maxVotedTermId is persistent to disk and survives crashes and process restarts.

4.1.2 Voting changes

When voting in an authoritative elections, each replica considers the same conditions as in the old algorithm, except that we eliminate the restriction against voting “yes” in two elections in the same 30-second time span, and add a few new conditions:

1. If electionTermId ≤ maxVotedTermId, that is, the voter has already voted “yes” in another election with the same or higher electionTermId, it votes “no”. This makes sure that each replica may only vote for one candidate per electionTermId.

2. If the last GTID in the candidate’s oplog is less than some GTID in the voter’s oplog, the voter responds with “veto”. Note that this check was not done in the old algorithm. It is not necessary to veto at this point, a “no” vote would be sufficient to support “majority” Write Concern properly, but we will discuss this choice later, in Section 7.

Since a replica only votes “yes” in elections where electionTermId > maxVotedTermId, and it updates maxVotedTermId when voting “yes”, this establishes that the sequence of maxVotedTermId values for each replica in the set is strictly monotonically increasing.

Additionally, a successful election requires a majority of “yes” votes, which implies that in every adjacent pair of successful elections there is at least one “yes” voter in common. Therefore, the replica set’s total sequence of successful electionTermIds (and therefore the sequence of terms in GTIDs in the oplog) is also strictly monotonically increasing.

4.1.3 Election changes’ effects

These changes are enough to solve the problems of multiple primaries not resolving themselves intelligently (Problem 3.2), and of elections possibly taking a long time due to the 30 second rule (Problem 3.3). However, they are not yet enough to prevent the primary problem that “majority” Write Concern is not enough to prevent rollback (Problem 3.1).

4.2 Write Concern changes

To solve Problem 3.1 we make one more simple change: a replica never acknowledges an update from a primary after it votes “yes” in a later election.

Recall that once a replica votes “yes” in an election it updates its maxVotedTermId to that election’s electionTermId. The electionTermId must be greater than any term in the voter’s oplog, or it would not have voted “yes”.

This establishes a relationship between elections and Write Concern acknowledgement, through the GTIDs in the oplog. Namely, if a replica acknowledges an update, it may not vote “yes” for a candidate that doesn’t have that update, and once a replica has voted “yes” for a new primary, it will not acknowledge any more updates from older primaries, so it cannot acknowledge updates that might later be rolled back if that election succeeds.

Note that a replica may still copy and apply oplog entries from any member of the set, knowing that it may roll them back at any point in the future. This restriction only affects acknowledgement, and it is fundamentally a simple rule: a replica may only acknowledge updates that it thinks will not be rolled back.

With this, any successful election will cause a majority of replicas to cease acknowledgement of new updates to the old primary, which, if the client uses “majority” Write Concern, means that successful updates must have happened before those replicas voted for a new primary. Therefore those updates must be on the newly elected primary, and will not be rolled back. Updates with a weaker Write Concern may still be rolled back, but this is a design principle we accept, in accordance with the Write Concern design.

4.2.1 Primary step-down

This new change introduces a possible problem: after a failed election, all the replicas that voted “yes” will be ineligible to satisfy Write Concern from the still-legitimate primary. Over multiple failed elections, this could render a majority of the set ineligible to acknowledge updates, which would halt a system using “majority” Write Concern (no update could be satisfactorily acknowledged).

The fix for this is to make the primary more sensitive: each heartbeat message contains a node’s maxVotedTermId, and when a primary A sees a heartbeat with maxVotedTermId greater than the electionTermId for the election in which it was
elected, the primary immediately steps down. It does this because it knows that some nodes in the set are not acknowledging its updates (because they’ve voted “yes” in a later election). If A should continue as primary, it may of course re-elect itself immediately, but it will not continue accepting updates with GTIDs that may not be acknowledged.

Once an election succeeds, the old primary will be in one of two cases:

- It may still see a majority of the set, in which case it will shortly receive a heartbeat containing a newer maxVotedTermId and step down.
- It may not see a majority of the set, in which case it will determine that it is out of touch with the majority component and will step down.

Thus, a deposed primary will necessarily step down after at most one heartbeat period plus the heartbeat timeout period (which as of now totals to about 12 seconds, and is configurable).

It is sufficient, to cause an old primary to step down, to have each replica broadcast only the maxVotedTermId for elections in which it actually voted “yes”. However, to speed things up, we add some optimizations.

Definition 4.3 (maxKnownTermId) A replica’s maxKnownTermId is the maximum electionTermId for any election it knows of where at least one replica voted “yes”.

Because a replica knows about itself,

$$\text{maxKnownTermId} \geq \text{maxVotedTermId}$$

no matter what.

Every heartbeat carries with it the node’s maxKnownTermId. If a replica receives a heartbeat with a higher maxKnownTermId than its own, it replaces its own with the higher value, and in the future will broadcast and use that value.

It is an optimization for replicas to rebroadcast their neighbors’ higher maxKnownTermId value to attempt to propogate the news of an election faster through a partially connected set. A primary will then step down if it sees a heartbeat with maxKnownTermId greater than its electionTermId.

An additional optimization is that, upon successful election, the newly elected primary will ask all replicas to immediately send a heartbeat broadcasting this news, rather than waiting for the heartbeat timer to announce it.

4.3 Addressing the problems

Let’s take a moment to look back at the original problems we introduced in Section 3 and reiterate how they are addressed.

Problem 4.1 Write Concern of “majority” may not prevent the rollback of updates.

No single machine will elect two different primaries with the same electionTermId. Because a majority is needed to elect a primary, any two successful elections must have one voter in common, that voted “yes” in both elections. Because no replica ever votes “yes” in two different elections with the same electionTermId, no two successful elections can have the same electionTermId.

Each voter that acknowledges an update will not vote “yes” in an election that will rollback the update. A majority that acknowledge an update must include at least one member in the majority that vote “yes” in a subsequent election. Therefore, if an update is acknowledged by a majority, it must be on the new primary and so won’t be rolled back.

For the contrapositive, a replica that votes “yes” to elect a new primary will stop acknowledging updates from the old primary. Therefore, in a successful election, a majority of replicas will agree to stop acknowledging updates from the old primary, and this will ensure that those updates cannot have had “majority” Write Concern satisfied.

Problem 4.2 Multiple primaries don’t resolve themselves deterministically.

Because each elected primary generates GTIDs with increasing terms, we can predictably get the primary with the lower electionTermId to step down, and know which updates were accepted by the deposed primary. Because all members communicate the highest known electionTermId throughout the set via heartbeats, we are assured that the primary with the lower electionTermId will eventually step down, regardless of who it is connected to.

Problem 4.3 Elections may take a long time because a member can vote “yes” at most once every 30 seconds.

This timer has been removed. Because Ark is robust enough to handle multiple primaries and resolves each such case deterministically, we don’t need to have this 30 second timer.
That being said, collisions may still occur. We may have two candidates, $B$ and $C$, happen very close in time to each other.

After the first round trip, suppose they both decide on the same $electionTermId_B = electionTermId_C$. Both could run authoritative elections, get a handful of votes, and neither one could get elected. This is what Raft would call a “split brain”. In this case, neither wins, and another election needs to run.

Alternatively, these two elections can happen with different values of $electionTermId_B < electionTermId_C$, and both might succeed in a short period of time. In that case, $B$ is going to become primary and then almost immediately step down when it sees $electionTermId_C$ has been voted on. From a correctness standpoint, that’s fine, but it could be confusing for clients to have to switch primaries too frequently.

These problems exist with the current election protocol. The symptom in each protocol is different:

- Ark can cause two replicas to be primary in quick succession, or effectively concurrently for some clients, due to delayed messages.

- MongoDB’s replication incurs a 30 second freeze after unsuccessful simultaneous elections.

The root cause of these problems is the same: two replicas simultaneously try to elect themselves. To mitigate this, the current MongoDB protocol sleeps for a random amount of time (50-1050ms) before kicking off an election. This random delay is used in Raft as well (150-300ms), and is also used for the same purpose in Ark.

A remaining concern is whether the sleep is sufficient. Is a random sleep of up to one second sufficient for replica sets that span across data centers and may have high ping times? Raft experiments with a cluster of 5-9 servers with a broadcast time of 15ms determined the recommended sleep time of 150-300ms.

5 The solution, in Raft’s terms

Raft’s safety and liveness properties follow directly from five fundamental properties described in Figure 3 in the Raft paper:

- **Election Safety**: at most one leader can be elected in a given term.

- **Leader Append-Only**: a leader never overwrites or deletes entries in its log; it only appends new entries.

- **Log Matching**: if two logs contain an entry with the same index and term, then the logs are identical in all entries up through the given index.

- **Leader Completeness**: if a log entry is committed in a given term, then that entry will be present in the logs of the leaders for all higher-numbered terms.

- **State Machine Safety**: if a server has applied a log entry at a given index to its state machine, no other server will ever apply a different log entry for the same index.

**Election Safety** is provided by the addition and treatment of the $electionTermId$. Since each replica can only vote “yes” once for each $electionTermId$, this ensures that in each $electionTermId$ at most one leader may be elected.

**Leader Append-Only** is an existing property of the oplog and how the GTID is defined.

**Log Matching** is a consequence of rollback. Whenever a replica attempts to sync from another, it must have the Log Matching property, and if the source replica’s log doesn’t contain its oplog as a prefix, the syncing replica rolls back operations until its oplog matches a prefix of the source’s oplog. Only after this point may it proceed and copy new entries. Multiple concurrent primaries’ oplogs may diverge at the end (and their followers’ oplogs would as well), but these entries would have different terms and therefore would not invalidate the Log Matching property.

**Leader Completeness** is ensured only for updates acknowledged with “majority” Write Concern. But according to the refusal of replicas to acknowledge updates after voting for a new primary, Leader Completeness is ensured for these updates.

**State Machine Safety** makes sense if we consider the long-term state of the replica set. In MongoDB/TokuMX, the state machine refers to the user data collections. Since updates are applied separately from their Write Concern acknowledgement, there may be a period of time when an update is reflected in the state machine of some replicas, before the operation rolls back. In this case, the operation’s “index” within the log will eventually be taken by a different operation, which would at this point be applied on other replicas.

This complexity is due to the asynchronous nature of replication in MongoDB/TokuMX, essentially that application may happen before replication and then the operation would be rolled back. However, once a
replica establishes contact with another replica and decides to roll back an operation (in Raft, this would be when a leader forces its followers to replace log entries with its own), that operation is rolled back before any new operations are synced and applied, which maintains logical separation of the rolled back operation and the legitimately applied operations.

We needed to tweak the definitions of a few of Raft’s fundamental properties, but not in ways inconsistent with an asynchronous interpretation of Raft, nor in ways that invalidate its safety and liveness proofs. We leave the translation of Raft’s safety and liveness arguments to our asynchronous context as a straightforward but exciting exercise for the reader.

6 Conclusions

We have presented Ark, a new consensus algorithm based on and supporting the existing MongoDB replication algorithm and semantics, with minimal changes. Ark is inspired by Raft and provably provides safety and liveness according to the same arguments as Raft.

Ark has many of the same understandability properties of Raft. The oplog in Ark does not permit holes anywhere in an agreed-upon prefix which limits the ways in which replicas can diverge from each other. By virtue of the MongoDB replication architecture, Ark decouples the mechanisms of replication and elections, and brings them together just enough to provide safety.

In contrast with Raft, Ark implements an asynchronous, pull-based replication model. This supports a wider range of client semantics that allows application developers to choose points along a tradeoff between safety and latency. In addition, Ark supports different replication topologies like chained replication and multi-data center replication with more flexibility than Raft does with its synchronous push model.

While Ark is an implementation of a consensus protocol that works in a real database system, it is also evidence of the flexibility in the Raft consensus algorithm. It was relatively straightforward to tweak Raft in safe ways to make it fit the MongoDB architecture and programming model, and we think this is an important feature of Raft.

7 Future work

We still have some things to think about. The basics of Ark are correct, but it’s possible there is some tweaking to be done to improve the user experience. Likely, most of the below questions can be answered with experiments and user feedback.

Question 7.1 Should we veto based on the oplog contents?

In an authoritative election, if the GTID of the candidate B’s last oplog entry is less than the GTID of the voter’s, we currently veto. We could theoretically vote “no” and still have “majority” Write Concern work properly. This is a user experience question and not a correctness question. Here are reasons why we do this:

- This should happen in rare circumstances, because speculative election does this check and does not proceed if it fails.
- Users don’t just run with “majority” Write Concern. They run with other custom Write Concerns to give them different assurances.

Consider a replica set spread across three data centers, called DC1, DC2, and DC3. Suppose each data center has three members of the replica set, so the entire replica set is nine members. Users may set a custom Write Concern that means “make sure my update has made it to at least one other data center”.

The idea is that the user is assuming either all members in a data center remain up or none do, and that the probability of two data centers being down is negligible. Now, suppose the primary is in DC1 and DC1 goes down. In this case, if the update only made it to one replica in DC2, and that replica just votes “no” in the authoritative election, then the update got the proper acknowledgement but may be rolled back, because the 5 other members that don’t have this update may elect a different primary. But with veto power, the update will not be rolled back, because the one replica in that did receive the update won’t let a primary be elected without the update.

Essentially, this choice to allow replicas to veto based on the contents of the oplog lends more consistency to updates that use weaker Write Concern settings, which seems to be a valuable property for many MongoDB applications.
**Question 7.2** Should there be some timer so members cannot vote as often as they do?

30 seconds is too long, but should there be something like 1 second? To help prevent multiple primaries being elected simultaneously?

In the Raft paper, they spend some time talking about the election timeout, but in Raft this is the window of time an election stays open to hear votes. It is not particularly related to the number of elections a given node can participate in in a given time slice (apart from this timeout divided by the number of replicas).

This timer also seems to be valuable in ensuring that the primary doesn’t move too quickly around the set for a client to follow.

**Question 7.3** Is the random sleep of about 1 second before starting an election sufficient to keep two competing elections from happening at roughly the same time too often?

The sleep time should not be too long, but the range should be significantly longer than the range of typical message delays in the cluster.

Should cross-data center replica sets do something different? One idea is to pick the sleep time based on ping times we see in heartbeats.

**Question 7.4** Should we make heartbeats more sophisticated?

Currently, all members heartbeat all other members every 2 seconds regardless of role or topology. Heartbeat traffic is one of the things that limits a replica set’s size, and for XDCR this could be more traffic across the WAN than we’d like.

Perhaps each node could heartbeat what it thinks is the primary once a second, and all other members every 5 seconds? This could improve failover time by causing members to notice a down primary faster, and reduce the overall heartbeat traffic in the cluster.

Another option is to send heartbeats along a different topology than a complete graph. Other systems[3][4][9] use rings, trees, or other incomplete graphs to propagate the same information being exchanged here with heartbeats.

**Question 7.5** How should we handle dynamic cluster membership?

Raft has an elegant solution to dynamic membership: membership changes are recorded in the log stream, and the cluster uses an intermediate stage where replicas are aware of both configurations temporarily, until they have agreed on the new configuration.

MongoDB’s existing configuration management is currently stored outside of the log, and the in-memory representation of configuration is not well suited to maintaining the intermediate dual-configuration state used by Raft. It is still an open question as to the right way to adapt a safe dynamic membership protocol to the existing MongoDB architecture.

Storing configuration changes in the log seems fairly straightforward and appropriate, but managing the dual-configuration state properly seems like a challenge.

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