Bits and pieces

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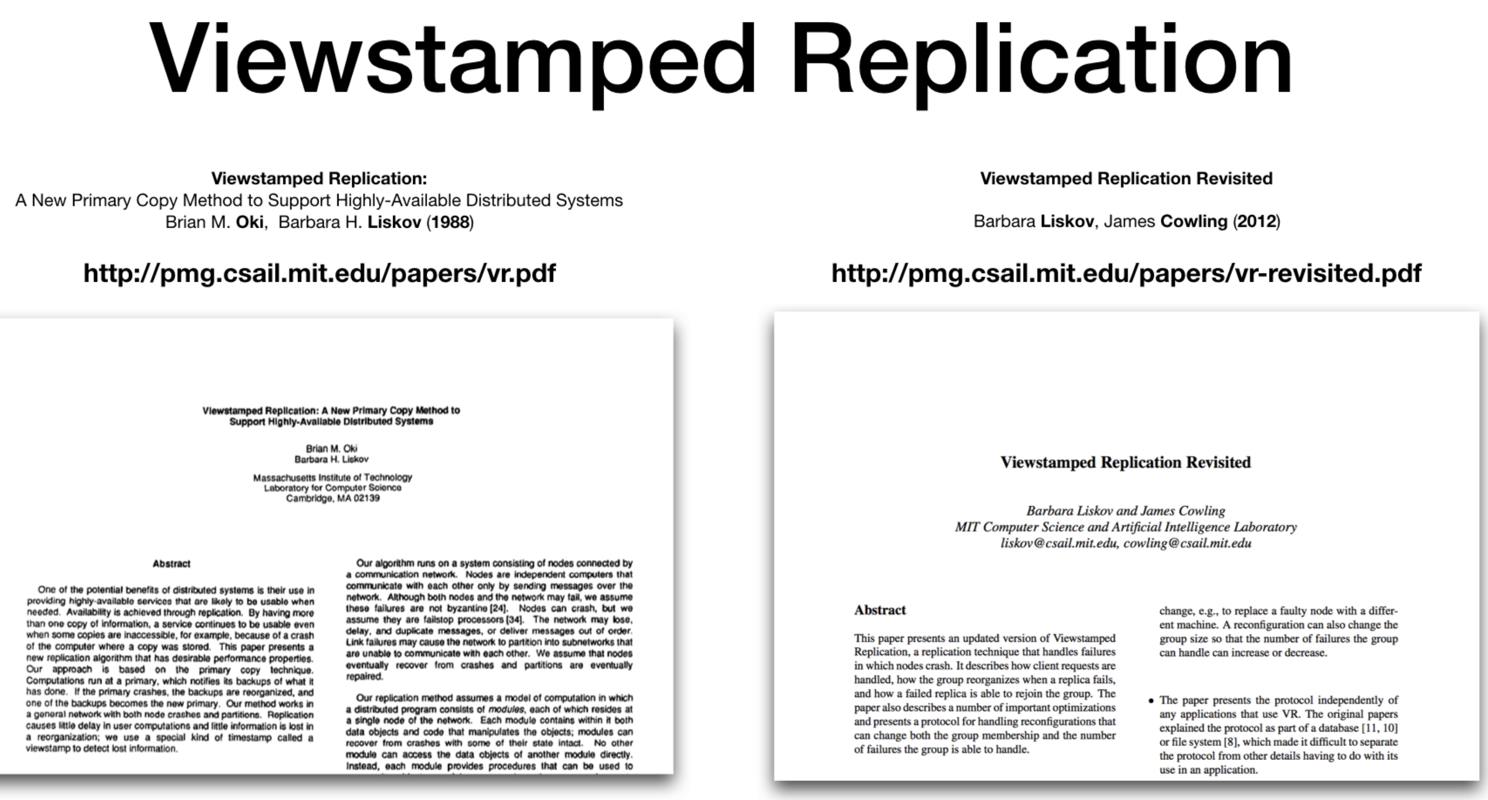
Viewstamped Replication explained

Viewstamped Replication is one of the earliest consensus algorithms for distributed systems. It is designed around the log replication concept of state machines and it can be efficiently implemented for modern systems. The revisited version of the paper offers a number of improvements to the algorithm from the original paper which both: simplifies it and makes it more suitable for high volume systems. The original paper was published in 1988 which is ten years before the Paxos algorithm [1] was published.

I will explain how the protocol works in detail covering as well a number of optimizations which are described in the papers. The "revisited" version offers a simplified version of the protocol with improvements which were made by the authors in later works and published after the original paper. Therefore most of the content here will be driven from the more 2012 paper.



- Paper links:

Available Distributed Systems, B. Oki, B. Liskov, (1988) 2
http://pmg.csail.mit.edu/papers/vr.pdf
- *Viewstamped Replication Revisited, B. Liskov, J.Cowling (2012)* 3
http://pmg.csail.mit.edu/papers/vr-revisited.pdf
- *Viewstamped Replication presentation at PapersWeLove London* 4

What is "Viewstamped Replication"?

It is a replication protocol. It aims to guarantee a consistent view over replicated data. And it is a "consensus algorithm". To provide a consistent view over replicated data, replicas must agree on the replicated state.

It is designed to be a pluggable protocol which works on the communication layer between the clients and the servers and between the servers themselves. The idea is that you can take a non-distributed system and using this replication protocol you can turn a single node system into a high-available, fault-tolerant distributed system.

To achieve fault-tolerance, the system must introduce redundancy in time and space. *Redundancy in time* is to combat the unreliability of the network. Messages can be dropped, reordered or arbitrarily delayed, therefore protocol must account for it and allow requests to be replayed if necessary without causing duplication in the system. *Redundancy in space* is generally achieved via adding redundant copies in different machines with different fault-domain isolation. the aim is to be able to stay in operation in face of a node failure, whether is a system crash or a hardware failure, the system must be able to continue normal operation within certain limits.

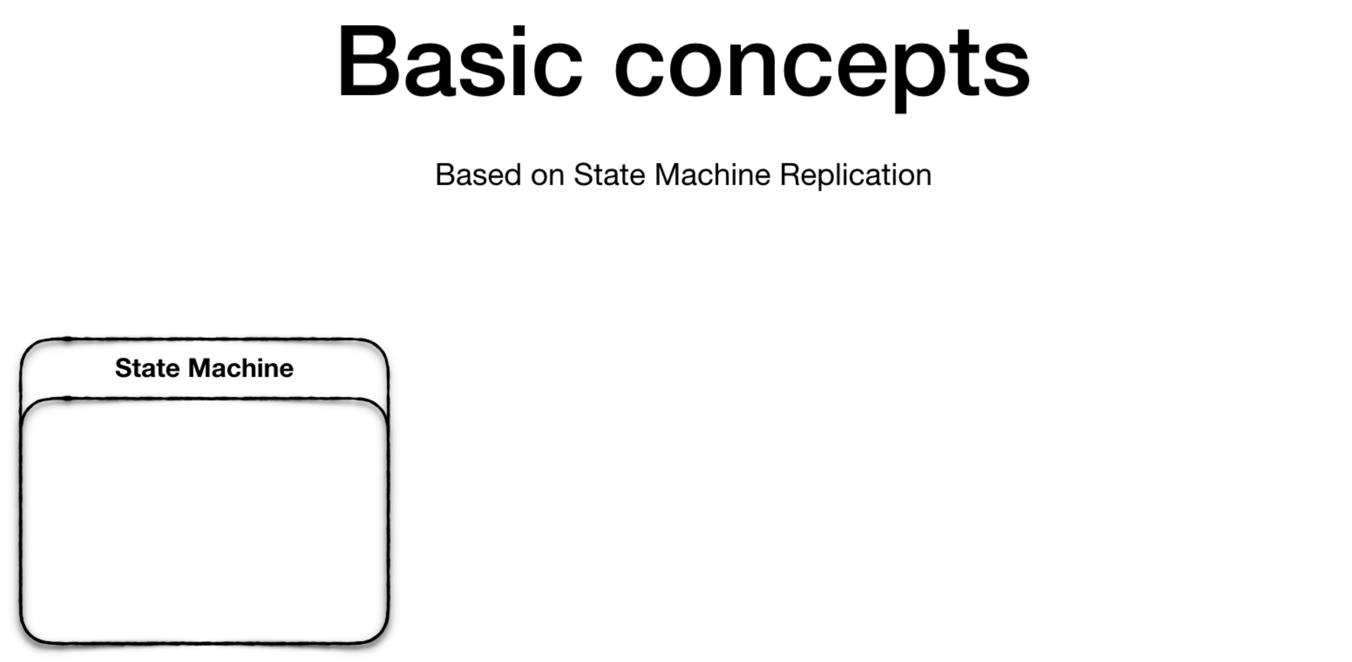
Together, the *redundancy in time and space* provide the ability to tolerate and recover from temporary network partitions, systems crashes, hardware failure and a wide range of network related issues.

However, the system can only tolerate a number of failures depending on the cluster (or **ensemble** size). In particular to tolerate f failures it requires an ensemble of $2f + 1$ replicas. The type of failures that the protocol can tolerate are **non-Byzantine failures** 5 which means that all the nodes in the ensemble will be either in a working state, or in a failed state or simply isolated. However, every node in the system will not deviate from the protocol and it will not lie about its state. Therefore, if the system must be able to tolerate one node to be unresponsive, then the minimum ensemble size is 3 nodes. If the system must be able to tolerate 2 concurrent failures, then the minimum size of the cluster required is 5 nodes, and so on. $f + 1$ nodes is called **quorum**. It is not possible to create a quorum with less than 3 nodes, therefore the minimum ensemble size is 3.

Replicated State Machines

Machine has an *initial state* and an *operation log*. The idea is that if you apply the ordered set of operation in the operation log to the initial state you will end up always with the same final state, *given that all the operations in the operation log are **deterministic***.

Therefore, if we replicate the initial state and the operation log into other machines and repeat the same operations the final state on all the machines will be the same.

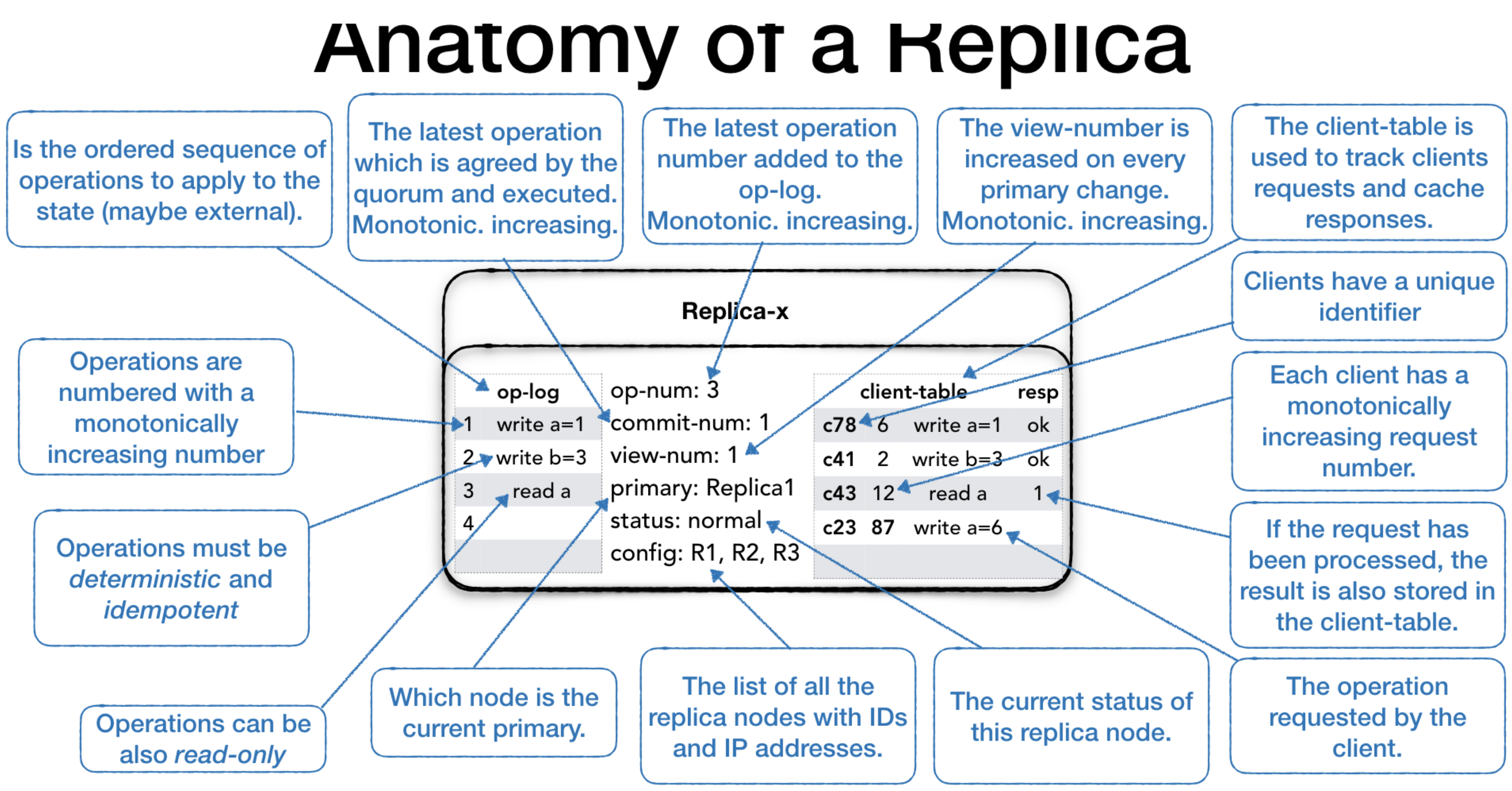


It is crucial that the *order of operations is preserved* as operations are not required to be commutative. Additionally *all sources of indeterminism must be eliminated* before the operation is added to the operation log. For example, if you have an operation which generate a unique random id, the primary replica will need to generate the random id and then add an operation in the log which already contains the generated number such that when the replicas apply the operation won't need to generate the random unique id themselves which will cause the replica state to diverge.

The objective of Viewstamped Replication is to ensure that there is a strictly consistent view on the operation log. In other words, is ensures that all replicas agree on which operations are in the log and their exact order.

Anatomy of a Replica

The ensemble or cluster is made of replica nodes. Each replica is composed of the following parts.



The operation log (`op-log`) is a (mostly) append-only sequence of operations. Operations are applied against the current state which could be external to the replica itself. Operations must be *deterministic* which means that every application of the same operation with the same arguments must produce the same result. Additionally, if the operations produce side effect or write to an external system you have to ensure the operation is applied only once by the use of transactional support or by making operation *idempotent* so that multiple application of the same operation won't produce duplication in the target system. Each operation in the operation-log has a positional identifier which is a monotonically increasing number.

The last inserted operation number is the high water mark for the operation log and it is recorded as the `op-num` which is a monotonically increasing number as well. It identifies which operation has been already received and it is used in parts of the protocol.

Operations in the `op-log` are appended first, then shared with other replicas and once there is a confirmation that enough replicas have received the operation then it is actually executed. We will see how this process works in more details later. The `commit-num` represents the number of the last operation which was executed in the replica. It also implies that all the previous operations have been executed as well. `commit-num` is a monotonically increasing number.

The *view-number* (`view-num`) is a monotonically increasing number which changes every time there is a change of primary replica in the ensemble.

Each replica must also know who the current primary replica is. This is stored in the `primary` field.

The `status` field shows the current replica operation mode. As we will see later, the `status` can assume different values depending on whether the replica is ready to process client requests, or it is getting ready and doing internal preparation.

addresses and their unique identifiers. Some parts of the protocol require the replicas to communicate with other replicas therefore they must know how to contact the other nodes.

The `client-table` is used to keep track of client's requests. Clients are identified by a unique id, and each client can only make one request at the time. Since communication is assumed to be unreliable, clients can re-issue the last request without the risk of duplication in the system. Every client request has a monotonically increasing number which identifies the request of a particular client. Each time the primary receives a client requests it add the request to the client table. If the client re-sends the same requests because didn't receive the response the primary can verify that the request was already processed and send the cached response.

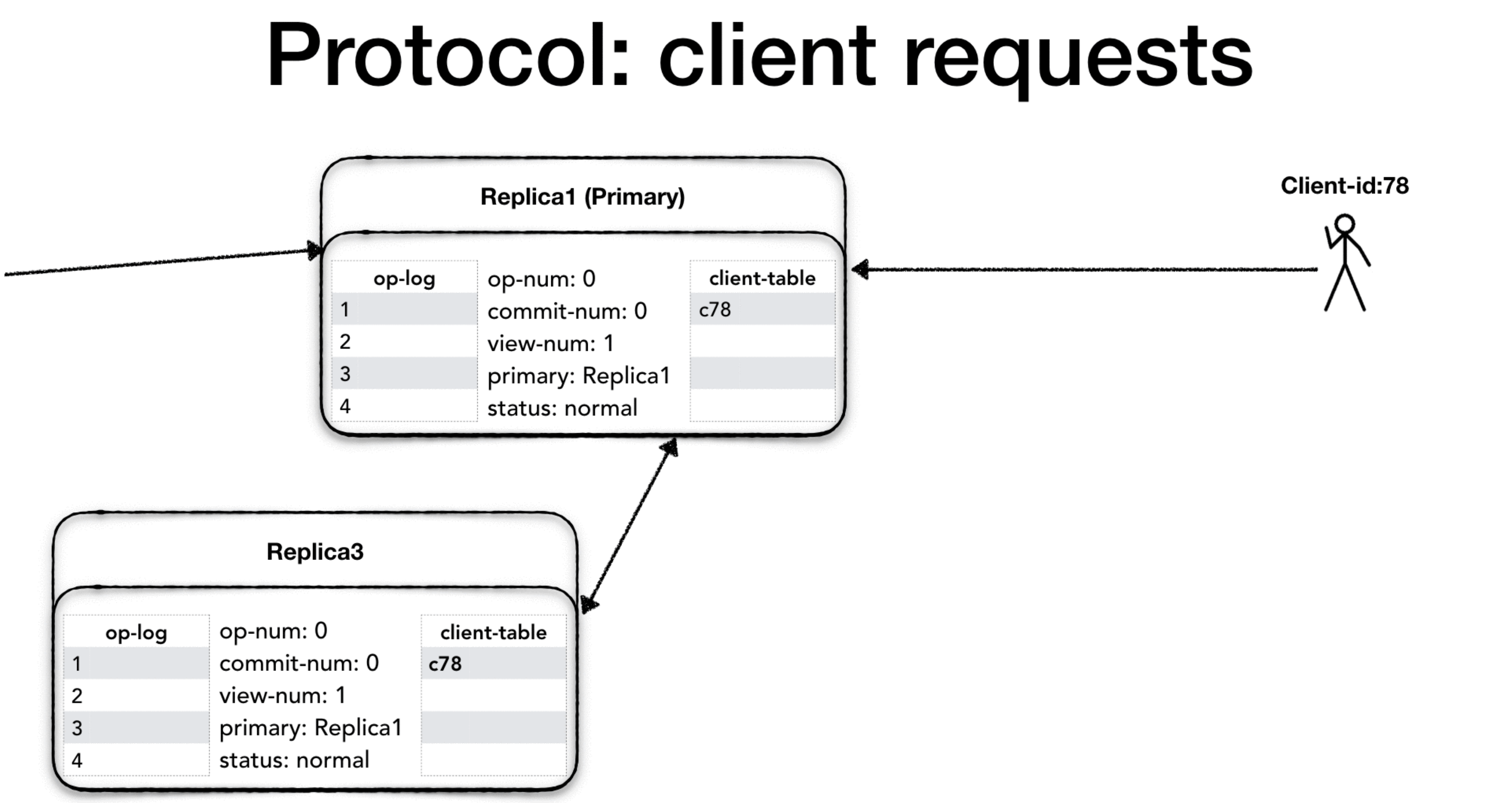
For brevity, the pictures which will follow will omit some details.

The Protocol

Next, we are going to analyse the protocol in details. The protocol is presented in the paper in its simplest form first. Then the paper goes on describing a number of optimisations which do not change the basic structure of the protocol but make it efficient and practical to implement for real-world application. Efficiency is a major concern throughout both papers as the authors were building real-world systems.

Client requests handling

In this section, we are going to see how a client request is processed and the data replicated. We are going to see, in details, how the protocol ensures that at least a quorum of replicas acknowledges the request before executing the request.



If a client contacts a replica which is not the primary, the replica drops the requests and returns an error message to the client advising it to connect to the primary. Each client can only send one request at the time, and each request has a request number (`request#`) which is a monotonically increasing number. The client prepares `<REQUEST>` message which contains the `client-id`, the request `request#` and the operation (`op`) to perform.

The primary only processes the requests if its `status` is `normal`, otherwise, it drops the request and sends an error message to the client advising to try later. When the primary receives the request from the client, it checks whether the request is already present in the client table. If the request's number is greater of the one in the client table then it is a new request, otherwise, it means that the client might not have received last response and it is re-sending the previous request. In this case, the request is dropped and the primary re-send last response present in the client table.

If it is a new request, then the primary increases the operation number (`op-num`), it appends the requested operation to its operation log (`op-log`) and it updates the `client-table` with the new request.

Then it needs to notify all the replicas about the new request, so it creates a `<PREPARE>` message which contains: the current view number (`view-num`), the operation's `op-num`, the last commit number (`commit-num`), and the `message` which is the client request itself, and it sends the message to all the replicas.

When a replica receives a `<PREPARE>` request, it first checks whether the view number is the same `view-num`, if its view number is different than the message `view-num` it means that a new primary was nominated and, depending on who is behind, it needs to get up to date. If its view-number is smaller than the message `view-num`, then it means that this particular node is behind, so it needs to change its `status` to `recovery` and initiate a state transfer from the new primary (we will see the primary change process called **view change** later). If its view-number is greater than the message `view-num`, then it means that the other replica needs to get up-to-date, so it drops the message. Finally, if the `view-num` is the same, then it looks at the `op-num` in the message. The `op-num` needs to be *strictly consecutive*. If there are gaps it means that this replica missed one or more `<PREPARE>` messages, so it drops the message and it initiates a recovery with a state transfer. If the `op-num` is *strictly consecutive* then it increments its `op-num`, appends the operation to the `op-log` and updates the client table.

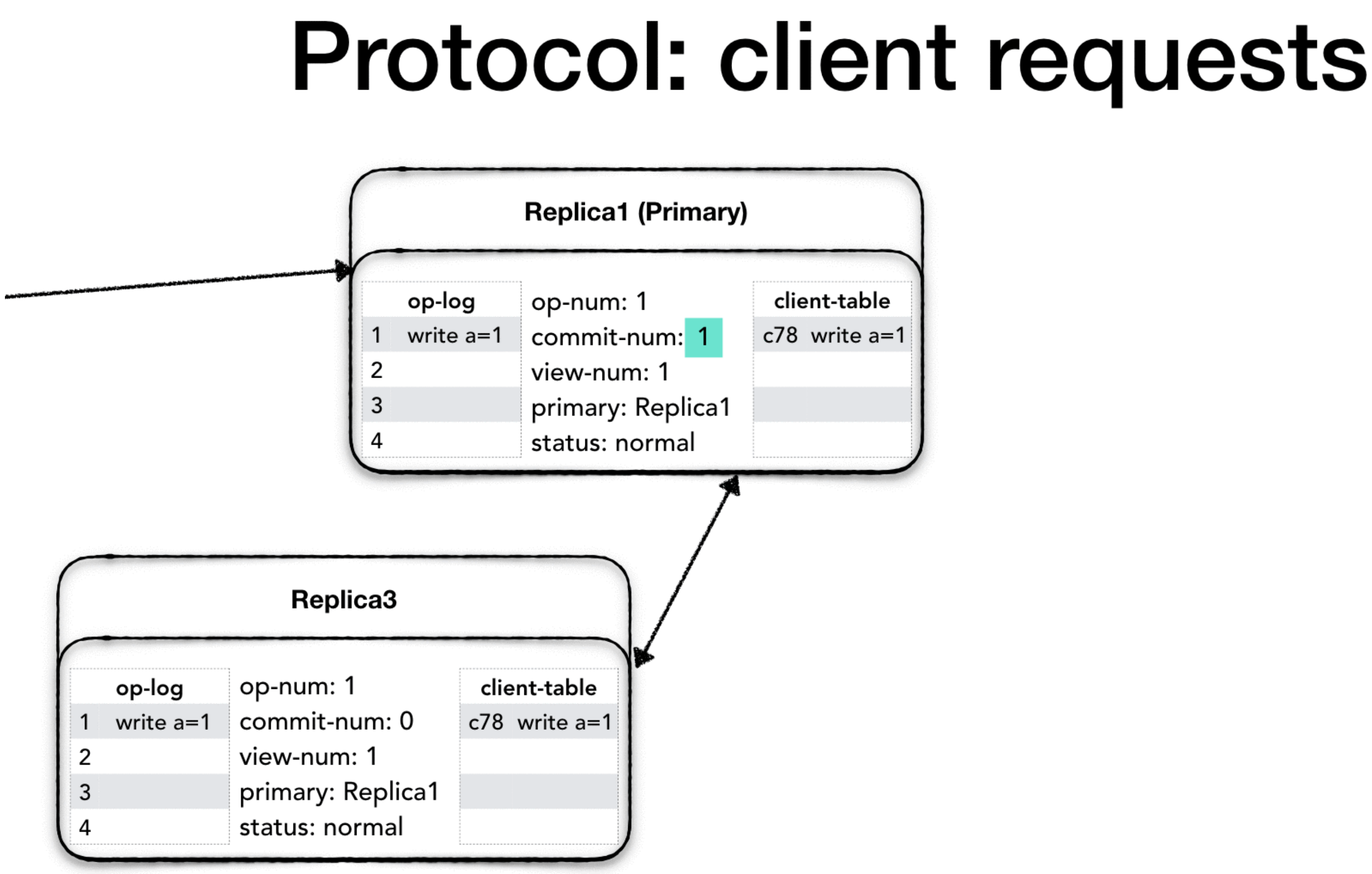
Now the replica sends an acknowledgment to the primary that the operation, and all previous operations, were successfully prepared. It creates a `<PREPARE-OK>` message with its `view-num`, the `op-num` and its identity. Sending a `<PREPARE-OK>` for a given `op-num` means that all the previous operations in the log have been prepared as well (no gaps).

The primary waits for $f + 1$ including itself `<PREPARE-OK>` messages, at which point it knows that a **quorum** of nodes knows about the operation to perform therefore it is nodes. When it receives enough `<PREPARE-OK>` then it performs the operation, possibly with side effect, it increases its commit number `commit-num`, and update the client table with the operation result. Again, advancing the `commit-num` must be done in strict order, and it also means that **all previous operations have been committed** as well.

Finally, it prepares a `<REPLY>` message with the current `view-num` the client request number `request#` and the operation result (`response`) and it sends it to the client.

At this point, the primary is the only node that has performed the operation (and advanced its `commit-num`) while the replicas have only prepared the operation but not applied. Before they can safely apply they need confirmation from the primary that it is safe to do so.

This can happen in two ways.



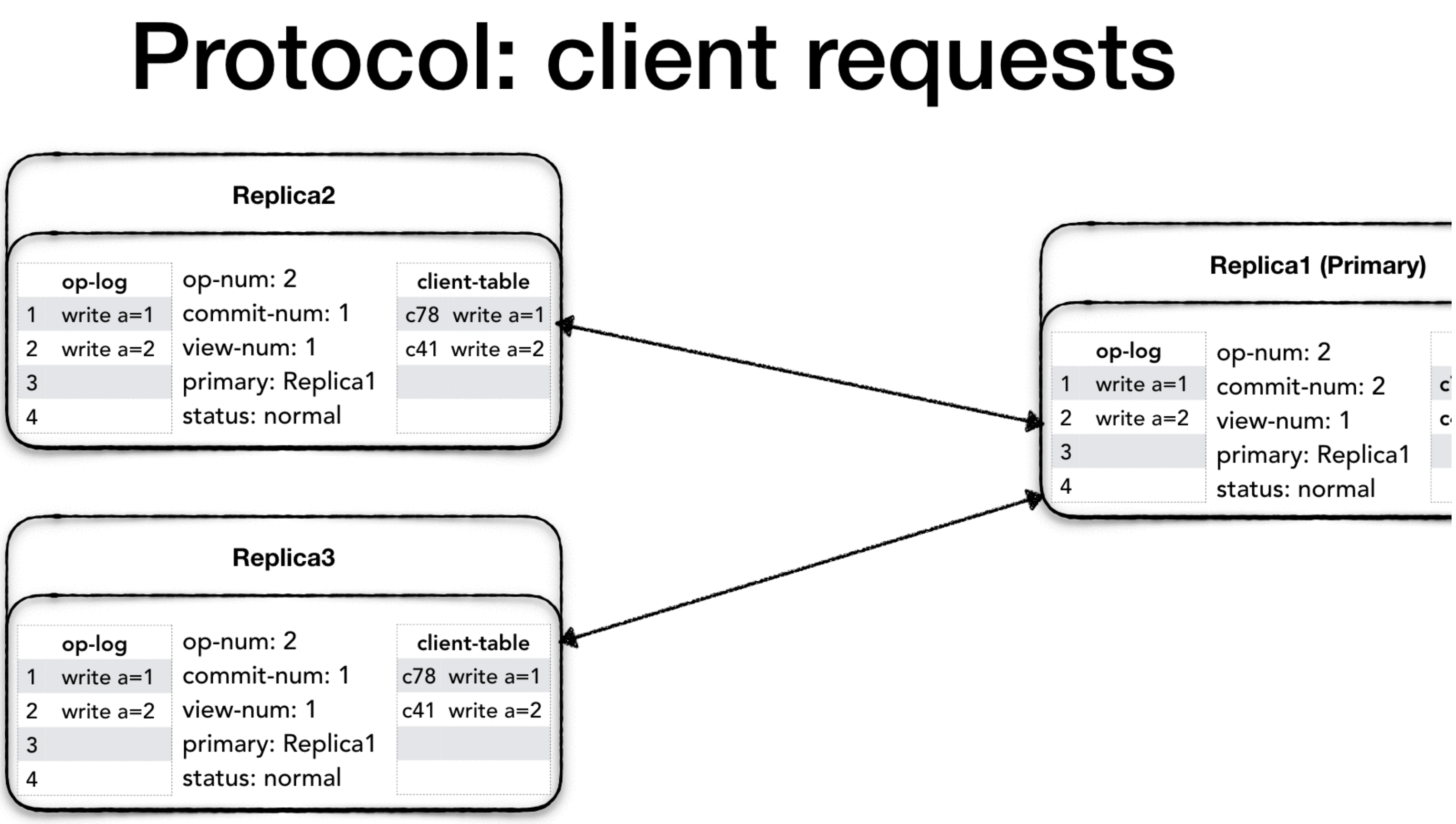
Let's assume that the same client or a new client comes along and makes a new request. The client will create a `<REQUEST>` message and send it to the primary as well. The primary will process the request as usual, check the client table, increase the `op-num` and append to the `op-log`, then it creates a `<PREPARE>` message with the `view-num`, the `op-num`, the client's `message` *but it also includes its* `commit-num` *which now shows that the primary advanced its position.*

When the replicas receives the `<PREPARE>` it follows the normal process; It checks the `view-num`, checks the `op-num`, increment its operation number append to the `op-log` and update the client table, then it sends a `<PREPARE-OK>` to the primary for the operation it received.

However, the `<PREPARE>` message from the primary also contained the `commit-num` which showed that the primary has now executed the operation against its state and it is notifying the replicas that it is safe to do so as well. So the replicas will perform all requests in their

strictly following the order of operations and advance its `commit-num` as well. At this point both, primary and replicas have performed the *committed* operations in their state.

So we seen how the primary uses the `<PREPARE>` message to inform replicas about new operations as well as operations which are now safe to perform. But what if there is not a new request coming in? what if the system is experiencing a low request rate, maybe because it is the middle of the night and all users are asleep? If the primary doesn't receive a new client request within a certain time then it will create a `<COMMIT>` message to inform replicas about which operations can now be performed.



The `<COMMIT>` message will only contain the current view number (`view-num`) and the last committed operation (`commit-num`). When a replica receives a `<COMMIT>` it will execute all operation in their `op-log` between the last `commit-num` and the `commit-num` in the `<COMMIT>` message **strictly following the order of operations** and advance its `commit-num` as well.

The `<PREPARE>` message together with the `<COMMIT>` message act as a sort of heartbeat for the primary. Replicas use this to identify when a primary might be dead and elect a new primary. This process is called **view change** and it is what we are going to discuss next.

View change protocol

The *view change protocol* is used when one of the replicas detects that the current primary is unavailable and it proceeds to inform the rest of the ensemble. If a quorum of nodes agrees then the ensemble will transition to a new primary. This part of the protocol ensures that the new primary has all the latest information to act as the new leader.

Leader "selection"

the way the new primary node is selected. Other consensus protocols (such as Paxos and Raft) have a rather sophisticated way to elect a new primary (or leader) with candidates having to step up, ask for votes, ballots, turns etc. ViewStamped Replication takes a completely different approach. It uses a **deterministic function** over a fixed property of the replica nodes, something like a unique identifier or IP address.

For example, if the replica nodes IP addresses don't change you could use the `sort` function which given a list of nodes IPs will return a deterministic sequence of nodes. The ViewStamped Replication algorithm simply uses the sorted list of IPs to determine who is the next primary node, and *in round-robin fashion* all nodes will, in turn, become the new primary when the previous one is unavailable. I find this strategy very simple and effective. There is no vote to cast, candidates stepping up, election turns, ballots, just a predefined sequence of who's turn is.

For example, if you have a three nodes cluster with the following IP addresses

```
10.5.3.12           10.5.1.20  (1)
10.5.1.20  ~sort~>  10.5.2.28  (2)
10.5.2.28           10.5.3.12  (3)
```

The node `10.5.1.20` will be the first primary, and everybody knows that it will be the first. When that node dies or is partitioned away from the rest of the cluster, the next node to become the primary will be the `10.5.2.28` followed by `10.5.3.12` and then starting from the beginning again.

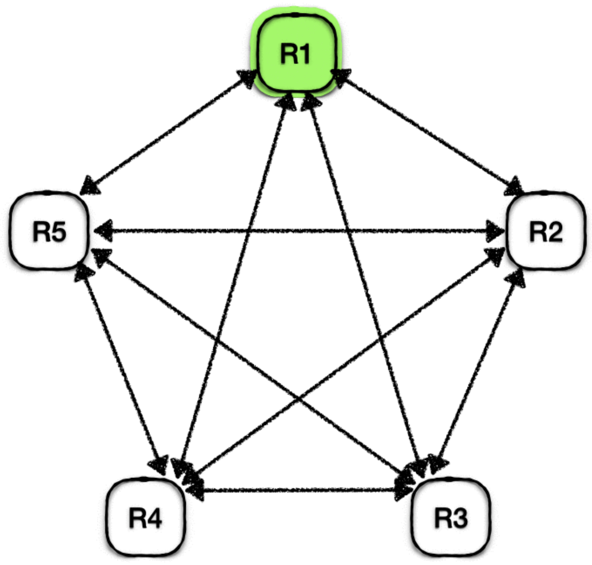
The protocol ensures that if the node who is set to be the next primary, somehow, has fallen behind and it is not the most up-to-date, it will be able to gather the latest information from the other nodes and get ready for the job. We will see this in more details in this section.

The view change

Let's start with a working cluster. Replicas `R1` to `R5` are all up and running, `R1` is the first primary node, followed by `R2` and so on. Since ensembles are formed by `2f + 1` nodes, this cluster can survive and continue processing requests in the face of two failed nodes.

`R1` is currently accepting client's requests and those are handled as seen earlier. Therefore for each client request, a `<PREPARE>` message is sent to all replicas and they reply with a `<PREPARE-OK>`. `<COMMIT>` messages are also used to signal which operations are committed by the primary.

Protocol: view change



Let's assume that the primary `R1` crashes or is isolated from the rest of the cluster. No more `<PREPARE>` or `<COMMIT>` messages will be received by the rest of the cluster. As said previously these messages act as a heartbeat for the primary health.

At some point, in one of the nodes (`R4` for example) a timeout will expire, and it will detect that it didn't hear from the primary since a predefined amount of time. At this point the replica will change its `status` to `view-change`, increase its view number (`view-num`) and create a `<START-VIEW-CHANGE>` message with the new `view-num` and its identity. It will then send this message to all the replicas.

When the other replicas receive a `<START-VIEW-CHANGE>` message with a `view-num` bigger than the one they have, they set their `status` to `view-change` and set the `view-num` to the view number in the message and reply with `<START-VIEW-CHANGE>` to all replicas.

When a replica receives `f + 1` (including itself) `<START-VIEW-CHANGE>` message with its `view-num` then it means that the majority of the nodes agrees on the view change so it sends a `<DO-VIEW-CHANGE>` to the new primary (selected as described above). The `<DO-VIEW-CHANGE>` message contains the new `view-num` the last view number in which the state was normal `old-view-number`, its `op-num` and its operation log (`op-log`) and its commit number (`commit-num`).

When the new primary, in this case, node `R2`, it receives `f + 1` (including itself) `<DO-VIEW-CHANGE>` with the same `view-num` it compares the messages against its own information and pick the most up-to-date. It will set the `view-num` the new `view-num`, it will take the operation log (`op-log`) from the replicas with the highest `old-view-number`. If many replicas have the same `old-view-number` it will pick the one with the largest `op-log`, it will take the `op-num` from the chosen `op-log` and the highest `commit-num` and execute all committed operations in the operation log between its old `commit-num` value and the new `commit-num` value. At this point, the new primary is ready to accept requests from the replicas with the new `view-num`, the most up to date `op-log`, the corresponding `op-num` and the highest `commit-num`.

When the other replicas receive the `<START-VIEW>` message they replace their own local information with the data in the `<START-VIEW>` message, specifically they take: the `op-log`, the `op-num` and the `view-num`. They change their `status` to `normal` and they execute all the operation from their old `commit-num` to the new `commit-num` and they send a `<PREPARE-OK>` for all operation in the `op-log` which haven't been committed yet.

Some time later the failed node (`R1`) might come back alive either because the partition is now terminated or because the crashed nodes it has been restarted. At this point, the `R1` might still think it is the primary and be waiting for requests from clients. However, since the ensemble transitioned to a new primary in the meantime, it is likely that clients will be sending requests to the new primary and it is likely that the new primary is sending `<PREPARE>`/`<COMMIT>` messages to all the replicas, including the one which previously failed. At this point, the failed replica will notice that `<PREPARE>`/`<COMMIT>` messages have a `view-num` greater than its `view-num` and it will understand that the cluster transitioned to a new primary and that it needs to get up to date.

In this case, it will set its `status` to `recovery` and issue a `<GET-STATE>` request to any of the other replicas. The `<GET-STATE>` will contains its current values of the `view-num`, `op-num` and `commit-num` together with its identity. The `<GET-STATE>` message is the same message used by the replicas to get up to date when the fall behind. The replica who receives the `<GET-STATE>` message will only respond if its `status` is `normal`.

If the `view-num` in the `<GET-STATE>` message is the same as its `view-num` it means that the requesting node just fell behind, so it will prepare a `<NEW-STATE>` message with its `view-num`, its `commit-num` and its `op-num` and the portion of the `op-log` between the `op-num` in the `<GET-STATE>` and its `op-num`.

If the `view-num` in the `<GET-STATE>` message is different, then it means that the node was in a partition during a view change. In this case it will prepare a `<NEW-STATE>` message with new `view-num`, its `commit-num` and its `op-num` and the portion of the `op-log` between the `commit-num` in the `<GET-STATE>` this time and its `op-num`, this is because some operations in the minority group might not have survived the view-change.

This is concludes the discussion about the ViewStamped Replication protocol. We seen how requests are handled in the normal case, and we have seen how the ensemble safely transition to a new primary in case it detects a failure or partition in the previous one. We also seen how the protocol design accounts for unreliable network and allows for any message to be dropped, delayed or reordered and still work correctly.

Protocol optimisations

over the protocol correctness and clarity. In this section we'll see how some of the optimisations proposed by the authors make this protocol not only realistic to implement for a real world system, but also efficient and practical.

Persistent state

While the protocol as described above doesn't require the internal replica state to be persisted to work properly you can store the state in a durable storage to speed up crash recovery. In fact in a large system the operation log (`op-log`) could become, over time, quite large. It would be unreasonable and ineffective to keep the entire operation log only in memory. Upon a crash, or when a replica is restarted it will require to get a copy of the `op-log` from another replica (via `<GET-STATE>`) and if the replica has to transfer terabytes of data the operation could take a long time.

Storing the internal replica state into a durable storage can speed up the recovery in the event the process is crashed or restarted. In fact in this case, new replica process will only need to fetch the tail of the operation log since its last committed operation (`commit-num`).

Since the persistent state is not required to run the protocol correctly, then the implementer can make design decisions based on the efficient use of the storage. For example it could decide to `fsyinc` only when there are enough changes to fill a buffer, as supposed to *fsync-ing* on every request which it would be slow and inefficient. Additionally the durability of the state could be managed completely asynchronously from the protocol execution.

Witnesses

Running the protocol has a cost. As we seen the primary has to wait for a *quorum* of nodes to respond on every `<PREPARE>` request before executing the client request. In a large cluster, as the number of nodes increases, it also increases the number of nodes that the primary has to wait for a response and it increases the likelihood the at one being slower and having to wait for longer. In such cases we can divide the ensemble into *active replicas* and *witness replicas*.

Active replicas account for `f + 1` nodes which run the full protocol and keep the state. The *primary* is *always* an active replica. The remainder of the nodes are called *witnesses* and only participate to the view changes and recovery.

Batching

In a high volume system there will be a huge number of `<PREPARE>` messages flying around. To reduce the latency cost of running the protocol the *primary replica* could batch a number of operation before sending a `<PREPARE>` messages to the other replicas. In this case the `<PREPARE>` messages will include *all the operations* in the batch and the `<PREPARE-OK>` message will confirm that *all operations* in the batch have been prepared.

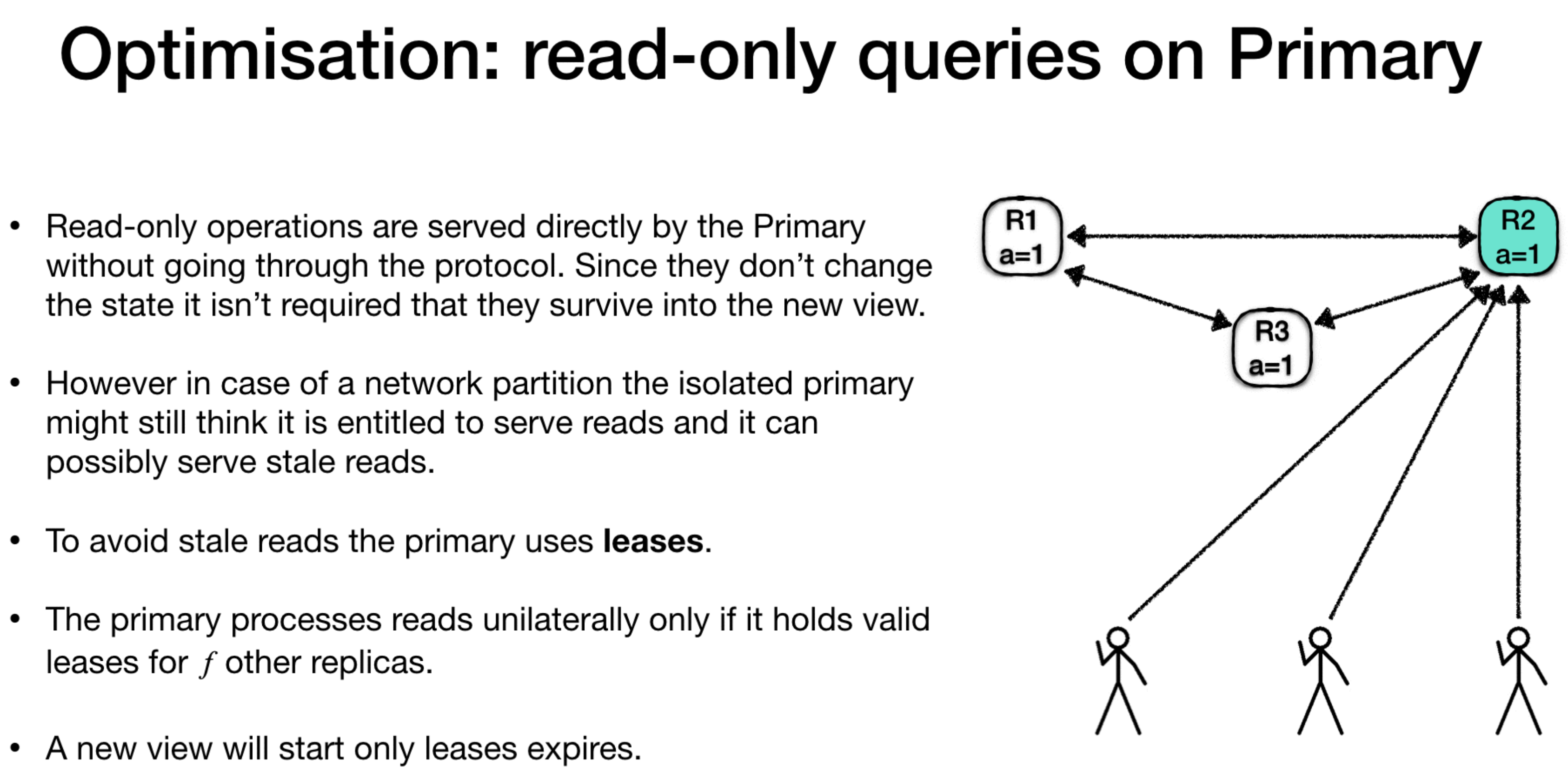
20 milliseconds or when 50 operations have been batched or whichever comes first, and then send the batch in a single `<PREPARE>` message.

The same strategy could be applied on the client side for batching client's requests, given that the client table is adjusted to accommodate a batch of requests.

Fast read-only requests on Primary

In the general definition of the protocol, read-only requests, which do not alter the state are served via the normal request processing. However since read requests do not need to survive a partition, they could be served *unilaterally* by the *primary* without contacting the other replicas.

The advantage of this optimisation is that read requests could benefit of shorter latency as there is no additional cost of running the protocol. However, in some case it is possible for the *primary* to serve *stale responses*. Let's consider the following case:



An ensemble with three replica nodes (`R1`, `R2`, `R3`) and `R2` is the current *primary*. A bunch of clients are connected to the primary and issuing requests. Requests manipulate a set of named registers. The current value of the register `a` is `1`. At a certain point a partition occur which isolates the primary (`R2`) from the rest of the ensemble and from most of the clients. Once the *view change protocol* kicks in replica `R3` will be elected as a new primary, and clients will reconnect to the new primary.

At this point one of the clients could request a change of the registry `a = 2` and the change would succeed because a *quorum* of replica nodes is available (`R1` and `R3`).

In the meanwhile the old primary (`R2`) is unaware of the change to the register `a` because the partition is still isolating communications. Therefore is not even aware that a new primary replica has been selected and it is no more the current primary.

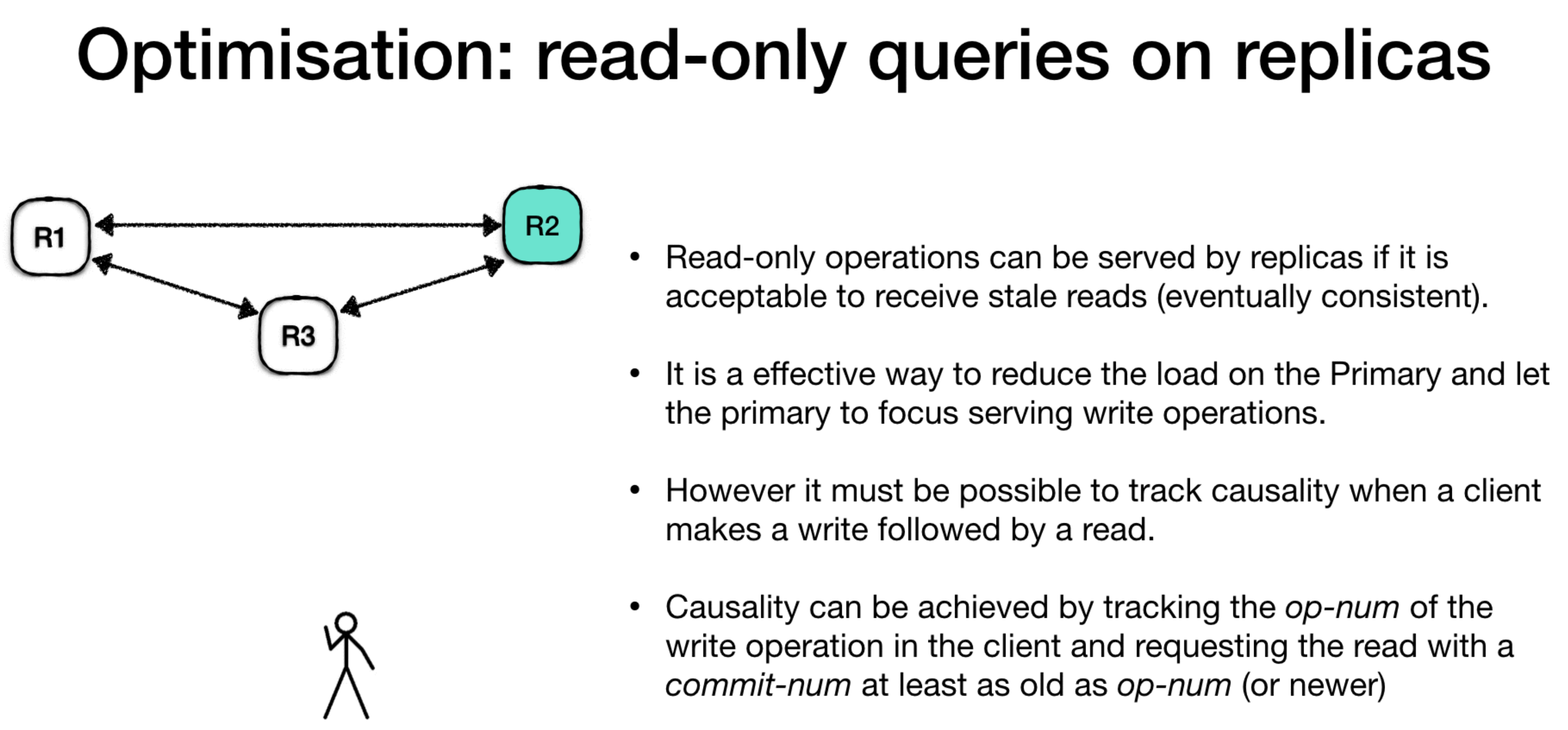
might still be able to talk to the old primary. In this case if the client is requesting the current value of register `a`, it will get a stale value.

To avoid this problem and make read-only requests possible to be served unilaterally by the primary we can make the use of **leases**. *A primary can only serve read-only requests without running the protocol and consulting with the other replicas if and only if, its lease is not expired.* When the lease expires, the primary must run the protocol and get the grant for a new lease which will ensure the view hasn't changed in the meantime. In case of a partition, the ensemble will have to wait for the lease to expire before triggering a view-change and select a new primary.

Read-only requests on other replicas

In high request volume systems, where the number of read requests are much higher than the write requests, and if clients systems can accept stale reads (eventually consistent reads), then read-only requests can be made directly to the follower replicas. It is a effective way to reduce the load on the Primary and scale out the reads across all replicas. The primary is always handling the writes.

In this situations it might be useful to track causality of client requests, for example a client makes a write followed by a read of the same value (read your own writes). Causality can be achieved by tracking the operation number `op-num` for a client write request and propagating back this information to the client. Clients interested in causal ordering can issue a read request to a follower replica stating the `op-num`. In this case the replica knows that it must respond to that request only after it advanced its `commit-num` past the request's `op-num`.



For example the client is connecting to the primary and ask for a write operation such as a registry increment (`write a = a + 1`), the primary will process the request as usual, but request. The client records the `op-num` and it uses to make subsequent requests to the follower replicas for a read-only request. The replica, if it hasn't processed the operation in the client request `op-num` it will have to wait until it the primary communicate that it is safe to do so and then reply.

Ensemble reconfiguration

As seen so far, each node needs to be known to the others for the protocol to work correctly. However, modern systems, especially in a cloud environment, tend to change frequently their ensemble configuration. Maybe as a response to the increasing or decreasing of load (elastically scalable systems), or just as a consequence of operational necessities (hardware replacement, network reconfiguration etc).

To face this increasingly common requirement the authors proposed a protocol extension to allow a reconfiguration of the ensemble. With this extension is possible to add, remove, or replace some or all nodes. The only limit is that the minimum allowed number of nodes is three, below this limit is not possible to achieve a quorum.

In order to support reconfiguration the replicas have to track additional properties. A monotonically increasing number called `epoch-num` tracks every reconfiguration, a property called `old-config` holds the previous configuration (list of nodes IPs, names, and IDs). Finally a new status called `transitioning` is used to mark when a reconfiguration is in progress.

A special client, typically with admin rights, will issue a `<RECONFIGURATION>` request. The request includes the current `epoch-num`, the `client-id`, the `request#` and the `new-config` with the list of all ensemble nodes which is expected to replace the current configuration.

The request will be sent to the primary and processed as a normal request. However, as soon as a `<RECONFIGURATION>` request is received by the primary it will stop accepting new client's requests. The other replicas will process the request as usual and send a `<PREPARE-OK>` message back to the primary. Once the primary receives a quorum of `<PREPARE-OK>` responses it will increase the `epoch-num` and send a `<COMMIT>` message to all replicas. At this point it sends a `<START-EPOCH>` to all new replicas (all the replicas which are part of the new configuration but not of the old configuration) and it sets the `status = transitioning`. The `<START-EPOCH>` contains the new `epoch-num` the primary `op-num` and both: the old and new configuration.

When the new replicas receive the `<START-EPOCH>` message they update the configuration taking `old-config` and `new-config` from the message itself, they reset the `view-num` to zero and set their `status = transitioning`. If a new replica is missing data in their `op-log` it will issue a `<GET-STATE>` request to the old replicas. Once the new replica is up to date, then it sets its `status = normal`, send a `<EPOCH-STARTED>` with the new `epoch-num` and its identity to the old group, and finally, the new primary will start to accept client requests.

sizing down. Additionally it can be used to replace a defective machine or also to migrate the entire cluster to a new set of more powerful machines.

Conclusions

As we seen the Viewstamped Replication algorithm is a fairly simple consensus algorithm and quite interesting replication protocol. It is quite simple to understand and, together with the many optimisations proposed, it can be implemented efficiently for real world application. Since it operates only on the interactions between replicas and clients it can be used as a "*library*" wrapper atop an existing system rendering the system distributed, high available and strictly consistent. For example it possible to take a single node file system and turn it into a distributed high available file system, which it was the initial motivation of the viewstamped replication protocol in first place. Moreover it could be used to wrap communications of systems such as Redis and Memcache or any other non-distributed system and turn it into a distributed, fault tolerant, high available and strictly consistent system.

Links and resources:

1. Paxos algorithm - The Part-Time Parliament, Leslie Lamport (1998) ↩

2. Viewstamped Replication: A New Primary Copy method to Support Highly-Available Distributed Systems, B. Oki, B. Liskov, (1988) ↩

3. Viewstamped Replication Revisited, B. Liskov, J.Cowling (2012) ↩

4. Viewstamped Replication presentation at PapersWeLove London ↩

5. The Byzantine Generals Problem, L. Lamport (1982) ↩

6. Implementing Fault-Tolerant Services Using the State Machine Approach: A Tutorial, Schneider, Fred (1990) ↩

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