Abstract

Consus is a strictly serializable geo-replicated transactional key-value store. The key contribution of Consus is a new commit protocol that reduces the cost of executing a transaction to three wide area message delays in the common case. Augmenting the commit protocol are multiple Paxos implementations optimized for different purposes. Together the different implementations and optimizations provide a cohesive system that provides low latency, high availability, and strong guarantees. This paper describes the techniques implemented in the open source release of Consus, and lays the groundwork for evaluating Consus once the system implementation is sufficiently robust for a thorough evaluation.

1 Introduction

Geo-replication is a common feature among distributed storage systems. A geo-replicated system can withstand correlated failures up to and including entire data centers, and may reduce latency for clients by directing them to nearby data centers. These systems differ from systems designed for a single data center because they must account for latencies in the wide area that are orders of magnitude larger than the latency for communication in a single data center; a system designed for low latency settings will likely perform poorly if geo-distributed.

The latency between geographically distinct locations forces systems to navigate an inherent tradeoff between latency and fault tolerance. Systems may make an operation withstand a complete data center failure by incurring the latency cost to propagate it to other data centers before reporting that the operation has finished. On the other side of the tradeoff, systems may avoid the latency cost by reporting that an operation is complete before it propagates to other data centers—at the risk that the operation is lost in a failure and never takes effect. An optimal point in this tradeoff would uphold a desired fault tolerance guarantee while minimizing latency.

This paper introduces Consus, a geo-replicated key-value store that supports strictly serializable cross-key transactions and executes transactions with three wide area message delays in the common case. It is easy to see why avoiding latency is desirable: any latency incurred on the critical path of a transaction directly impacts the performance of the application built on top. The decision to uphold strong guarantees is more a matter of taste; in practice, organizations building on eventually consistent systems teach developers anti-patterns to avoid or build special-purpose storage systems for apps that are sensitive to consistency anomalies.

The core idea that enables Consus to reduce inter-data center latency is a commit protocol based upon generalized consensus. Consus defers all inter-data center communication to the commit protocol—leaving the commit protocol to both globally replicate transactions and decide their outcomes. The commit protocol distributes the decision making process across all data centers and typically completes in three inter-data center message delays. Simply sending a message to a remote data center and receiving acknowledgement of its receipt—the bare minimum necessary to tolerate a failure—requires two such delays. Conventional commit protocols, such as 2-phase commit or Paxos, choose a single ensemble member to aggregate and disseminate information and communicating with this distinguished member necessarily incurs multiple inter-data center delays. Because Consus avoids a distinguished ensemble member, Consus commits with 33% less latency than other protocols, and incurs one more delay than the minimum necessary to uphold any degree of fault tolerance.

Consus’ design makes a concerted effort to build on existing protocols—primarily Paxos—to provide a principled argument for the system’s correctness.
ply reusing an existing implementation of multi-Paxos would suffice to uphold the safety guarantees of Consus and its commit protocol; however, we will see that a generic Paxos implementation introduces latency and failure sensitivities that negatively impact performance. To overcome these limitations, Consus uses multiple optimizations to Paxos that specialize Paxos to the task at hand, rather than treating it as a black-box component. Each Paxos implementation relies upon a different set of architectural constraints and protocol optimizations in order to decrease latency or improve availability without sacrificing the safety guarantees made by Paxos.

Overall, this paper makes three contributions. First and foremost, this paper presents a new commit protocol which reduces the inter-data center communication required to commit a transaction across multiple data centers. Second, it describes the optimized Paxos implementations within Consus outlining both the rationale behind each optimization and the way in which it differs from generic algorithms. Finally, this paper describes the future direction of the project.

The rest of this paper is as follows: Section 2 lays out the design of Consus, the inter-data center commit protocol, and the intra-data center structure. Section 3 describes optimized or modified Paxos protocols used within the design of Consus. Section 4 describes the state of the Consus implementation. Section 5 puts Consus into context with related work. Section 6 discusses future work on Consus and its publication. The paper concludes with Section 7.

2 Design

Consus uses well defined abstractions and builds upon proven protocols in order to constrain complexity. At the global scale, Consus treats each data center as a singular entity and runs a commit protocol across these entities. Internally each data center is not a singular entity, but a cluster providing its own partitioning and fault tolerance guarantees. Each cluster is further subdivided into a component for managing transaction execution, a component for storing the key-value pairs, and a component for executing the commit protocol. The commit protocol serves as the singular point for inter-data center communication and communicates with the local storage through a narrowly defined interface; consequently, it is agnostic to the internals of the transaction manager or key-value store. Figure 1 summarizes this architecture.

Consus’ design has a realistic set of assumptions. It assumes that networks are asynchronous and that servers may experience crash or omission failures. Servers are assumed to recover all state from durable storage that was acknowledged as durable. Additionally, Consus assumes that there is some means by which servers that permanently fail will eventually be tagged as failed and removed from the cluster in order to restore the fault tolerance guarantees of Paxos. This mechanism need not be timely or accurate; a slow detection leaves the cluster available, but with slightly weaker fault tolerance, while an erroneous detection will be treated like any other crash failure.

2.1 Commit Protocol

The Consus commit protocol handles the task of executing a transaction across multiple data centers. The protocol takes as input a transaction from one data center, replays it in other data centers, and outputs a decision to commit or abort the transaction. It is intentionally constrained to focus solely on committing or aborting a transaction leaving all transaction execution and concurrency control considerations to other components.

Consus decides the outcome of a transaction in three logically distinct phases. In the first phase, a single data center executes the transaction; if the transaction executes to completion, it is sent to other data centers along with sufficient information to determine that these data centers’ executions match the execution in the original
In the second phase, each data center broadcasts the result of its own execution—whether it was able to reproduce the original execution—to all other data centers. In the final phase, the data centers feed these results to an instance of Generalized Paxos that allows all data centers to learn the transaction’s outcome.

It is the information learned during the final phase, combined with the flexibility of Generalized Paxos, that enables the commit protocol’s efficiency improvements. In 2-phase commit [4] and similar protocols [5, 13], the decision to commit is placed in an entity called a coordinator. Regardless of the coordinator’s construction, its fundamental purpose is to aggregate and disseminate information between participants in the protocol. This necessarily introduces at least one message delay for the coordinator to learn any information, and at least two message delays before the other participants learn any information. As we shall see as we explore the full Consus commit protocol, all participants are able to learn the requisite information—and be assured that all other participants will learn the same information—in just one message delay during phase three.

Phase One

Phase one of the commit protocol executes a transaction in one data center and then re-executes it in the remaining data centers. A re-execution is deemed successful if and only if committing the transaction would leave the underlying data affected by the transaction in a state that is indistinguishable from the state of the same data in the initial data center. In this way, the re-execution preserves the original execution, and ensures all data centers present a consistent view of the data.

Re-execution may fail for a variety of environmental or workload reasons. For example, re-executions may diverge when concurrently executing transactions operate on the same data. The process executing a transaction informs the commit protocol when a re-execution diverges. This enables each data center participating in the commit protocol to use information about its own execution in subsequent stages.

At the end of phase one, a data center knows its own (re-)execution outcome, and, if the outcome is successful, is willing to hold the transaction ready to commit until the protocol finishes. The commit protocol requires that the transaction manager guarantee the transaction can commit if the protocol outputs a commit decision.

Phase Two

Phase two of the commit protocol consists of each data center independently broadcasting the result of its phase one execution to all other data centers. It is not necessary for other data centers to finish—or have even started—executing a transaction before receiving the phase two message from another data center as long as the message’s receipt is durably recorded.

There is no special insight to phase two because its purpose is exactly what it seems: Phase 2 informs most data center about most other data center’s executions. Because failure is inevitable, it is impossible for every data center to know about every other data center, nor whether any broadcasts were received. For this reason, while phase two is presented as a logically discrete action, even completely operational data centers will continually broadcast their execution to other data centers until the protocol runs to completion.

Phase Three

Phase three of the commit protocol enables data centers to combine the information broadcast by phase two into a single result learned by all data centers. Whereas phase two disseminates the outcome of the executions, phase three aggregates them in a durable manner and ensures that all data centers agree upon the aggregated value.

The value learned by data centers in phase three is a set of commit or abort results from the data centers involved in the transaction. This set of results is maintained by an instance of Generalized Paxos. As individual data centers learn the set of results from the Generalized Paxos protocol, the data centers count the results and decide whether to commit or abort the transaction.

The Generalized Paxos protocol learns a partially ordered set (poset) of values. In phase three, these values are the phase two results, and there exists no order across these results. The primary contribution of Generalized Paxos is to provide a fast path by which acceptors can extend the accepted value poset by directly adding elements, so long as each acceptor has the same partial order across elements. Because phase two results are inherently unordered, acceptors can always propose these results and remain on the fast path of Generalized Paxos.

The structure of phase three allows each data center’s acceptor to independently accept a value with sufficient information to decide to commit or abort. The data centers can then broadcast this accepted value with a single Paxos Phase 2B message to the other data centers. Once each data center receives a quorum of these Phase 2B messages, it can independently learn the poset of results without consulting other data centers.

In summary, at the beginning of phase three, each data center has the result from every other data center. Each data center proposes to its own local acceptor these values and then broadcasts its acceptor’s state. This third broadcast is the third message delay in the commit protocol. Upon receiving the majority of these broadcasts, every data center can calculate the learned value of these accepted values without any single data center coordinating the learned value.
Avoiding Deadlock

The invariants that the Consus commit protocol imposes on the rest of the system make it possible for transactions to deadlock. Specifically, the constraint that a transaction remain committable until the commit protocol returns a decision will introduce behavior analogous to the classic problem of deadlock in a lock-based database system. Figure 2 shows an example deadlock arising from three data centers each touching the same data.

To prevent deadlock, the commit protocol accepts upcalls from the transaction execution component that indicate when a transaction may be potentially deadlocked. Such an upcall signals to the commit protocol that the transaction might not ever commit and the protocol should act to avoid the deadlock. For some transactions, the transaction’s outcome may already be decided by the time the upcall reaches the commit protocol. These transactions require no special consideration.

The commit protocol will attempt to abort transactions that have no outcome at the time of the upcall. This process is complicated by the fact that an upcall may be generated within any data center, but all data centers must uniformly agree on a transaction’s outcome. Consequently, all data centers must also agree to act to abort a transaction in response to a potential deadlock.

In response to deadlock, data centers may atomically signal their intent to retract a previously-recorded commit result and replace it with an abort result. To do this, the data center proposes the upcall to the Generalized Paxos instance of phase three of the commit protocol. Other data centers can then negate the previous commit result and count it as an abort result instead.

In order to ensure that a retraction is treated the same by all data centers, retractions are totally ordered with respect to all other elements in the learned poset. This partial ordering guarantees that data centers will not diverge when counting results. The data center tallies results in accordance with the partial order present in the set. If the commit total exceeds a quorum before a retraction is processed, the retraction is ignored; otherwise, the total shifts toward aborting the transaction. The partial order induced on the set ensures that results may be seen in any order, but the total commit and abort results encountered before a retraction are the same in all learned values. Similarly, because retractions are totally ordered all data centers will see the retractions in the same order.

The deadlock avoidance algorithm may force Generalized Paxos protocol to fall back to a classic Paxos round to resolve conflicts. These conflicts occur when the partial order at one acceptor differs from the partial order at another acceptor. Generalized Paxos will fall back to one or more rounds of the traditional Paxos protocol to resolve these conflicts. Because these additional rounds of Paxos take place in the wide area, they increase the number of message delays a transaction will encounter—however this cost is incurred only when data centers are attempting to abort a transaction due to deadlock.

Heuristics can be used to propose retractions to Generalized Paxos in a way that is unlikely to generate conflicts. For example, each data center may delay proposing any retractions to its local acceptor until the set of results it has previously proposed combined with the unproposed retractions would yield an abort outcome. The data center could then propose the retractions in a pre-determined order that ensures that all data centers propose retractions in the same order. This is the simplest heuristic one could employ to keep Generalized Paxos from reverting to Classic Paxos; it is certainly worth investigating other heuristics alongside an investigation of ways to reduce the likelihood of abort upcalls in the underlying transaction execution engine.

Data Center Failure

Thus far, we have explored the commit protocol without regard to data center failure. While the protocol is resilient to a minority of data center failures, additional considerations are necessary to make the protocol return to a steady state after a data center recovers from failure. Specifically, any transactions executed while a data center is unavailable will not be propagated to the data center by the commit protocol; an additional mechanism is necessary to propagate any missed transactions.

A simple, but inefficient, approach is to have every data center continually synchronize state with other data centers. This ensures that any data committed in a majority of data centers will eventually propagate to all other data centers. The downside to this technique is that it requires background synchronization and any transaction that relies upon data that has yet to propagate will abort
at all out-of-sync data centers.

In order to quickly bring data centers up to date and avoid background communication, Consus also uses the information embedded in the phase one execution log to bring a data center up to date. The execution log includes information about every data item read during the transaction. Because transactions will only read committed data, it stands to reason that any read performed within a transaction is reading data that must exist in the key-value store. Consequently, the transaction execution engine can turn a read for missing data into an implicit write that restores missing data. While this is less efficient than reading the data, it incurs no latency waiting for the data center to become up-to-date—the data center can immediately commit the transaction.

Consus employs both of these techniques to recover from data center failure. The former technique ensures that all data becomes replicated to all requisite data centers, while the latter technique prevents a data center from appearing unavailable between cross-data center synchronization events.

2.2 Intra-Data Center Design

Within each data center, Consus is divided into two distinct execution components: a transaction manager and key-value storage. The transaction manager presents the sole interface to the client and uses two-phase locking as its concurrency control mechanism. The key-value storage serves as the component of record for each object stored within Consus and also stores the locks used by the transaction manager.

Transaction Manager

The transaction manager component durably records transactions during their execution. This ensures that all information about a transaction is recorded in one location and not scattered about the cluster. Upon failure of an entire data center, this logically centralized location provides a direct means to resume a transactions’ execution without having to gather the information from many disparate points around the cluster.

For scalability and fault tolerance, the transaction manager is partitioned across multiple Paxos groups. Each transaction executes as a replicated state machine at exactly one of these Paxos groups. Consequently, the transaction can be scaled to accommodate more transactions by adding additional servers and Paxos groups. With each additional Paxos group comes the ability to log more operations to disk. For workloads with low contention, this leads to a direct increase in performance. Figure 3 summarizes this architecture.

Transactions execute as a replicated state machine at a single Paxos group. Clients submit begin, read, write, and commit operations to the group, which then durably records and agrees upon the sequence of events issued by the client. The group interacts with the rest of the cluster on behalf of the client, acquiring locks, proxying reads, buffering writes, and releasing locks.

When the client commits the transaction, the Paxos group will hand the entire record of the transaction to the commit protocol. If the transaction commits, the transaction manager will flush the buffered writes to the key-value store before releasing locks, while immediately acknowledging the commit to the client. Thus, even when the client fails, the transaction manager group may push a transaction to completion, or abort the transaction and clean up any state affected by the transaction.

One benefit of this sharded and replicated structure that is not immediately obvious is the ability to isolate multiple tenants’ transaction managers by directing different tenants or applications to different Paxos groups. This isolation at the hardware level makes it impossible for one overly aggressive application to affect the performance of other, possibly higher priority, applications’ transaction execution. This isolation only goes as far as isolation at the transaction manager level. Transactions that touch the same data are not isolated because of contention at the key-value store.

Key-Value Storage

The key-value store maintains a partitioned sorted map from bytestring keys to stored objects. It internally handles replication and partitioning of the data across multiple storage servers to enable the cluster to scale to many petabytes in size. By keeping the details of the key-value store’s replication and partitioning mechanisms internal to the key-value component, the component’s interface may be simplified to a small number of well-defined RPCs that may be issued to any server in the key-value store. This decision is in contrast to systems like HyperDex that maintain logic in the client library for routing requests to servers, and re-routing or failing re-
mapping. The stable marriage algorithm then determines which ranges of partitions servers will adopt. Ranges left empty by the stable marriage algorithm are assigned to new servers.

Consus divides the key-value space into a constant number of partitions in order to simplify the implementation and allow for global decisions during repartitioning events. By maintaining a constant number of partitions, Consus can compactly represent a mapping from each server to a range of partitions the server stores. Replicas of the data are stored by the servers adjacent to the data in the key space; this enables the servers to takeover serving a partition with minimal movement of data across servers. This design is in contrast to systems which store fixed-size ranges of the key-space and maintain a lookup table between keys and the range they map to. Such a scheme can grow to an unlimited number of constant-sized ranges and require that extra state be maintained to track the ranges themselves.

When servers join or depart the cluster, a single fault tolerant process within the cluster determines a globally optimal rebalanced form of the cluster and issues this new mapping to servers within the cluster. The process uses a variant of the stable marriage algorithm to rebalance the cluster. The algorithm creates a new ideal mapping to the key-value storage nodes that divides the constant number of partitions in the cluster into contiguous ranges of partitions, each of which will be assigned to a single node. It then assigns a preference each server has for each of these ranges by counting the number of partitions the server has that fall within the range. This preference between servers and partitions serves as input to the stable marriage algorithm, which will align each server with a range of partitions with a guarantee analogous to a stable marriage in the original algorithm. Figure 4 shows an 8-partition cluster growing from five nodes to seven, the preferences between the old nodes and new partitions, and how new nodes are distributed to the unassigned partitions.

To maximize the effectiveness of this assignment, the key-value store incrementally changes from one assignment to the next. Servers will incrementally adopt their assigned ranges, one partition at a time to ensure that at all times they are assigned to a contiguous range of partitions. This guarantees that any incremental assignment between two mappings can also serve as an input to the global optimization algorithm. Thus, work performed migrating from one configuration to the next will can be reused—even when the cluster dramatically changes in structure.

One open question regarding the stable marriage algorithm is the extent to which replication should be considered. The current design considers only a singular server for each partition, but could be adapted to consider replication when computing the weighting. In practice, this would likely produce a very similar result, but would be complex when disparate key spaces hosted on the key-value store specify different replication factors.

3 Paxos Optimizations

Consus uses multiple optimizations to Paxos to provide better performance than off-the-shelf Paxos implementations. In this section we will explore these optimizations and examine how they can improve on an off-the-shelf Paxos protocol. For each technique described, we will look at why the technique retains the safety that Consus requires of Paxos and, where relevant, why the technique is not generally applicable to all Paxos implementations.

3.1 Avoiding Paxos

The most elementary optimization is to avoid using Paxos entirely. The transaction state machine in the transaction manager was originally implemented using a standard Multi-Paxos protocol. Because of the unique structure of the transaction state machine, namely that there is a single source of all proposals, it was easy to completely avoid using Paxos with no loss of safety.

Because there is a single proposer, sequencing the operations does not require consensus—the single proposer has already sequenced the operations. The members of the ensemble need only durably log this sequence. In an off-the-shelf Multi-Paxos library, the single client would send all operations through a single member that would propose the operations to the cluster.

The reason that Consus is able to avoid Paxos entirely in this particular instance is because the client and the transaction have a shared fate. If the client dies, there cannot be any more proposals issued to the clus-
ter. Therefore when the client dies, the transaction log will not grow further. If a client dies, or takes too long to issue additional operations to a transaction, the transaction will be garbage collected and further operations will be rejected. This optimization can only be applied when there exists a shared fate between the state machine and the source of proposed values.

3.2 Capturing Side Effects

The transaction state machine in Consus records the operations a client wishes to execute. These operations drive a state machine that acquires locks, performs reads, and checks that writes may succeed. Before a transaction may commit, these side effects must complete. The fact that operations are logged by the state machine does not imply that their side effects have completed.

In order to determine when a transaction has executed and may be passed to the commit protocol, Consus uses another application of consensus to achieve agreement among the state machine ensemble. Consus instantiates a new instance of the Paxos Synod protocol for each member of the state machine ensemble. These Synod instances use the ensemble as the set of acceptors. Each Synod instance captures the outcome of the transaction for a different member of the ensemble. Thus, the execution of a transaction—specifically its side effects—is captured in these Synod instances.

Once a quorum of these Synod instances capture a successful execution, the transaction can proceed with the global commit algorithm. This guarantees that the entire transactions log is recoverable so long as any quorum of the transaction ensemble remains live.

This structure is intended to prevent a case where each individual operation in the transaction log is replicated to a quorum of the ensemble, but no one server knows the entire log. Because the entire log is necessary to invoke the commit protocol, it is necessary to ensure that the log is not only durable to a minority of failures, but that the complete log is fully replicated on a majority of the ensemble. Table 1 shows a simple example of a log that is durably replicated, but that does not uphold the invariants necessary for Consus.

| Operation | S1 | S2 | S3 | S4 | S5 |
|-----------|----|----|----|----|----|
| begin()   | ✓  | ✓  | ✓  | ✓  | ✓  |
| read(x)   | ✓  | ✓  | ✓  | ✓  | ✓  |
| write(x)  | ✓  | ✓  | ✓  | ✓  | ✓  |
| commit()  | ✓  | ✓  | ✓  | ✓  | ✓  |

Table 1: An example where every transaction operation is learned by a quorum of the servers (3), but no operation is learned by all servers, and no server learns of all operations.

mark that a server is failed. Invoking Synod instances in this manner ensures that all servers will only ever learn a success or a failure value for an instance of the Synod protocol. The invariant upheld by Consus is that a server may propose any value for its own Synod instance, but may only propose failure for other servers. This allows any server to unilaterally decide that a data center aborts a transaction, but requires a majority of servers agree that the data center can commit the transaction.

The additional Synod instances also allow the transaction garbage collection mechanism referred to earlier to safely abort local transactions. The garbage collector cannot directly propose to abort a transaction because the client is the only entity allowed to append operations to the transaction’s log. Instead, the garbage collector can prevent the transaction from ever making progress by proposing failure to each Synod instance and running the protocol until they complete. Because this only ever happens on transactions that have expired, it will not delay their execution.

3.3 Implicit Phase 1 Paxos

Consus instantiates multiple instances of Paxos and the Paxos Synod protocol per transaction. This is in contrast to traditional uses of Paxos where there is one long-lived instance of Paxos. Consequently, Phase 1 of Paxos is invoked much more often than would otherwise happen. Because Phase 1 includes durably logging on remote machines, it can be expensive, and to invoke it multiple times per transaction adds unnecessary overhead.

Often, one member of a Paxos ensemble will be a suitable default leader for the Paxos group because it is through its actions that the group is created. In such an instance where the entity driving the Paxos group is known in advance, Consus implicitly sets the entity as having lead a successful Phase 1 ballot. This avoids the network latency associated with the proposer actually following Phase 1 of the protocol and the I/O cost of each acceptor durably recording its Phase 1 promise. When both are almost surely to succeed, actually executing the protocol along the regular path is wasteful. In the rare event that the first proposer for a Paxos instance is not leading the implicitly chosen ballot, the proposer
could have thrashed with the likely proposer; the implicit Phase 1 delays the implicit proposer from thrashing because it will only learn of the new ballot when one of its proposals is rejected by an acceptor.

This is purely a performance optimization that largely amounts to changing a variable’s initialization. All members of the Paxos group must still retain the code paths necessary to perform Phase 1 of Paxos.

### 3.4 Recursive Generalized Paxos

The commit protocol discussed in Section 2.1 presents each data center as a singular entity participating in the protocol and running an instance of Generalized Paxos. Of course, if this were actually the case, a single server failure in one data center would make an entire data center appear offline, introducing more failure handling than would otherwise be desirable.

Consus makes the acceptors for the commit protocol’s Generalized Paxos protocol fault tolerant by sequencing its inputs through a data center-local Generalized Paxos instance. Running the global protocol’s acceptor on top of a local replicated state machine immediately makes the whole commit protocol withstand the failure of a single server without downtime; running it as a generalized state machine admits more concurrency and availability than would otherwise be available.

In a standard Paxos-replicated state machine, a single member of the ensemble operates as the leader for a ballot and proposes values using the authority of that ballot. If this member fails, another member of the ensemble must lead a higher ballot to continue proposing values to the cluster. This results in high latency during the transition, and deciding when a server is actually unavailable rather than executing slightly behind the others is a non-trivial task to do both quickly and without introducing thrashing between leaders.

In a Generalized Paxos-replicated state machine, any member of the ensemble may propose any value by directly adding it to its local acceptor’s partially ordered set (poset) of values. The value becomes accepted when the value appears in the greatest-upper-bound of the values accepted by a quorum of acceptors. Consequently, a value may be chosen once it reaches a quorum of the ensemble, without funneling the value through any single acceptor’s code paths necessary to perform Phase 1 of Paxos.

The partially ordered set of messages in recursive Generalized Paxos permits a higher degree of concurrency than a total order of messages would permit. By default any pair of messages will be ordered in the poset of messages unless a rule specifically exists that allows the messages to be unordered. The rules are:

- Phase 1B messages are always unordered with respect to other Phase 1B messages for the same ballot. These messages signal an acceptor following a new ballot and the order in which the acceptors follow the ballot is not significant.
- Phase 2B messages are unordered if there exists a greatest upper bound for the poset of the accepted values and the GUB is not ⊥. In Consus each of these values is a poset of results used in the commit protocol. These messages can commute because updating the acceptor’s accepted value to the one contained in the Phase 2B message can only extend the learned value and cannot violate the safety invariants of Generalized Paxos.
- Proposals are ordered using the same ordering rules used for the relation over the values being proposed. In Consus, this means that proposed results may always commute, while proposed retractions will never commute.
- Proposals may commute with Phase 2B messages so long as the value being proposed is unordered with respect to every element in the accepted value contained within the Phase 2B message; again, this ordering uses the ordering relation over the inner state machine’s poset elements.

These constraints are sufficient to enable recursive Generalized Paxos to efficiently decide the commit results without sending the results through any single machine for sequencing. The inner state machine is implicitly initialized to follow a ballot from the origin data center for a transaction. Then, absent a deadlock-triggered retraction, any number of Phase 2B and Proposal messages may arrive for the inner state machine and all will be unordered with respect to each other. At a high level of abstraction, each inner state machine is maintaining a set of commit or abort results and retractions for each data center. Each outer state machine maintains a copy of this inner state machine. At any instant in time the outer state machines may contain a different set of commit or abort results; however, the set will always be a subset
what could be learned by a global observer who can see every message. A single retraction will force the outer state machines to converge on a single agreed-upon sequence to the inner state machine before continuing, thus forcing the inner state machine’s values to converge as well. It is an open question whether the ordering over the inner state machine’s input could be further relaxed to admit more concurrency; it is certainly worth investigating more relaxed constraints alongside an investigation of ways to reduce the likelihood of abort upcalls in the transaction execution engine.

4 Implementation

The current Consus implementation is approximately 26 k lines of code that depends upon more than 44 k lines of supporting code that was originally written as dependencies of HyperDex. The Consus and HyperDex code-bases are distinct. Because HyperDex was written with a different set of assumptions from Consus, with a different set of desiderata, the HyperDex implementation was not a useful starting point on which to build Consus.

The biggest difference between HyperDex and Consus is in its approach to fault tolerance. HyperDex makes an $f + 1$ fault tolerance assumption, where each unit of $f + 1$ nodes can withstand a concurrent failure of any $f$ of those nodes. The implementation could not stand a concurrent failure of all $f + 1$ nodes without possibly losing data. Consus assumes that any or all nodes may fail and resume and its implementation has made this assumption from day one. Practically, this means that Consus is more conservative in its approach to data handling, opting to log data to disk rather than rely purely upon replication for fault tolerance. If Consus is to fluidly run in multiple data centers in the presence of failures, it must be able to run and restart in a single data center without incident, operator involvement, or a recovery procedure.

A more subtle result of the difference in fault tolerance assumptions is that Consus is engineered to hide latency anomalies to the extent possible. The Paxos tricks in Section 2 outline some of the methods used to hide latency. The implementation also takes as much system coordination off the critical path as it can. In HyperDex a replicated coordinator maintains group membership for the system. This coordinator is on the critical path for failure recovery in HyperDex and must issue a new configuration after each failure to enable value-dependent chaining to route around the failure. Consus employs a similar replicated coordinator, but keeps the configuration out of the critical path for maintaining availability in the face of failures—Paxos provides higher availability under failure than HyperDex’s chain-based protocol. The replicated coordinator is backed by Paxos, so ultimately both Consus and HyperDex remain available during a failure, but Consus does a better job of masking a failure and keeping latency consistent during a failure than HyperDex will.

4.1 Not Implemented Here

Consus is an early work-in-progress. While the commit protocol described in Section 2.1 and the Paxos optimizations described in Section 3 are both implemented to the extent described in this paper, Consus is not yet a fully implemented system. Specifically, the isolation described for transaction managers is not implemented, and there is no concept of schema management. Applications can write to arbitrary tables with arbitrary keys and values without restriction. In a future version of Consus, the system would provide support for independent schemas, each of which map a different key-space to the partitions of the key-value store, so that different skewed workloads can coexist side-by-side.

In a similar vein, Consus has only partially implemented fault tolerance code paths. Most modules can be written as a state machine that takes an input and has side effects. This state machine can be augmented with a no-input transition that repeats the side effects necessary to receive an end-to-end confirmation that the state machine has succeeded in its purpose. These transitions are all implemented. The missing fault tolerance code paths are largely confined to migrating data when moving partitions from one key-value store to another. The key-value stores will not move any of the data and instead converge to a new mapping almost immediately. This is simply an omission from the implementation; it will be added as the system matures.

Finally, the Consus implementation is not sufficiently mature for a thorough evaluation. While it is mature enough to demonstrate the functional basics of the system, and the core code paths necessary for steady state functioning do exist, the system needs further development in order to reach a state where a thorough and proper evaluation can take place. This is largely a performance-related concern: Any sufficiently large system must undergo a development phase where performance anomalies are systematically removed in order to provide consistent, reproducible performance results. Any evaluation of the current system is as likely to measure implementation anomalies as it is to measure the performance of the system’s contributions, and is unlikely to report stable results.

5 Related Work

Consus sits at the cross-section of distributed systems and transaction management. The commit protocol in particular makes a concerted effort to distinguish between the transaction execution—whose core ideas de-
To our knowledge, the recursive Generalized Paxos optimization described in that section is the first such algorithm that uses Paxos to make a Paxos state machine’s acceptors more fault tolerant than a single machine.

Recent work has presented Egalitarian Paxos [11], which provides high performance Paxos in the wide area. The authors show that Egalitarian Paxos can provide higher performance in the wide area than other Paxos protocols, including Generalized Paxos. Consus’ use of Generalized Paxos is much more specialized than the general replication that Egalitarian Paxos readily supports in order to tightly control latency.

6 Discussion

This paper presents a preliminary, and as of yet, untested, description of the contributions of Consus. The paper accompanies an open source release of the complete Consus code base. This is, in and of itself, an experiment to see to what extent a system can undergo review and feedback prior to formal publication.

Often the evaluation of a system is seen as the single biggest determining factor in whether a particular piece of work is worthy of publication, or one of the many papers rejected from a conference. While the evaluation of a system is important, it is inherently biased; systems researchers may unconsciously illuminate the most flattering aspects of a system while overlooking critical flaws. Good systems builders will often know what to evaluate in a system before the system itself is capable of such evaluation. During construction of an artifact, they will naturally tend to favor development in these areas and pay less attention to other aspects of the artifact's development. These other areas may be orthogonal concerns, relevant concerns that can be hand-waved away with black box applications of existing work, or relevant concerns that go unaddressed in the final evaluation.

Even the most well-intentioned of researchers have blind spots and the peer review process is intended to compensate for this by providing objective evaluation of the work. The extent to which a system is implemented is often implicitly stated by the paper; more importantly, the extent to which a system is not implemented is almost never stated. Thus, the peer review process operates through a layer of paper indirection where there is a description of an artifact and its evaluation, without any strong insight into the state of the artifact itself or how accurately the paper reflects the measured artifact. If the actual artifact is released at all, it often comes after publication, and possibly through restricted and less open means than the publication process itself.

The ACM recognizes the importance of artifact evaluation in the publication process [6]; this pre-publication is an effort to go one step further. By opening up Consus to review and feedback from academics and curious engi-
neers alike, we are able to better understand its strengths, limitations, and shortcomings prior to any formal publication. This is almost certainly an endeavor that is not without some degree of risk to the authors. Every publication has the possibility of being “scooped” when another publication is able to make enough of a substantially similar contribution as to render the original publication untenable. For authors, there is a real tension between withholding information in order to ensure that a publication is not scooped, and publishing information in order to receive feedback on it from ones peers. This process typically takes place behind closed doors, and often via a layer of paper indirection.

With Consus, the authors have chosen to release this preliminary description of the contributions of the system alongside the complete artifacts that will be evaluated in the eventual peer-reviewed publication. At the time of this publication, the artifact itself is not sufficiently robust to provide a rigorous evaluation platform. The development and testing necessary for a thorough evaluation test the limits of a small development team; to delay the process of outside review until such time that the system is robust for evaluation could quite literally consume years of developer resources. Any review that questions fundamentals of the system could require duplicating much of that effort. Releasing the code and a description of the system outside normal peer review channels can accelerate the critical feedback loop that makes peer review such a useful tool. It is our hypothesis that doing so will ease the eventual formal peer review and publication process; it is our hope that doing so will serve as a case study in ways to improve the review process as a whole as artifact evaluation becomes more pertinent to our field.

7 Conclusion

This paper introduces Consus, a new strictly serializable, geo-replicated key-value store. The key contribution of Consus is a commit protocol that can enable commit in three wide area message delays in the common case. Through the application of some Paxos optimizations, Consus is able to provide theoretically better performance than other geo-replicated systems.

This paper lays the ground work for understanding the properties of Consus, and points to the eventual evaluation of the system. The Consus source code is available in parallel to this work in order to facilitate more effective review of the work, and to permit a broader community to inspect and work with the artifact prior to a peer-reviewed publication.

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