Modular Composition of Coordination Services

Kfir Lev-Ari, ***Technion—Israel Institute of Technology;*** **Edward Bortnikov,** ***Yahoo Research;***
Idit Keidar, ***Technion—Israel Institute of Technology and Yahoo Research;***
Alexander Shraer, ***Google***

https://www.usenix.org/conference/atc16/technical-sessions/presentation/lev-ari

This paper is included in the Proceedings of the
2016 USENIX Annual Technical Conference (USENIX ATC '16).

June 22–24, 2016 • Denver, CO, USA

978-1-931971-30-0

Open access to the Proceedings of the
2016 USENIX Annual Technical Conference
(USENIX ATC '16) is sponsored by USENIX.

Modular Composition of Coordination Services

Kfir Lev-Ari[1], Edward Bortnikov[2], Idit Keidar[1,2], and Alexander Shraer[3]

[1]Viterbi Department of Electrical Engineering, Technion, Haifa, Israel
[2]Yahoo Research, Haifa, Israel
[3]Google, Mountain View, CA, USA

Abstract

Coordination services like ZooKeeper, etcd, Doozer, and Consul are increasingly used by distributed applications for consistent, reliable, and high-speed coordination. When applications execute in multiple geographic regions, coordination service deployments trade-off between performance, (achieved by using independent services in separate regions), and consistency.

We present a system design for modular composition of services that addresses this trade-off. We implement ZooNet, a prototype of this concept over ZooKeeper. ZooNet allows users to compose multiple instances of the service in a consistent fashion, facilitating applications that execute in multiple regions. In ZooNet, clients that access only local data suffer no performance penalty compared to working with a standard single ZooKeeper. Clients that use remote and local ZooKeepers show up to 7x performance improvement compared to consistent solutions available today.

1 Introduction

Many applications nowadays rely on coordination services such as ZooKeeper [28], etcd [9], Chubby [24], Doozer [8], and Consul [5]. A coordination service facilitates maintaining shared state in a consistent and fault-tolerant manner. Such services are commonly used for inter-process coordination (e.g., global locks and leader election), service discovery, configuration and metadata storage, and more.

When applications span multiple data centers, one is faced with a choice between sacrificing performance, as occurs in a cross data center deployment, and forgoing consistency by running coordination services independently in the different data centers. For many applications, the need for consistency outweighs its cost. For example, Akamai [40] and Facebook [41] use strongly-consistent globally distributed coordination services (Facebook's Zeus is an enhanced version of ZooKeeper) for storing configuration files; dependencies among configuration files mandate that multiple users reading such files get consistent versions in order for the system to operate properly. Other examples include global service discovery [4], storage of access-control lists [1] and more.

In this work we leverage the observation that, nevertheless, such workloads tend to be highly partitionable. For example, configuration files of user or email accounts for users in Asia will rarely be accessed outside Asia. Yet currently, systems that wish to ensure consistency in the rare cases of remote access, (like [40, 41]), globally serialize all updates, requiring multiple cross data center messages.

To understand the challenge in providing consistency with less coordination, consider the architecture and semantics of an individual coordination service. Each coordination service is typically replicated for high-availability, and clients submit requests to one of the replicas. Usually, update requests are serialized via a quorum-based protocol such as Paxos [32], Zab [29] or Raft [37]. Reads are served locally by any of the replicas and hence can be somewhat stale but nevertheless represent a valid snapshot. This design entails the typical semantics of coordination services [5, 9, 28] – atomic (linearizable [27]) updates and sequentially-consistent [31] reads. Although such weaker read semantics enable fast local reads, this property makes coordination services non-composable: correct coordination services may fail to provide consistency when combined. In other words, a workload accessing *multiple* consistent coordination services may not be consistent, as we illustrate in Section 2. This shifts the burden of providing consistency back to the application, beating the purpose of using coordination services in the first place.

In Section 3 we present a system design for modular composition of coordination services, which addresses this challenge. We propose deploying a single coor-

dination service instance in each data center, which is shared among many applications. Each application partitions its data among one or more coordination service instances to maximize operation locality. Distinct coordination service instances, either within a data center or geo-distributed, are then composed in a manner that guarantees global consistency. Consistency is achieved on the client side by judiciously adding synchronization requests. The overhead incurred by a client due to such requests depends on the frequency with which that client issues read requests to *different* coordination services. In particular, clients that use a single coordination service do not pay any price.

In Section 4 we present ZooNet, a prototype implementation of our modular composition for ZooKeeper. ZooNet implements a client-side library that enables composing multiple ZooKeeper ensembles, (i.e., service instances), in a consistent fashion, facilitating data sharing across geographical regions. Each application using the library may compose ZooKeeper ensembles according to its own requirements, independently of other applications. Even though our algorithm requires only client-side changes, we tackle an additional issue, specific to ZooKeeper – we modify ZooKeeper to provide better isolation among clients. While not strictly essential for composition, this boosts performance of both stand-alone and composed ZooKeeper ensembles by up to 10x. This modification has been contributed back to ZooKeeper [21] and is planned to be released in ZooKeeper 3.6.

In Section 5 we evaluate ZooNet. Our experiments show that under high load and high spatial or temporal locality, ZooNet achieves the same performance as an inconsistent deployment of independent ZooKeepers (modified for better isolation). This means that our support for consistency comes at a low performance overhead. In addition, ZooNet shows up to 7.5x performance improvement compared to a consistent ZooKeeper deployment (the "recommended" way to deploy ZooKeeper across data centers [13]).

We discuss related work in Section 6, and conclude the paper, and discuss future directions in Section 7.

In summary, this paper makes the following contributions:

- A system design for composition of coordination services that maintains their semantics.
- A significant improvement to ZooKeeper's server-side isolation and concurrency.
- ZooNet – a client-side library to compose multiple ZooKeepers.

2 Background

We discuss the service and semantics offered by coordination services in Section 2.1, and then proceed to discuss possible ways to deploy them in a geo-distributed setting in Section 2.2.

2.1 Coordination Services

Coordination services are used for maintaining shared state in a consistent and fault-tolerant manner. Fault tolerance is achieved using replication, which is usually done by running a quorum-based state-machine replication protocol such as Paxos [32] or its variants [29, 37].

In Paxos, the history of state updates is managed by a set of servers called *acceptors*, s.t. every update is voted on by a quorum (majority) of acceptors. One acceptor serves as *leader* and manages the voting process. In addition to acceptors, Paxos has *learners* (called *observers* in ZooKeeper and *proxies* in Consul), which are lightweight services that do not participate in voting and get notified of updates after the quorum accepts them. In the context of this paper, acceptors are also (voting) learners, i.e., they learn the outcomes of votes.

Coordination services are typically built on top of an underlying key-value store and offer read and update (read-modify-write) operations. The updates are linearizable, i.e., all acceptors and learners see the same sequence of updates and this order conforms to the real-time order of the updates. The read operations are sequentially consistent, which is a weaker notion similar to linearizability in that an equivalent sequential execution must exist, but it must only preserve the program order of each individual client and not the global real-time order. A client can thus read a stale value that has already been overwritten by another client. These weaker semantics are chosen in order to allow a single learner or acceptor to serve reads locally. This motivates using learners in remote data centers – they offer fast local reads without paying the cost of cross data center voting.

As an aside, we note that some coordination service implementations offer their clients an asynchronous API. This is a client-side abstraction that improves performance by masking network delays. At the server-side, each client's requests are handled sequentially, and so the interaction is well-formed, corresponding to the standard correctness definitions of linearizability and sequential consistency.

Unfortunately, these semantics of linearizable updates and sequentially consistent reads are not composable, i.e., a composition of such services does not satisfy the same semantics. This means that the clients cannot predict the composed system's behavior. As an example, consider two clients that perform operations concurrently

as we depict in Figure 1. Client 1 updates object x managed by coordination service s_1, and then reads an old version of object y, which is managed by service s_2. Client 2 updates y and then reads an old version of x. While the semantics are preserved at both s_1 and s_2 (recall that reads don't have to return the latest value), the resulting execution violates the service semantics since there is no equivalent sequential execution: the update of y by client 2 must be serialized after the read of y by client 1 (otherwise the read should have returned 3 and not 0), but then the read of x by client 2 appears after the update of x by client 1 and therefore should have returned 5.

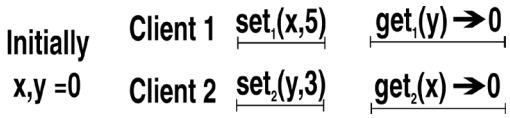


Figure 1: Inconsistent composition of two coordination services holding objects x and y: each object is consistent by itself, but there is no equivalent sequential execution.

2.2 Cross Data Center Deployment

When coordination is required across multiple data centers over WAN, system architects currently have three main deployment alternatives. In this section we discuss these alternatives with respect to their performance, consistency, and availability in case of partitions. A summary of our comparison is given in Table 1.

Alternative 1 – Single Coordination Service A coordination service can be deployed over multiple geographical regions by placing its acceptors in different locations (as done, e.g., in Facebook's Zeus [41] or Akamai's ACMS [40]), as we depict in Figure 2a. Using a single coordination service for all operations guarantees consistency.

This setting achieves the best availability since no single failure of a data center takes down all acceptors. But in order to provide availability following a loss or disconnection of any single data center, more than two locations are needed, which is not common.

With this approach, voting on each update is done across WAN, which hampers latency and wastes WAN bandwidth, (usually an expensive and contended resource). In addition, performance is sensitive to placement of the leader and acceptors, which is frequently far from optimal [39]. On the other hand, reads can be served locally in each partition.

Alternative 2 – Learners A second option is to deploy all of the acceptors in one data center and learners in others, as we depict in Figure 2b. In fact, this architecture was one of the main motivations for offering learners (observers) in ZooKeeper [13]. As opposed to acceptors, a learner does not participate in the voting process and it only receives the updates from the leader once they are committed. Thus, cross data center consistency is preserved without running costly voting over WAN. Often, alternatives 1 and 2 are combined, such as in Spanner [25], Megastore [22] and Zeus [41].

The update throughput in this deployment is limited by the throughput of one coordination service, and the update latency in remote data centers is greatly affected by the distance between the learners and the leader. In addition, in this approach we have a single point of failure, i.e., if the acceptors' data center fails or a network partition occurs, remote learners are only able to serve read requests.

Alternative 3 – Multiple Coordination Services In the third approach data is partitioned among several independent coordination services, usually one per data center or region, each potentially accompanied by learners in remote locations, as depicted in Figure 2c. In this case, each coordination service processes only updates for its own data partition and if applications in different regions need to access unrelated items they can do so independently and in parallel, which leads to high throughput. Moreover, if one cluster fails all other locations are unaffected. Due to these benefits, multiple production systems [4, 11, 18] follow this general pattern. The disadvantage of this design is that it does not guarantee the coordination service's consistency semantics, as explained in Section 2.1.

3 Design for Composition

In Section 3.1 we describe our design approach and our client-side algorithm for modular composition of coordination services while maintaining consistency. In Section 3.2 we discuss the properties of our design, namely correctness (a formal proof is given in an online Technical Report [33]), performance, and availability.

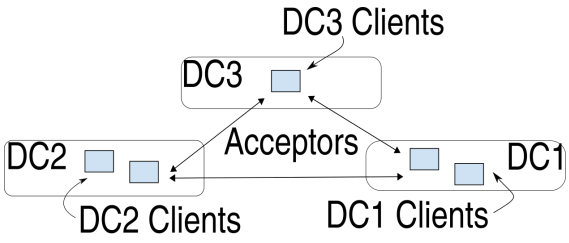
3.1 Modular Composition of Services

Our design is based on multiple coordination services (as depicted in Figure 2c), to which we add client-side logic that enforces consistency.

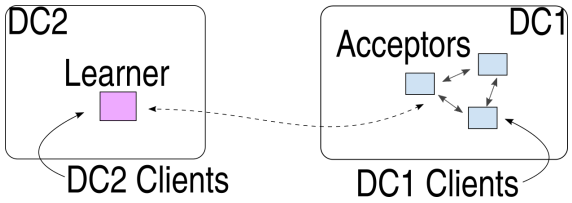
Our solution achieves consistency by injecting *sync* requests, which are non-mutating update operations. If the coordination service itself does not natively support such operations, they can be implemented using an update request addressed to a dummy object.

Alternative	Performance		Correctness	Availability during partitions	
	Updates	Reads		Updates	Reads
`Single Service`	Very slow	Fast	Yes	In majority	Everywhere
`Learners`	Slow	Fast	Yes	In acceptors	Everywhere
`Multiple Services`	Fast	Fast	No	Local	Everywhere
`Modular Composition`	Fast	Fast	Yes	Local	Local

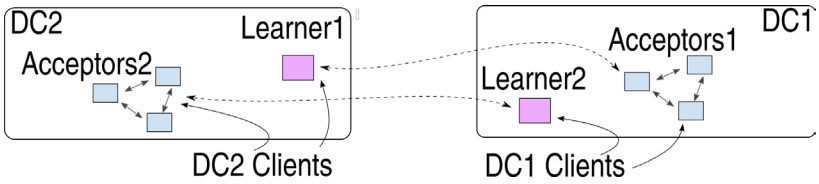
Table 1: Comparison of different alternatives for coordination service deployments across data centers. The first three alternatives are depicted in Figure 2. Our design alternative, *modular composition*, is detailed in Section 3.



(a) Single Service – Coordination service acceptors are deployed in all data centers, no single point of failure.



(b) Learners – Coordination service acceptors are deployed in one data center and learners in all other data centers.



(c) Multiple Services – A single coordination service is deployed in each data center and a learner is deployed in every other data center.

Figure 2: Different alternatives for coordination service deployment across data centers.

The client-side logic is implemented as a layer in the coordination service client library, which receives the sequential stream of client requests before they are sent to the coordination service. It is a state machine that selectively injects sync requests prior to some of the reads. Intuitively, this is done to bound the staleness of ensuing reads. In Algorithm 1, we give a pseudo-code for this layer at a client accessing multiple coordination services, each of which has a unique identifier.

An injected sync and ensuing read may be composed into a single operation, which we call *synced read*. A synced read can be implemented by buffering the local read request, sending a sync (or non-mutating update) to the server, and serving the read immediately upon receipt of a commit for the sync request. Some coordination services natively support such synced reads, e.g., Consul calls them consistent reads [6]. If all reads are synced the execution is linearizable. Our algorithm only makes some of the reads synced to achieve coordination service's semantics with minimal synchronization overhead.

Since each coordination service orders requests independently, concurrent processing of a client's updates at two coordination services may inverse their order. To avoid such re-ordering (as required, e.g., by ZooKeeper's FIFO program order guarantee), we refrain from asynchronously issuing updates to a new coordination service before responses to earlier requests arrive. Rather, we buffer requests whenever we identify a new coordination service target for as long as there are pending requests to other coordination services. This approach also guarantees that coordination service failures do not introduce gaps in the execution sequence of asynchronous requests.

3.2 Modular Composition Properties

We now discuss the properties of our modular composition design.

Algorithm 1 Modular composition, client-side logic.

```
1:  lastService ← nil            // Last service this client accessed
2:  numOutstanding ←0 // #outstanding requests to lastService
3:  onUpdate(targetService, req)
4:    if targetService ≠ lastService then
5:      // Wait until all requests to previous service complete
6:      wait until numOutstanding = 0
7:      lastService ← targetService
8:    numOutstanding++
9:    send req to targetService
10: onRead(targetService, req)
11:   if targetService ≠ lastService then
12:     // Wait until all requests to previous service complete
13:     wait until numOutstanding = 0
14:     lastService ← targetService
15:     numOutstanding++
16:     // Send sync before read
17:     send sync to targetService
18:   numOutstanding++
19:   send req to targetService
20: onResponse(req)
21:   numOutstanding−−
```

3.2.1 Correctness

The main problem in composing coordination services is that reads might read "from the past", causing clients to see updates of different coordination services in a different order, as depicted in Figure 1. Our algorithm adds sync operations in order to make ensuing reads "read from the present", i.e., read at least from the sync point. We do this every time a client's read request accesses a different coordination service than the previous request. Subsequent reads from the same coordination service are naturally ordered after the first, and so no additional syncs are needed.

In Figure 3 we depict the same operations as in Figure 1 with sync operations added according to our algorithm. As before, client 1 updates object x residing in service s_1 and then reads y from service s_2. Right before the read, the algorithm interjects a sync to s_2. Similarly, client 2 updates y on s_2, followed by a sync and a read from s_1. Since s_2 guarantees update linearizability and client 1's sync starts after client 2's update of y completes, reads made by client 1 after the sync will retrieve the new state, in this case 3. Client 2's sync, on the other hand, is concurrent with client 1's update of x, and therefore may be ordered either before or after the update. In this case, we know that it is ordered before the update, since client 2's read returns 0. In other words, there exists an equivalent sequential execution that consists of client 2's requests followed by client 1's requests, and this execution preserves linearizability of updates (and syncs) and sequential consistency of read requests, as required by the coordination service's semantics. See [33] for a formal discussion.

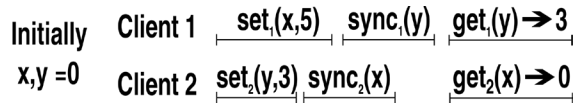


Figure 3: Consistent modular composition of two coordination services holding objects x and y (as in Figure 1): adding syncs prior to reads on new coordination services ensures that there is an equivalent sequential execution.

3.2.2 Performance

By running multiple independent coordination services, the modular composition can potentially process requests at a rate as high as the sum of the individual throughputs. However, sync requests take up part of this bandwidth, so the net throughput gain depends on the frequency with which syncs are sent.

The number of syncs corresponds to the temporal locality of the workload, since sync is added only when the accessed coordination service changes.

Read latency is low (accessing a local acceptor or learner) when the read does not necessitate a sync, and is otherwise equal to the latency of an update.

3.2.3 Availability

Following failures or partitions, each local coordination service (where a quorum of acceptors remains available and connected) can readily process update and read requests submitted by local clients. However, this may not be the case for remote client requests: If a learner in data center A loses connectivity with its coordination service in data center B, sync requests submitted to the learner by clients in A will fail and these clients will be unable to access the coordination service.

Some coordination services support state that corresponds to active client sessions, e.g., an ephemeral node in ZooKeeper is automatically deleted once its creator's session terminates. Currently, we do not support composition semantics for such session-based state: clients initiate a separate session with each service instance they use, and if their session with one ZooKeeper ensemble expires (e.g., due to a network partition) they may still access data from other ZooKeepers. Later, if the session is re-instated they may fail to see their previous session-based state, violating consistency. A possible extension addressing this problem could be to maintain a single virtual session for each client, corresponding to the composed service, and to invalidate it together with all the client's sessions if one of its sessions terminates.

4 ZooNet

We implement *ZooNet*, a modular composition of ZooKeepers. Though in principle, modular composition requires only client-side support, we identified a design issue in ZooKeeper that makes remote learner (observer) deployments slow due to poor isolation among clients. Since remote learners are instrumental to our solution, we address this issue in the ZooKeeper server, as detailed in Section 4.1. We then discuss our client-side code in Section 4.2.

4.1 Server-Side Isolation

The original ZooKeeper implementation stalls reads when there are concurrent updates by other clients. Generally speaking, reads wait until an update is served even when the semantics do not require it. In Section 4.1.1 we describe this problem in more detail and in Section 4.1.2 we present our solution, which we have made available as a patch to ZooKeeper [21] and has been recently committed to ZooKeeper's main repository.

4.1.1 ZooKeeper's Commit Processor

ZooKeeper servers consist of several components that process requests in a pipeline. When an update request arrives to a ZooKeeper server from a client, the server forwards the update to the leader and places the request in a local queue until it hears from the leader that voting on the update is complete (i.e., the leader has *committed* the request). Only at that point the update can be applied to the local server state. A component called *commit processor* is responsible for matching incoming client requests with commit responses received from the leader, while maintaining the order of operations submitted by each client.

In the original implementation of the commit processor, (up to ZooKeeper version 3.5.1-alpha), clients are not isolated from each other: once some update request reaches the head of the request stream, all pending requests by all clients connected to this server stall until a commit message for the head request arrives from the leader. This means that there is a period, whose duration depends on the round-trip latency between the server and the leader plus the latency of quorum voting, during which all requests are stalled. While the commit processor must maintain the order of operations submitted by each client, enforcing order among updates of *different* clients is the task of the leader. Hence, blocking requests of other clients in this situation, only because they were unlucky enough to connect via the same server, is redundant.

In a geo-distributed deployment, this approach severely hampers performance as it does not allow read operations to proceed concurrently with long-distance concurrent updates. In the context of modular composition, it means that syncs hamper read-intensive workloads, i.e., learners cannot serve reads locally concurrently with syncs and updates.

4.1.2 Commit Processor Isolation

We modified ZooKeeper's commit processor to keep a separate queue of pending requests per client. Incoming reads for which there is no preceding pending update by the same client, (i.e., an update for which a commit message has not yet been received), are not blocked. Instead, they are forwarded directly to the next stage of the pipeline, which responds to the client based on the current server state.

Read requests of clients with pending updates are enqueued in the order of arrival in the appropriate queue. For each client, whenever the head of the queue is either a committed update or a read, the request is forwarded to the next stage of the server pipeline. Updates are marked committed according to the order of commit messages received from the leader (the linearization order). For more details, see our ZooKeeper Jira [21].

4.2 The ZooNet Client

We prototyped the ZooNet client as a wrapper for ZooKeeper's Java client library. It allows clients to establish sessions with multiple ZooKeeper ensembles and maintains these connections. Users specify the target ZooKeeper ensemble for every operation as a znode path prefix. Our library strips this prefix and forwards the operation to the appropriate ZooKeeper, converting some of the reads to synced reads in accordance with Algorithm 1. Our sync operation performs a dummy update; we do so because ZooKeeper's sync is not a linearizable update [28]. The client wrapper consists of roughly 150 lines of documented code.

5 Evaluation

We now evaluate our modular composition concept using the ZooNet prototype. In Section 5.1 we describe the environment in which we conduct our experiments. Section 5.2 evaluates our server-side modification to ZooKeeper, whereas Section 5.3 evaluates the cost of the synchronization introduced by ZooNet's client. Finally, Section 5.4 compares ZooNet to a single ZooKeeper ensemble configured to ensure consistency using remote learners (Figure 2b).

5.1 Environment and Configurations

We conduct our experiments on Google Compute Engine [10] in two data centers, DC1 in eastern US (South Carolina) and DC2 in central US (Iowa). In each data center we allocate five servers: three for a local ZooKeeper ensemble, one for a learner connected to the remote data center, and one for simulating clients (we run 30 request-generating client threads in each data center). Each server is allocated a standard 4 CPU machine with 4 virtual CPUs and 15 GB of memory. DC1 servers are allocated on a 2.3 GHz Intel Xeon E5 v3 (Haswell) platform, while DC2 servers are allocated on a 2.5GHz Intel Xeon E5 v2 (Ivy Bridge). Each server has two standard persistent disks. The Compute Engine does not provide us with information about available network bandwidth between the servers. We use the latest version of ZooKeeper to date, version 3.5.1-alpha.

We benchmark throughput when the system is saturated and configured as in ZooKeeper's original evaluation (Section 5.1 in [28]). We configure the servers to log requests to one disk while taking snapshots on another. Each client thread has at most 200 outstanding requests at a time. Each request consists of a read or an update of 1KB of data. The operation type and target coordination service are selected according to the workload specification in each experiment.

5.2 Server-Side Isolation

In this section we evaluate our server-side modification given in Section 4.1. We study the learner's throughput with and without our change. Recall that the learner (observer in ZooKeeper terminology) serves as a fast local read cache for distant clients, and also forwards update requests to the leader.

We experiment with a single ZooKeeper ensemble running three acceptors in DC1 and an observer in DC2. Figure 4 compares the learner's throughput with and without our modification, for a varying percentage of reads in the workload. DC1 clients have the same workload as DC2 clients.

Our results show that for read-intensive workloads that include some updates, ZooNet's learner gets up to around 4x higher throughput by allowing concurrency between reads and updates of different clients, and there is 30% up to 60% reduction in the tail latency. In a read-only workload, ZooNet does not improve the throughput or the latency, because ZooKeeper does not stall any requests. In write-intensive workloads, reads are often blocked by preceding pending updates by the same client, so few reads can benefit from our increased parallelism.

Our Jira [21] provides additional evaluation (conducted on Emulab [43]) in which we show that the throughput speedup for local clients can be up to 10x in a single data center deployment of ZooKeeper. Moreover, ZooNet significantly reduces read and write latency in mixed workloads in which the write percentage is below 30 (for reads, we get up to 96% improvement, and for writes up to 89%).

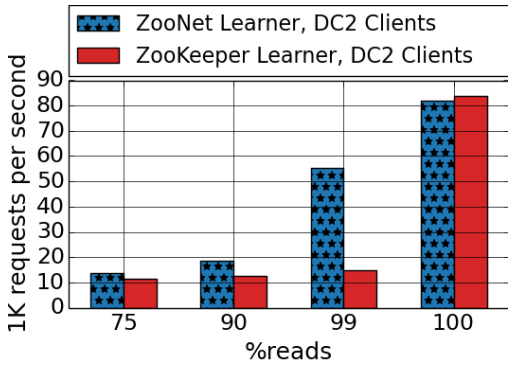


Figure 4: Improved server-side isolation. Learner's throughput as a function of the percentage of reads.

5.3 The Cost of Consistency

ZooNet is a composition of independent ZooKeepers, as depicted in Figure 2c, with added sync requests. In this section we evaluate the cost of the added syncs by comparing our algorithm to two alternatives: (1) Sync-All, where all reads are executed as synced reads, and (2) Never-Sync, in which clients never perform synced reads.

Never-Sync in not sequentially consistent (as illustrated in Figure 1). It thus corresponds to the fastest but inconsistent ZooKeeper deployment (Figure 2c), with ZooKeeper patched to improve isolation. At the other extreme, by changing all reads to be synced, Sync-All guarantees linearizability for all operations, including reads. ZooNet provides a useful middle ground (supported by most coordination services in the single-data center setting), which satisfies sequential consistency for all operations and linearizability for updates.

As a sanity check, we study in Section 5.3.1 a fully partitionable workload with clients accessing only local data in each data center. In Section 5.3.2 we have DC1 clients perform only local operations, and DC2 clients perform both local and remote operations.

5.3.1 Local Workload

In Figure 5 we depict the saturation throughput of DC1 (solid lines) and DC2 (dashed lines) with the three alternatives.

ZooNet's throughput is identical to that of Never-Sync in all workloads, at both data centers. This is because

ZooNet sends sync requests only due to changes in the targeted ZooKeeper, which do not occur in this scenario. Sync-All has the same write-only throughput (leftmost data point). But as the rate of reads increases, Sync-All performs more synced reads, resulting in a significant performance degradation (up to 6x for read-only workloads). This is because a read can be served locally by any acceptor (or learner), whereas each synced read, similarly to an update, involves communication with the leader and a quorum.

The read-only throughput of ZooNet and Never-Sync is lower than we expect: since in this scenario the three acceptors in each data center are dedicated to read requests, we would expect the throughput to be 3x that of a single learner (reported in Figure 4). We hypothesize that the throughput is lower in this case due to a network bottleneck.

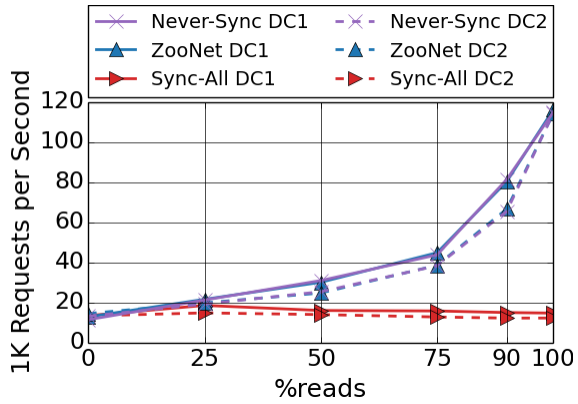


Figure 5: Saturated ZooNet throughput at two data centers with local operations only. In this sanity check we see that the performance of Never-Sync is identical to ZooNet's performance when no syncs are needed.

5.3.2 Remote Data Center Access

When clients access remote data, synced reads kick-in and affect performance. We now evaluate the cost of synced reads as a function of workload locality. We define two workload parameters: *local operations*, which represents spatial locality, namely the percentage of requests that clients address to their local data center, and *burst*, which represents the temporal locality of the target ZooKeeper. For simplicity, we consider a fixed burst size, where the client sends *burst* requests to the same ZooKeeper and then chooses a new target ZooKeeper according to the local operations ratio. Note that a burst size of 1 represents the worst-case scenario for ZooNet, while with high burst sizes, the cost of adding syncs is minimized.

Our design is optimized for partitionable workloads where spatial locality is high by definition since clients rarely access data in remote partitions. In ZooKeeper, another factor significantly contributes to temporal locality: ZooKeeper limits the size of each data object (called znode) to 1MB, which causes applications to express stored state using many znodes, organized in a hierarchical manner. ZooKeeper intentionally provides a minimalistic API, so programs wishing to access stored state (e.g., read the contents of a directory or sub-tree) usually need to make multiple read requests to ZooKeeper, effectively resulting in a high burst size.

In Figure 6 we compare ZooNet to Sync-All and Never-Sync with different burst sizes where we vary the local operations ratio of DC2 clients. DC1 clients perform 100% local operations. We select three read ratios for this comparison: a write-intensive workload in which 50% of the requests are updates (left column), a read-intensive workload in which 90% of the requests are reads (middle column), and a read-only workload (right column). DC1 clients and DC2 clients have the same read ratio in each test.

Results show that in a workload with large bursts of 25 or 50 (bottom two rows), the addition of sync requests has virtually no effect on throughput, which is identical to that of Never-Sync except in read-intensive workloads, where with a burst of 25 there is a slight throughput degradation when the workload is less than 80% local.

When there is no temporal locality (burst of 1, top row), the added syncs induce a high performance cost in scenarios with low spatial locality, since they effectively modify the workload to become write-intensive. In case most accesses are local, ZooNet seldom adds syncs, and so it performs as well as Never-Sync regardless of the burst size.

All in all, ZooNet incurs a noticeable synchronization cost only if the workload shows no locality whatsoever, neither temporal nor spatial. Either type of locality mitigates this cost.

5.4 Comparing ZooNet with ZooKeeper

We compare ZooNet with the fastest cross data center deployment of ZooKeeper that is also consistent, i.e., a single ZooKeeper ensemble where all acceptors are in DC1 and a learner is located in DC2 (Figure 2b). The single coordination service deployment (Figure 2a) is less efficient since: (1) acceptors participate in the voting along with serving clients (or, alternatively, more servers need to be deployed as learners as in [41]); and (2) the voting is done over WAN (see [13] for more details). We patch ZooKeeper with the improvement described in Section 4.1 and set the burst size to 50 in order to focus the current discussion on the impact that data locality has on performance.

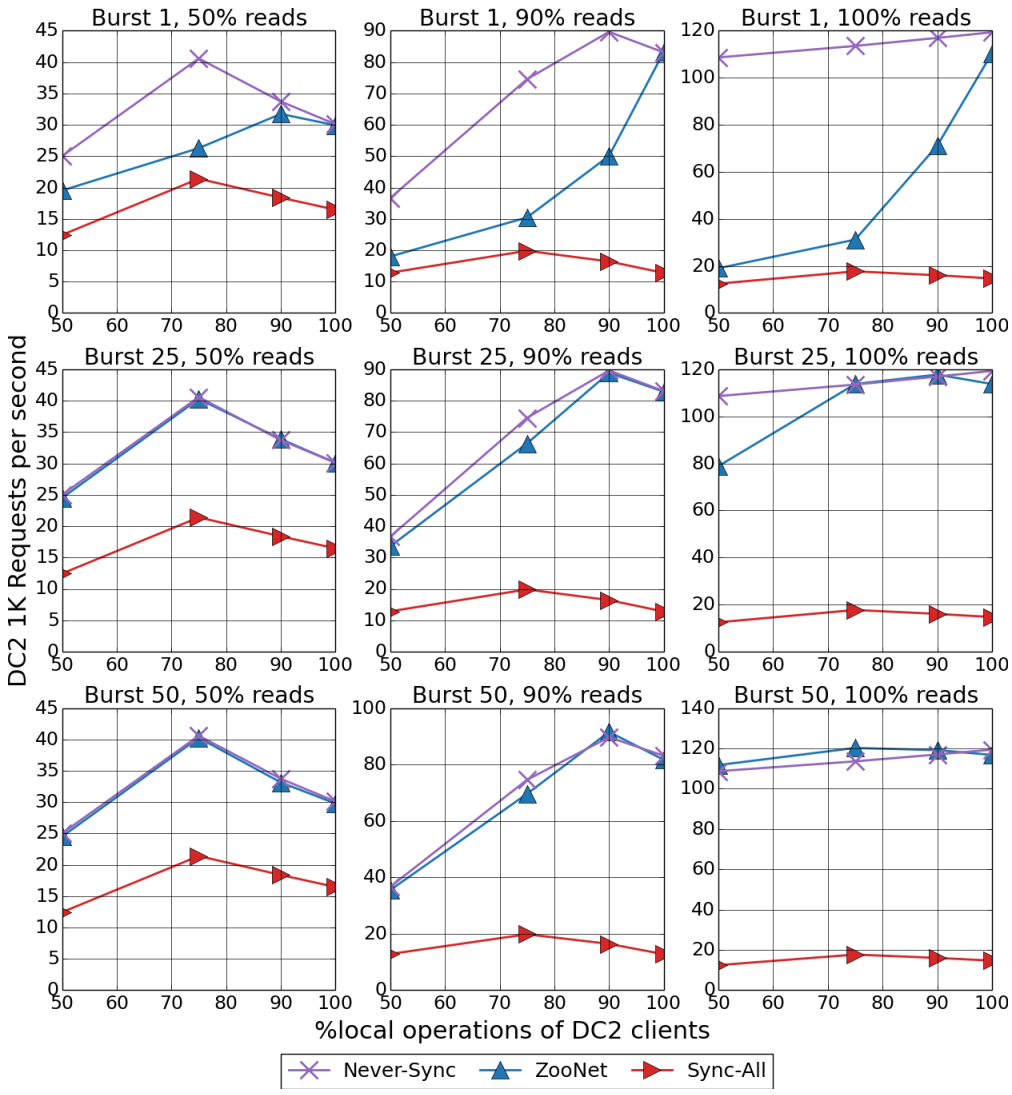


Figure 6: Throughput of ZooNet, Never-Sync and Sync-All. Only DC2 clients perform remote operations.

We measure aggregate client throughput and latency in DC1 and DC2 with ZooKeeper and ZooNet, varying the workload's read ratio and the fraction of local operations of the clients in DC2. We first run a test where all operations of clients in DC1 are local. Figure 7a shows the throughput speedup of ZooNet over ZooKeeper at DC1 clients, and Figure 7b shows the throughput speedup for DC2 clients.

Our results show that in write-intensive workloads, DC2 clients get up to 7x higher throughput and up to 92% reduction in latency. This is due to the locality of update requests in ZooNet, compared to the ZooKeeper deployment in which each update request of a DC2 client is forwarded to DC1. The peak throughput saturates at the update rate that a single leader can handle. Beyond that saturation point, it is preferable to send update operations to a remote DC rather than have them handled locally, which leads to a decrease in total throughput.

In read-intensive workloads (90% – 99% reads), DC2 clients also get a higher throughput with ZooNet (4x to 2x), and up to 90% reduction in latency. This is due to the fact that in ZooKeeper, a single learner can handle a lower update throughput than three acceptors. In read-only workloads, the added acceptors have less impact on throughput; we assume that this is due to a network bottleneck as observed in our sanity check above (Figure 5).

In addition, we see that DC1 clients are almost unaffected by DC2 clients in read-intensive workloads. This is due to the fact that with both ZooKeeper and ZooNet, reads issued by clients in DC2 are handled locally in DC2. The added synced reads add negligible load to the acceptors in DC1 due to the high burst size and locality

of requests (nevertheless, they do cause the throughput speedup to drop slightly below 1 when there is low locality). With a write-intensive workload, DC1 clients have a 1.7x throughput speedup when DC2 clients perform no remote operations. This is because remote updates of DC2 clients in ZooKeeper add to the load of acceptors in DC1, whereas in ZooNet some of these updates are local and processed by acceptors in DC2.

Finally, we examine a scenario where clients in both locations perform remote operations. Figure 8a shows the throughput speedup of ZooNet over ZooKeeper achieved at DC1 clients, and Figure 8b shows the throughput speedup of DC2 clients. All clients have the same locality ratio. Each curve corresponds to a different percentage of reads.

There are two differences between the results in Figure 8 and Figure 7. First, up to a local operations ratio of 75%, DC1 clients suffer from performance degradation in read-intensive workloads. This is because in the ZooKeeper deployment, all the requests of DC1 clients are served locally, whereas ZooNet serves many of them remotely. This re-emphasizes the observation that ZooNet is most appropriate for scenarios that exhibit locality, and is not optimal otherwise.

Second, the DC1 leader is less loaded when DC1 clients also perform remote updates (Figure 8). This mostly affects write-intensive scenarios (top blue curve), in which the leaders at both data centers share the update load, leading to higher throughput for all clients. Indeed, this yields higher throughput speedup when locality is low (leftmost data point in Figures 8a and 8b compared to Figures 7a and 7b, respectively). As locality increases to 70%–80%, the DC2 leader becomes more loaded due to DC2s updates, making the throughput speedup in Figures 7b and Figure 8b almost the same, until with 100% local updates (rightmost data point), the scenarios are identical and so is the throughput speedup.

6 Related Work

Coordination services such as ZooKeeper [28], Chubby [24], etcd [9], and Consul [5] are extensively used in industry. Many companies deploying these services run applications in multiple data centers. But questions on how to use coordination services in a mutli-data center setting arise very frequently [4, 11, 15, 16, 17], and it is now clear that the designers of coordination services must address this use-case from the outset.

In what follows we first describe the current deployment options in Section 6.1 followed by a discussion of previously proposed composition methods in Section 6.2.

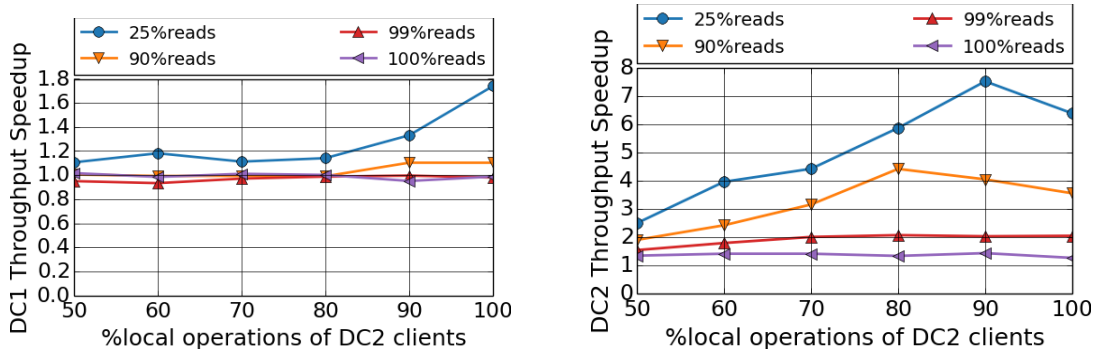
A large body of work, e.g., [30, 34, 35], focuses on improving the efficiency of coordination services. Our work is orthogonal – it allows combining multiple instances to achieve a single system abstraction with the same semantics, while only paying for coordination when it is needed.

6.1 Multi-Data Center Deployment

In Section 2 we listed three prevalent strategies for deploying coordination services across multiple data centers: a single coordination service where acceptors are placed in multiple data centers, a single coordination service where acceptors run in one data center, or multiple coordination services. The choice among these options corresponds to the tradeoff system architects make along three axes: consistency, availability, and performance (a common interpretation of the CAP theorem [7]). Some are willing to sacrifice update speed for consistency and high-availability in the presence of data center failures [22, 25, 40, 41]. Others prefer to trade-off fault-tolerance for update speed [13], while others prioritize update speed over consistency [4, 11]. In this work we mitigate this tradeoff, and offer a fourth deployment option whose performance and availability are close to that of the third (inconsistent) option, without sacrificing consistency.

Some systems combine more than one of the deployment alternatives described in Section 2. For example, Vitess [20] deploys multiple local ZooKeeper ensembles (as in Figure 2c) in addition to a single global ensemble (as in Figure 2a). The global ensemble is used to store global data that doesn't change very often and needs to survive a data center failure. A similar proposal has been made in the context of SmartStack, Airbnb's service discovery system [12]. ZooNet can be used as-is to combine the local and global ensembles in a consistent manner.

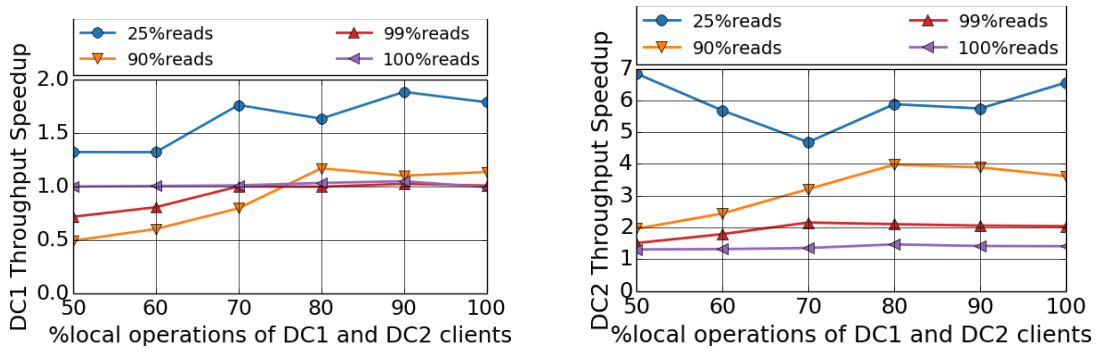
Multiple studies [38, 44] showed that configuration errors and in particular inconsistencies are a major source of failure for Internet services. To prevent inconsistencies, configuration stores often use strongly consistent coordination services. ACMS [40] is Akamai's distributed configuration store, which, similarly to Facebook's Zeus [41], is based on a single instance of a strongly consistent coordination protocol. Our design offers a scalable alternative where, assuming that the stored information is highly partitionable, updates rarely go through WAN and can execute with low latency and completely independently in the different partitions, while all reads (even of data stored remotely) remain local. We demonstrate that the amortized cost of sync messages is low for such read-heavy systems (in both ACMS and Zeus the reported rate of updates is only hundreds per hour).



(a) Throughput speedup of DC1 clients.

(b) Throughput speedup of DC2 clients.

Figure 7: Throughput speedup (ZooNet/ZooKeeper). DC1 clients perform only local operations. The percentage of read operations is identical for DC1 clients and DC2 clients.



(a) Throughput speedup of DC1 clients.

(b) Throughput speedup of DC2 clients.

Figure 8: Throughput speedup (ZooNet/ZooKeeper). DC1 clients an DC2 clients have the same local operations ratio as well as read operations percentage.

6.2 Composition Methods

Consul [5], ZooFence [26] and Volery [23] are coordination services designed with the multi-data center deployment in mind. They provide linearizable updates and either linearizable or sequentially consistent reads. Generally, these systems follow the multiple coordination services methodology (Figure 2c) – each coordination service is responsible for part of the data, and requests are forwarded to the appropriate coordination service (or to a local proxy). As explained in Section 2, when the forwarded operations are sequentially-consistent reads, this method does not preserve the single coordination service's semantics. We believe that, as in ZooKeeper, this issue can be rectified using our modular composition approach.

ZooFence [26] orchestrates multiple instances of ZooKeeper using a client-side library in addition to a routing layer consisting of replicated queues and executors. Intuitively, it manages local and cross-data center partitions using data replication. Any operation (including reads) accessing replicated data must go through ZooFence's routing layer. This prevents reads from executing locally, forfeiting a major benefit of replication. In contrast, ZooNet uses learners, (which natively exist in most coordination services in the form or proxies or observers), for data replication. This allows local reads, and does not require orchestration of multiple ZooKeeper instances as in ZooFence.

Volery [23] is an application that implements ZooKeeper's API, and which consists of partitions, each of which is an instance of a state machine replication algorithm. Unlike ZooKeeper, all of Volery operations are linearizable (i.e., including reads). In Volery, the different partitions must communicate among themselves in order to maintain consistency, unlike ZooNet's design in which the burden of maintaining consistency among ZooKeepers is placed only on clients. In addition, when compared to ZooKeeper, Volery shows degredated performance in case of a single partition, while ZooNet is identical to ZooKeeper if no remote operations are needed.

In distributed database systems, composing multiple partitions is usually done with protocols such as two-phase commit (e.g., as in [25]). In contrast, all coordination services we are familiar with are built on key-value stores, and expose simpler non-transactional updates and reads supporting non-ACID semantics.

Server-side solutions were also proposed for coordination services composition [14] but were never fully implemented due to their complexity, the intrusive changes they require from the underlying system, as well as the proposed relaxation of coordination service's semantics required to make them work. In this paper we show that composing such services does not require expensive server-side locking and commit protocols among partitions, but rather can be done using a simple modification of the client-side library and can guarantee the standard coordination service semantics.

7 Conclusions and Future Work

Coordination services provide consistent and highly available functionality to applications, relieving them of implementing common (but subtle) distributed algorithms on their own. Yet today, when applications are deployed in multiple data centers, system architects are forced to choose between consistency and performance. In this paper we now shown that this does not have to be the case. Our modular composition approach maintains the performance and simplicity of deploying independent coordination services in each data center, and yet does not forfeit consistency.

We demonstrated that the simplicity of our technique makes it easy to use with existing coordination services, such as ZooKeeper – it does not require changes to the underlying system, and existing clients may continue to work with an individual coordination service without any changes (even if our client library is used, such applications will not incur any overhead). Moreover, the cost for applications requiring consistent multi-data center coordination is low for workloads that exhibit high spatial or temporal locality.

In this work we have focused on the advantages of our composition design in wide-area deployments. It is possible to leverage the same design for deployments within the data center boundaries that currently suffer from lack of sharing among coordination services. Indeed, a typical data center today runs a multitude of coordination service backend services. For example, it may include: Apache Kafka message queues [2], backed by ZooKeeper and used in several applications; Swarm [19], a Docker [36] clustering system running an etcd backend; Apache Solr search platform [3] with an embedded ZooKeeper instance; and Apache Storm clusters [42], each using a dedicated ZooKeeper instance. Thus, installations end up running many independent coordination service instances, which need to be independently provisioned and maintained. This has a number of drawbacks: (1) it does not support cross-application sharing; (2) it is resource-wasteful, and (3) it complicates system administration. Our modular composition approach can potentially remedy these short comings.

Our composition algorithm supports individual query and update operations. It can natively support transactions (e.g., ZooKeeper's *multi* operation) involving data in single service instance. An interesting future direction could be to support transactions involving multiple service instances. This is especially challenging in the face of possible client and service failures, if all cross-service coordination is to remain at the client side.

Acknowledgements

We thank Arif Merchant, Mustafa Uysal, John Wilkes, and the anonymous reviewers for helpful comments and suggestions. We gratefully acknowledge Google for funding our experiments on Google Cloud Platform. We thank Emulab for the opportunity to use their testbeds. Kfir Lev-Ari is supported in part by the Hasso-Plattner Institute (HPI) Research School. Research partially done while Kfir Lev-Ari was an intern with Yahoo, Haifa. Partially supported by the Israeli Ministry of Science.

References

[1] Access Control in Google Cloud Storage. `https://cloud.google.com/storage/docs/access-control`. [Online; accessed 28-Jan-2016].

[2] Apache Kafka – A high-throughput distributed messaging system. `http://kafka.apache.org`. [Online; accessed 1-Jan-2016].

[3] Apache Solr – a standalone enterprise search server with a REST-like API. `http://lucene.apache.org/solr/`. [Online; accessed 1-Jan-2016].

[4] Camille Fournier: Building a Global, Highly Available Service Discovery Infrastructure with ZooKeeper. `http://whilefalse.blogspot.co.il/2012/12/building-global-highly-available.html`. [Online; accessed 1-Jan-2016].

[5] Consul – a tool for service discovery and configuration. Consul is distributed, highly available, and extremely scalable. `https://www.consul.io/`. [Online; accessed 1-Jan-2016].

[6] Consul HTTP API. `https://www.consul.io/docs/agent/http.html`. [Online; accessed 28-Jan-2016].

[7] Daniel Abadi: Problems with CAP, and Yahoos little known NoSQL system. `http://dbmsmusings.blogspot.com/2010/04/problems-with-cap-and-yahoos-little.html`. [Online; accessed 28-Jan-2016].

[8] Doozer – a highly-available, completely consistent store for small amounts of extremely important data. `https://github.com/ha/doozerd`. [Online; accessed 1-Jan-2016].

[9] etcd – a highly-available key value store for shared configuration and service discovery. https://coreos.com/etcd/. [Online; accessed 1-Jan-2016].

[10] Google Compute Engine – Scalable, High-Performance Virtual Machines. https://cloud.google.com/compute/. [Online; accessed 1-Jan-2016].

[11] Has anyone deployed a ZooKeeper ensemble across data centers? https://www.quora.com/Has\anyone\deployed\a\ZooKeeper\ensemble\across\data\centers. [Online; accessed 1-Jan-2016].

[12] Igor Serebryany: SmartStack vs. Consul. http://igor.moomers.org/smartstack-vs-consul/. [Online; accessed 28-Jan-2016].

[13] Observers: Making ZooKeeper Scale Even Further. https://blog.cloudera.com/blog/2009/12/observers-making-zookeeper-scale-even-further/. [Online; accessed 1-Jan-2016].

[14] Proposal: mounting a remote ZooKeeper. https://wiki.apache.org/hadoop/ZooKeeper/MountRemoteZookeeper. [Online; accessed 28-Jan-2016].

[15] Question about cross-datacenter setup (ZooKeeper). http://goo.gl/0sDOMZ. [Online; accessed 28-Jan-2016].

[16] Question about multi-datacenter key-value consistency (Consul). https://goo.gl/XMWCcH. [Online; accessed 28-Jan-2016].

[17] Question about number of nodes spread across datacenters (ZooKeeper). https://goo.gl/oPC2Yf. [Online; accessed 28-Jan-2016].

[18] Solr Cross Data Center Replication. http://yonik.com/solr-cross-data-center-replication/. [Online; accessed 28-Jan-2016].

[19] Swarm: a Docker-native clustering system. https://github.com/docker/swarm. [Online; accessed 1-Jan-2016].

[20] Vitess deployment: global vs local. http://vitess.io/doc/TopologyService/#global-vs-local. [Online; accessed 28-Jan-2016].

[21] ZooKeeper's Jira - Major throughput improvement with mixed workloads. https://issues.apache.org/jira/browse/ZOOKEEPER-2024. [Online; accessed 16-May-2016].

[22] BAKER, J., BOND, C., CORBETT, J. C., FURMAN, J., KHORLIN, A., LARSON, J., LEON, J.-M., LI, Y., LLOYD, A., AND YUSHPRAKH, V. Megastore: Providing scalable, highly available storage for interactive services. In *Proceedings of the Conference on Innovative Data system Research (CIDR)* (2011), pp. 223–234.

[23] BEZERRA, C. E. B., PEDONE, F., AND VAN RENESSE, R. Scalable state-machine replication. In *44th Annual IEEE/IFIP International Conference on Dependable Systems and Networks, DSN 2014, Atlanta, GA, USA, June 23-26, 2014* (2014), pp. 331–342.

[24] BURROWS, M. The chubby lock service for loosely-coupled distributed systems. In *Proceedings of the 7th Symposium on Operating Systems Design and Implementation* (Berkeley, CA, USA, 2006), OSDI '06, USENIX Association, pp. 335–350.

[25] CORBETT, J. C., DEAN, J., EPSTEIN, M., FIKES, A., FROST, C., FURMAN, J. J., GHEMAWAT, S., GUBAREV, A., HEISER, C., HOCHSCHILD, P., HSIEH, W., KANTHAK, S., KOGAN, E., LI, H., LLOYD, A., MELNIK, S., MWAURA, D., NAGLE, D., QUINLAN, S., RAO, R., ROLIG, L., SAITO, Y., SZYMANIAK, M., TAYLOR, C., WANG, R., AND WOODFORD, D. Spanner: Google's globally-distributed database. In *Proceedings of the 10th USENIX Conference on Operating Systems Design and Implementation* (Berkeley, CA, USA, 2012), OSDI'12, USENIX Association, pp. 251–264.

[26] HALALAI, R., SUTRA, P., RIVIERE, E., AND FELBER, P. Zoofence: Principled service partitioning and application to the zookeeper coordination service. In *33rd IEEE International Symposium on Reliable Distributed Systems, SRDS 2014, Nara, Japan, October 6-9, 2014* (2014), pp. 67–78.

[27] HERLIHY, M. P., AND WING, J. M. Linearizability: A correctness condition for concurrent objects. *ACM Trans. Program. Lang. Syst. 12*, 3 (July 1990), 463–492.

[28] HUNT, P., KONAR, M., JUNQUEIRA, F. P., AND REED, B. Zookeeper: Wait-free coordination for internet-scale systems. In *Proceedings of the 2010 USENIX Conference on USENIX Annual Technical Conference* (Berkeley, CA, USA, 2010), USENIXATC'10, USENIX Association, pp. 11–11.

[29] JUNQUEIRA, F. P., REED, B. C., AND SERAFINI, M. Zab: High-performance broadcast for primary-backup systems. In *Proceedings of the 2011 IEEE/IFIP 41st International Conference on Dependable Systems&Networks* (Washington, DC, USA, 2011), DSN '11, IEEE Computer Society, pp. 245–256.

[30] KAPRITSOS, M., WANG, Y., QUEMA, V., CLEMENT, A., ALVISI, L., AND DAHLIN, M. All about eve: Execute-verify replication for multi-core servers. In *Proceedings of the 10th USENIX Conference on Operating Systems Design and Implementation* (Berkeley, CA, USA, 2012), OSDI'12, USENIX Association, pp. 237–250.

[31] LAMPORT, L. How to make a multiprocessor computer that correctly executes multiprocess programs. *IEEE Trans. Comput. 28*, 9 (Sept. 1979), 690–691.

[32] LAMPORT, L. The part-time parliament. *ACM Trans. Comput. Syst. 16*, 2 (1998), 133–169.

[33] LEV-ARI, K., BORTNIKOV, E., KEIDAR, I., AND SHRAER, A. Modular composition of coordination services. Tech. Rep. CCIT 895, EE, Technion, Januar 2016.

[34] MAO, Y., JUNQUEIRA, F. P., AND MARZULLO, K. Mencius: Building efficient replicated state machine for wans. In *8th USENIX Symposium on Operating Systems Design and Implementation, OSDI 2008, December 8-10, 2008, San Diego, California, USA, Proceedings* (2008), pp. 369–384.

[35] MARANDI, P. J., BEZERRA, C. E., AND PEDONE, F. Rethinking state-machine replication for parallelism. In *Proceedings of the 2014 IEEE 34th International Conference on Distributed Computing Systems* (Washington, DC, USA, 2014), ICDCS '14, IEEE Computer Society, pp. 368–377.

[36] MERKEL, D. Docker: Lightweight linux containers for consistent development and deployment. *Linux J. 2014*, 239 (Mar. 2014).

[37] ONGARO, D., AND OUSTERHOUT, J. In search of an understandable consensus algorithm. In *Proceedings of the 2014 USENIX Conference on USENIX Annual Technical Conference* (Berkeley, CA, USA, 2014), USENIX ATC'14, USENIX Association, pp. 305–320.

[38] OPPENHEIMER, D. L., GANAPATHI, A., AND PATTERSON, D. A. Why do internet services fail, and what can be done about it? In *4th USENIX Symposium on Internet Technologies and Systems, USITS'03, Seattle, Washington, USA, March 26-28, 2003* (2003).

[39] SHAROV, A., SHRAER, A., MERCHANT, A., AND STOKELY, M. Take me to your leader!: Online optimization of distributed storage configurations. *Proc. VLDB Endow. 8*, 12 (Aug. 2015), 1490–1501.

[40] SHERMAN, A., LISIECKI, P. A., BERKHEIMER, A., AND WEIN, J. ACMS: the akamai configuration management system. In *2nd Symposium on Networked Systems Design and Implementation (NSDI 2005), May 2-4, 2005, Boston, Massachusetts, USA, Proceedings.* (2005).

[41] TANG, C., KOOBURAT, T., VENKATACHALAM, P., CHANDER, A., WEN, Z., NARAYANAN, A., DOWELL, P., AND KARL, R. Holistic configuration management at facebook. In *Proceedings of the 25th Symposium on Operating Systems Principles* (New York, NY, USA, 2015), SOSP '15, ACM, pp. 328–343.

[42] TOSHNIWAL, A., TANEJA, S., SHUKLA, A., RAMASAMY, K., PATEL, J. M., KULKARNI, S., JACKSON, J., GADE, K., FU, M., DONHAM, J., BHAGAT, N., MITTAL, S., AND RYABOY, D. Storm@twitter. In *Proceedings of the 2014 ACM SIGMOD International Conference on Management of Data* (New York, NY, USA, 2014), SIGMOD '14, ACM, pp. 147–156.

[43] WHITE, B., LEPREAU, J., STOLLER, L., RICCI, R., GURUPRASAD, S., NEWBOLD, M., HIBLER, M., BARB, C., AND JOGLEKAR, A. An integrated experimental environment for distributed systems and networks. In *Proc. of the Fifth Symposium on Operating Systems Design and Implementation* (Boston, MA, Dec. 2002), USENIX Association, pp. 255–270.

[44] YIN, Z., MA, X., ZHENG, J., ZHOU, Y., BAIRAVASUNDARAM, L. N., AND PASUPATHY, S. An empirical study on configuration errors in commercial and open source systems. In *Proceedings of the Twenty-Third ACM Symposium on Operating Systems Principles* (New York, NY, USA, 2011), SOSP '11, ACM, pp. 159–172.