Scalable Fine-Grained Reconfigurable Replica Coordination

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Abstract

Many large distributed systems today use sophisticated combinations of replication and partitioning of data and compute, but traditional distributed system designs steer developers towards a monolithic design, wherein the distributed principal–a slice of the state or the state machine–is heavyweight and replication and partitioning decisions are infrequently reconfigured if at all.

We present GigaPaxos, a novel system for scalable, fine-grained, reconfigurable replica coordination. A key capability in GigaPaxos is maximal object-group configurability, i.e., the ability to easily manage and quickly reconfigure a very large number of replica groups, one for each lightweight fault-tolerant principal as small as a single record in a key-value store or an ephemeral service replica created on the fly for each user. GigaPaxos achieves this goal by driving down the marginal memory overhead of a replicated state machine to a few hundred bytes while keeping the messaging overhead, throughput, and latency of each group independent of the total number of groups and comparable to or vastly better than state-of-the-art consensus systems. We study the benefits of object-group configurability using several case studies including myCloud, a hypothetical application that creates a custom, reconfigurable replica group for each user's personal cloud data, and show that agile reconfigurability can significantly enhance user-perceived performance.

1 Introduction

Many large-scale distributed systems use a combination of replication and partitioning of data and computation for balancing several different objectives such as fault-tolerance, performance, scalability, resource cost, or ease of management. These competing objectives are often conflicting, e.g., increasing the degree of replication across failure-independent machines improves availability but increases the overhead by a proportional or worse factor. Thus, a common approach is to partition the overall system, i.e., the state and the associated computation, into smaller distributed principals spread across different subsets of machines, thereby improving performance by increasing concurrency; fault isolation across partitions placed on fault-independent sets of machines; overall capacity by not restricting it to a single machine's capacity; and manageability via the flexibility to independently provision resources across partitions.

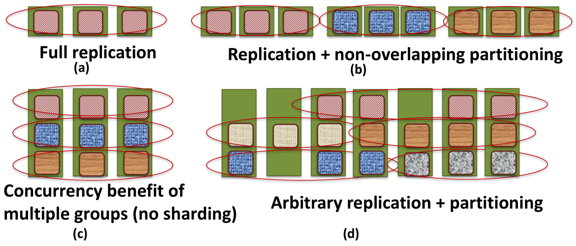

Figure 1: Replication and partitioning combinations.

Figure 1 shows increasingly finer-grained replication and partitioning schemes. Compared to the full replication baseline (e.g., replicated state machine based systems [27, 16, 11]), sharding or partitioning principals across non-overlapping machines significantly improves overall capacity provided the system's consistency semantics allow operations on different shards to proceed in parallel. Figure 1(d) shows the most general combination of replication and partitioning wherein different partitions may not necessarily be replicated on non-overlapping machines, a popular approach today [15, 17, 13, 32]. This option further improves performance by increasing concurrency when different replica groups isolate principals into independent consistency groups. Indeed, simply increasing the logical number of partitions even with full replication can improve overall system capacity, as shown in Figure 1(c).

Our position is that these traditional distributed system designs are monolithic, i.e., they stop well short of the finest achievable grain of object-group configurability, informally the flexibility to assign different subsets of machines to manage fine-grained distributed principals and quickly reconfigure this assignment (formalized in §4.3). The extent of object-group configurability permitted by a design, as argued in §4.3, has non-trivial operational implications. For example, imagine a user of `myCloud`–a hypothetical personal cloud application that also forms one of our prototype-driven end-to-end case studies (§4.3.1)–who expects her personal cloud data like documents, calendar, mail, media metadata, etc. to be readily available right at or close to the (virtualized) access points across which she zips by in her hyper-mobile always-connected life; or imagine her editing a cloud-based shared document collaboratively with a colocated co-worker. In such use cases of "edge clouds" (also variously referred to as cloudlets, multi-tenant gateways, micro-clouds, etc.), caching of static content alone is insufficient because of consistency required of mutable data; instead, they need system support for agile object-group configurability, in line with the vision of "fluid replication" from the 90s.

Our contribution, GigaPaxos, is a small but concrete step towards realizing the fluid replication vision. We envision applications "sprinkling" principals as small as a single record in a key-value store, a counter, a user's calendar, a shared document, etc. wherever and whenever needed without sacrificing consistency. A key challenge that GigaPaxos addresses is group scalability, i.e., the ability to scale to a very large number (millions or more) of independent consensus groups. Although a large body of prior work has focused on improving the performance, cost, or robustness of consensus-based systems, group scalability is a dimension that appears to have not been explored before. Indeed, we find that state-of-the-art Paxos or other consensus implementations can barely sustain tens or hundreds of groups, whereas GigaPaxos can scale to millions of Paxos groups on commodity machines with little performance or cost penalty.

GigaPaxos achieves group scalability through a novel design and implementation that carefully separates idle and active Paxos groups so as to drive down the memory overhead of an idle Paxos instance to a few hundred bytes; uses a novel hot-swap technique to pause idle Paxos instances; amortizes the overhead of failure detection and logging across groups; enables programmatic policy for automating group reconfiguration at scale; and uses a highly event-driven design that does not rely on any per-instance background tasks that are commonplace in consensus implementations (refer §3.1).

We have implemented a prototype of GigaPaxos with a simple API that allows any "black-box" application, even those not originally designed with fault-tolerance or replication in mind, to leverage object-group configurability. Our prototype-driven experiments show that:
(1) GigaPaxos achieves comparable or vastly superior performance compared to state-of-the-art consensus implementations even for a single group but comfortably scales to orders of magnitude more groups (§4.1).
(2) GigaPaxos' `Replicable` API and support for programmatic reconfiguration policies are easy to use with a number of third-party applications (§4.3).
(3) Per-object reconfigurability can significantly enhance end-to-end client-perceived performance for massively geo-distributed edge cloud services (§4.3).

2 Case for object-group configurability

A founding position of our work is that object-group configurability, informally the flexibility to assign different subsets of machines to manage different groups of replicated principals (objects or services) is a valuable abstraction in large-scale distributed systems. We inspect many recent and classical distributed systems in order to make qualitative and quantitative arguments to support this position.

Consistency vs. concurrency: Any system managing distributed state must reckon with consistency requirements. Any consistency semantics, including weak or eventual consistency, necessitates imposing some restriction on the ordering of or isolation across operations accessing that state, i.e., ensuring consistency fundamentally reduces the concurrency permitted by the system and consequently the throughput capacity of the system. (Note that this claim is true even of undistributed systems, e.g., a single-machine database with atomicity, consistency, isolation, and durability (ACID) requirements, but is even more so in distributed systems.) Object-group configurability improves performance by allowing operations across independent sets of objects to proceed concurrently.

Availability vs. overhead: High availability entails larger replica groups (with proportional or worse overhead) until the marginal benefit of increasing the replication factor is outweighed by its overhead, at which point it is more effective to partition the data across non-overlapping groups of machines. Partitioning data across non-overlapping replica groups is a special case of object-group configurability.

Scalability vs. manageability: Any scalable distributed system design must choose between two conflicting goals: on one extreme are randomization-based approaches (leftmost in in Figure 2) that are simple and scale elegantly with no single point of failure or congestion; on the other extreme are increasingly planned approaches that are easier to manage offering superior fault isolation and the flexibility to provision resources or tailor usage to individual user preferences.

To concretize the high-level exposition above, let's study these tradeoffs in the context of several modern large-scale distributed systems as shown in Figures 2(a)–

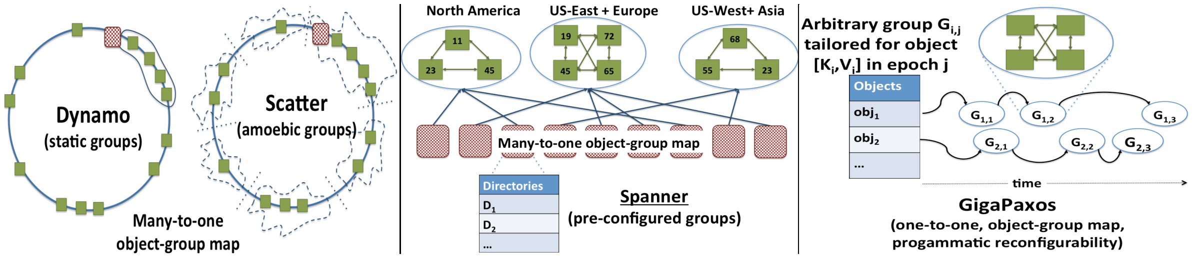

Figure 2: Extent of object-group configurabilityin recent geo-replicated systems.

2(c) that show that the extent of object-group configurability allowed by a system's design has nontrivial operational implications, as illustrated in Figures 2(a)–2(c). A baseline example with little flexibility is consistent hashing with replication, e.g., Amazon Dynamo is a key-value system that uses consistent hashing to determine the replica group of machines that manage an object. While this approach is simple and scales well when machines and object workload patterns exhibit predictable characteristics, it is cumbersome in environments with more unpredictability and flux such as peer-to-peer (P2P) environments. Sharing this motivation, Scatter [17], a P2P storage system uses consistent, configurable groups as a defining abstraction. Scatter's support for "amoebic" reconfiguration of groups, i.e., the ability to split, merge, or migrate members of objects across adjacent consensus groups, enhances a group's ability to self-organize under dynamic conditions while maintaining linearizability consistency for operations to a single object.

A system like Google's Spanner [13] significantly increases object-group configurability over static or amoebic replica groups. Spanner has a fixed number of predefined (or slow-changing) Paxos groups to which it maps a large number of directory objects (i.e., a bag of key-value mappings) in a many-to-one manner. Spanner allows administrators to control the "number and types of replicas, and the geographic placement of those replicas", for example, by specifying policies such as [Object A: North America, replicated 5 ways with 1 witness]; [Object B: Europe, replicated 3 ways], etc. However, Spanner is designed to remap objects across existing Paxos groups, not reconfigure the Paxos groups themselves. The distinction is important as the total number of conceivable consensus groups is exponential in the total number of machines, so a practical system is forced to create a manageable[1] number of packaged groups (like N. America, Europe, etc.) and adopt a many-to-one principal-to-group mapping, an approach that works well in the common case.

Our goal is to take object-group configurability to the extreme, namely, allow for each arbitrarily small object to be mapped to an arbitrary consensus group specifically for that object. We refer to this flexibility as maximal object-group configurability, wherein object-group configurability is defined as the ratio of the total number of objects to the total number of separate consensus groups in the system. Thus, the maximal value is 1; for Spanner, it is typically much lower than 1; for Scatter or Dynamo, it is roughly equal to the ratio of the number of machines and the product of the number of keys and the average replication factor.

Our vision is similar to that of fluid replication [30] proposed by Noble et al. in the late 90s or more recently referred to as "dispersable computing" [14]. Our goal of agile reconfigurability also overlaps with more recent systems like Tuba [8] but differs significantly in its focus on group scalability and the powerful RSM abstraction.

This paper requires the reader to be familiar with Paxos[21]. The techreport[3] has a brief primer, and [22] and [33] are good resources respectively for a simplified conceptual and implementation-oriented exposition.

3 GigaPaxos design

GigaPaxos is designed to meet the following goals.
(1) **Agile object-group configurability**: An application should be able to easily request or change a consensus group for a fine-grained fault-tolerant object.
(2) **Group scalability**: The aggregate performance (capacity and latency) across consensus groups should be independent of the total number of consensus groups.
(3) **Application agnosticism**: The design must provide a simple API for black-box applications, remaining agnostic to application-specific details.
(4) **Automated reconfiguration**: Applications should be able to specify policies to programmatically reconfigure the membership of the consensus instances.
(5) **Control plane scalability**: There must be no single point of congestion or failure including the control plane managing dispersion of distributed principals.

3.1 Design overview

To address the above goals, GigaPaxos is designed as a two-tier reconfigurable consensus engine consisting of two logically distinct types of nodes: app-containers and reconfigurators. A group of app-containers form a consensus group for a named object that they manage. A

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[1] "Typical deployments might have up to hundreds or thousands of paxos groups per machine, but not much more." [5]

group of reconfigurators form a consensus group that is responsible for making decisions about when and how to reconfigure the app-container group for a subset of objects, and to help correctly redirect client requests to the current group. An app-container encapsulates a third-party application that contains the logic needed to process a client request, modify the corresponding object state, and send a reply back to the client.

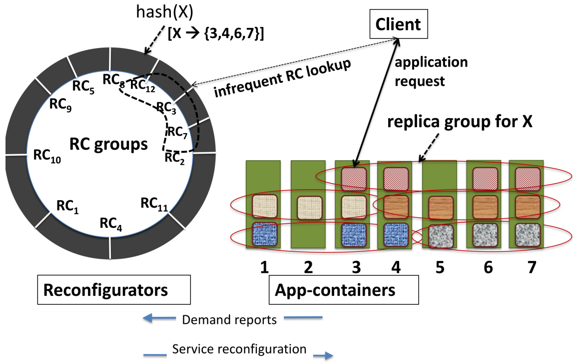


Figure 3: GigaPaxos group-scalable architecture combining randomization and planned placement benefits.

Figure 3 shows reconfigurators on the left organized as a consistent hash ring with a fixed number of clockwise contiguous nodes on the ring forming a consensus group to manage all principals mapping to the first node. Unlike traditional consistent hashing based schemes however, reconfigurators only maintain directory information about app-container nodes managing each principal. For example, the figure shows principal X being managed by reconfigurators 12, 3, and 7 and the corresponding application replica group being maintained on app-containers 3, 4, 6, 7. Lookup requests to reconfigurators are expected to be infrequent as clients opportunistically cache this information until it becomes stale.

Applications can specify if only a subset of request types need replica coordination, allowing them to use consensus as a building block for different consistency semantics. For example, enforcing consensus for every client request to a named object ensures linearizability (as in [17]) across all operations to that object while enforcing consensus for writes alone (or reads alone) ensures sequential consistency for all operations to that object [9]. Relaxing it further to eventual consistency does not need consensus among replicas, but reconfigurators must still rely on consensus to make reconfiguration decisions in a fault-tolerant and consistent manner (§3.6.1).

GigaPaxos as described has no single point of failure or congestion (design goal #5). Reconfigurators form the control plane and consistent hashing with replication ensures availability and load balance. Reconfigurators are homogeneous as they perform quick predictable control plane tasks. The separation of reconfigurators and app-containers combines the best of randomization and planned placement. Reconfigurators periodically receive demand reports from app-containers and, based on a configurable principal-specific policy, reconfigure app-container replica group managing the principal.

We describe how GigaPaxos achieves its remaining goals using the following key mechanisms described in the following subsections: (1) a compact representation of Paxos instances; (2) separating and amortizing machine-specific overhead from group-specific overhead; (3) a hot-swap mechanism to relieve memory pressure while maintaining correctness; (4) a group-scalable persistent logger; and (5) simple client API and programmatic reconfigurability support.

The following terms are used throughout the paper: a Paxos instance is the Paxos-related, application-agnostic state stored at a machine for a single, named object; a Paxos group is the set of distributed Paxos instances managing a single object, which in conjunction with the application logic forms the corresponding RSM.

3.2 Managing compact Paxos instances

GigaPaxos' core consists of a `PaxosManager` per machine that is responsible for machine-specific functions of which there are four key ones: (1) Paxos instance management, (2) persistent logging, (2) failure detection, and (3) messaging and demultiplexing.

`PaxosManager` maintains a map from the name of a Paxos group, `objectID`, to a data structure maintaining the minimum Paxos instance state necessary for safety, i.e., the state blocks marked "Fixed Instance", "Acceptor Idle", and "Coordinator Idle" respectively in Fig. 4. The first remains unchanged throughout the lifetime of this Paxos instance, i.e., until the `epoch` and `group` are reconfigured or the object is deleted. The latter two are referred to as idle state because this state must be remembered by each Paxos group member even during periods when the group is not actively processing client requests.

3.2.1 Idle Paxos instance state

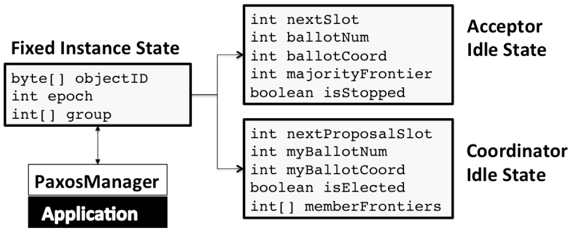


Figure 4: Idle Paxos instance state.

An acceptor's idle state must maintain (1) `nextSlot`, the highest slot number below which all proposals have been executed by the local application replica in agreement order; (2) its current ballot, ⟨`ballotNum`, `ballotCoord`⟩, which is the highest ballot it has received across all PREPARE messages from any group member seeking to become coordinator; (3) `majorityFrontier`, the slot number up to which a majority of group members have cumulatively executed application requests, which is needed in order to safely garbage-collect logged messages corresponding to lower slots [33]; (4) `isStopped`, whether or not the paxos group has been stopped, which is needed to perform reconfiguration safely (§3.6.1).

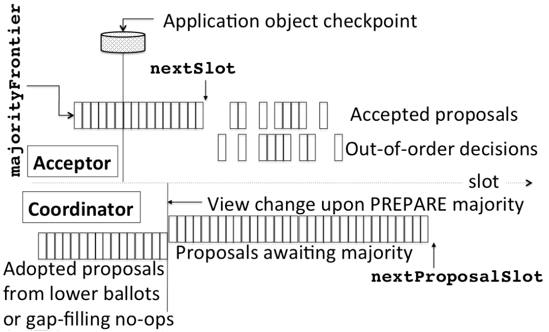


Figure 5: Active Paxos instance state.

A coordinator, strictly speaking, does not have to persistently maintain any idle state at all as coordinators are already presumed to be perishable. However, garbage collecting coordinator state during idle periods means that a new coordinator must be elected (with the first PREPARE phase) upon the arrival of a client request. In order to maintain Paxos' low, essentially optimal, message overhead per client request during graceful execution, i.e., just the second ACCEPT/DECISION phase, it is important to support long-lived coordinators. So, each GigaPaxos coordinator instance must either maintain all of the coordinator idle state in Fig. 5 or immediately relinquish its role as coordinator by ceasing to commandeer further proposals in its ballot.

The coordinator's idle state must thus maintain: (1) `nextProposalSlot`, the lowest slot such that the coordinator has not yet used that or any higher slots to commandeer any proposals; (2) its ballot that in general may be out of sync with the local acceptor's perceived ballot; (3) `isElected`, indicating whether its ballot has been accepted by a majority of acceptors, at which point it can garbage-collect its pre-election state (§3.2.2); and (4) `memberFrontiers`, the slot numbers up to which, in its view, acceptors have cumulatively executed application requests; the coordinator piggybacks the median slot number in its ACCEPT and DECISION messages to all acceptors who use it to refresh their `majorityFrontier`.

Compactness. The point of listing the seemingly mundane details above is to emphasize that this state–the variables in the three shaded boxes in Fig. 4 plus the connecting pointers–is literally all of the state GigaPaxos adds per idle Paxos instance to whatever state the application itself maintains. The size of this idle state is ≈350 bytes for Paxos instances with three members in our implementation; larger groups cost 8 more bytes (or one integer each in the two `int` arrays).

3.2.2 Active Paxos instance state

An active Paxos instance, i.e., one that is currently agreeing on the order of client requests for the underlying application, typically needs to maintain much more state than the idle state above. Fig. 5 illustrates the active state that must be maintained for safety.

An acceptor's active state consists of (1) a sequence of accepted proposals in slot number order, possibly with gaps, that it has previously accepted, and (2) a set of committed decisions received out-of-order. The former sequence starts at `majorityFrontier`+1 or higher, and the latter sequence starts strictly higher than `nextSlot`, the first slot for which no decision has been received.

A coordinator's active state additionally consists of (1) adopted proposals, i.e., lower-ballot proposals received from acceptors in their replies to this coordinator's PREPARE message, wherein the coordinator picks for each slot the proposal with the highest ballot; (2) one `waitFor` data structure (not shown) to track whether a majority of acceptors have replied successfully to the PREPARE message; and (3) `myProposals`, a sequence of proposals being commandeered by the coordinator, i.e., proposals for which it has or will send out ACCEPT messages, and for each of which it maintains a `waitFor` structure to track a majority of acceptances. The first two are needed only until the coordinator gets elected by receiving a majority of suppo PREPARE replies. If a coordinator receives any client requests during this election, it enqueues them with the first available (tentative) slot number in `myProposals`. When a coordinator receives a PREPARE majority ("view change" in Fig. 5), it merges all of the adopted proposals into and with strict priority over `myProposals`, marks itself as active, and begins commandeering `myProposals`. An active coordinator thus only maintains a single queue, `myProposals`, of proposals awaiting majority acceptance; when that happens, they are announced as committed decisions to all acceptors and are dequeued.

Bulk. The size of an active Paxos instance can be orders of magnitude larger than an idle Paxos instance, e.g., a burst of rapid requests to a group can result in thousands [18] of requests being concurrently processed, each causing hundreds or thousands of bytes of queued entries at acceptors as well as coordinators, thereby easily inducing megabytes of state. This active state needs to be maintained at an acceptor until a majority of acceptors have caught up, i.e., `majorityFrontier`+1 equals `nextSlot`, and at a coordinator until it is no longer commandeering any proposals, i.e., `myProposals` is empty.

3.3 Bounded number of active instances

We claim that under realistic conditions, with a very large number of consensus instances, the number of idle instances will overwhelmingly dominate active ones. This insight motivates GigaPaxos' hot-swap mechanism.

Consider a GigaPaxos application distributed across M machines managing a total of N objects with each object managed by a separate consensus group. Let T denote the average response time of a request with state machine replication, inclusive of both the unreplicated application execution time and the latency to establish its consensus order. Suppose the maximum request throughput that can be steadily sustained by the underlying (unreplicated) application on a single machine is C per second. By Little's law [25], the average number of outstanding requests being processed at any single machine is $A = C \cdot T$. Note that, if C and T are fixed, A is independent of the size of a consensus group, the total number of machines M, or the total number N of objects in the system.

For example, if C is 25,000 requests/sec and the average response time of a request is as high as $T = 500$ ms, then the average number of outstanding requests at a machine is 12,500. In practice, the throughput of most applications employing an RSM approach is likely to be much lower, e.g., for a database application, synchronous random write throughput is typically on the order of a hundred/sec with hard drives, and up to several thousands/sec with typical solid state drives.

The number of active consensus instances at a machine is at most the total number of outstanding requests being processed at that machine. Indeed, the worst case workload is one that, in a round-robin manner, issues requests to all other objects (or consensus groups) before returning to the first. Thus, in a GigaPaxos system with millions of consensus groups, the vast majority of consensus instances must be idle.

There are two caveats however: (1) this analysis implicitly assumes graceful or failure-free execution; (2) even if the average size of an idle consensus instance is small the total number of Paxos groups that can fit in memory on commodity hardware is limited, e.g., with 16GB memory and 400 bytes per Paxos instance, the number of sustainable idle instances is 40 million. To address these issues, GigaPaxos uses hot swapping, a mechanism that helps GigaPaxos scale to billions of groups per machine with commodity disk capacities.

3.3.1 Hot swapping Paxos instances

A simple hack to juggle too many Paxos instances on a machine is for the manager to simply "soft-crash" that Paxos instance, i.e., to dequeue it from its instances map allowing for the state get garbage collected. This action will preserve safety as it will just appear to the rest of its group like a member failure. However, this simplistic approach has several shortcomings. First, it forces a roll forward of the Paxos instance from the most recent checkpoint when a request for a Paxos group arrives at a manager, stalling the request handling until the recovery is complete. The alternative of simply not handling the request is not viable, as that will over time prevent most Paxos groups from making any progress at all, a much worse state of affairs than the theoretical lack of guarantee of liveness under asynchrony. Second, the overhead of doing a checkpoint recovery upon a request arrival as a common case operation can itself overwhelm memory, computation, and I/O cycles on a machine severely hurting overall performance.

GigaPaxos instead employs a far nimbler hot swapping technique that capitalizes on the two observations above: (1) most Paxos instances will be idle when the total number of instances on a machine is very large; and (2) idle state is extremely compact (Fig. 4 as opposed to 5). To this end, the manager on each machine maintains a background process that periodically but infrequently (e.g., every few minutes), makes a sweep over all active instances and pauses instances that have been idle for the threshold interval, i.e., it synchronously dequeues the instance from its map and writes the compact idle state to a database. Subsequently, upon the arrival of a client request or a Paxos protocol message for that instance, the manager's demultiplexer as usual first consults its instance map to route the message. If the instance is not found, the manager must check the database for paused state that, if found, must be used to reconstruct the Paxos instance. Hot swapping shares some similarities with Cheap Paxos [24] or ZZ [34] for bringing up virtual machines, but those approaches are comparable to the "crash" option above.

A downside of hot swapping is that it imposes a small latency penalty (<10ms typically) for the unpause operation. However, this penalty only impacts the first client request (or Paxos protocol message) in a burst of activity for that group. Subsequent requests do not incur any penalty as the instance will not be re-paused until it has been idle for the threshold duration. On the flip side, hot swapping will disproportionately affect unpopular Paxos instances with longer-than-threshold idle periods between successive client requests. Still, we believe that the penalty—an additional database lookup for a small record—is unlikely to significantly impact most applications as (1) most applications using consensus are likely to touch the disk for common operations anyway; and (2) with persistent logging, enabled by default in GigaPaxos, each client request must encounter at least one synchronous disk write in order for acceptors to log an ACCEPT message before responding. Finally, in geo-distributed scenarios, the unpause penalty is unlikely to affect end-to-end latency as that is dominated by network delays fundamental to Paxos.

3.3.2 Graceful vs. failure-prone operation

With machine failures, the fraction of active instances at GigaPaxos machines can be higher. The reason is that a Paxos instance can not fully gabage-collect the log of accepted proposals at an acceptor as that requires a majority of replicas in the group to have executed (or persistently logged the corresponding decision) the application up to that slot. Nevertheless, during periods of synchrony when at least a majority of replicas in all groups are available—exactly when Paxos guarantees liveness—healthy machines will be unaffected and only see a small number (as quantified above) of active instances. Fate sharing makes the number of active Paxos instances at failed machines a non-issue.

However, under more severe machine failure patterns that result in a significant fraction of Paxos instances on a machine being unable to make progress because of a lack of a quorum in their respective groups, the number of active instances on otherwise healthy machines can grow to unsustainable levels. There are several reasonable ways to handle this case: (1) the strawman outlined above that crashes an instance to pause it; (2) checkpointing immediately at `nextSlot` and then crashing the instance so as to reduce the length of the roll forward; (3) pausing and unpausing active state (that could be potentially much larger than the compact idle state). All options incur higher overhead compared to hot swapping idle instances, but will not impact client-perceived latency as they are required only when the corresponding Paxos group is not live anyway. Our current implementation supports the second option.

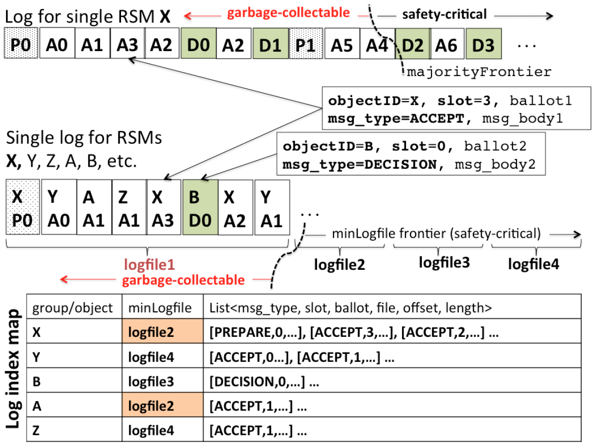
3.4 Amortized fault detection and logging

Failure detection is a key component of any consensus implementation. Although failure detection need not be reliable (a problem as hard as consensus itself [12]), it needs to be responsive in order to ensure prompt replacement of a failed coordinator. Failure detectors are typically implemented using keep-alives between all or a nontrivial subset of machine pairs in a consensus group. However, unlike typical Paxos implementations, group scalability in GigaPaxos makes it impractical to maintain a separate failure detector per group; for example, 1000 groups each of size 5 and a keep-alive frequency of 4 secs imply 1000 packets/sec for failure detection; with 100K groups, failure detection alone becomes a full-time job! Thus, GigaPaxos pushes failure detection to `PaxosManager` maintaining just one failure detector per machine as opposed to one per group.

Likewise, the persistent logger resides in the manager and is common across all Paxos instances on the machine. This design not only amortizes the overhead of logging `PREPARE`/`ACCEPT`/`DECISION` messages across all instances, but also allows log messages from different Paxos instances to be batched, driving down the overhead of persistent logging to negligible levels. Without such batching, GigaPaxos' request throughput will be limited by the synchronous disk write throughput.

3.5 Log indexing, pruning, compaction

In a traditional RSM, garbage collecting safety-critical acceptor logs is easy; they can simply be tail-pruned below the highest slot, `majorityFrontier`, up to which a majority (or even just $f+1$ if at most f can fail) have received all decisions. This just requires tracking file offsets on disk or maintaining slot-indexed records in a database such that it is easy to check whether all logs before some offset are below `majorityFrontier`. Looking up logged messages when needed is efficient as the number of log messages is at most the checkpoint interval.



group/object	minLogfile	List<msg_type, slot, ballot, file, offset, length>
X	logfile2	[PREPARE,0,…], [ACCEPT,3,…], [ACCEPT,2,…] …
Y	logfile4	[ACCEPT,0…], [ACCEPT,1,…] …
B	logfile3	[DECISION,0,…] …
A	logfile2	[ACCEPT,1,…] …
Z	logfile4	[ACCEPT,1,…] …

Figure 6: GigaPaxos' group-scalable logger (bottom) compared to traditional RSM logger (top).

Indexing. In GigaPaxos, this indexing problem is harder. As shown in Figure 7, a single write-ahead log for all groups is extremely efficient (e.g., disabling logging improves capacity by barely 15%), but makes it difficult to track where what is logged; for example, upon a coordinator change or a catch-up request from a lagging acceptor for a group X, an acceptor needs to retrieve logged `ACCEPT`s or `DECISION`s for X in a specific slot range. To this end, GigaPaxos needs to additionally maintain a log index map keyed by group names that tracks the `[file,offset,length]` and `[slot,ballot]` information for every logged message. This is tricky because, by design, the number of groups can be much larger than that can be stored in memory, and simply using a traditional database (even with batching) makes the critical path about two orders of magnitude slower.

Pruning. GigaPaxos's log index is a swappable in-memory map that is as fast as a hash table lookup for working sets that fit in memory, but swaps infrequently used records to a database table indexed by the group name. The log itself is split across logically timestamped files each of a fixed maximum size, and each log index record in addition to the information above tracks `minLogfile`, the log file storing that group's log message with the lowest slot number, i.e., the lower of `majorityFrontier` (for ACCEPTs) and the most recent checkpointed slot (for DECISIONs). The garbage collector periodically queries the database for the `minLogfile` frontier, i.e., the set of `minLogfiles` across all groups, and then removes log files older than the oldest log file in that frontier set from the file system.

Compaction. Alas, the logger's garbage collection woes do not end here. With highly skewed workloads, for example, one where most requests go to just one (or a small number) of group(s) but a request occasionally goes to a "rare" group, it is possible that every log file contains at least one (or a few) log message that prevents the log file from being safely removed. In pathological cases, with pruning alone as above, the number of log files can be as high as $N \cdot I$ with N groups and a checkpoint interval of I requests (proof deferred to [3]). So, GigaPaxos needs to infrequently (1) compact sparse log files, i.e., files with very few safety-critical entries; (2) merge them with other sparse log files; and (3) update the log index map entries in a consistent manner.

With all of the above mechanisms, GigaPaxos' logger scales to a very large number of consensus groups while imposing negligible overhead when the working set fits in memory. Indeed, secondary storage, not memory, is what limits GigaPaxos' group scalability. The worst-case disk storage overhead for N groups is $O(INR)$, where I is the checkpoint interval and R the average request size, e.g., with I=100 and R=100B, a machine needs over 1TB of storage to safely participate in N=100M groups.

3.6 Automated reconfiguration

A large number of consensus groups means it is impractical for an operator to manually reconfigure group membership, so GigaPaxos provides support for programmable policies that automate reconfiguration. For example, a principal could specify a simple policy to reconfigure upon, say, 10 requests from near an app-container location where it is not already replicated. Much more sophisticated policies including those optimizing global placement across all principals are straightforward to implement. We first describe the reconfiguration protocol below.

3.6.1 Reconfiguration protocol

GigaPaxos' reconfiguration protocol is similar to Liskov and Cowling's Viewstamped Replication Revisited (VRR) [26], but differs in important ways. First, GigaPaxos uses an external reconfigurator (similar in spirit to Vertical Paxos[23]) that also integrates the function of group location, i.e., determining the current group for an object, a concern outside the scope of VRR (that suggests that clients could obtain this information from a "web site run by the administrator"). With a very large number of application RSMs and frequent reconfigurations, group location requires a systematic, scalable solution. Second, the reconfigurator for each application RSM itself must be replicated in order to prevent the application RSM from stalling permanently because of a reconfigurator failure.

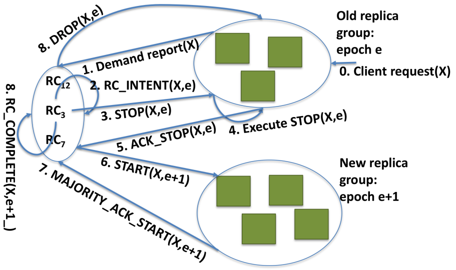


Figure 7: GigaPaxos' scalable reconfiguration protocol reconfiguring principal X from epoch e to epoch $e+1$.

Replicated GigaPaxos reconfigurators must agree on when to initiate a reconfiguration for an application RSM and on the composition of the new group as divergence can result in reconfigurators permanently losing track of the group. So each reconfigurator replica group is itself organized as an RSM whose state is the set of all application RSMs mapped to it via consistent hashing. In keeping with its completely event-driven design, programmatic reconfiguration in GigaPaxos is initiated by a client request (step 0) that happens to result in a demand report (step 1) from one or more app-containers to some reconfigurator(s). Upon receiving a demand report, any reconfigurator can propose an RC_INTENT(X) (step 2) command to reconfigure an application RSM X it manages and, when committed, the proposing reconfigurator in the common case single-handedly conducts the STOP/START /DROP reconfiguration sequence [26] for X (steps 3–7). When done, it proposes and commits RC_COMPLETE(X) (step 8) in its group. Persistently logging every state change in its RSM ensures that, upon the proposing reconfigurator's failure or upon recovery, a reconfigurator can detect and complete unfinished reconfigurations of its managed application RSMs. A formal protocol description of the above reconfiguration protocol is deferred to a techreport [3], which also describes how reconfigurators or app-containers themselves are added or removed.

3.6.2 Extensible reconfiguration policy support

GigaPaxos enables applications to specify flexible policies that automate reconfiguration. Each reconfigurator RSM accepts periodic statistics about load or other metrics from any application RSM it manages and uses a customizable reconfiguration policy to decide whether and how to reconfigure the reconfiguree RSM. It is trivial also to let the application RSM simply send a request to its reconfigurator RSM when it deems a reconfiguration as necessary (or self-reconfigure as in VRR [26] and update the group location service), but allowing reconfigurators to make this decision allows implementing global reconfiguration policies, i.e., policies that take into account statistics across many RSMs to make reconfiguration decisions for each RSM. Applications using GigaPaxos extend an abstract class, `DemandProfile`, to specify sophisticated reconfiguration policies based on failure, demand, or access patterns, performance, etc.

3.7 Replicable API and implementation

We implemented GigaPaxos with all of the features described above largely in Java with 23.9K semi-colons (83.6K newlines including documentation) of which 9.4K is for a stoppable Paxos implementation; 9.2K is for the reconfiguration protocol. The persistent logger uses an embedded database, Apache `derby`, by default, and also supports `mysql`. All transport is based on TCP; our `nio` library maintains and reuses a persistent connection to each machine, automatically attempts to create a new one if machine failures or other events cause I/O exceptions, and buffers a bounded number of messages to each destination to mask intermittent network failures. The size of an idle Paxos instance is ≈350B in our Java implementation; a leaner language like C can reduce it further to ≈100B.

In order to remain agnostic to application-specific details, GigaPaxos requires an application to implement the following simple `Replicable` interface in order to be both replicable and reconfigurable, and an application may choose to use just one of the two features, for example, to create an unreconfigurable RSM or reconfigure an unreplicated state machine:

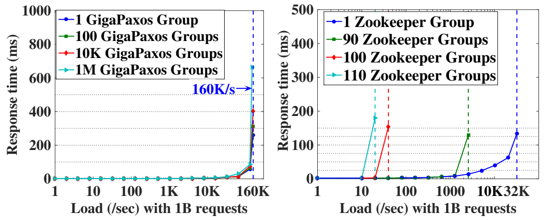
```
boolean execute(Request request, boolean dontReply);
String checkpoint(String name);
boolean restore(String name, String state);
```

4 Evaluation

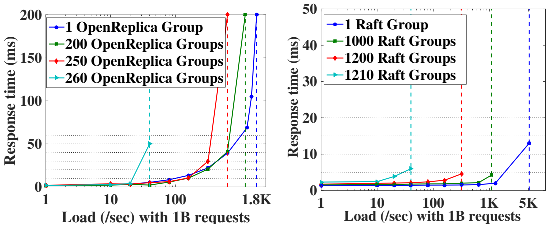
Our high-level goal is to quantify the costs and benefits of group scalability in GigaPaxos. We conduct the following experiments: (1) Comparison of GigaPaxos against state-of-the-art Paxos-based systems w.r.t. the number of supported groups and the impact on client-perceived performance; (2) Microbenchmarks evaluating the benefit and overhead of mechanisms in GigaPaxos; and (3) Case studies involving a number of third-party applications evaluating GigaPaxos' usability and the benefits.

4.1 Group scalability comparison

We study the load vs. latency profile and the memory overhead for varying numbers of groups for three state-of-the-art systems that either are or comprise a consensus system, namely, ZooKeeper [18], OpenReplica [7], and Raft [31], compared to GigaPaxos. Unless otherwise specified, all experiments were performed on Amazon EC2 t2.medium (2 vCPUs, 4GB memory, and 8GB SSD disk) servers and sufficiently many c4.4xlarge clients to saturate the servers in the same region.



(a) GigaPaxos (b) ZooKeeper



(c) OpenReplica (d) Raft

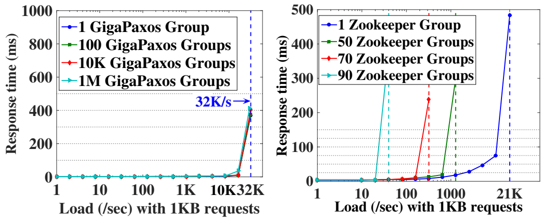
Figure 8: Group scalability: Load vs. latency for 1B requests with varying numbers of idle groups.

4.1.1 Load vs. latency with varying no. groups

In this experiment, clients send requests at increasing rates to a single active RSM at servers that maintain varying numbers of mostly idle RSMs. There are 3 servers in all and each RSM's consensus group is the set of all 3 servers. We measure the average response time over at least five runs each lasting 60s after discarding at least one or more warmup runs as needed to stabilize the servers. The request rate is increased until the system can not sustain that load, i.e., one or more servers either crashes, or the response time exceeds 1s, or the response rate drops below 99.9%.

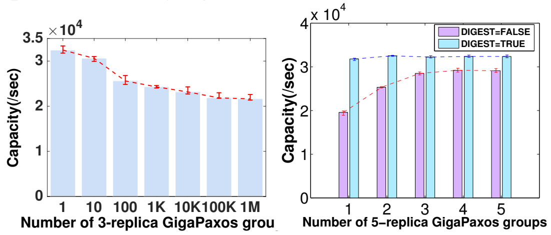
Fig. 8 shows the load vs. response time profile of GigaPaxos, ZooKeeper, OpenReplica, and the Raft authors' LogCabin [31] implementation for 1B no-op requests. Among the latter three systems, ZooKeeper scales to the highest capacity (32K/s) with a single group, but breaks down at barely hundred groups, while OpenReplica and Raft have significantly lower capacities with one group but don't hit breakdown point until hundreds of groups. ZooKeeper scales to fewer groups in part because of the overhead of running separate JVMs with servers listening on different sets of three ports for each RSM, which, though cumbersome, we confirmed with its developer forums [6] as well as via code inspection was the most reasonable option to maintain separate consensus groups. Raft's C++ implementation is leaner, so it scales to more groups. All three systems show a stark, qualitatively similar degradation with increasing groups.

In contrast, GigaPaxos is fast, scaling up to 160K/s capacity with a negligible performance drop as the number of groups increases all the way to a million. Given that



(a) GigaPaxos (b) Zookeeper

Figure 9: Group scalability: Load vs. latency for 1KB requests with varying number of idle groups.



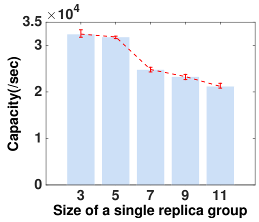
(a) Reduced batching (b) Coordinator balancing

Figure 10: (a) Reduced opportunistic batching hurts; (b) Coordinator load balancing helps.

3-replica groups with 4GB RAM/replica

Latency under light load (up to a few million groups)	**2.8ms ± 0.3**
Latency of requests to paused instances (>10M groups)	**12.4ms ± 0.6**
Capacity w/ 1KB round-robin workload (>10M groups)	**2.6K/s ± 30**
Capacity w/ 10B round-robin workload (>10M groups)	**4.6K/s ± 67**

(a) Hot-swapping overhead



(b) #replicas vs. capacity

Figure 11: (a) Group scalability "fine print" with very large number of groups; (b) Fault scaling.

only a single group is active in this experiment, GigaPaxos mainly benefits from amortizing failure detection across groups, its holistic, single-process design, and its compact representation of idle Paxos instances.

Impact of request size. 1B requests measure the raw agreement throughput, but are hardly useful for any real application. We repeat the above experiment with 1KB requests and (because of space limits) show the results only for GigaPaxos and ZooKeeper in Fig. 9. Both systems are network bottlenecked [19], and see a significant drop in capacity. Both have ≈100-120B of protocol overhead for each ACCEPT/ACCEPT_REPLY/DECISION message (or their one-one equivalents in ZooKeeper's Zab protocol [19]) on the critical path. So, 1KB vs. 1B requests increase the ACCEPT message size by ≈8-10×.

4.2 GigaPaxos microbenchmarks

4.2.1 Impact of batching on group scalability

The results above (§4.1) with a single active group may suggest that GigaPaxos is phenomenally group-scalable with no apparent costs, but that is hardly the case. Next, we stress-test GigaPaxos when a large number of groups are simultaneously active. We use 1KB requests and repeat the experiment above with the only difference that requests are sent in a round-robin manner across groups.

Fig. 10(a) shows that the throughput capacity of the system drops as the number of groups increases. The reason is reduced opportunities for batching requests. Opportunistic batching, i.e., without explicitly waiting for more requests to arrive, is well known to significantly improve the performance of Paxos-like protocols. However, it is in general not possible to batch requests across different RSMs as their group membership may be different. With increasing groups, GigaPaxos' capacity drops until it hits ≈22K/s, which we have verified is its capacity with 1KB requests with batching disabled.

Fig. 10(b) shows an experiment similar to that in 10(a) but with 5-replica groups (instead of 3). Seemingly contradictorily, the first set of bars show the capacity increasing with the number of groups. However, there is a simple explanation–coordinator load balancing–for this observation. As the number of groups increases from 1 to the total number of physical servers 5, the capacity increases because the coordinators for different 5-replica groups get randomly assigned to the servers. As the coordinator's role—receiving every request and sending them as ACCEPTs to the group—is a key bottleneck, multiple groups naturally increase capacity. In contrast, the latter set of bars enable the `digest_requests` option wherein the entry replica broadcasts the request to all acceptors and the coordinator issues ACCEPTs only with request digests. Safety is preserved since an acceptor acknowledges an ACCEPT only if it has received the corresponding body.

The benefit of coordinator balancing has been noted before, e.g., S-Paxos [10] proposes an optimization similar to GigaPaxos' request digests (albeit with a more complex protocol), and others such as Mencius[28], E-Paxos[29] etc. [20] take different approaches to coordinator load balancing. In GigaPaxos, such optimizations are needed only when the number of groups is very small and the request size is not small (≫tens of bytes).

4.2.2 Hot swapping overhead

Table 11(a) summarizes the "fine print" limiting GigaPaxos' group scalability. The experiments thus far considered up to a million groups that barely consume half a gigabyte of memory. However, 10 million instances is higher than what can be supported on the 4GB RAM servers. With such a large number of instances and a round-robin workload, every request encounters a paused instance, so the average latency is over 12ms compared to under 3ms for up to a few million instances (both measured under a round-robin light load of 100/s). Unpausing an instance currently requires two database

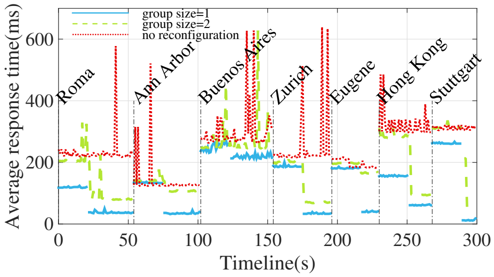


Figure 12: The placement of `etherpad` servers significantly affects user-perceived response times.

lookups, one each for the paused instance state and the corresponding log index record (§3.5) that are currently paused and looked up independently; combining them (not yet implemented) will further reduce this penalty. The throughput takes a much more severe hit at 2.6K/s for 1KB requests vs. 22K/s for 1M groups (Fig. 10(a)).

4.3 Application usability case studies

In this section, we present several application case studies to show (1) that GigaPaxos' `Replicable` API (§3.7) can be implemented easily for third-party applications, with or without intrinsic support for replication, so as to make them replicable and reconfigurable; (2) the latency benefit of object-group configurability.

4.3.1 `myCloud`: Share document editing and storage

We implemented a `Replicable` wrapper for `etherpad` [1], an open-source, document editor that allows users to collaboratively edit documents or "pads" in real-time via a web browser (similar to the popular, proprietary Google Docs). `etherpad` does not intrinsically support replication or fault-tolerance. Client libraries for its API are available in a variety of languages; we used the Java API [2] to make it fault-tolerant and reconfigurable via the `Replicable` wrapper. We also used GigaPaxos' general-purpose support for applications to easily delegate messaging of replies back to the originating client.

In this wide-area experiment, we deploy 7 `etherpad` servers respectively at California, Frankfurt, Ireland, Sydney, Seoul, Tokyo, and Virginia. A GigaPaxos client creates a single pad using the `createService(.)` client API, which by default is set to create an RSM group of all 7 replicas. A controller script in our lab then emulates a "mobile" `etherpad` client that trots across different cities as shown in Fig. 12 sending tens of requests from each city. The `DemandProfile` policy is designed to reconfigure the RSM once every 20 requests to either 1 (blue/solid) or 3 (green/dashed) closest app-container locations.

Fig. 12 shows that the carefully-chosen 3-replica RSMs can significantly reduce end-to-end client-perceived latency, sometimes by over 200ms. The 1-replica RSM as expected yields the lowest latency but only ensures durability, not availability amidst failures, and is included just to show the best-case. Reconfiguration itself roughly takes as much time as 2-3 Paxos operations, so requests are occasionally lost when sent to an app-container where the Paxos instance no longer exists.

4.3.2 Usability and performance overhead

Implementing `Replicable` for `etherpad` was rather easy and involved just 60 lines of code to GigaPaxos' abstract, general-purpose "hello world" client and application classes to support `etherpad`'s three basic request types used in this experiment; supporting its full API will increase the integration work.

Application	#semicolons
Etherpad OpenKM [4]	60 89
MySQL Cassandra Mongo Redis	79 78 53 40

Table 1: LOC for `Replicable` wrappers.

We have implemented `Replicable` wrappers for a number of third-party applications as listed in Table 1 including OpenKM [4] (comparable to Google Drive) and popular key-value stores. Despite the simplicity, some of the wrappers are powerful, e.g., the mysql wrapper is schema-agnostic and anyone can reuse it to designate either each row or each table as an independently reconfigurable RSM. We could do this because `Replicable`'s `checkpoint` and `restore` methods can naturally avail of `sqldump` to checkpoint a single record, table, or database in a schema-agnostic manner.

With the help of tutorials and starter code, GigaPaxos has been used by a distributed systems classes consisting of undergraduate as well as masters students to implement a simple, in-memory map that is gratuitously durable, fault-tolerant, per-key reconfigurable, and ultra-fast (Fig. 8(a)) for small keys and values.

5 Conclusions

Perhaps because of pedagogical challenges or because of the "costly" mental image replication already invokes, consensus implementations today inherently embed assumptions appropriate for monolithic applications. We presented GigaPaxos, a novel system that enables group-scalable replicated state machines, easily allowing any application to create an object managed by a consensus group on the fly and reconfigure it as needed. We have conducted a number of application case studies to show that agile reconfiguration and object-group configurability in GigaPaxos can significantly improve client-perceived performance. The GigaPaxos code with tutorials, case study example code, and documentation is available at: `https://github.com/MobilityFirst/gigapaxos`

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