Blade: A Data Center Garbage Collector

David Terei Amit Levy
Stanford University
{dterei,alevy}@cs.stanford.edu

Abstract

An increasing number of high-performance distributed systems are written in garbage collected languages. This removes a large class of harmful bugs from these systems. However, it also introduces high tail-latency do to garbage collection pause times. We address this problem through a new technique of garbage collection avoidance which we call BLADE. BLADE is an API between the collector and application developer that allows developers to leverage existing failure recovery mechanisms in distributed systems to coordinate collection and bound the latency impact. We describe BLADE and implement it for the Go programming language. We also investigate two different systems that utilize BLADE, a HTTP load-balancer and the Raft consensus algorithm. For the load-balancer, we eliminate any latency introduced by the garbage collector, for Raft, we bound the latency impact to a single network round-trip, (48 μs in our setup). In both cases, latency at the tail using BLADE is up to three orders of magnitude better.

1. Introduction

Recently, there has been an increasing push for low-latency at the tail in distributed systems [18, 45, 54]. This has arisen from the needs of modern data center applications which consist of hundreds of software services, deployed across thousands of machines. For example, a single Facebook page load can involve fetching hundreds of results from their distributed caching layer [42], while a Bing search consists of 15 stages and involves thousands of servers in some of them [31]. These applications require latency in microseconds with tight tail guarantees.

Recent work addressed this at the operating system and networking layer [3, 9, 32, 48]. However, this is only half the picture. Increasingly, application developers choose to build

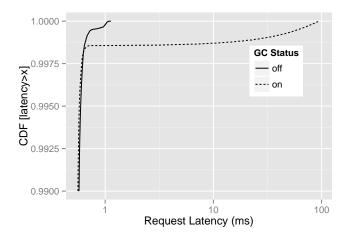


Figure 1: CDF of request latency for a ZooKeeper-like [29] replicated key-value store using the Raft [44] consensus algorithm written in Go. System was configured with 3 nodes and 10 clients generating a total of 250 requests-per-second (3:1 get/set ratio) over 10 minutes. A parallel, stop-the-world (STW) mark-sweep collector was used, with a heap size of 500 MB for a 200 MB working set.

distributed systems in garbage collected lagnuages. For example, a large number of distributed systems are written in Java [29, 58, 65], and Go [21, 24–26]. Garbage collected languages are attractive because manual memory management is extremely bug-prone [13, 17].

Unfortunately, garbage collection introduces high taillatencies due to long pause times. For example, Figure 1 shows the impact of garbage collection on the tail-latency of one such distributed system. While many distributed systems require average and tail-latencies in microseconds, garbage collection pause times can range from milliseconds for small workloads to seconds for large workloads.

Moreover, dealing with pause times in the application is hard. The impact of garbage collection is often unpredictable during development and difficult to debug once deployed. First, from the programmers perspective, garbage collection can occur at any point during execution. Second, performance can vary greatly from system to system, or even over the lifetime of a single system [20, 59]. Finally, tuning the garbage collector of a deployed system is hard because performance is workload dependent. As a result, users must continually

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adjust run-time system parameters (e.g., generation sizes) based on production workloads.

None of the current approaches to garbage collection are suitable for this new set of requirements where the 99.9th percentile matters. On one side, language implementers attempt to build faster collectors [23, 27, 51, 61]. However they are generally concerned with average case behaviour and optimising across a large set of use-cases [11]. As such, pause times at the tail are still too long. Moreover, the effort to build better collectors must be replicated for each language runtime. On the other side, developers deploying such systems in production may turn off the garbage collector all together¹, or switch to manual memory management, giving up the productivity gains of memory-safe languages [49].

We propose a new approach to building distributed systems in garbage collected languages, called BLADE, that gives control over tail-latency back to the programmer. Instead of attempting to minimise pause times, distributed systems should treat pause times as a frequent, but predictable *failures*. BLADE is an interface to the run-time system that allows programmers to participate in the decision to pause for collection, customising the collection policy to their system.

BLADE's simple API allows systems builders to:

- 1. eliminate garbage collection related latency
- 2. by leveraging system-specific failure recovery mechanisms to mask pause times,
- 3. and model the performance impact of garbage collection without knowledge of the production workload.

In this paper, we describe and evaluate the BLADE API. We implemented BLADE for the Go programming language and used it to eliminate garbage collection related tail-latency in two different distributed systems. The first system is a cluster of web application servers behind a load-balancer, and the second is the Raft [44] consensus algorithm.

We compare BLADE in both systems against the default Go garbage collector, and the optimal solution for performance of no garbage collection at all. For the HTTP cluster, BLADE completely eliminates any latency impact on requests caused by garbage collection, while for the Raft consensus algorithm, it bounds the latency impact to a single extra network RTT ($48 \, \mu s$ in our experimental setup). In end-to-end tests, this matches the performance of the optimal system with no GC.

The rest of the paper is organized as follows. In Section 2, we motivate the problem and explain why existing solutions do not work. In Section 3 we outline BLADE. In Section 4 we explore two end-to-end distributed systems that use BLADE and in Section 5 we evaluate both systems. In Section 6 we

discuss the results and limitations, while in Section 7 we describe related work. Finally, we conclude in Section 8.

2. Background

2.1 Data Center Performance Today

The performance demands of applications running in data centers are changing significantly. To enable rich interactions between services without impacting the overall latency experienced by users, average latencies must be in the few tens or low hundreds of microseconds [8, 54]. Because a single user request may touch hundreds of servers, the long tail of the latency distribution we must also consider [18, 31], with each service node ideally providing tight bounds on even the 99.9th percentile request latency.

Today, most commercial Memcached deployments provision each server so that the 99th percentile latency does not exceed $500\,\mu s$ [35]. Recent academic results such as the IX operating system can run Memcached with 99th percentile latencies of under $100\,\mu s$ at peak [9]. The MICA key-value store can achieve 70 million requests-per-second with tail-latencies of $43\mu s$ [37]. Current research projects such as RAMCloud [45, 47] are targeting $10\,\mu s$ or lower RPC latencies.

2.2 State of Garbage Collection

We give a brief overview of garbage collection and the tradeoffs for the main approaches. Garbage collectors deal with two major concerns: finding and recovering unused memory, and dealing with heap fragmentation, often by relocating live objects. We will look at four collector designs: stop-the-world (STW), concurrent, real-time and reference counting.

Stop-the-world Stop-the-world collectors are the oldest, simplest and highest throughput collectors available [22]. A STW GC works by first completely stopping the application, then starting from a root set of pointers (registers, stacks, global variables) traces out the applications live set. Objects are either marked as live, or relocated to deal with fragmentation. Next, the application can be resumed and any unmarked objects added to the free list.

Their simplicity and high-throughput make them common. For example, Go, Ruby, and Oracle's JVM (by default) use STW collectors. The downside is that pause times are proportional to the number of live pointers in the heap. As a result, state-of-the-art STW collectors can have pause times of 10–40 ms per GB of heap [22].

Concurrent Concurrent collectors attempt to reduce the pause time caused by STW collectors by enabling the GC to run concurrently with application threads. They achieve this by using techniques such as read and write barriers to detect and fix concurrent modifications to the heap while tracing live data and/or relocating objects. For example, a common approach to concurrent tracing is to use write barriers, either through inline code or virtual memory protection, whereby

 $[\]overline{\ }$ Generational garbage collectors often allow users only to disable collection for the old generation, but this just serves to delay, not eliminate, memory exhaustion

any modification to the heap will enter a slow path handler that adds the pointer to the list of pointers to trace [23, 27, 64]. For handing concurrent relocation of objects to reduce fragmentation, either Brook's style read barrier [12] are used, where all pointer dereferences check to see if the object has been replaced with a forwarding pointer pointing to the objects new location, or, direct access barriers [7, 15, 23], where a read barrier is used to fix up any pointer to point to the new location as the pointer is read from the heap.

Because of these techniques, pause times for the best concurrent collectors are measured in the few milliseconds [4, 23, 30]. However, concurrent collecters have lower-throughput, higher implementation complexity and edge cases that still require GC pauses. First, concurrent collectors reduce application throughput between 10-40% and increase memory usage by 20% compared to STW collectors [19, 22, 64]. This is due to the overhead of handling barriers, forwarding pointers and synchronization between the GC threads and application. Second, most concurrent collectors have corner cases that trigger long pauses. For example, STW pauses are often used to start or end collector phases [27, 64], the amount of work that can occur in a slow-path for an allocation or barrier is variable and often unbounded [27, 50], and high-allocation rates can cause the application to outpace the collector and pause [51]. Finally, concurrent collectors are incredibly complex. Oracle's JVM, for example, has two concurrent collectors, CMS and G1, but both have pause times in the hundreds of milliseconds due to significant stages of their collection cycle being STW.

Real-time Garbage collectors designed for real-time systems take the approaches of concurrent collectors even further, many offering the ability to bound pause times. The best collectors can achieve bounds in the tens of microseconds [50, 51], however doing so comes at a high throughput cost ranging from 30%–100% overheads, and generally increased heap sizes of around 20% [50, 51]. This is due to techniques such as fragmented allocation [6] to avoid the recompacting stage taken by most non-real-time concurrent collectors to handle fragmentation. Fragmented allocation allocates all objects at small, fixed size chunks, breaking up logical objects larger than the chunk size. The extra indirection can greatly impact system performance.

Reference counting A completely different approach to a tracing garbage collector is reference counting. Each object has an integer attached to it to count the number of incoming references, which once it reaches zero, indicates the object can be freed. It's largely predictable behaviour and simple implementation makes it common, for example, Python, Objective-C and Swift all use reference counting.

In general, reference counting greatly improves pause times since there is no background thread for collection, instead reclaiming memory is a incremental and localised operation. However, three problems emerge: lower throughput, free-chains and cycles. First, reference counting suffers from poor throughput due to the need for atomic increments and decrements on pointer modifications. On average reference counting has 30% lower throughput compared to tracing collectors [10, 56]. Recent work has improved this to be competitive [56, 57] but does so by incorporating techniques from tracing collectors and bringing pauses. Second, reference counting collectors can suffer from long pauses on free operations when doing so causes a long chain of decrements and frees to other objects in the heap. Third, and finally, reference counting suffers from it's inability to collect cyclic data structures. This is solved by either complicating the interface to the developer and asking them to break cycles, or by including a backup tracing collector to collect cycles periodically [56]. Python for example takes this approach.

3. Design

BLADE is an interface to the run-time system (RTS) of the language that allows programmers to participate in the decision to pause for collection, letting them customize the collection policy to their system. BLADE is not a new approach to garbage collection, but a new approach to dealing with its performance impact in distributed systems.

Table 1 summarises the API for BLADE, which consists of three simple functions. The regGCHand (handler) simply setups a function as a target for an upcall from the RTS. The startGC (id) starts the collector, passing in an id number previously given to the application through an upcall. The id argument is a monotonically increasing argument over upcalls and serves to make the function idempotent. Finally, the upcall function gcHand (id, allocated, pause), is invoked by the RTS at the start of every collection and allows the application developer to decide if the collection should occur immediately or be delayed. The id argument identifies this collection event, while the a argument indicates the current heap size. Finally, the p argument gives an estimate by the collector on the time that this collection will take. The function can either return a boolean result of true to indicate that the RTS should immediately perform the collection, or it can return false to delay the collection until startGC is

This API is simple enough that most garbage collected languages can implement it in a hundred lines of code or so. For example, it took 112 lines of code to implement BLADE for the Go programming language.

While there are a few different design choice for the API, we decided on this one as it is minimal and easily supported by languages, yet expressive enough for supporting our end-to-end systems. The parameters passed through to the gcHand function are where we had the most choice, and indeed the right choice here will likely vary slightly from language to language. For exampe, in Java, a third parameter of the amount of heap remaining would be appropriate, but our target language of Go doesn't support any notion of bound-

Table 1: BLADE API

Operation	Description
void regGCHand (handler) bool gcHand (id, allocated, pause) void startGC (id)	Set function to be called on GC Upcall to schedule GC event Start the GC

ing the heap size. The purpose of the arguments to gcHand is to allow the application developer to make appropriate policy decisions on when to collect. This will generally be a binary choice of collecting now, or deferring collection until appropriate failure recovery actions have been taken to minimize the latency impact. The right decision for the application will depend on the expected latency impact of the collection as short collection do not make sense to coordinate globally. The estimated pause time in our current Go implementation is derived by simple linear extrapolation from previous collection pause times at different heap sizes.

As BLADE allows delaying collection, the RTS must decide both when to make the upcall to the application and what to do if memory is exhausted before the collection is scheduled. For the first situation we add a configurable low-watermark parameter to the RTS to allow specifying how much room for delay should be left when upcalling into the application. For the exhaustion situation, we simply have the collector run immediately. Any future call to startGC (id) with that collection events id number will be ignored. This retains safety and simply reduces performance in the worst case to one without BLADE. We initially tried adding a second upcall from the RTS to the application to notify them when this timeout occured, but found that it was both complex to handle and generally of little benefit. Given that this is also expected to be rare, moving startGC (id) to be idempotent resulted in what we believe to be a stronger design.

4. BLADE Systems

In this section, we apply BLADE to two different end-to-end distributed systems. First we look at the simplest case for BLADE, a cluster of stateless HTTP servers behind a load-balancer, next, we look at the Raft [44] consensus algorithm.

4.1 HTTP Proxy: No shared state

The most natural application domain for BLADE is a fully replicated service where any server can service a request. Here we consider a load-balanced HTTP service where a single coordinating load-balancer proxies client requests to many backend servers. Typically, all backend servers are identical and the load-balancer uses simple round-robin to schedule requests. The load-balancer can also detect when backend servers fail by imposing a timeout on requests. However, since some HTTP requests might take a while to service, the load-balancer cannot easily distinguish between a misbehaving server servicing a fast request, and a properly

behaving server servicing a slow request. As a result, timeouts are typically set high – for example, in the NGINX web server [2], the default timeout is 60 seconds.

The HTTP load-balanced distributed system has a few unique properties. First, each request can be routed to any of the replicas. Second, any mutable state is either stored externally (e.g., in a shared SQL database) or is not relevant for servicing client requests (e.g., performance metrics). Third, the HTTP load-balancer acts as a single, centralized coordinator for all requests². These three properties make BLADE easy to utilize.

The approach is to have a HTTP server explicitly notify the load-balancer when it needs to perform a collection, and then wait for the load-balancer to schedule it. Once the collection has been scheduled, the load-balancer will not send any new requests to the HTTP server, and the HTTP server will finish any outstanding requests. Once all requests are drained, it can start the collection, and once finished, notify the loadbalancer and begin receiving new requests. In most situations, the load-balancer will schedule a HTTP server to collect immediately. However, it may decide to delay the collection if a critical number of other HTTP servers are currently down for collection. This allows the load-balancer to make decisions with throughput impacts in mind. Figure 2 shows the pseudocode for how a backend server uses BLADE. One subtlety is when deciding to handle a collection, the application starts a new thread (a cheap operation in Go) as the thread that invoked the callback is another application thread that just tried to allocate, so may be holding locks.

4.1.1 HTTP: Performance

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Using BLADE with the HTTP cluster allows us to trade capacity for better latency, as such, no request should ever block waiting for the garbage collector. We can model this formally to investigate the impact of a GC event on the system. We break down the stages involved at a single HTTP backend for performing a garbage collection using BLADE; this can be seen in Figure 3. It consists of $T_{schedule}$, the time to both request and be scheduled to GC by the load-balancer, $T_{trailers}$, the time for the HTTP server to service any outstanding requests, T_{gc} , the time to perform the garbage collection, and

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² Some deployments have multiple HTTP load-balancers, themselves load-balanced with DNS or IP load-balancing, however, commonly each load-balancer in this case manages a separate cluster anyway to make more effective load-balancing decisions.

```
func bladeGC(id)
prpc(controller, askGC)
waitTrailers()
startGC(id)
prpc(controller, doneGC)

func handGC(id, allocd, pause) bool
if threshold(allocd, pause)
return true
else
// start in new thread
go bladeGC(id)
return false
```

Figure 2: Pseudocode (Go) for HTTP Cluster using BLADE.

 T_{rpc} , the time to send an RPC notifying the load-balancer the GC is finished. This gives us the following model:

HTTP Cluster GC Model			
LatencyImpact	=0		
CapacityLoss	= 1 server		
CapacityDowntime	$=T_{trailers}+T_{gc}+T_{notify}$		
Event Time	$=T_{schedule}+CapacityDowntime$		

In general, we expect $T_{schedule}$ to be 1 network round-triptime (RTT), while T_{notify} should be $\frac{1}{2}$ the network RTT. The value of $T_{trailers}$ is application specific, but importantly, is a term expressed in units that the application developer is intimately familiar with.

The latency impact of zero is of course only true when the current throughput demand on the cluster is low enough to be satisfied by the remaining servers without queuing. However, even when this isn't the case as the load-balancer spreads all requests evenly over the remaining servers, no individual request experiences a disproportionate latency impact. Without BLADE, the latency impact on requests of garbage collection would be the length of the GC pause, T_{gc} , potentially far longer than 0. On the downside, using BLADE does extend the duration of the capacity downtime by $T_{trailers} + T_{notify}$, which has a lower bound of half the RTT.

Importantly this model show how BLADE allows developers to achieve the three goals we started with: bounding latency, do so using failure recovery mechanisms present in the system, and model the performance impact of garbage collection on the system. For a HTTP cluster, BLADE bounds latency to 0 by using the load-balancer and allows us to model this without concern for workload, heap size or the underlying garbage collection algorithm.

4.2 Raft: Strongly consistent replication

In the HTTP load-balancer, because there is no shared mutable state at the server, any server can service any request and, as a result, we can treat garbage collection events as temporary failures. The same is true when mutable state is consis-

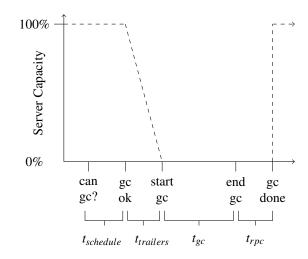


Figure 3: Capacity of a HTTP server over time during a garbage collection cycle with BLADE.

tently shared between all servers, for example, as in a Paxoslike [34] system that uses a consensus algorithm for strongly consistent replication. In this section we consider how to use BLADE for the Raft [44] consensus algorithm.

In Raft, during steady-state, all write requests flow through a single server referred to as the 'leader'. Other servers run as 'followers'. Writes are committed within a single round-trip to a majority of the other servers, leading to sub-millisecond writes in the common case³. Garbage collection pauses can hurt cluster performance in two cases. First, when the leader pauses, all requests must wait to be serviced until GC is complete. If GC pause time exceeds the leader timeout (typically 150ms), the remaining servers will elect a new leader before GC completes. Second, if a majority of the servers are paused for GC, no progress can be made until a majority are live again. The second case is worse, because if garbage collection pauses are very long, there is no built-in way for the system to make progress during this time. The probability of this occurring is higher than expected as the memory consumption will be roughly synchronized across servers because of the replicated state machine each on is executing.

We use BLADE with Raft as follows. First, when a follower needs to GC, we follow a protocol similar to the HTTP load-balanced cluster. The follower notifies the leader of it's intention to GC and waits to be scheduled. The leader schedules the collection as long as doing so will leave enough servers running for a majority to be formed and progress made. We only consider servers offline due to GC for this, as servers down for other reasons could be down for an arbitrary amount of time. The leader must also timeout servers considered down for garbage collection to prevent blocking, marking their GC as completed, in the rare event that they become unavailable during a collection. One important differ-

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³ In a low-latency network topology and persistent storage (such as flash drives).

```
// run in own thread
     func bladeClient()
       reqInFlight := 0
 4
       forever
          select
           case id := \leftarrow gcRequest:
              reqInFlight = id
 8
              rpc(leader, askGC)
            case id := \leftarrow \texttt{gcAllowed}:
              reqInFlight = 0
              startGC(id)
              rpc(leader, doneGC)
            case leader := ← leaderChange:
              if reqInFlight != 0
                rpc(leader, askGC)
18
     func handGC(id, allocd, pause) bool
       if threshold(allocd, pause)
         return true
22
       else
         // start in new thread
24
         go\ func()\ \{\ \texttt{gcReq}\ \leftarrow\ \texttt{id}\ \}()
         return false
```

Figure 4: Pseudocode (Go) for Raft server, when functioning as a follower and not a leader, using BLADE. The \leftarrow symbols represent message passing between threads using channels.

ence with Raft compared to the HTTP load-balancer is that the leader doesn't need to stop sending requests to followers while they are collecting, and neither do followers need to wait to finish any outstanding requests. As Raft is designed to make progress with servers unavailable, we can rely on this and have a follower proceed with GC. We present the pseudocode for the follower situation in Figure 4, including the retry logic for sending requests to the new leader if it changes over the course of a collection request. The code makes use of *channels*, a message passing mechanism provided in Go.

The second situation, when a server is acting as leader for the cluster, is more interesting. Since the cluster cannot make progress when the leader is unavailable, we switch leaders before collecting. Once the leadership has been transferred, the old leader (now a follower) runs the same algorithm as presented previously for followers in Figure 4. A leadership switch like this can be done in just $\frac{1}{2}$ the RTT of the network by having the current leader send a broadcast to all servers in the cluster notifying of the new leader [43]. The current leader may need to delay switching leadership until it knows that the next chosen leader is up-to-date, but during this time, the cluster can continue servicing requests. We present the Pseudocode for the leader situation in Figure 5. In this design the current leader chooses the last server that collected to be the next leader, or a random server if this information isn't known. Since the current leader acts as the coordinator for garbage collection, it also keeps track of how many servers

```
// run in own thread
     func bladeLeader() void
                  := 0
       used
        pending := queue.New()
        lastGC := cluster.RandomServer()
        forever
          select
             case \ \texttt{from} \ \texttt{:=} \ \leftarrow \ \texttt{gcRequest:}
                if used + 1 > quorum
                  pending.End(from)
                else
                  used++
                  if from == myID
                     switchLeader(lastGC)
                  else
                     rpc(from, allowGC)
             case \ \texttt{from} \ \texttt{:=} \ \leftarrow \ \texttt{gcFinished:}
18
               lastGC = from
                if pending.Len() == 0
                  used--
                else
                  from = pending.Front()
24
                  if from == myID
                     switchLeader(lastGC)
26
                     rpc(from, allowGC)
             case \ \texttt{leader} := \leftarrow \ \texttt{leaderChange} \colon
               used = 0
               pending.Clear()
     }
```

Figure 5: Pseudocode (Go) for Raft server, when functioning as a leader, using BLADE.

are currently collecting, and queues requests for future collections from servers that cannot be scheduled immediately.

Finally, outstanding client requests at the old leader must be handled. One method is to notify clients of the new leader and have them retry. This is simple but incurs more latency than required. Instead, the old leader can act as a proxy for these requests, forwarding them to the new leader in the same RPC as the election switch message. The new leader can either reply to clients through the old leader, or directly to them, depending on the client design.

4.2.1 Raft: Performance

As before with the HTTP cluster, we can model the performance impact on Raft of a GC event when using BLADE. First, we model the impact when a follower collect, and secondly, when the leader collects.

In the first case, when a follower collects, the Raft cluster can service this GC without any impact on the latency of the system. Throughput should also be unaffected, although we are making the assumption that the cost to bring a unavailable server up-to-date after a GC does not noticeably affect the throughput and latency of the cluster. This gives us the model below for the impact of a follower GC event, where we expect $T_{schedule}$ to be the network RTT in the common case:

Raft Follower GC Model			
LatencyImpact	=0		
CapacityLoss	=0		
EventTime	$= T_{schedule} + T_{gc}$		

In the second case, when a leader collects, then we will take the additional cost of a fast leader election and proxying queued client requests to the new leader. This gives us the model below:

Raft Leader GC Model			
LatencyImpact	$=T_{fastelect}+T_{proxy}$		
	= 1RTT		
CapacityLoss	=0		
EventTime	$=T_{fastelect}+T_{proxy}+T_{gc}$		
	$= \frac{1}{2}RTT + T_{proxy} + T_{gc}$		

One complication with the leader case, captured by the T_{proxy} value, is that the leader needs to both forward any queued requests from clients to the new leader, and also should inform clients that a leadership change has occurred. The time it takes to do this, and so for how long the leader should delay beginning its GC, is highly dependent on the system setup. With a small number of known clients, the leader can broadcast to them that a new leader has been elected. With a larger, or unknown number of clients, a proxy layer may be desirable that clients go through.

5. Evaluation

To evaluate BLADE, we used it in two distributed systems, first a HTTP cluster behind a load-balancer, and second, the Raft consensus algorithm. Both systems are previously described in Section 4.

For evaluating the performance of the GC system, we use the standard Go garbage collector since all our systems are written in the Go programming language. We use Go version 1.4.2, the latest at the time of writing. Go currently uses a parallel mark-sweep collector, with marking done as a stopthe-world phase and sweeping done concurrently with the application (mutator) threads. Because this GC design is far from state-of-the-art (although still very common in modern languages), we also compare against the ideal case of no garbage collection at all. We do this by simply disabling Go's garbage collector, so memory is never reclaimed. Go by default also runs the collector every two minutes if not run recently in order to give memory back to the operating system. For all of the evaluations below we disable this as we felt it unfairly favoured BLADE by being a explicit source of synchronization.

All experiments were run over a 10 GbE network, using machines with Intel Xeon E3-1220 4 core CPU's with 64 GB

Component	SLOC
Web Application	54
Load-balancer Coordinator	174

Table 2: Source code changes needed to utilize BLADE with a web application cluster.

of RAM and running FreeBSD 10.1. The network RTT was measured to be $48\mu s$ on average.

5.1 HTTP Load-Balancer Performance

In this section we investigate the performance impact of using BLADE with a HTTP load-balanced cluster.

We built a simple web application that allows users to search and retrieve movie information from a backing SQL database. The web app keeps an in-memory local cache of recent movie insertions and retrievals to improve performance by avoiding a DB lookup on each requests. The application does not allow updates to existing records. We run HAProxy [60] version 1.5 (latest at time of writing) in front of three servers, using round-robin to load balance requests across all three.

Adding support for BLADE to the web application required 228 SLOC to be added. Of these, 54 were added to the web application itself, while the other 174 were for implementing a controller for the load balancer to coordinate the GC at each web application server and ensure only one was ever collecting at any point in time. As HAProxy already supports a TCP interface for enabling and disabling backends, the coordinator is only required when enforcing capacity SLAs.

We also evaluated the latency behaviour of the three different configurations of the cluster using a fifth machine to generate load. A CDF of the request tail-latency when generating 6,000 requests-per-second can be seen in Figure 6. We ran the experiment for six minutes, during which each node collects three times. We ran the experiment four times in total for each configuration and averaged the results. BLADE achieves a result so similar to the GC-Off configuration that we have to present them on the same line in Figure 6. Overall performance of each configuration can be seen in Table 3. The GC-On configuration has tail-latencies far beyond the time the application is paused by the garbage collector. This appears to be due to the impact of queues building up, occasional network retransmissions when buffers overflow, and unfair servicing of pending sockets by Go. This amplification affect has previously been explored [36, 63].

During these runs we also observed occasions when the garbage collection event at a backend server overlapped with another. An example of such an overlap can be seen in Figure 7, with the latency of requests to each server shown as the GC event occurs at servers *B* and *C*. Out of a total of 36 observed collections across the three servers, 8 of them overlapped for an average of 22.2% of collections. While this is likely high due to the experimental setup, real-world systems

	GC-Off	BLADE	GC-On
Mean	2.312	2.311	2.403
Median	2.296	2.294	2.297
Std. Dev.	0.579	0.582	3.395
Max	7.847	7.443	164.206
Avg. GC-Pause	0	12.423	12.339

Table 3: Latency measurements of requests to 3-node HTTP cluster behind a load-balancer under different GC configurations. Timings are in milliseconds (ms). Same experiment as Figure 6.

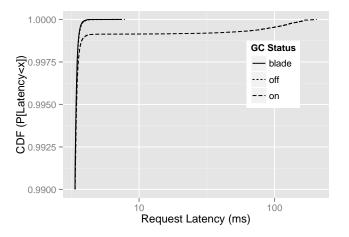


Figure 6: CDF of request tail-latency to 3-node HTTP cluster behind a load-balancer. BLADE and the GC-Off configuration are so similar that their lines overlap. Load generator is simulating 400 connections to the cluster, sending 6,000 requests-per-second. Each node has a 1GB heap for a 150MB live set, and allocates on average at 12.5 MB/s. Each node collects 3 times during the 6 minute experiment.

often have external sources of synchronization that increase the chances of these overlaps occurring. For example, the Go default GC policy of running every two minutes (which we disabled), or when sudden surges of traffic hits the cluster.

Finally, we ran a second experiment on the same cluster to check the throughput that each configuration is capable of, the results of which are presented in Table 4. As expected, BLADE doesn't cause any drop in throughput compared to the regular GC-On setup, both achieving around 52,000 requests-per-second. The GC-Off configuration however achieves a lower throughput due to the overhead of constantly requesting fresh memory from the OS, consuming a 34GB heap by the end of the experiment. We used these numbers to run one final latency test, but generating 40,000 requests-per-second this time, close to the peak for all three configurations. The results can be seen in Figure 8. The slight penalty that the BLADE configuration pays at the tail, from reduced capacity, when under load, can be seen when comparing GC-Off with

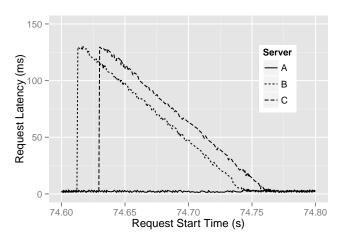


Figure 7: Request latency of HTTP cluster broken out by backend server during a collection event at two of the workers. Over four runs of the latency experiment we observed 36 collections, with 8 of them overlapping, or 22.2%.

	GC-Off	BLADE	GC-On
Requests/s	42,643	51,624	51,983
Std. Dev.	2,213	2,573	672

Table 4: Max throughput of each configuration for the HTTP cluster. Results are averaged from three runs, each run being 6 minutes long.

BLADE. BLADE is on average $100-300 \,\mu s$ slower from the 95th percentile on.

5.1.1 Web Application Frameworks

Using BLADE in a web application is generic enough in nature that we can package it as a library. To demonstrate this we wrote a Go package that can be included by any web application that uses the popular Gorilla Web Toolkit [1]. It's tied specifically to Gorilla because we need to be able to detect when all trailing requests have completed (or be able to cancel them if desired). By including this package, any Gorilla web application that can work with a client session being handled by different servers, can benefit from BLADE.

5.2 Raft Performance

In this section we investigate the performance impact of using BLADE with the Raft consensus algorithm. As Raft is not a standalone system, we use Etcd [16], a replicated key-value store with a ZooKeeper [29] inspired API that uses Raft for the consensus algorithm.

To efficiently use BLADE in Etcd involved implementing support for fast-leadership transfers, and also handling GC upcalls using the algorithms outlined in Figure 4 and Figure 5. This required 563 lines of code to be changed (largely additions) in Etcd, with the breakdown shown in Table 5. As fast-

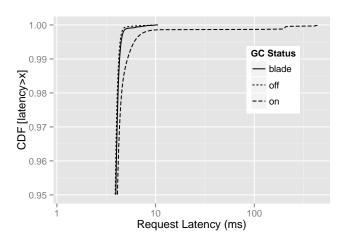


Figure 8: CDF of request tail-latency to 3-node HTTP cluster behind a load-balancer. Load generator is simulating 400 connections to the cluster, sending 40,000 requests-per-second. Each node has a 1.5GB heap for a 200MB live set, and allocates on average at 83.3 MB/s. Each node collects 17 times during the 6 minute experiment, with an average pause time of 14.45 ms.

Component	SLOC
Fast-leader switch	214
Blade GC support	349

Table 5: Source code changes needed to utilize BLADE in Etcd.

leadership transfers are useful for purposes beyond BLADE, it is fair to count the effort needed to support BLADE in Etcd as 349 SLOC.

For evaluating the performance of BLADE with Raft, we set up a three node Etcd cluster under three different configurations. First, when running with the standard Go garbage collector, secondly, when running with the garbage collector disabled, and finally, when using BLADE. We ran a single experiment were we loaded 600,000 keys into Etcd and then sent 100 requests per second at regular intervals for 10 minutes to the cluster using a mixture of reads and writes in a 3:1 ratio. We track the latency of each request after the initial load of keys. We ran the experiment three times for each configuration and took the average of the three. In all configurations the standard deviation between the three runs was less than 5%. We use a low request rate as at this time, Etcd is early in its development and doesn't support a high request rate, (peaking at around 400 requests/s on our setup) becomes very unstable anywhere close to its peak

With the GC enabled, this experiment peaks at consuming 473 MB of memory. While very small by modern server standards, it is sufficient to evaluate our results since BLADE thankfully is not affected by heap size in terms of latency impact on requests.

	Mean	Median	Std. Dev.	Max
GC-Off	0.532	0.530	0.031	1.127
BLADE	0.505	0.499	0.030	1.015
GC-On	0.589	0.517	2.112	95.969

Table 6: Latency measurements of SET requests to Etcd cluster under different GC configurations. Timings are in milliseconds (ms).

	BLADE	GC-Off	GC-On
95th	0.52	0.54	0.54
99th	0.57	0.57	0.56
99.9th	0.62	0.67	28.81
99.99th	0.70	1.03	86.98
99.999th	0.80	1.08	94.22
99.9999th	0.97	1.12	95.96

Table 7: SLA measurements for different Etcd configurations. Timings are in milliseconds (ms).

The results for set request latencies for all three configurations are shown in Table 6. Excluding tail-latency, all three achieve similar performance levels, although BLADE outperforms each configuration across the board. BLADE achieves a mean of $505\,\mu s$ and a worst-case of $1.01\,\mathrm{ms}$, GC-Off a mean of $532\,\mu s$ and a worst-case of $1.13\,\mathrm{ms}$, and GC-On a mean of $589\,\mu s$ and a worst-case of $95.96\,\mathrm{ms}$. The reason BLADE even outperforms the GC-Off configuration is due to the penalty GC-Off pays from the extra system calls and lost locality from requesting new memory rather than ever recycling it. Results for get requests show the same relation among the three configurations.

When looking at the tail-latency of each configuration, a different story emerges. A CDF of slowest 1% of both get and set requests can be seen in Figure 9. As expected, performance of the standard GC configuration has a very long tail from GC pauses. The results for the GC-Off configuration and the BLADE configuration however are nearly identical. This is expected from the performance model we established in Section 4.2.1, that showed latency has an expected increase of 1 network RTT during a GC, a value of $48\,\mu s$ in our experimental setup. Indeed, as can be seen in the detailed breakout of the performance in Table 7, BLADE slightly outperforms the GC-Off configuration. This is due to the GC-Off configuration paying a penalty from the higher memory use as mentioned previously, and the $48\,\mu s$ being within the tail-latency caused by other sources of jitter such as the OS scheduler.

6. Discussion & Limitations

Understanding Performance With BLADE we set out to achieve three goals: bound tail-latency in distributed systems, do so using system specific failure recovery mechanisms, and to allow the performance impact of garbage collection to be modelled without knowledge of production workloads. For

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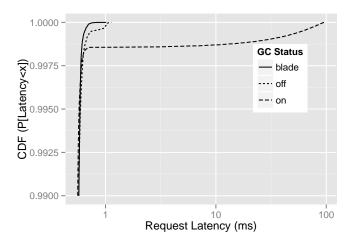


Figure 9: CDF of Etcd replicated key-value store request latency for all GC configurations

the final point, the performance models for each system in Section 3 demonstrate how BLADE can achieve this. With Raft for example, we know that the latency impact of using a garbage collected language will be a single extra network RTT. As the time to complete any request is at least one network RTT, using a garbage collector with BLADE limits the tail-latency from GC to twice the mean in the worst case. Importantly, the impact of GC is now in units comparable to the rest of the system. Furthermore, as network speeds improve over time, so will BLADE. While our test setup had a network RTT of $48\,\mu s$, $10\,\text{Gbps}$ NICs are currently available that achieve less than $1.5, \mu s$ latency at the end-host [40]. Garbage collectors are chasing a continually moving target, but BLADE scales with the performance of the distributed system.

Limitations Another important outcome from using BLADE in a distributed system, is the changed requirements for the garbage collector. As BLADE deals with the latency impact, in most situations a concurrent collector will no longer be the best fit. Instead, a simpler and high-throughput stop-the-world collector is best suited [22]. These collectors are already readily available in most languages, unlike high-performance concurrent collectors.

There are, however, a number of limitations with BLADE.

- First and foremost, BLADE is not a universal solution. We specifically target distributed systems as this is an important area where low-latency matters and we've had bad experiences with garbage collected languages. Even then, BLADE wil not work for every distributed system as it relies on their being a failure recovery mechanism that can be exploited. Common, but not universal.
- Secondly, BLADE requires developers to write code and doesn't apply transparently. This, however, is by design and we believe our results show that the amount of work

- needed is low. Even with garbage collection, developers do not ignore memory management and still apply techniques such as local allocation caches to improve performance, BLADE is one more technique that can be used.
- Third, BLADE takes whole servers offline during a garbage collection, which may be too large a capacity loss for some systems. If, for example, BLADE was used for a HTTP cluster with only two servers, then using 50% of the cluster capacity is likely to be unworkable.

7. Related Work

Trash Day Mass et al. have recently done work on coordinating garbage collection in a distributed system [38]. They look at two different systems, Spark [65] and Cassandra [33], noting that for Spark, having all nodes collect at the same time improves performance, while for Cassandra, staggering collection and routing requests around nodes can reduce tail latency. They design a run-time system to provide a general approach to this problem, allowing different coordination strategies across multiple nodes to be implemented.

Process Restarts We have heard of a few different companies in industry that disable garbage collection, either completely or for the old generation, and then kill and restart the process as needed. They will often attempt to drain requests before restarting the process. This is similar to BLADE but less principled, support is not provided directly in the programming language and as it requires that programs can support arbitrary restarts, it only works for a subset of the programs that BLADE supports. Restarting should also be a slower operation as it needs to reload state from permanent storage. As far as we are aware, none of these companies apply this technique to stateful systems such as Raft.

HTTP Load-balancing Portillo-Dominguez et al. have recently done work on HTTP load-balancers in Java to avoid the impact of garbage collection on latencies [52, 53]. Their approach is very similar to BLADE, modifying a round-robin routing algorithm to avoid the collecting server. They do not modify the language or RTS however as we propose, instead they model the GC and try to predict when it will collect. Mispredictions mean lower performance than BLADE, and also no ability to deal with overlapping collections. They also deal with a very different level of performance than we are concerned with, starting with worst case request latencies in the hundreds of seconds and reducing that to the tens of seconds. We are instead concerned with microseconds.

JVM & .NET The Java Virtual Machine (JVM) supports two programmable interfaces to the garbage collector. One is the System.gc() function that suggest to the RTS to start the GC. The other is the *Garbage Collection Notifications API* (JGCN) optional extension [46]. JGCN supports callbacks, like BLADE, to the application, but it only supports notifying the application after a collection has complete. JGCN is intended for performance monitoring and debugging.

Microsoft's .NET platform supports an API very similar to BLADE, the *Garbage Collection Notifications* API (MGCN) [41]. MGCN, like BLADE, supports application callbacks before garbage collection occurs. MGCN doesn't, however, allow the application to delay collection, only to start it earlier than the RTS planned. MGCN is suggested for use by Microsoft in a similar manner to BLADE, but as of this time we are unaware of any reports on it's usage or evaluation of it. The lack of control with MGCN to coordinate nodes, and avoid GC overlaps at servers, appears to be a concern with some potential users. The popular Stack Overflow website, for example, chose not to use MGCN partially for this reason [55].

Concurrent Tracing Garbage Collectors A vast amount of work has been done in improving pause times of garbage collectors. A sample of this was covered in Section 2. Azul Systems Zing GC [4, 15, 23, 30] is one of the best available today, with pause times in the low milliseconds or microseconds. This is still one to two orders of magnitude above what BLADE can achieve, and will get worse as faster networks with under $5 \mu s$ RTT become available. The work by Pizlo et al. such as Schism, on real-time collectors [50, 51] achieves the lowest pause times we are aware of, capable of bounds in the tens of microseconds but suffers from 30% lower throughput and 20% higher memory consumption compared to stopthe-world collectors. Other concurrent and real-time collectors that we are aware of [5, 6, 14, 19, 27, 28, 39, 64] all perform worse in latency and/or throughput than both Azul and Schism, with pause times in the tens of milliseconds. Finally, while many of these systems have STW pauses for some situations, work such as that of Tomoharu et al. [61] seeks to address these final cases.

Reference Counting The best reference counting collectors have very low and uniform latency impact on an application as demonstrated by the Ulterior Reference Counting [10] collector. However, they have historically suffered from lower throughput compared to tracing collectors. The work of Shahriyar et al. [56, 57] has made reference counting collectors competitive, but does so by incorporating background tasks and pauses. Unfortunately Shahriyar doesn't report the latency impact of these changes.

Tail tolerance Vulimiri et al. proposed [62] an approach to handling tail-latency for Internet services such as DNS, where requests were duplicated and sent to multiple servers. Dean and Barroso proposed and investigated a similar idea [18], but specifically for addressing tail-latency [18] in data centers. Servers then either race to fulfil the request, or coordinate with each other to claim ownership of the request when they start processing it. Jalaparti applied this idea, as well as allowing incomplete requests, to build a framework for constructing data center services [31]. BLADE takes a similar approach to tail tolerant systems, not attempting to reduce the impact of garbage collection on an individual server, but avoiding

it's impact on the end-to-end system. BLADE however solves a specific, but common problem, garbage collection, rather than treating servers as a black box. This allows BLADE to be used in situations such as Raft where tail tolerant systems do not apply as requests cannot be duplicated and sent to multiple servers.

8. Conclusion

BLADE is a new approach to garbage collection for a particular, but large and important class of programs: distributed systems. BLADE uses the ability of distributed systems to deal with failure, to also handle garbage collection, treating garbage collection as a partially predictable and controllable failure. We applied BLADE to two important and common systems, a cluster of web servers and the Raft consensus algorithm. For the first case, we eliminated the latency impact of garbage collection, and for the second, we reduced it to the order of a single network round-trip, or $48 \,\mu s$ in our experiment. As BLADE handles the impact of garbage collectors in distributed systems rather than attempt to improve them directly, it allows for a different set of choices when designing the collector. Simple, high-throughput designs are preferable with BLADE than the complexity of collectors that try to minimize pause times.

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