

Malacology: A Programmable Storage System Built on Ceph

Abstract

Storage systems are caught between rapidly changing data processing systems and the increasing speed of storage devices. This puts tremendous pressure on storage systems to adapt both in terms of their interfaces and their performance. But adapting storage systems can be difficult because unprincipled changes might jeopardize years of code-hardening and performance optimization efforts that were necessary for users to entrust their data to the storage system. We introduce Malacology, a prototype programmable storage system to explore how existing abstractions of common services found in storage systems can be leveraged to address new data processing systems and the increasing speed of storage devices. This approach allows unprecedented flexibility for storage systems to evolve without sacrificing the robustness of its code-hardened subsystems. We illustrate the advantages and challenges of programmability by constructing two new services out of existing abstractions POSIX metadata load balancer and a high-performance distributed shared-log that leverages flash devices. RESULTS

1 Introduction

New scale requirements for data processing architectures and the increasing speed of storage devices are disruptors for storage and data management. As a consequence, layers of the software stack become obsolete and code paths grow longer and more obfuscated. Evolution of the storage system can affect the robustness of code-hardened subsystems, yet there needs to be an equally flexible storage system to address the diverse performance requirements of the application.

For example, Ceph [1] addresses *durability* with its RADOS object store (e.g., replication, erasure coding, and data scrubbing), *consistent versioning* by having daemons

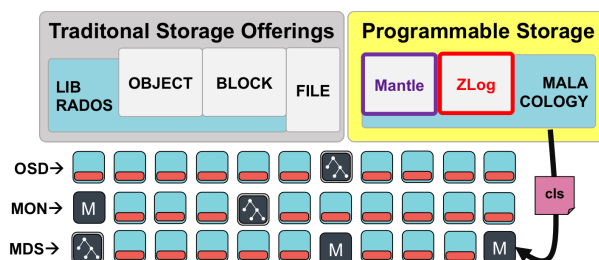


Figure 1: Ceph provides object, block, file and library client APIs; with Malacology we can implement 2 new services on Ceph: Zlog, Mantle. Malacology re-uses MON, OSD, and MDS subsystems.

exchange “maps” of the cluster configuration, and *consensus* by having monitor daemons (MONs) use PAXOS. We contend that re-using and re-purposing these code-hardened subsystems is paramount to successfully adapting storage systems to new APIs and new storage devices without losing the benefits from years of code-hardening work.

In this paper we examine the programmability of Ceph, the increasingly popular, production-level open-source distributed storage system. Something of a storage swiss army knife, Ceph supports file, block, and object interfaces simultaneously in a single cluster. While Ceph is well-regarded as software-defined storage, this label largely refers to the flexibility of a fixed, narrow set of APIs. By introducing programmability concepts into Ceph, we can build new services by carefully exposing internal storage services to applications.

We present Malacology, a programmable storage system capable of incorporating new functionality and re-purposing existing subsystems. We build the framework on Ceph by leveraging the subsystems in the monitor daemons (MONs), object storage daemons (OSDs), and metadata server daemons (MDSs). As shown in Figure 1, this frame-

work is expressive enough to provide the functionality necessary for implementing new services. Our contributions are:

- a programmable storage system implementation that re-uses existing and extends existing abstractions. It includes:
 1. inode abstractions for sequencer services
 2. consensus abstractions for policy versioning
 3. storage objects for persisting policies
 4. interface classes for new logical storage/metadata devices
- example systems that use this framework
 1. shared log service based on CORFU [2]
 2. metadata load balancer based on Mantle [3]

First, we describe existing techniques for bridging the gap between the performance of storage systems and the requirements of applications (§2). Next, we discuss the “distributed systems” inspired abstractions employed by Ceph (§3) and allude to their re-usability as components in other services. The next section enumerates the abstractions that Malacology exposes in the implementation section (§4). We then show how we use Malacology to synthesize entirely new storage services on an existing system through configuration and small changes (§5). We conclude by evaluating real-world use cases (§6).

2 Highly Tailored and Application-Specific Storage Systems

A consequence of complicated data management frameworks and faster devices is that the storage system cannot meet the needs of the general-purpose storage system. Workarounds for helping the application meet its performance goals roughly fall into one of three categories: “bolt-on” services, application changes, and storage changes.

2.1 “Bolt-on” services

So called “bolt-on” services are 3rd party systems that are integrated into the system to provide functionality and improve performance for common use-cases (e.g. a metadata

service). In addition to sacrificing simplicity, “bolt-on” services often duplicate functionality and execute redundant code, unnecessarily increasing the likelihood of bugs or worse, introducing unpredictable performance problems. For example, we are developing a distributed shared-commit log on Ceph called ZLog. ZLog uses a “sequencer” to distribute tokens to clients that want to append to the end of the log. When designing the sequencer, we considered bolting on Zookeeper [1] as a service. Zookeeper would satisfy our requirements by providing a network and transaction stack but it would perform poorly because Zookeeper persists its data and the sequencer can be in-memory and volatile. A Zookeeper sequencer would adhere to the pre-conceived notions of storage, namely that data in storage systems should be safe from data loss, but would introduce unnecessary scalability limits [?].

2.2 Application Changes

The second approach to adapting to a storage system deficiency is to extend the responsibility of the application. This means changing the application itself by adding more data management intelligence or domain-specific middleware (e.g., a new data layout). For instance, an application may change itself to exploit data locality or I/O parallelism in a distributed storage system.

For example, SciHadoop [4,5] changes both the Hadoop application and the Hadoop framework itself to leverage the structure of scientific (3D array-based data, more specifically) to increase performance, locality, and the number of early results. This is not a bad proposition, but creates a coupling that is highly tied to the underlying physical properties of the system, making it difficult to adapt to future changes at the storage system level.

2.3 Storage Changes

When these two approaches fail to meet the needs of the application, developers turn their attention to the storage system itself. Traditionally, storage system behaviour can be altered using two techniques: tuning the system or introducing changes to the system. The difficulty of both of these approaches has given rise to a third technique called active storage.

2.3.1 Tuning

Tuning large and complicated systems is difficult because of the number of parameters (e.g., Hadoop 2.7.1 has 210 tunables) and because the tunables are difficult to understand or quantify (e.g., Ceph tunables [3]). To successfully tune the system, the developer must have domain and system specific knowledge. Without this intimate knowledge, the tuning turns into somewhat of a black art, where the only way to figure out the best settings is trial and error.

Auto-tuning techniques attempt to find a good solution among a huge space of available system configurations. However, in practice auto-tuning is limited to only the configuration tunables that the storage system exposes (e.g. block size) and can be overwhelmed with too many parameters. Starfish [6] made an attempt of this for Hadoop but this technique would need to severely limit the space of parameters in order to be feasible, similar to the approach used in [7]. For instance, auto-tuning may be capable of identifying instances in which new data layouts would benefit a workload, but unless the system can provide such a transformation, the option is left off the table.

2.3.2 Software Changes

As a last resort, the application developer can introduce changes to the storage system itself. This endeavour is especially difficult because the developer must first familiarize themselves with the storage system, and even if they manage to make the necessary changes, they must get their changes upstream for that specific project or become maintainer for their in-house version. Being a maintainer means they re-base their versions against new versions of the storage system and address any bugs for their branched code. A successful example of this is the work that focused on HDFS scalability for metadata-intensive workloads [8]. This has led to modifications to its architecture or API [9] to improve performance.

2.3.3 Hybrid Approaches

As an alternative, some systems allow developers to extend the interfaces of the storage devices to perform arbitrary operations on data stored on disk. In Ceph, object interfaces are C/C++ plugins that add new functionality to the OSDs. As an example use-case, ZLog needs to store metadata information with each object so for each operation, it

Table 1: A variety of RADOS object storage classes exist to expose interfaces to applications. # is the number of methods that use these categories.

Category	Specialization	#
Locking	Shared	6
	Exclusive	
Logging	Replica	3
	State	4
	Timestamped	4
Metadata Management	RADOS Block Device	37
	RADOS Gateway	27
	User	5
	Version	5
Garbage Collection	Reference Counting	4

checks the epoch value and write capability (2 metadata reads) and writes the index (metadata write). Figure 1 shows the throughput (y axis) over time (x axis) of two OSD implementations for storing metadata: in the header of the byte stream (data) vs. in the object extended attributes (XATTR). The speed for appending data without any metadata operations (data raw) is also shown as a baseline for comparison. For append-heavy workloads storing metadata as a header in the data performs about 1.5x better than storing metadata as an extended attribute.

Object interface classes are used in production Ceph environments; Figure 3 shows a dramatic growth in the use of co-designed interfaces in the Ceph community since 2010. Figure 4 examines this growth in interfaces further by showing the lines of code that are changed (y axis) over time (x axis). The prevalence of blue dots indicates that users frequently update their interfaces close to release cycles and that massive changes come in bunches. This interface churn reflects both the popularity of object interfaces and the complexity of the processing being done by the OSDs. What is most remarkable about Figure 4 is that this trend contradicts the notion that API changes are a burden for users. The types of object interfaces, which are enumerated in Table 1, show that this active storage development is present throughout the Ceph software stack.

The popularity of the active storage component of Ceph

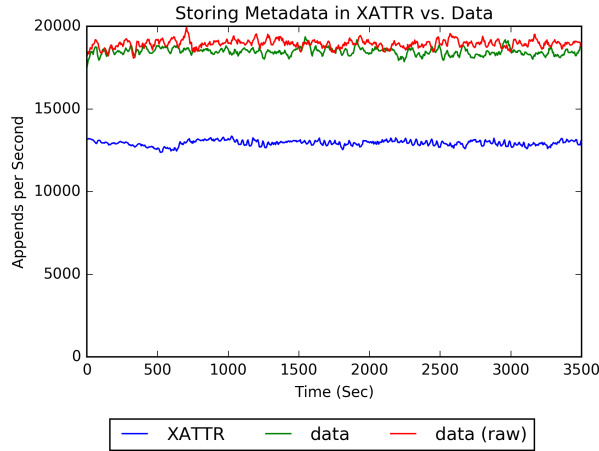


Figure 2: [source] When appending data to objects, the object class that stores metadata in a header in the data byte stream (data) performs 1.5x better than the object class that stores metadata in the extended attributes of the object (XATTR); it is almost as fast as appending data without updating metadata (data raw).

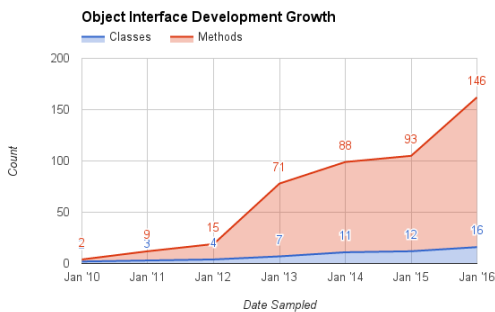


Figure 3: Since 2010, the growth in the number of co-designed object storage interfaces in Ceph has been accelerating. This plot is the number of object classes (a group of interfaces), and the total number of methods (the actual API end-points).

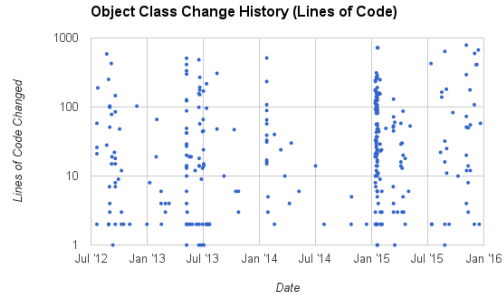


Figure 4: Source code changes over time indicate the dynamic interface development will need to support a high frequency of interface churn. Each dot represents a Ceph commit with a corresponding number of lines of code changed.

hint at three trends in the Ceph community: (1) increasingly, the default algorithms/tunables of the storage system are insufficient for the application's performance goals, (2) programmers are becoming more aware of their application's behavior, and (3) programmers know how to manage resources to improve performance. Programmers gravitate towards object interfaces because it gives them ability to tell the storage system about their application: if it is CPU or IO bound, if it has locality, if its size has the potential to overload a single proxy node, etc. The programmers know what the problem is and how to solve it, but until object interfaces, had no way to tell the storage system how to handle their data.

These implementations use the active storage interfaces in Ceph. We refer to this as *storage programmability* which is a method by which an application communicates its requirements to the storage system in a way that allows the application to realize a new behavior without sacrificing the correctness of the underlying system. This evaluation and resulting implementation would have been a burden without object classes.

3 Re-Usable Components in Ceph

Ceph is a production-quality distributed system and in this section we touch on some of the subsystems it uses to provide a general-purpose storage system. In the next

section, we describe how we leverage these subsystems to build new services.

3.1 Durability

Ceph provides storage by striping and replicating data across RADOS [10], the reliable distributed object store. RADOS uses many techniques to ensure that data is not corrupted or lost, such as erasure coding, replication, and data scrubbing. Furthermore, many of these techniques try to be autonomous so that work is distributed across the cluster. For example, when placement groups change the OSDs rebalance and re-shard data in the background in a process called placement group splitting.

3.2 Consistency/Versioning of Cluster State

Ceph needs to keep track of cluster state and it does this with separate “services”: client authentication, logging, MDS maps, MON maps, OSD maps and placement group (PG) maps. These services are all managed in the MONs and they all talk to a PAXOS instance; this PAXOS instance goes and talks to other PAXOS instances on other MONs so that they can all agree on the correct version of the service; essentially they reach an agreement about what the state of the cluster is.

3.3 Active Storage

Active storage attempts to push computation closer to the data by exposing interfaces to execute code remotely. For example, the storage server could process data before sending data over the network or sorting it. The active storage component in Ceph is called “object interface classes” (or `cls` for short). The Ceph object interface classes can be loaded at runtime and customized with user-defined functionality. The basic idea is shown in Figure~??, where the `libcls_md5.so` shared library performs the MD5 hash on an object at the OSD instead of transferring data over the network. This ability to carry out arbitrary operations on objects stored on OSDs helps applications improve performance by optimizing things like network round trips, data movement, and remote resources which may be idle.

While we consider active storage to be an excellent example of programmability, what separates our proposal from previous work is the observation that so much *more*

of the storage system can be reused to construct advanced, domain-specific interfaces.

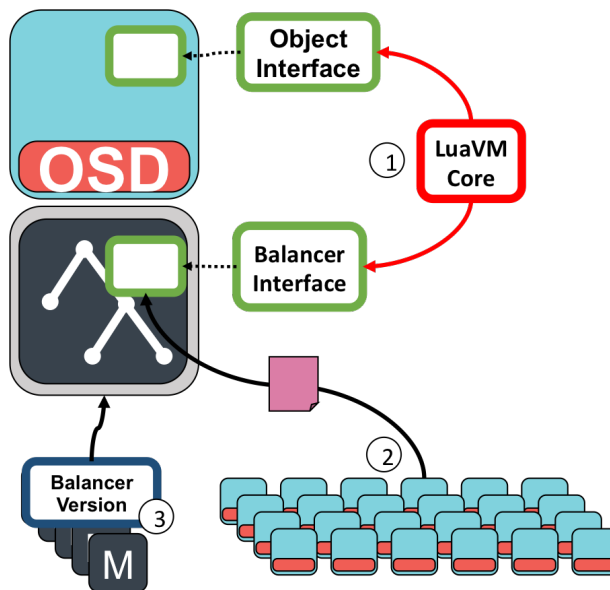


Figure 5: Malacology re-uses Ceph subsystems to manage interface classes. command. After the proposal is accepted by the cluster of monitors, the script is redundantly and consistently distributed to OSDs.

4 Malacology Implementation

To enable the re-use of Ceph subsystems, Malacology relies heavily on interface classes for introducing new functionality into the MDSs and OSDs. Malacology introduces 3 components to manage object/metadata interfaces:

1. additional interface hooks and classes for OSDs and MDSs using the existing Ceph `cls` infrastructure
2. durable interface classes using the Ceph object store
3. versioned and consistent interfaces using the Ceph MONs

Figure 4 shows how interfaces can be loaded into either the MDS or OSD (1), how interfaces are persisted to object storage (2), and how they are versioned by the MONs (3).

In the following section, we will discuss the existing Ceph infrastructure and the changes necessary for Malacology. We emphasize here that these implementations are not necessarily optimized but they help demonstrate the power of programmability.

4.1 Additional Interface Frameworks

For object interfaces, clients send Lua classes to the OSD and then they can invoke operations in that class remotely on the OSD. In reality, this feature is a statically loaded object class written in C/C++ that runs dynamically defined object interfaces, where clients access the classes using an `exec()` wrapper. Although sending the class with each client request is stateless (which has its own set of nice features), it is costly for network bandwidth and difficult to organize at the application level. Also, while the execute wrapper simplifies the implementation, it burdens the applications, since they need to be recompiled to use the `exec()` function.

Although these OSD interfaces are powerful, the current implementation has drawbacks. OSD interfaces are written in C/C++ and compiled into a shared library, so the developer must account for different target architectures. Second, C/C++ provides more functionality than is necessary since the snippets of interface code mainly set policies and perform simple operations. Finally, developing these interfaces in C/C++ has high overhead. The developer must learn how the OSD dynamically loads the shared libraries (*e.g.*, OSDs rely on a strict naming convention to find shared libraries), how to get their interfaces compiled using the Ceph `make` system, and how to debug issues that are not related to their specific interface (*e.g.*, the OSD cannot find the shared library) - this learning curve is unacceptable for non-Ceph developers, especially since most interfaces are one-off solutions specific to their applications.

4.1.1 New Interface Classes

Our framework has added a mechanism for defining and running object and metadata balancer classes using the Lua scripting language. Scripting is useful in large systems for 3 reasons:

- accelerates deployment: tweaking policies, like

changing a threshold or metric calculation, does not require a full recompile or system start-up.

- transparency: if the bindings carefully expose the correct metrics and functions, the user does not need to learn the internal functions, variables, or types of the system.
- portability: scripts can be exchanged across platforms and system versions without compatibility issues.

Our Lua bindings expose functions and symbols both ways; the host program can call functions defined in Lua and the Lua scripts can call functions defined in native C++. These bindings are merged upstream. Lua is frequently used in game engines to set policies but we use it here because most of the user-defined classes in Ceph are policies as well! We do not want to provide specific implementations, like pulling data from objects or transferring them over the network, but instead strive to say *what to do* with the data once we have it. Separating policy from mechanism is a driving factor in using Lua. We choose Lua for 4 reasons: performance, portability, size, and security.

Lua performs well as an embeddable scripting language. Although it is an interpreted language, the bindings are designed to make the exchange of variables and functions amongst languages straightforward. The LuaJIT virtual machine boasts near-native performance, making it a logical choice for scriptability frameworks in systems research [11]. In storage systems, it has been effectively used both on [12,13] and off [3] the critical path, where performance is important.

Because Lua is interpreted, it is also portable. The portability allows functions to be shipped around the cluster without having to compile or reason about compatibility issues. Traditionally, interfaces are written in C/C++, so they must be compiled into shared libraries before being injected into the daemon at runtime. Shared libraries need to be compiled on the host they will be run on to accommodate different architectures and dependencies. Embedding the Lua interpreter, on the other hand, gives us the flexibility to store the actual Lua code in other places, like RADOS, so we can enjoy all the other properties provided by that particular back-end.

The other two advantages, that Lua leaves a small memory footprint and that it is secure, are discussed at length

in [11,14]. In short, Lua provides relatively robust sandbox capabilities for protecting the system against some malicious cases, but does not protect the system from poor policies. Since Malacology does not use these features (yet), we will avoid discussion here.

4.2 New Interface Hooks

Malacology adds interface hooks to the MDS in the load balancing and capability subsystems. In contrast to the Mantle implementation, which had a large function hard-coded into the balancer subsystem, Malacology embeds code in the MDS using OSD subsystems. Ceph has a whole infrastructure for getting dynamic code into the OSD. The `ClassHandler` class safely opens object interfaces, executes commands defined by the shared library, and fails gracefully with helpful errors if anything goes wrong. Instead of injecting strings directly into Ceph (like we did with the original Mantle implementation), the `ClassHandler` class safely opens shared code, even code with dependencies that are not in Ceph itself (e.g., Lua).

With the `ClassHandler`, the MDS gets the safety and robustness of loading dynamic code, the ease of transferring state between object interfaces and the OSD internals, integration with testing and correctness suites, and `structs` for interface data and handlers. Using the OSD class handler hooks also gives the MDS the ability to load interfaces from the local file system.

We generalize the Lua VM since it will be used in both the OSD and MDS. We put the core sandbox wrapper for the Lua object interface in a common directory in Ceph and link against it. This core Lua wrapper contains just the dependencies, symbols, and functions, need to run the Lua VM. Some of these functions include `clslua_log()` for transferring logs to the daemon logs and `clslua_pcall()` for calling Lua functions.

Dependencies, symbols, and functions specific to the object or balancer interface are put in the `cls` or `bal` directories, respectively. For example, the Lua object interface uses functions that have placement group filters, cryptography functions, and object metadata (*it i.e.* `cxx_omap_getvals()`, object data, object extended attributes, and object versions – all these are dependencies, symbols, and functions are part of the OSD process but not the MDS process. As a result, we put interface code that

uses these in `cls` directory. With this scheme, The OSD will `dlopen()` the shared library created by Lua object interface shared library while the MDS will `dlopen()` the Lua balancer interface shared library; both shared libraries will the Lua core.

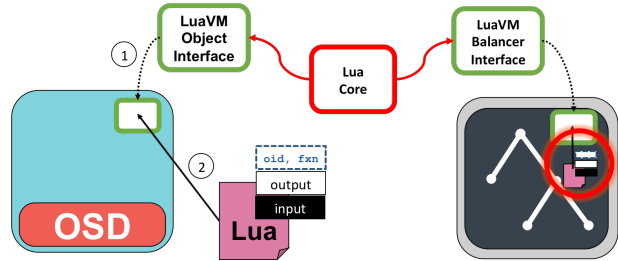


Figure 6: To generalize the LuaVM for use in both the OSD and MDS, Malacology detaches the core functionality into a Lua core module. The VM is dynamically loaded first (1) and then interfaces can execute (2).

Both the object and balancer interfaces define functions and attach them to the core Lua sandbox. For example, the Lua object storage interface class attaches data, extended attribute, object map, and object version functions, to the Lua core functions, as shown in Figure 6. The advantages of this is that we avoid duplicating code, we provide a framework for putting Lua code in other parts of the system, and we remove components and APIs that are too integrated with the OSD.

4.3 Storing Interfaces in RADOS

Traditionally, object storage interfaces are compiled into shared libraries and loaded into a running OSD daemon using `dlopen()`. Because the shared library has to link against symbols found in the running executable, the interfaces are stored on the local file systems of each OSD so they can be versioned and distributed alongside the same Ceph binaries. This policy is for safety, since the OSDs could be on different distros that provide different versioning capabilities. Also, this approach allows bug fixes to co-evolve with the rest of the Ceph installation.

Because of the portability of Lua and because the Lua virtual machine is compiled and loaded as a shared library, the MDS/OSD can store the balancers in a more redundant location. For our implementation, we store balancers in

RADOS and the daemons first search RADOS, then the local file system for their interface classes.

4.4 Versioning Interfaces with MONs

We added two new commands to Ceph command line client so the user can inject interface versions into the cluster::

```
ceph osd pool set-class <pool> <class>
<script>
ceph mds set lua_balancer_class
<version>
```

By leveraging the monitor daemons, our services get the consistency from the monitors version management, the distribution from the monitors data structures (which are already distributed), and the durability from the robustness of the monitors and persistence with Paxos. The implementation uses the placement group pool data structure which maintains the policies (*e.g.*, erasure coding) and organization details (*e.g.*, snapshots) for each pool. While stuffing the information into the monitor map, the structure that describes the the monitor topology, was an option, the placement group pool allows finer grain control over different types of data.

In regards to the consistency, each time the user injects a new Lua object class it enters the monitor quorum as a proposal; updates to the placement group pool need to wait until accepted, at which point the state will be propagated and versioned. We hooked up the monitor command to the `cls_lua` class by having the OSD pull the script from the placement group instead of trying to dynamically load the shared library with `dlopen()` or the Lua script.

The `cls-lua` branch lets users write object classes in Lua, the `lua-rados` client library lets users write applications that talk to RADOS with Lua, and the `cls-client` uses the `lua-rados` library to send Lua object classes to the OSDs equipped with the LuaJIT VM.

5 Services Built on Malacology

5.1 Mantle: A Programmable Metadata Load Balancer

Many distributed file systems decouple metadata and data I/O so that these services can scale independently [1,15–19]. Despite this optimization, scaling the metadata ser-

Cap Owner	Failure	ZLog Recovery
mds	mds	mds
client	mds	xfer client cap
mds	client	n/a
client	client	mds

Table 2: Failure and recovery scenarios.

vices is still difficult because metadata accesses impose small and frequent requests on the underlying storage system [20]. Many techniques for designing the metadata services have been proposed to accommodate this workload: Lustre [21], GFS [16], and HDFS [19] keep all metadata on one server; GIGA+ [22], IndexFS [23], Lazy Hybrid [24], GPFS [25], and pNFS [26] hash the file system namespace across a dedicated cluster and cache metadata; Panasas [18] and CephFS [27] partition the file system namespace into # d assign them to servers. These systems have novel mechanisms for Mantle [3] is a programmable metadata balancer that separates the metadata balancing policies from their mechanisms. Administrators inject code to change how the metadata cluster distributes metadata. In the paper, we showed how to implement a single node metadata service, a distributed metadata services with hashing, and a distributed metadata service with dynamic subtree partitioning.

The Ceph team wants to merge Mantle because the scriptability is useful for debugging, controlling the metadata balancer, and examining trade-offs for different balancers. Unfortunately, this research quality system is not as robust as Ceph and the Ceph team wants more safety, durability, and consistency for the new functionality. For example, the original Mantle API is fragile: the API is not enforced by the runtime, the system allows injectable strings through the admin daemon, constructing the Lua script in C++ is clunky, and the administrator can inject really bad policies (*e.g.*, while 1) that brings the whole system down.

5.2 Code Reduction

636 lines of code to embed the LuaVM, 37 lines to get the persistence via RADOS, and 17 lines of code to get the versioning/consistency of RADOS.

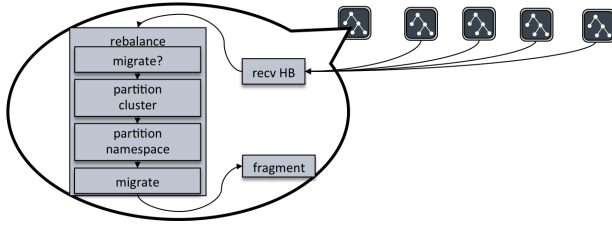


Figure 7: This is Mantle.

5.3 ZLog: A Distributed Shared Commit Log

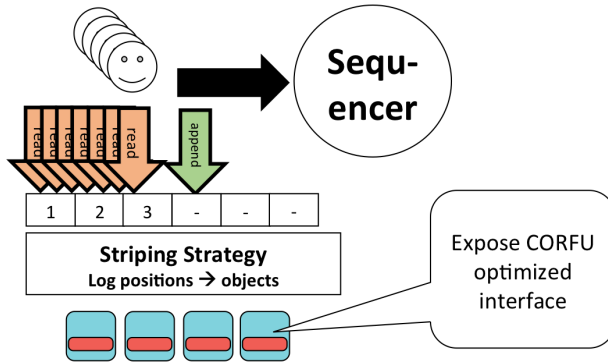


Figure 8: This is ZLog.

5.3.1 Consistency

5.3.2 Striping Strategies

5.3.3 Tiering

Malacology uses the same Active and Typed Storage module presented in DataMods [28]; Asynchronous Service and File Manifolds can be implemented with small changes to the Malacology framework, namely asynchronous object calls and Lua stubs in the inode, respectively.

5.4 MDS as a sequencer

5.4.1 Sequencer recovery with MDS

5.4.2 MDS Policy for Revoking Capability

The MDS has a queue of locks that it uses to revoke capabilities from the clients. If we put a Mantle-style hook here, we can control when those revoke messages go out.

5.4.3 Mantle Balancing Policies to Migrate Sequencers

6 Evaluation

1 Experiments: 2 3 1. mdtest separate directories 4 - just based on default traffic 5 - kill one of the MDSs 6 7 2. filebench profiles 8 - adaptable vs. greedy vs. fill&spill 9 10 3. sequencer balancer 11 - just based on default traffic 12 13 3. OpenSSL compile ~

6.1 Mantle

6.1.1 Experiment: FileBench

6.1.2 Experiment: OpenSSL Compile

6.2 MDS as ZLog Sequencer

6.2.1 Experiment: Object Class Programmability

Add quote from CORFU paper that talks about what they had to hack

6.2.2 Experiment: Multi-Client Burstiness

6.2.3 CUT THIS Experiment: Client v. MDS caps + Failures

6.2.4 Experiment: Mantle Sequencer Balancer

7 Conclusion and Future Work

Programmable storage is a viable method for eliminating duplication of complex error prone software that are used as workarounds for storage system deficiencies. However, this duplication has real-world problems related to reliability. We propose that system expose their services in

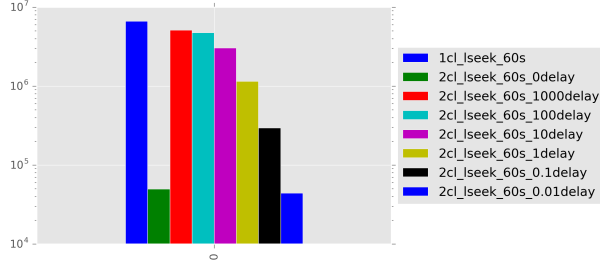


Figure 9: Forcing the client to drop their capabilities later (delay) improves throughput

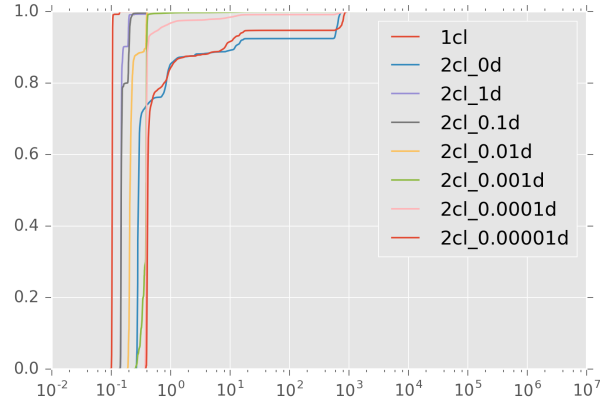


Figure 10: But if the clients hold their capabilities longer, it hurts latency for everyone.

a safe way allowing application developers to customize system behavior to meet their needs while not sacrificing correctness.

We are intend to pursue this work towards the goal of constructing a set of customization points that allow a wide variety of storage system services to be configured on-the-fly in existing systems. This work is one point along that path in which we have looked an a target special-purpose storage system. Ultimately we want to utilize declarative methods for expressing new services.

In conclusion, this paper should be accepted.

not sure why ./build fails without this

8 Bibliography

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