CERN

# Ceph Storage at CERN

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# Outline

I. What is Ceph and how does it work?

II. Ceph Use-Cases at CERN

III. CephFS for HPC

# I. What is Ceph?

*Slides credit: Sage Weil*

# WHAT IS CEPH?

<u>The buzzwords</u>

- "Software defined storage"
- "Unified storage system"
- "Scalable distributed storage"
- "The future of storage"
- "The Linux of storage"

<u>The substance</u>

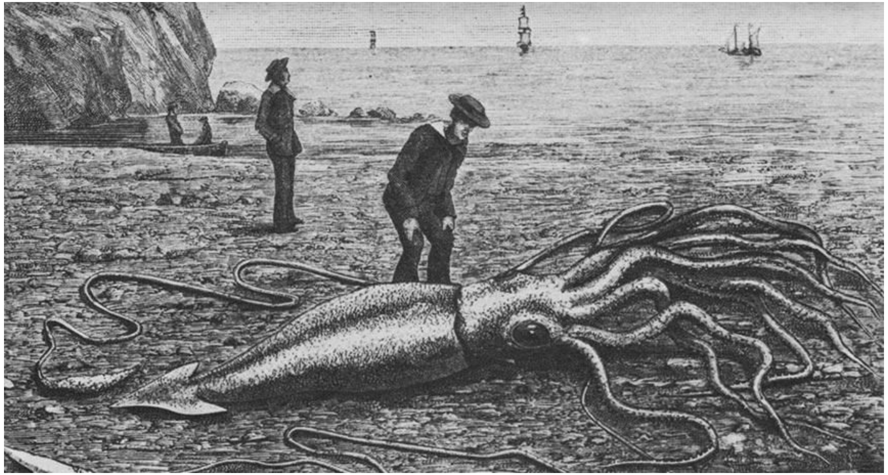
- Ceph is open source **software**
- Runs on commodity hardware
  - Commodity servers
  - IP networks
  - HDDs, SSDs, NVMe, NV-DIMMs, ...
- A single cluster can serve **object**, **block**, and **file** workloads

# CEPH IS RELIABLE

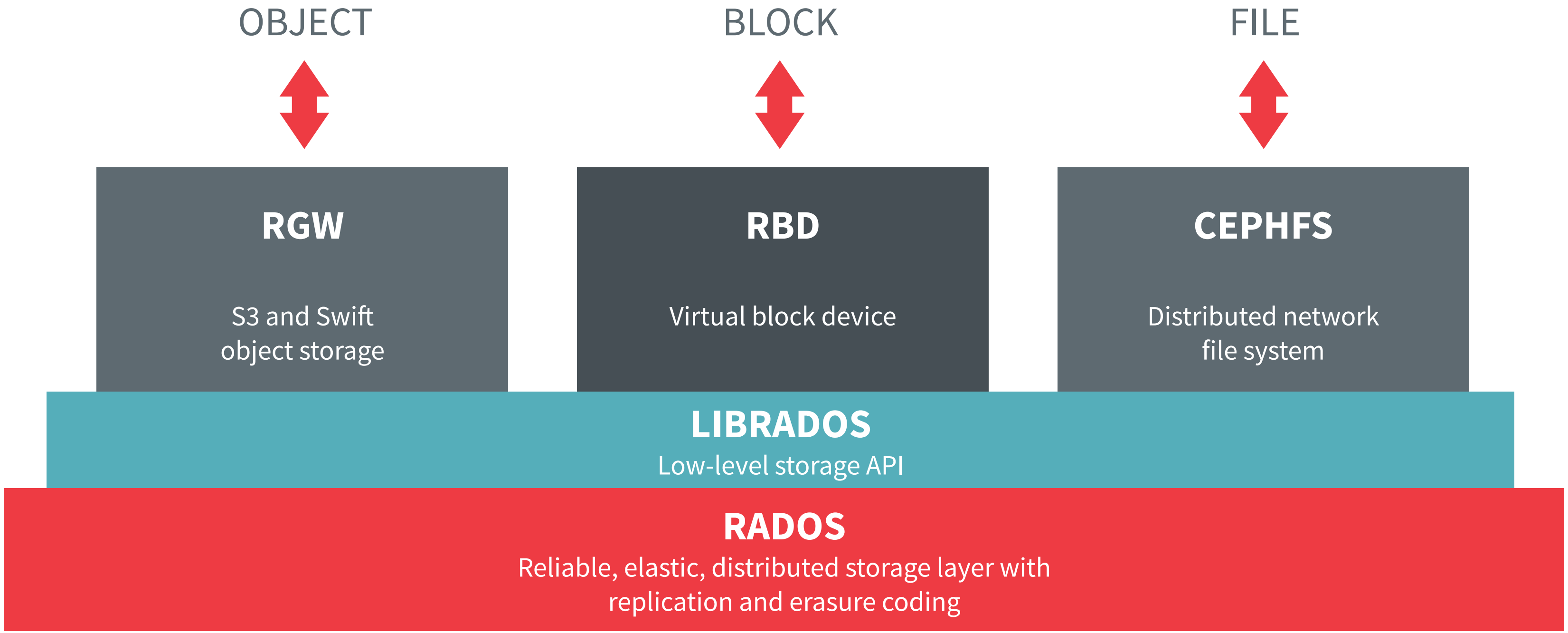
- **Reliable storage** service out of **unreliable components**
  - No single point of failure
  - Data durability via replication or erasure coding
  - No interruption of service from rolling upgrades, online expansion, etc.
- Favor consistency and correctness over performance

# CEPH IS SCALABLE

- Ceph is elastic storage infrastructure
  - Storage cluster may grow or shrink
  - Add or remove hardware while system is online and under load
- Scale **up** with bigger, faster hardware
- Scale **out** within a single cluster for capacity and performance
- **Federate** multiple clusters across sites with asynchronous replication and disaster recovery capabilities



# CEPH IS A UNIFIED STORAGE SYSTEM



# THE CEPH FOUNDATION

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SWITCH

# RADOS

# RADOS

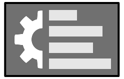
- **R**eliable **A**utonomic **D**istributed **O**bject **S**torage
  - Common storage layer underpinning object, block, and file services
- Provides low-level data object storage service
  - Reliable and highly available
  - Scalable (on day 1 and day 1000)
  - Manages all replication and/or erasure coding, data placement, rebalancing, repair, etc.
- Strong consistency
  - CP, not AP
- Simplifies design and implementation of higher layers (file, block, object)

# RADOS SOFTWARE COMPONENTS


ceph-mon

**Monitor**

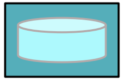
- Central authority for authentication, data placement, policy
- Coordination point for all other cluster components
- Protect critical cluster state with Paxos
- 3-7 per cluster



ceph-mgr

**Manager**

- Aggregates real-time metrics (throughput, disk usage, etc.)
- Host for pluggable management functions
- 1 active, 1+ standby per cluster



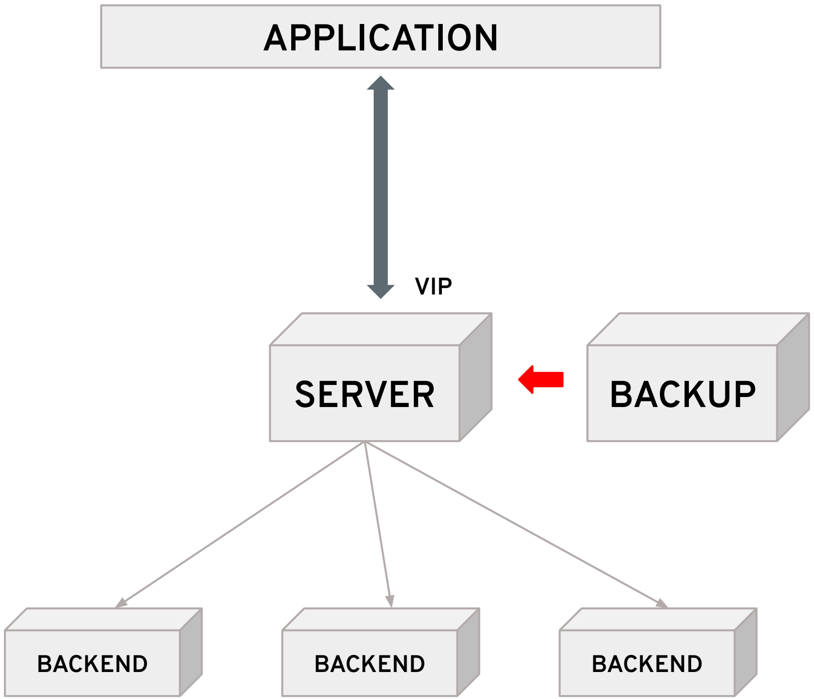
ceph-osd

**OSD (Object Storage Daemon)**

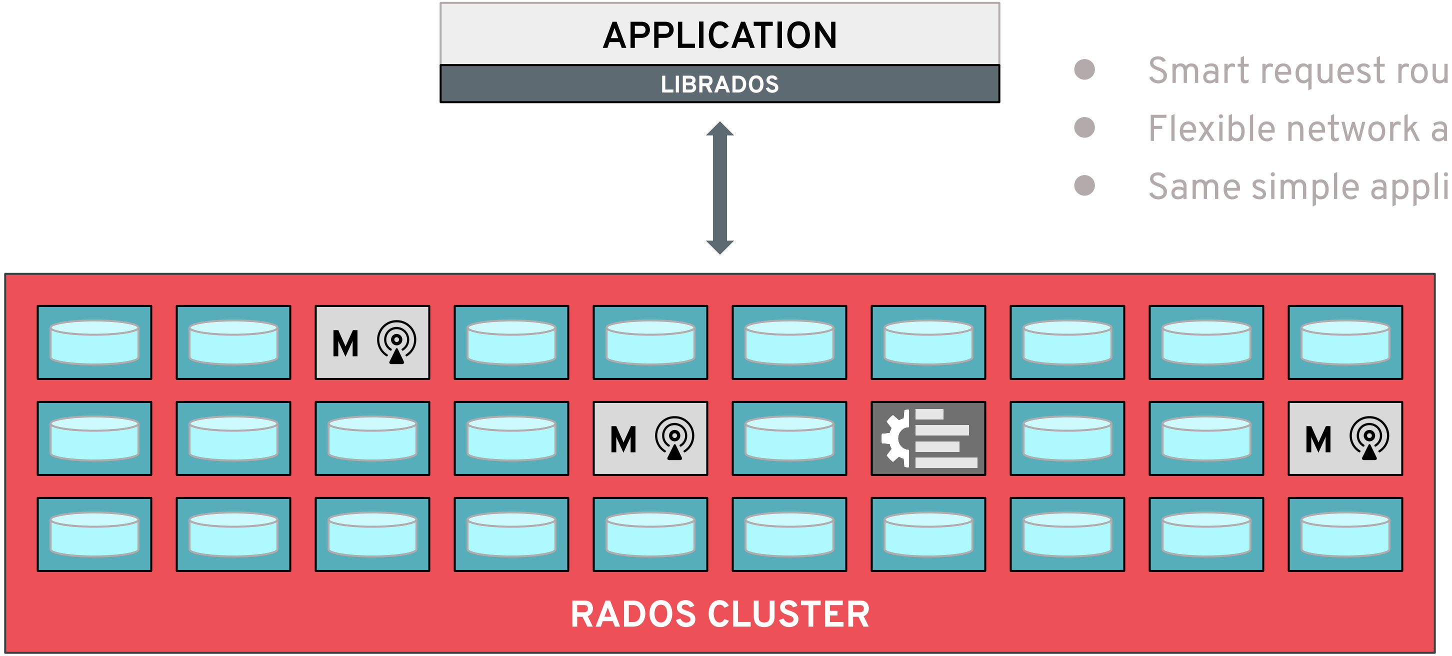
- Stores data on an HDD or SSD
- Services client IO requests
- Cooperatively peers, replicates, rebalances data
- 10s-1000s per cluster

# LEGACY CLIENT/SERVER ARCHITECTURE

- Virtual IPs
- Failover pairs
- Gateway nodes

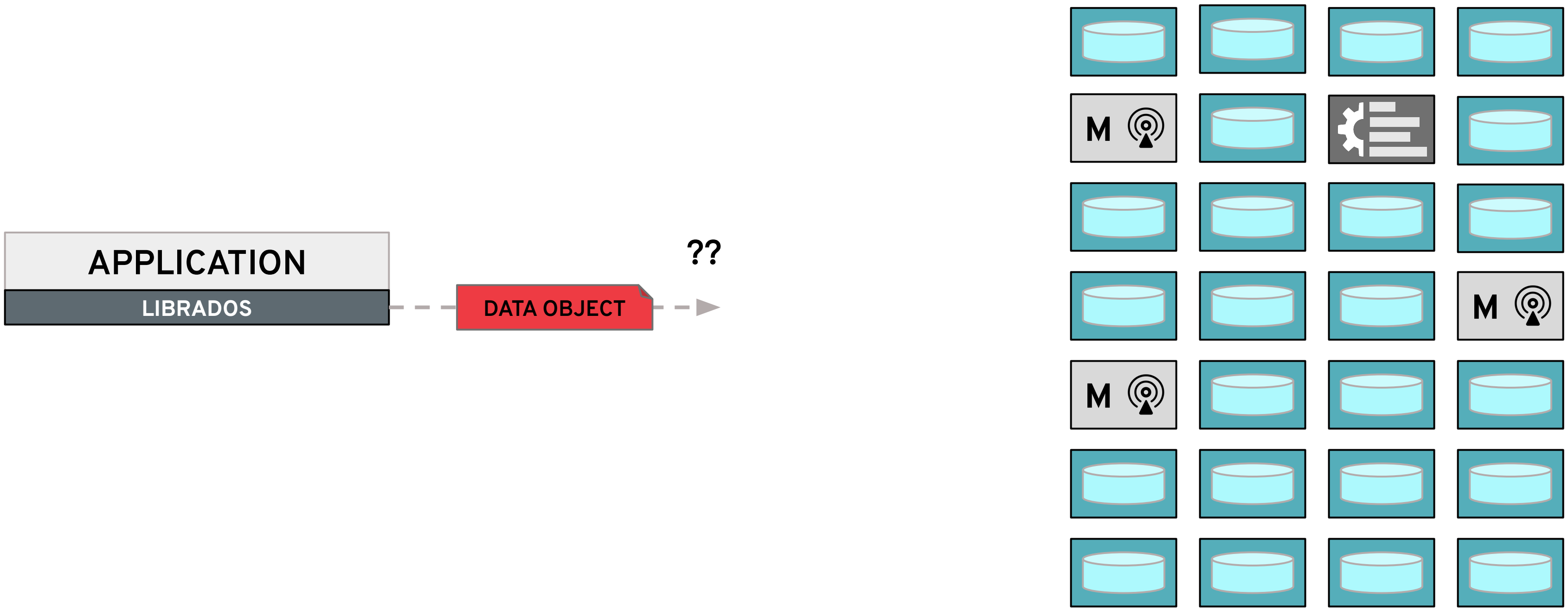


# CLIENT/CLUSTER ARCHITECTURE

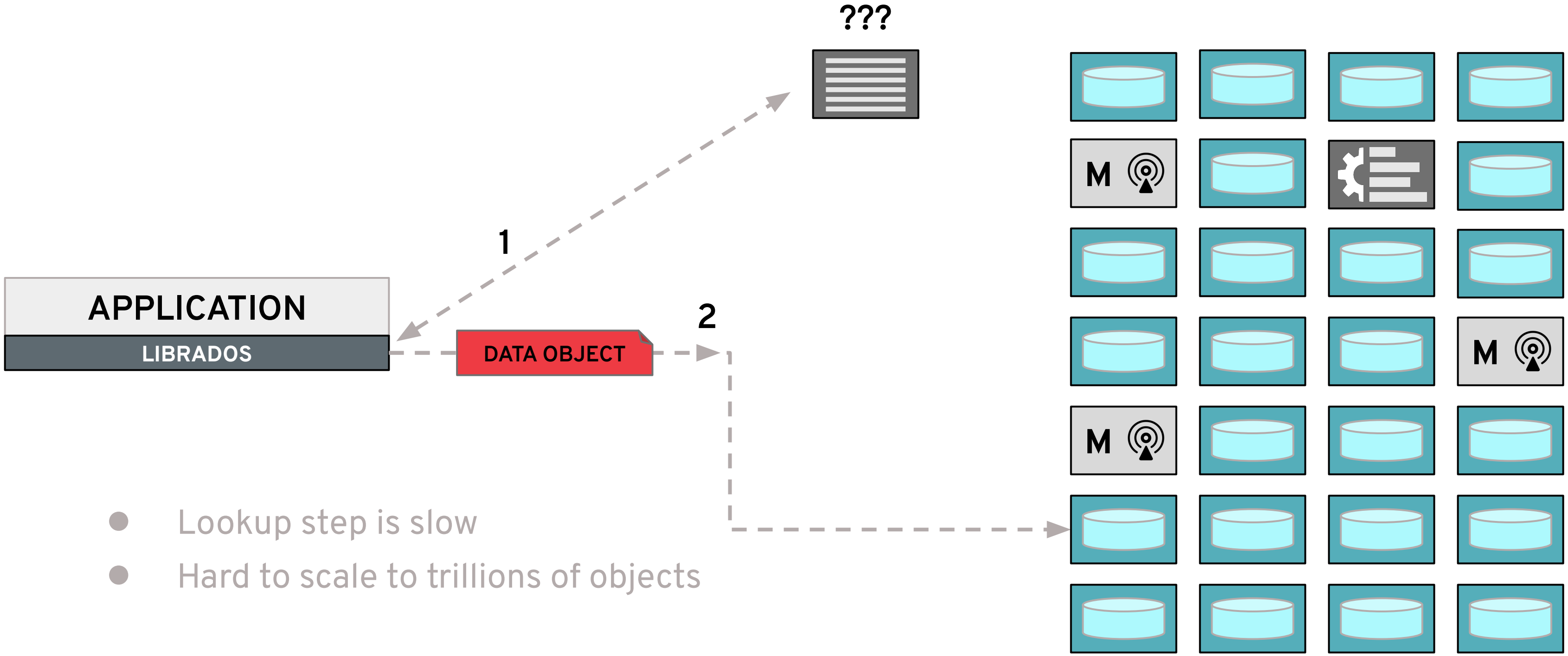



- Smart request routing
- Flexible network addressing
- Same simple application API

# DATA PLACEMENT

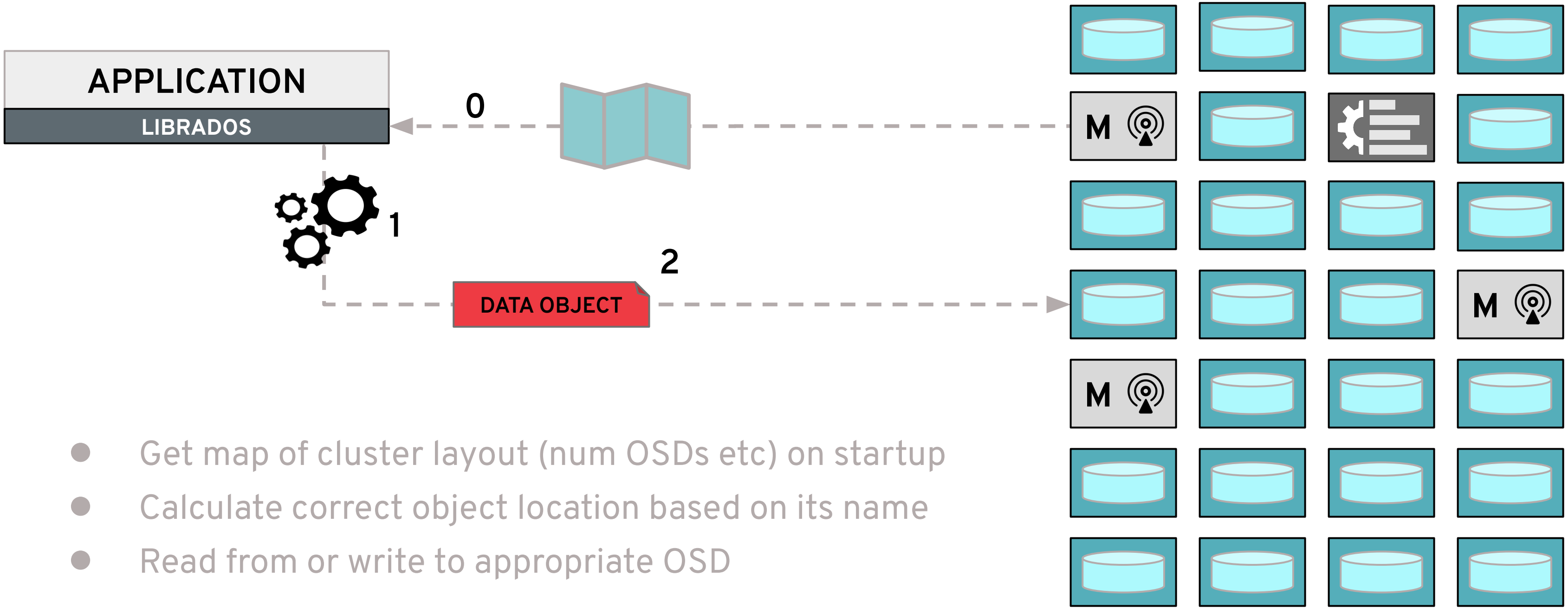


# LOOKUP VIA A METADATA SERVER?



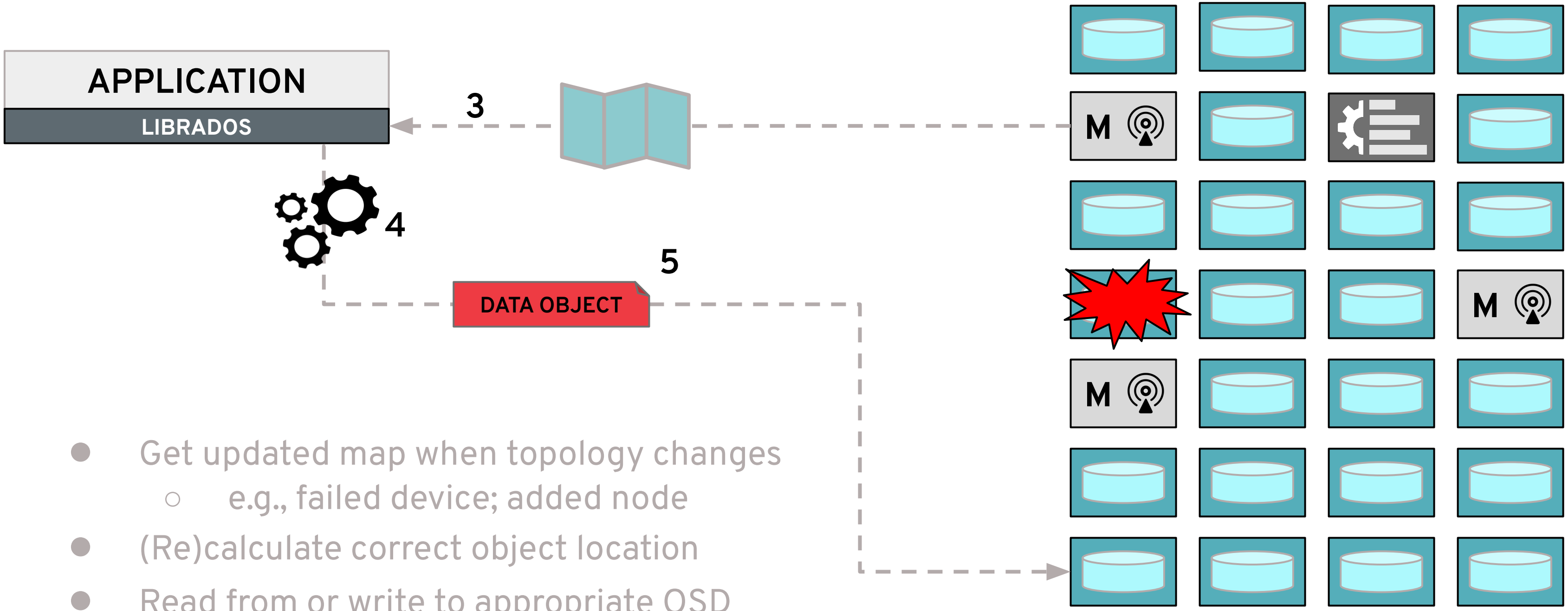

- Lookup step is slow
- Hard to scale to trillions of objects

# CALCULATED PLACEMENT




- Get map of cluster layout (num OSDs etc) on startup
- Calculate correct object location based on its name
- Read from or write to appropriate OSD

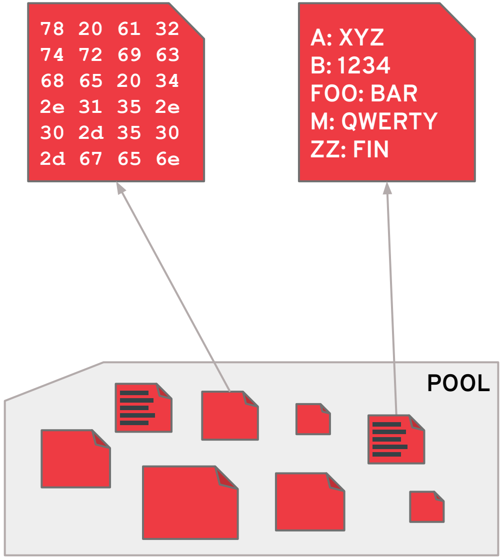
# MAP UPDATES WHEN TOPOLOGY CHANGES



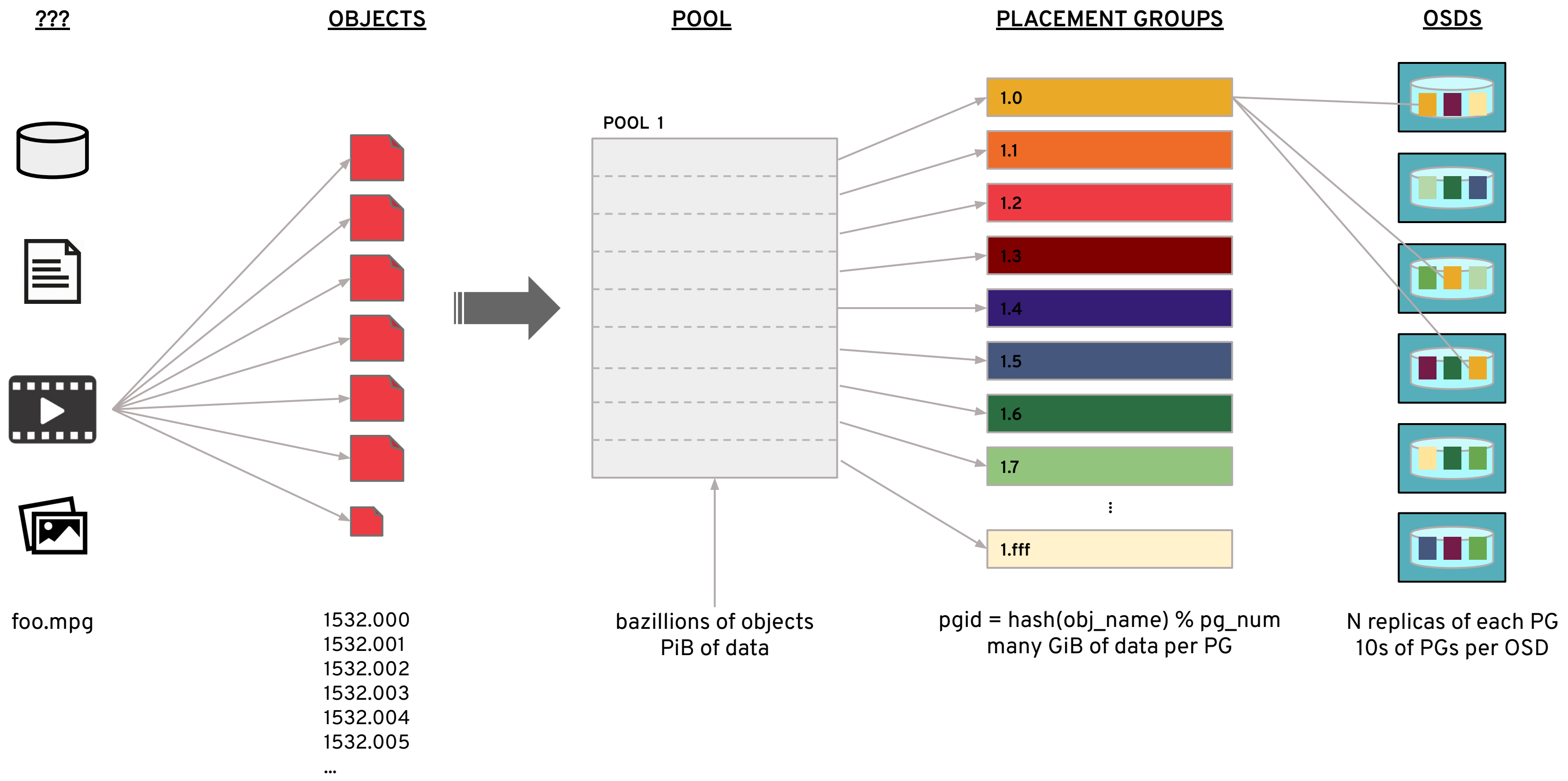

- Get updated map when topology changes
  - e.g., failed device; added node
- (Re)calculate correct object location
- Read from or write to appropriate OSD

# RADOS DATA OBJECTS

- Name
  - 10s of characters
  - e.g., “rbd_header.10171e72d03d”
- Attributes
  - 0 to 10s of attributes
  - 0 to 100s of bytes each
  - e.g., “version=12”
- Byte data
  - 0 to 10s of megabytes
- Key/value data (“omap”)
  - 0 to 10,000s of items
  - 0 to 10,000s of bytes each
- Objects live in named “pools”

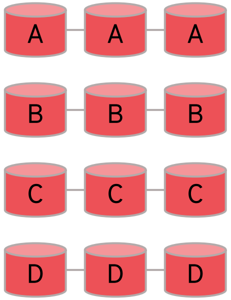


# ? → OBJECTS → POOLS → PGs → OSDs



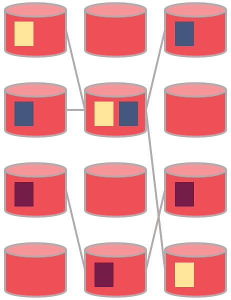
# WHY PLACEMENT GROUPS?

**REPLICATE DISKS**



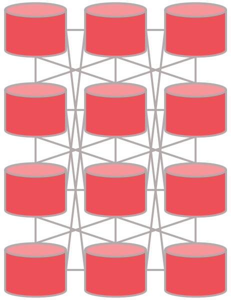

- Each device is mirrored
- Device sizes must match

**REPLICATE PGS**



- Each PG is mirrored
- PG placement is random

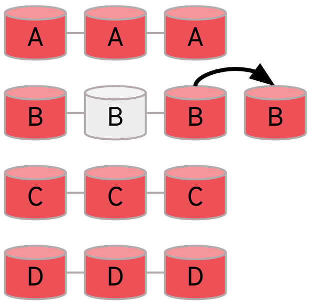
**REPLICATE OBJECTS**



- Each object is mirrored
- Object placement is random

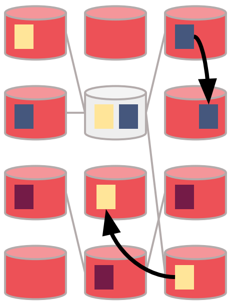
# WHY PLACEMENT GROUPS?

**REPLICATE DISKS**



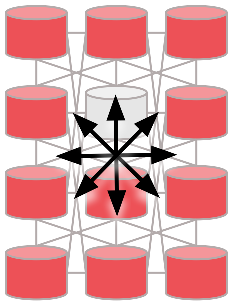

- Need an empty spare device to recover
- Recovery bottlenecked by single disk throughput

**REPLICATE PGS**



- New PG replicas placed on surviving devices
- Recovery proceeds in parallel, leverages many devices, and completes sooner

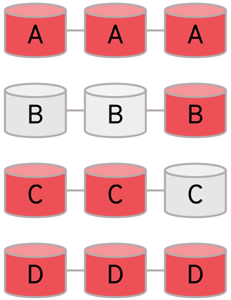
**REPLICATE OBJECTS**



- *Every* device participates in recovery

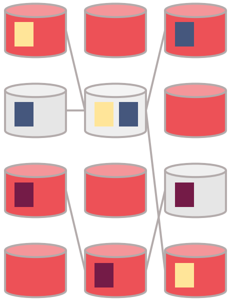
# WHY PLACEMENT GROUPS?

**REPLICATE DISKS**



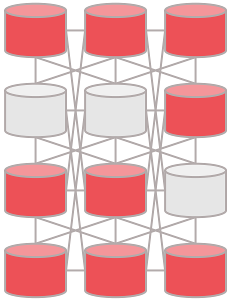

- Very few triple failures cause data loss (of an entire disk)

**REPLICATE PGS**



- Some triple failures cause data loss (of an entire PG)

**REPLICATE OBJECTS**



- **Every** triple failure causes data loss (of some objects)

**PGs balance competing extremes**

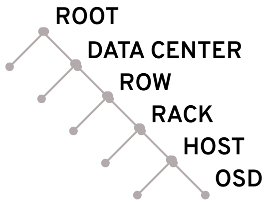
# KEEPING DATA SAFE

<u>"Declustered replica placement"</u>

- More clusters
  - Faster recovery
  - More even data distribution
- Fewer clusters
  - Lower risk of concurrent failures affecting all replicas
- Placement groups a happy medium
  - No need for spare devices
  - Adjustable balance between durability (in the face of concurrent failures) and recovery time

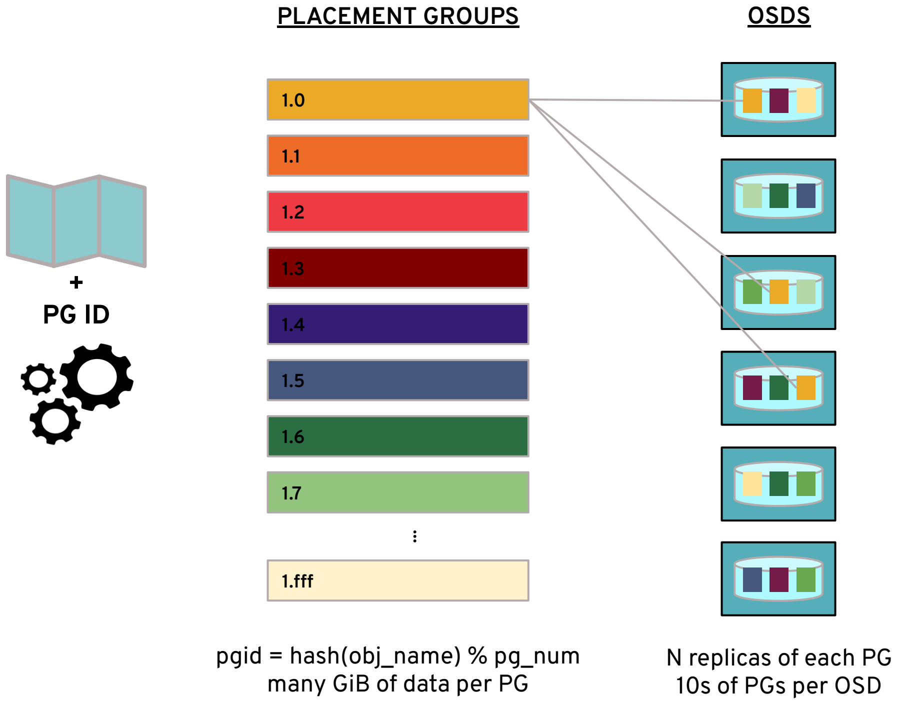
<u>Avoiding concurrent failures</u>

- Separate replicas across failure domains
  - Host, rack, row, datacenter
- Create a hierarchy of storage devices
  - Align hierarchy to physical infrastructure
- Express placement policy in terms hierarchy



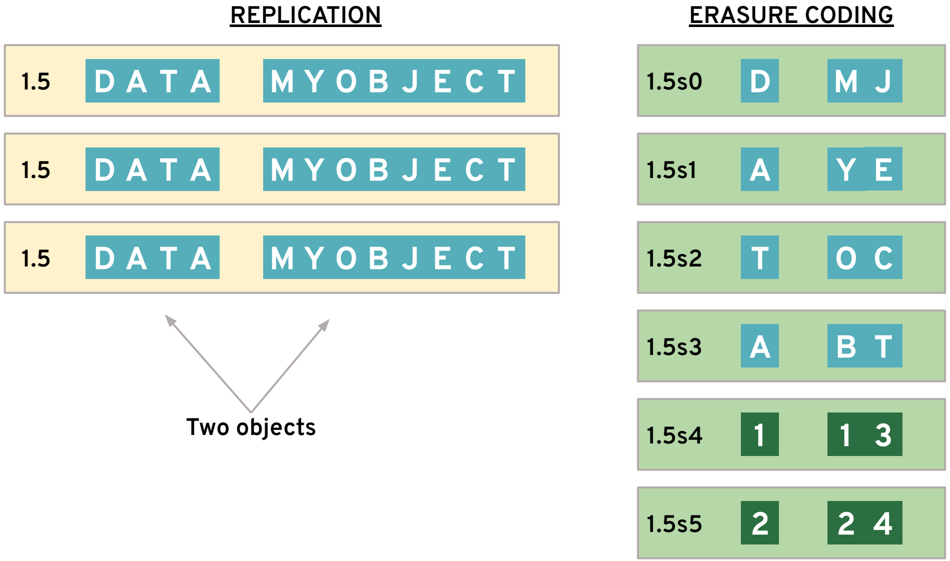
# PLACING PGs WITH CRUSH

- Pseudo-random placement algorithm
  - Repeatable, deterministic, calculation
  - Similar to “consistent hashing”
- Inputs:
  - Cluster topology (i.e., the OSD hierarchy)
  - Pool parameters (e.g., replication factor)
  - PG id
- Output: ordered list of OSDs
- Rule-based policy
  - “3 replicas, different racks, only SSDs”
  - “6+2 erasure code shards, 2 per rack, different hosts, only HDDs”
- Stable mapping
  - Limited data migration on change
- Support for varying device sizes
  - OSDs get PGs proportional to their weight



# REPLICATION AND ERASURE CODING

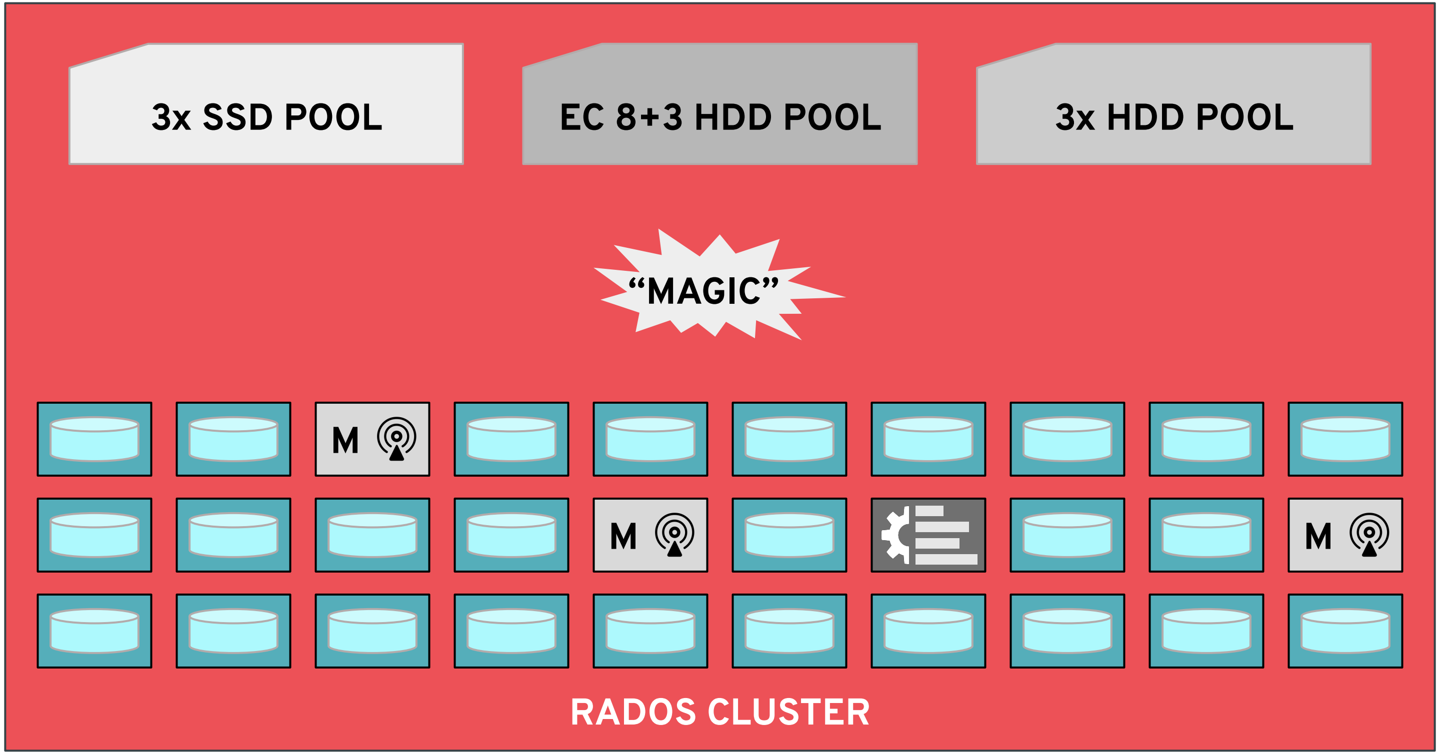
- Each RADOS pool must be durable
- Each PG must be durable
- Replication
  - Identical copies of each PG
  - Usually 3x (200% overhead)
  - Fast recovery--read any surviving copy
  - Can vary replication factor at any time
- Erasure coding
  - Each PG “shard” has different slice of data
  - Stripe object across **k** PG shards
  - Keep addition **m** shards with per-object parity/redundancy
  - Usually more like 1.5x (50% overhead)
  - Erasure code algorithm and **k+m** parameters set when pool is created
  - Better for large objects that rarely change



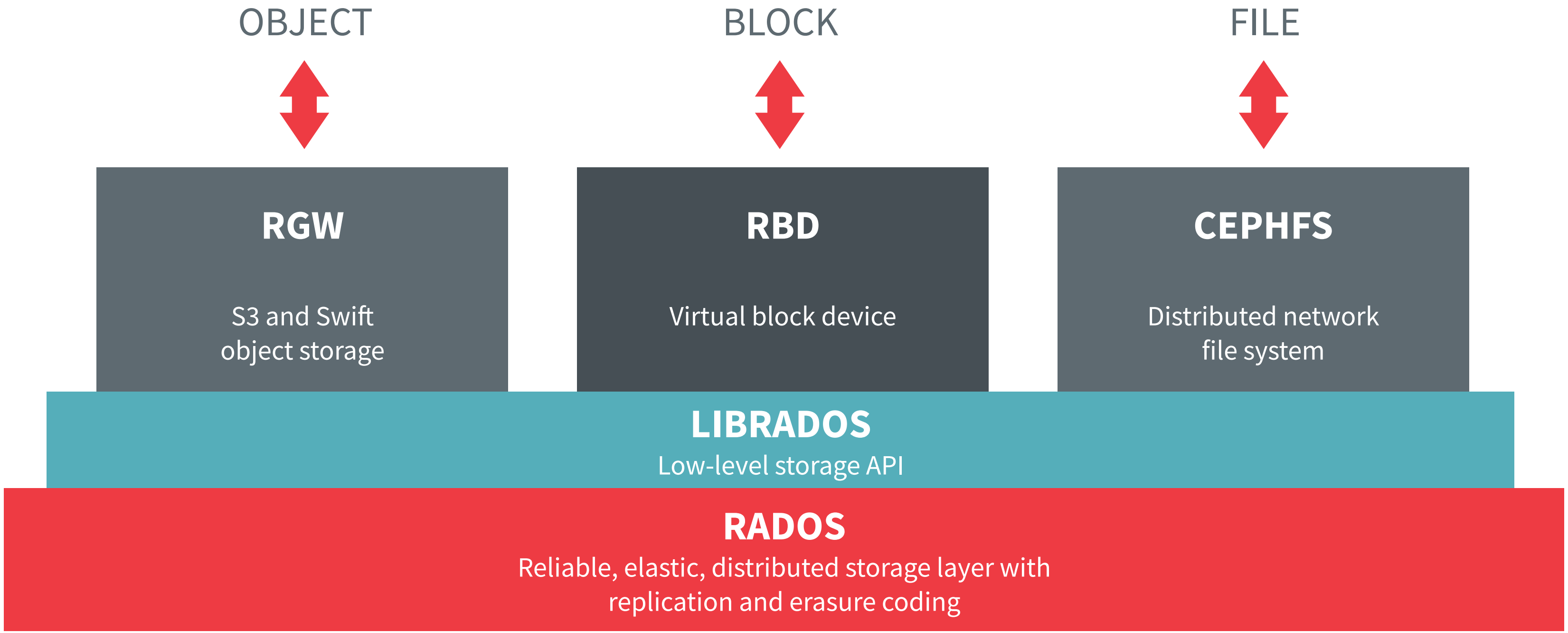
# SPECIALIZED POOLS

- Pools usually share devices
  - Unless a pool's CRUSH placement policy specifies a specific class of device
- Elastic, scalable provisioning
  - Deploy hardware to keep up with demand
- Uniform management of devices
  - Common "day 2" workflows to add, remove, replace devices
  - Common management of storage hardware resources

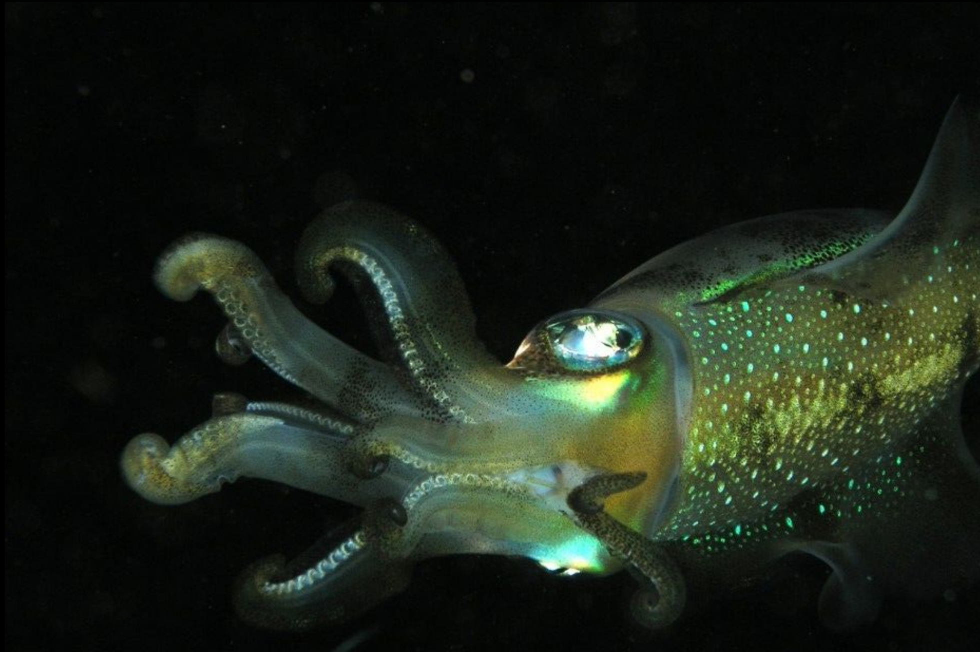
# RADOS VIRTUALIZES STORAGE



# PLATFORM FOR HIGH-LEVEL SERVICES

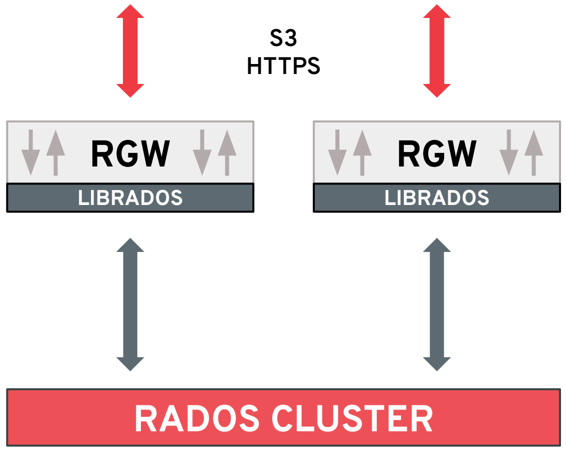


# RGW: OBJECT STORAGE

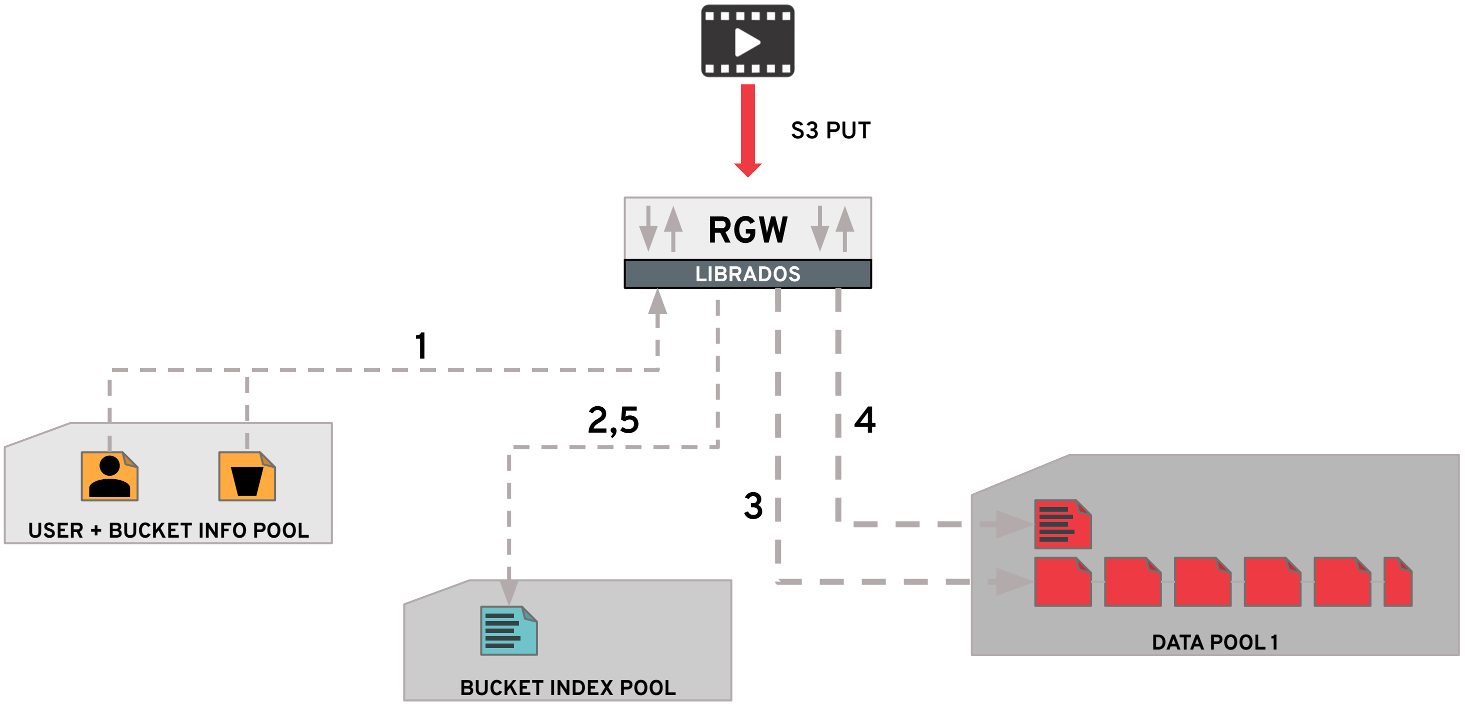


# RGW: RADOS GATEWAY

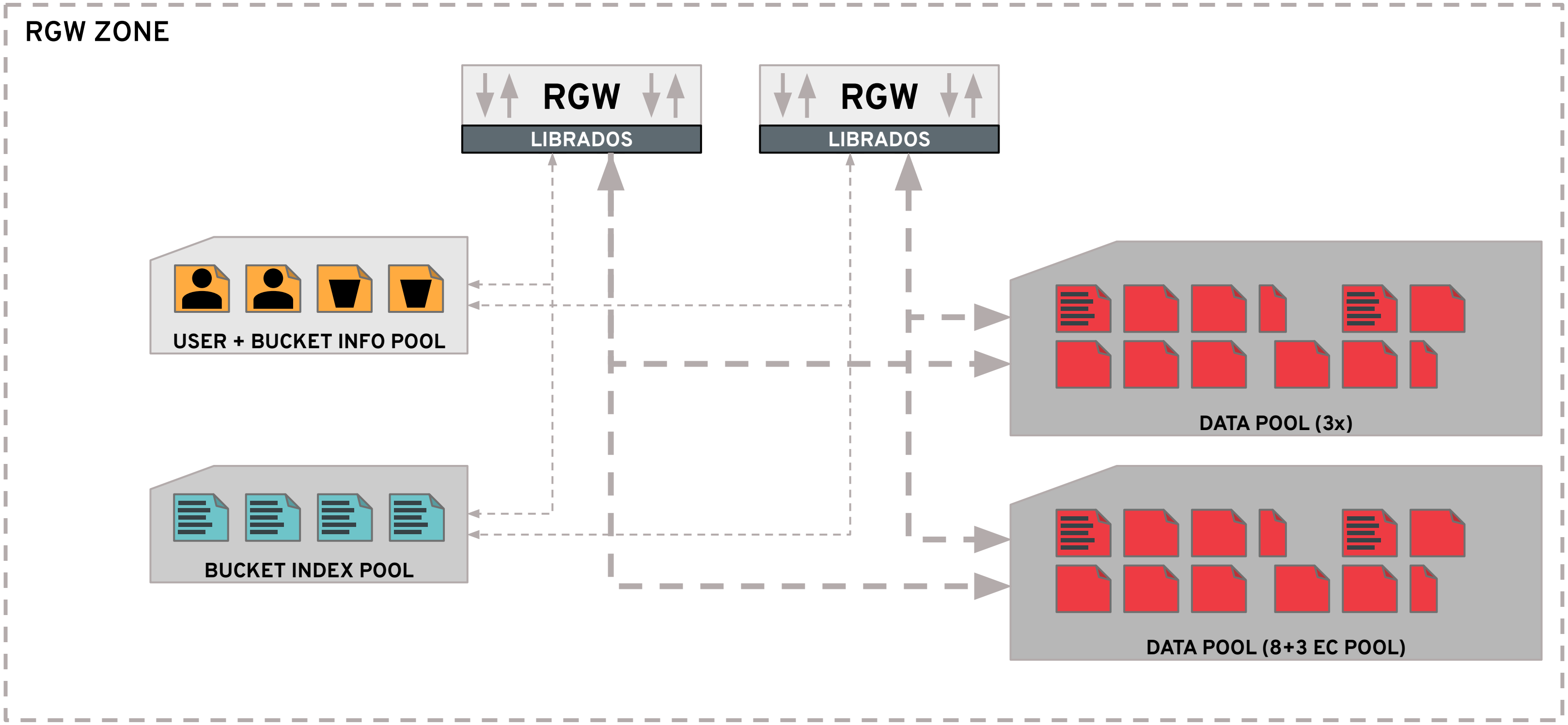
- S3 and Swift-compatible object storage
  - HTTPS/REST-based API
  - Often combined with load balancer to provide storage service to public internet
- Users, buckets, objects
  - Data and permissions model is based on a superset of S3 and Swift APIs
  - ACL-based permissions, enforced by RGW
- RGW objects not same as RADOS objects
  - S3 objects can be very big: GB to TB
  - RGW stripes data across RADOS objects



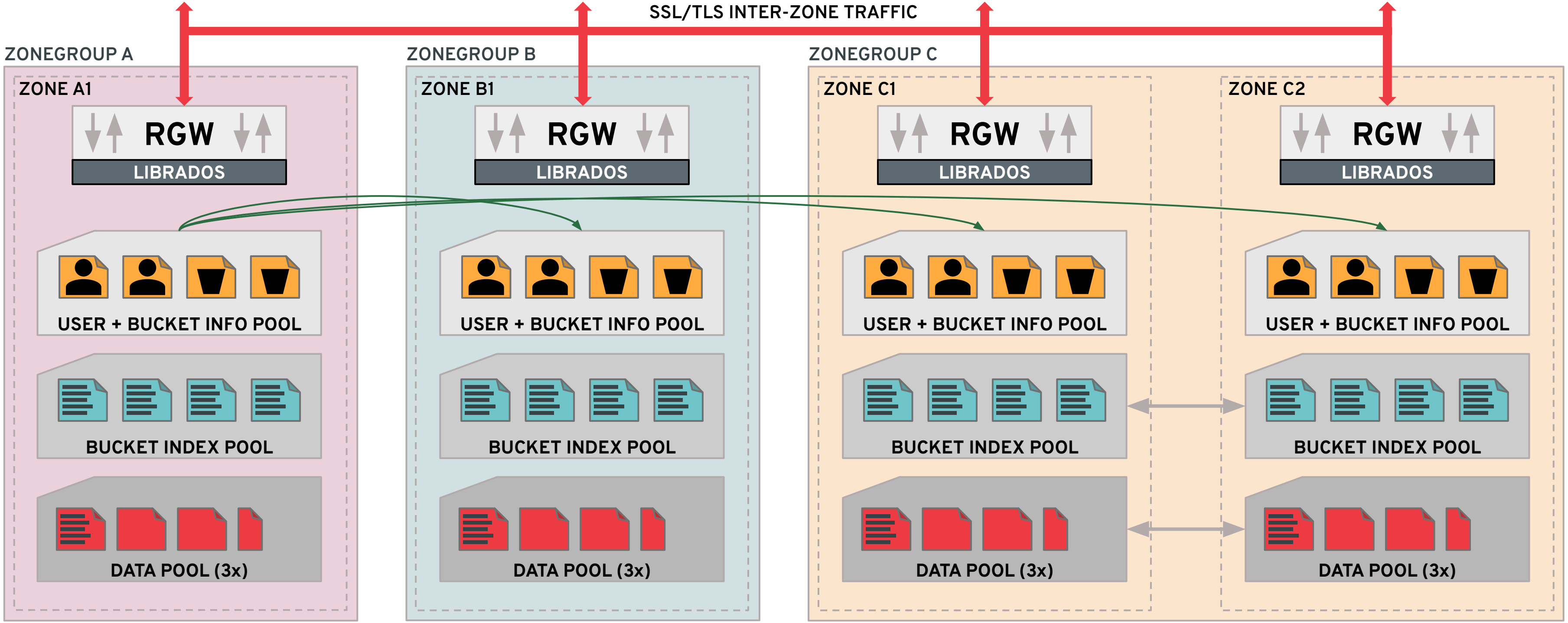
# RGW STORES ITS DATA IN RADOS



# RGW ZONE: POOLS + RGW DAEMONS



# RGW FEDERATION AND GEO-REP




- Zones may be different clusters and/or sites
- Global view of users and buckets
- Each bucket placed in a ZoneGroup
- Data replicated between all Zones in a ZoneGroup

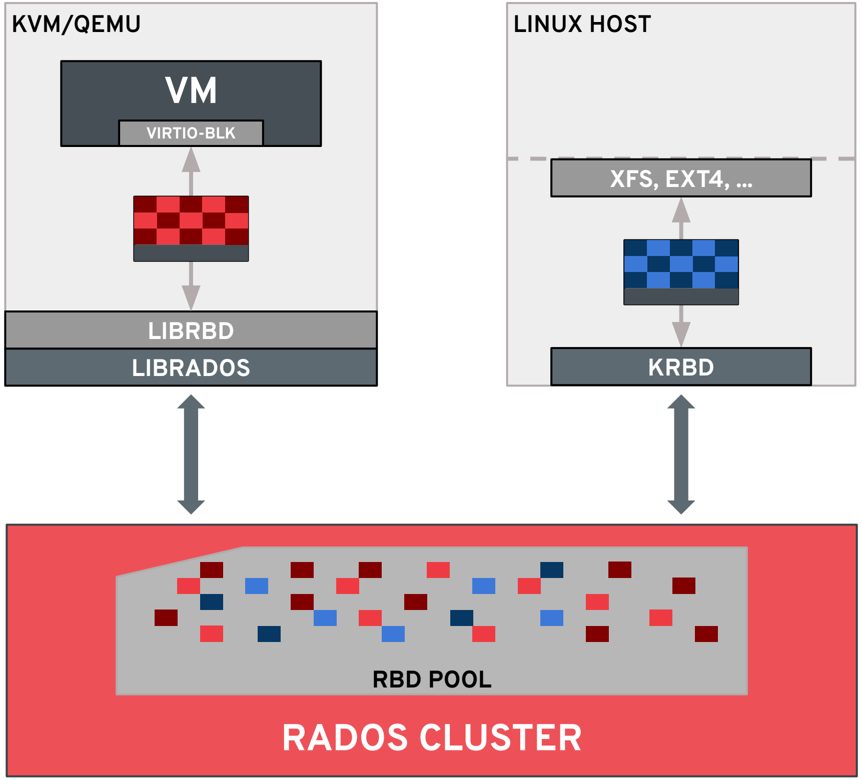
# OTHER RGW FEATURES

- Very strong S3 API compatibility
  - https://github.com/ceph/s3-tests functional test suite
- STS: Security Token Service
  - Framework for interoperating with other authentication/authorization systems
- Encryption (various flavors of API)
- Compression
- CORS and static website hosting
- Metadata search with ElasticSearch
- Pub/sub event stream
  - Integration with knative serverless
  - Kafka
- Multiple storage classes
  - Map classes to RADOS pools
  - Choose storage for individual objects or set a bucket policy
- Lifecycle management
  - Bucket policy to automatically move objects between storage tiers and/or expire
  - Time-based
- Archive zone
  - Archive and preserve full storage history

# RBD: BLOCK STORAGE

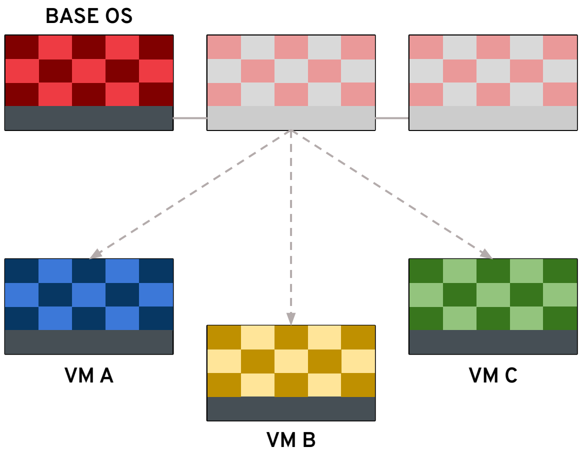
# RBD: RADOS BLOCK DEVICE

- Virtual block device
  - Store disk images in RADOS
  - Stripe data across many objects in a pool
- Storage decoupled from host, hypervisor
  - Analogous to AWS's EBS
- Client implemented in KVM and Linux
- Integrated with
  - Libvirt
  - OpenStack (Cinder, Nova, Glace)
  - Kubernetes
  - Proxmox, CloudStack, Nebula, …

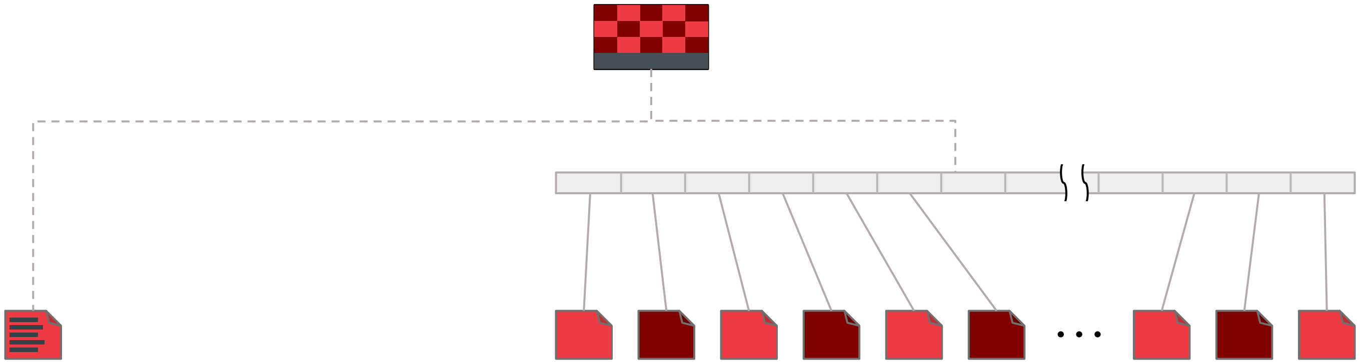


# SNAPSHOTS AND CLONES

- Snapshots
  - Read-only
  - Associated with individual RBD image
  - Point-in-time consistency
- Clones
  - New, first-class image
  - Writeable overlay over an existing snapshot
  - Can be snapshotted, resized, renamed, etc.
- Efficient
  - O(1) creation time
  - Leverage copy-on-write support in RADOS
  - Only consume space when data is changed



# RBD: DATA LAYOUT



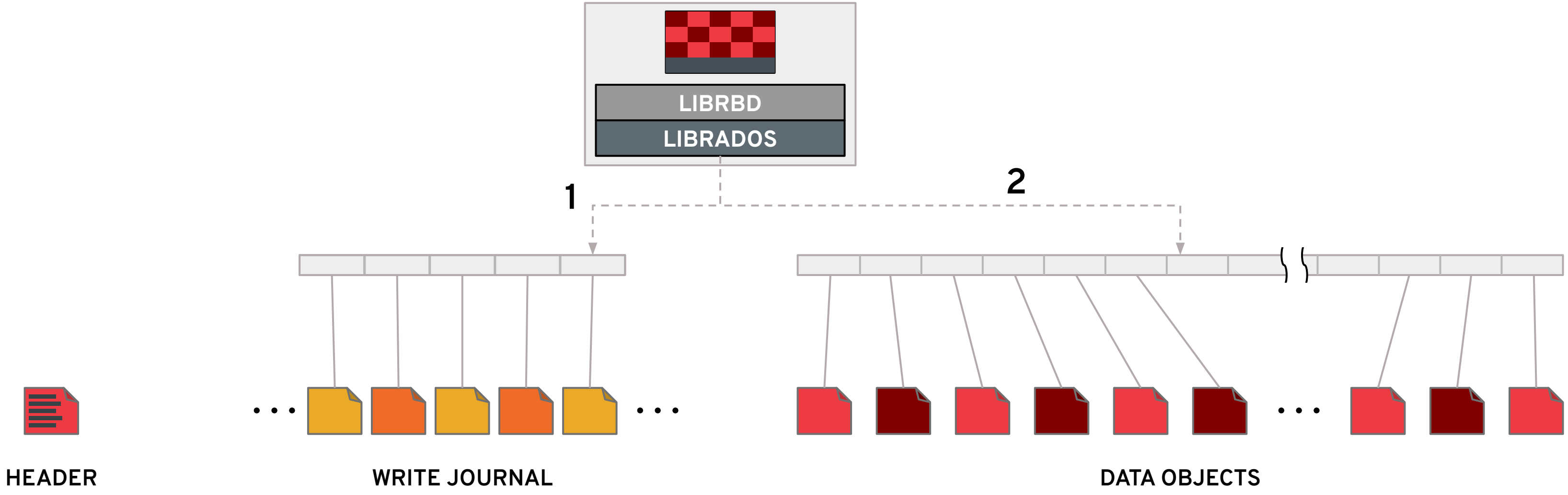
**HEADER**

- Image name
- Image size
- Striping parameters
- Snapshot metadata (names etc.)
- Options
- Lock owner
- ...

**DATA OBJECTS**

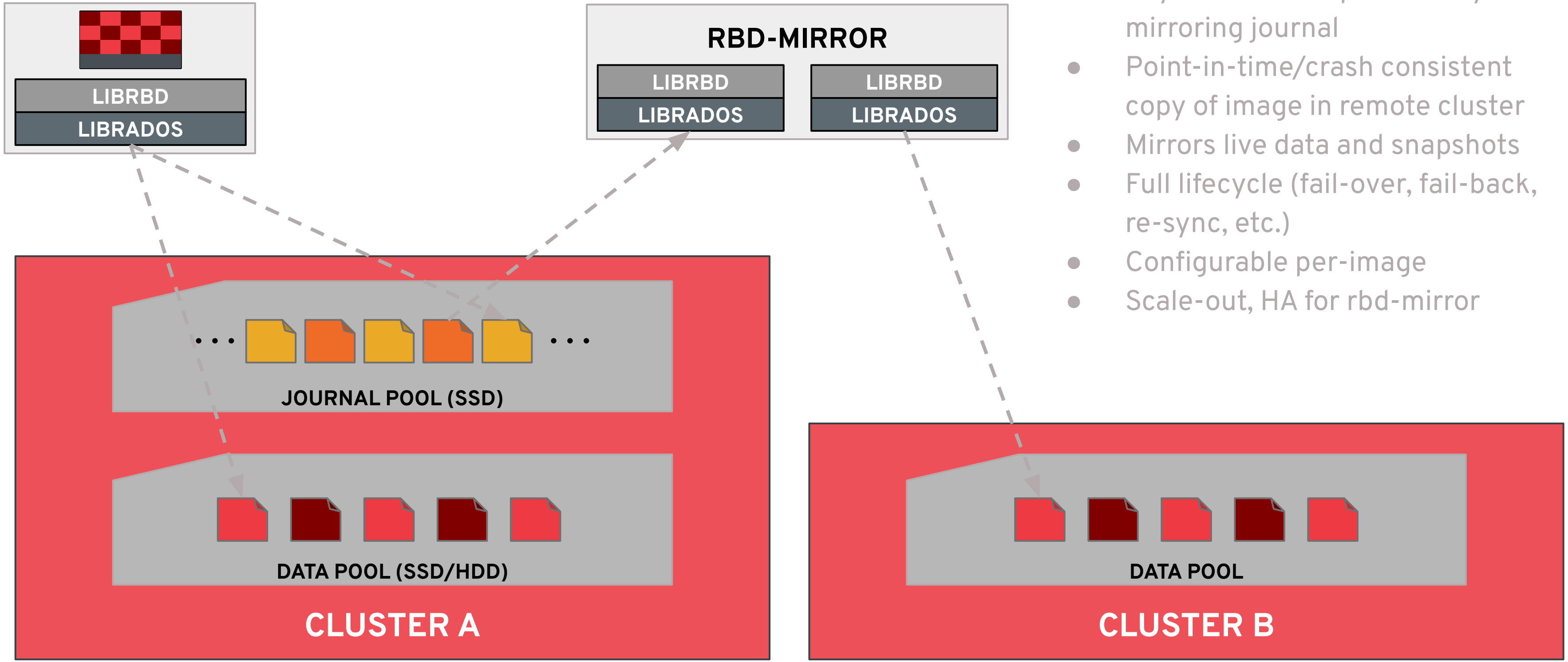
- Chunk of block device content
- 4 MB by default, but striping is configurable
- Sparse: objects only created if/when data is written
- Replicated or erasure coded, depending on the pool

# RBD: JOURNALING MODE




- Recent writes
- Metadata changes

# RBD MIRRORING




- Asynchronous replication by mirroring journal
- Point-in-time/crash consistent copy of image in remote cluster
- Mirrors live data and snapshots
- Full lifecycle (fail-over, fail-back, re-sync, etc.)
- Configurable per-image
- Scale-out, HA for rbd-mirror

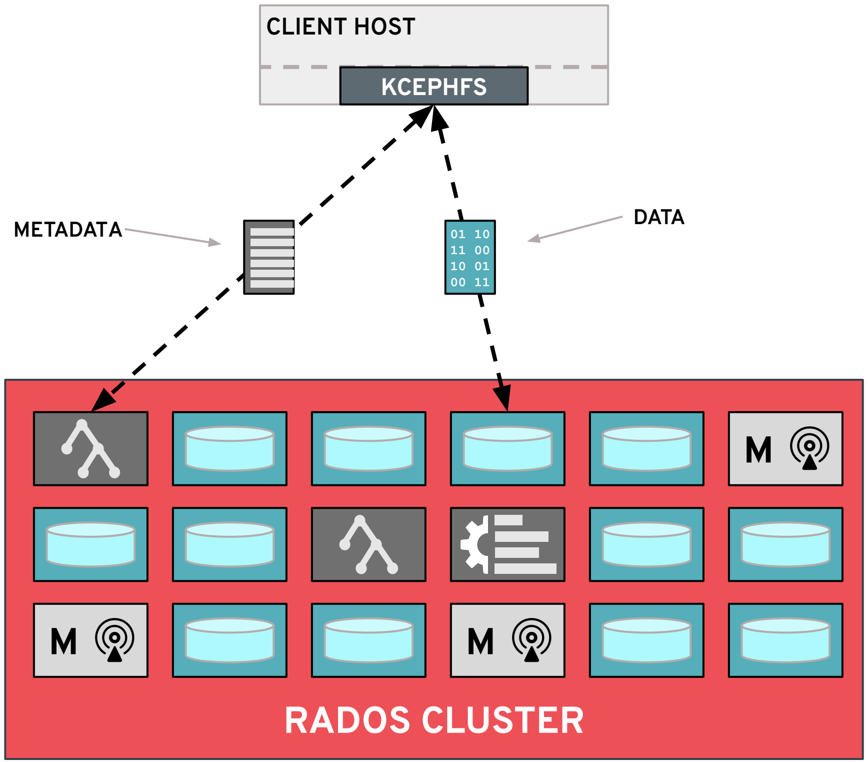
# OTHER RBD FEATURES

- ‘rbd top’
  - Real-time view of IO activity
- Quotas
  - Enforced at provisioning time
- Namespace isolation
  - Restrict access to a private namespace of RBD images
- Import and export
  - Full image import/export
  - Incremental diff (between snapshots)
- Trash
  - Keep deleted images around for a bit before purging
- Linux kernel client
  - ‘rbd map myimage’ → /dev/rbd*
- NBD
  - ‘rbd map -t nbd myimage’ → /dev/nbd*
  - Run latest userspace library
- iSCSI gateway
  - LIO stack + userspace tools to manage gateway configuration
- librbd
  - Dynamically link with application

# CEPHFS: FILE STORAGE

# CEPHFS: CEPH FILE SYSTEM

- Distributed network file system
  - Files, directories, rename, hard links, etc.
  - Concurrent shared access from many clients
- Strong consistency and coherent caching
  - Updates from one node visible elsewhere, immediately
- Scale metadata and data independently
  - Storage capacity and IO throughput scale with the number of OSDs
  - Namespace (e.g., number of files) scales with the number of MDS daemons



# CEPH-MDS: METADATA SERVER

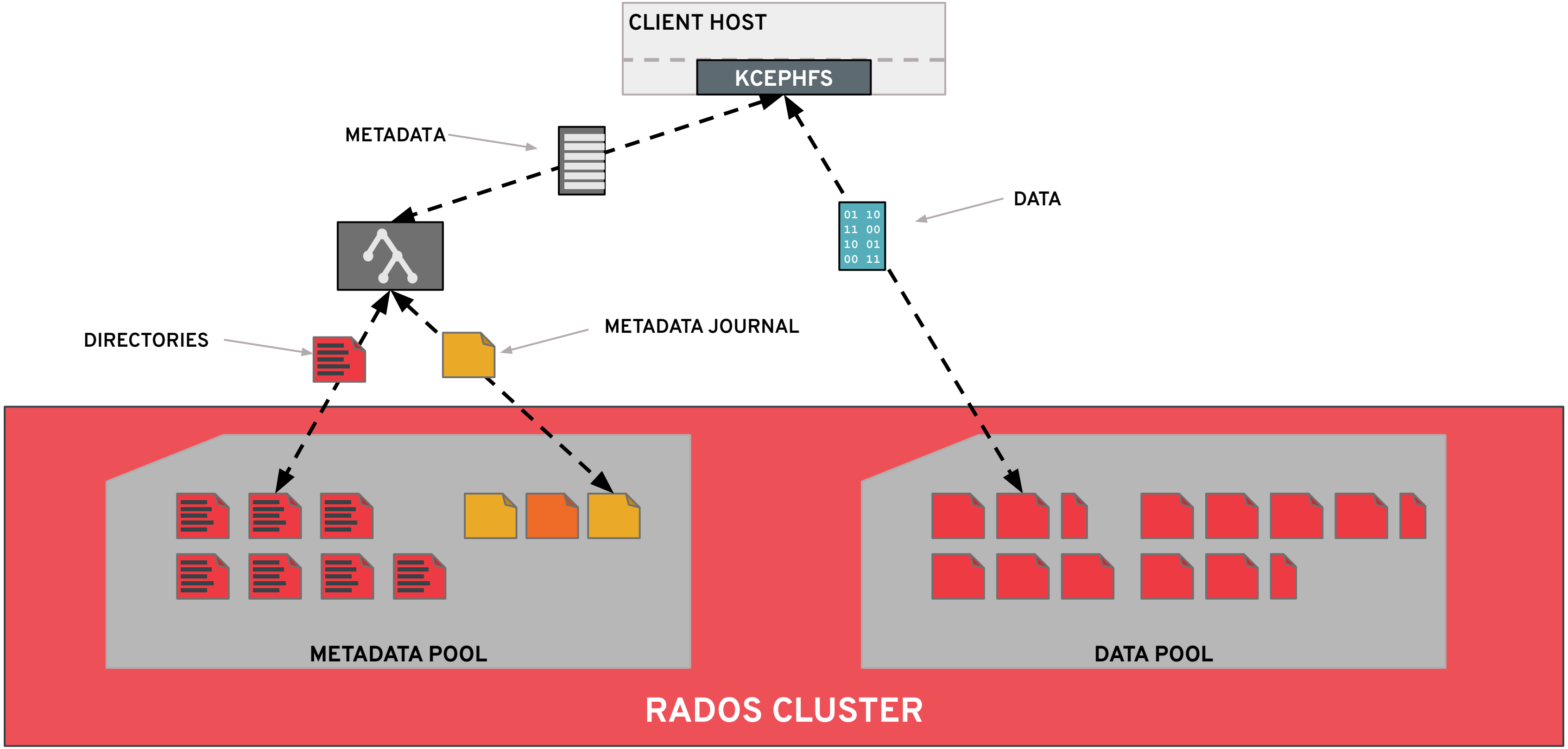
**ceph-mds**

<u>MDS (Metadata Server)</u>

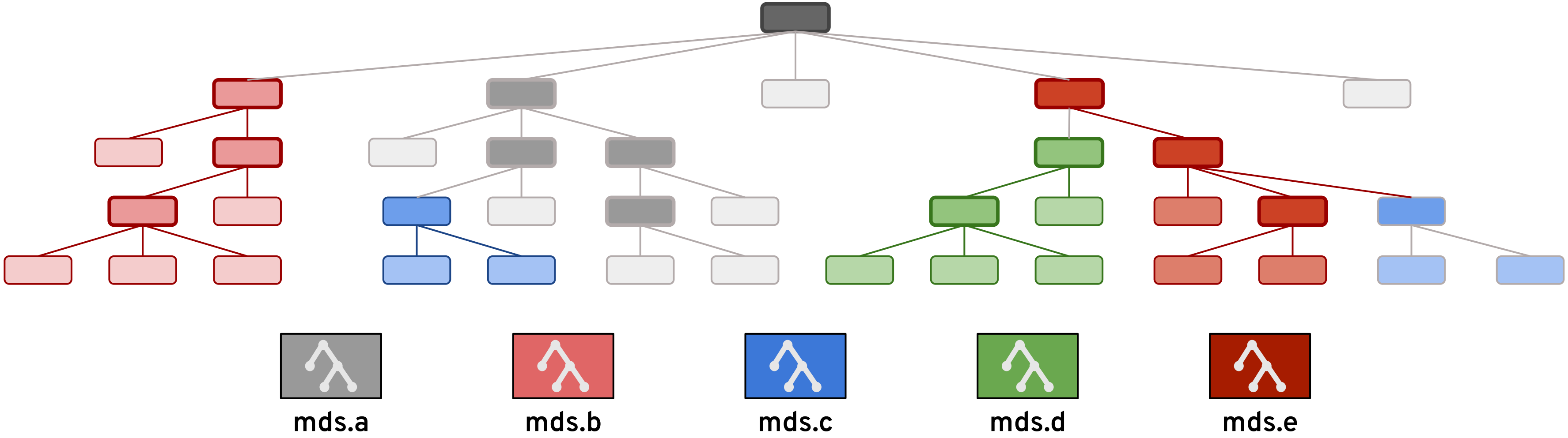
- Manage file system namespace
- Store file system metadata in RADOS objects
    - File and directory metadata (names, inodes)
- Coordinate file access between clients
- Manage client cache consistency, locks, leases
- Not part of the data path
- 1s - 10s active, plus standbys

**ceph-mon** **ceph-mgr** **ceph-osd**

# METADATA IS STORED IN RADOS



# SCALABLE NAMESPACE




- Partition hierarchy across MDSs based on workload
- Fragment huge directories across MDSs
- Clients learn overall partition as they navigate the namespace
- Subtree partition maintains directory locality
- Arbitrarily scalable by adding more MDSs

# CEPHFS SNAPSHOTS

- Snapshot any directory
  - Applies to all nested files and directories
  - Granular: avoid “volume” and “subvolume” restrictions in other file systems
- Point-in-time consistent
  - from perspective of POSIX API at *client*
  - *not* client/server boundary
- Easy user interface via file system
- Efficient
  - Fast creation/deletion
  - Snapshots only consume space when changes are made

```
$ cd any/cephfs/directory
$ ls
foo bar baz/
$ ls .snap
$ mkdir .snap/my_snapshot    ←
$ ls .snap/
my_snapshot/
$ rm foo
$ ls
bar baz/
$ ls .snap/my_snapshot
foo bar baz/
$ rmdir .snap/my_snapshot    ←
$ ls .snap
$
```

# CEPHFS RECURSIVE ACCOUNTING

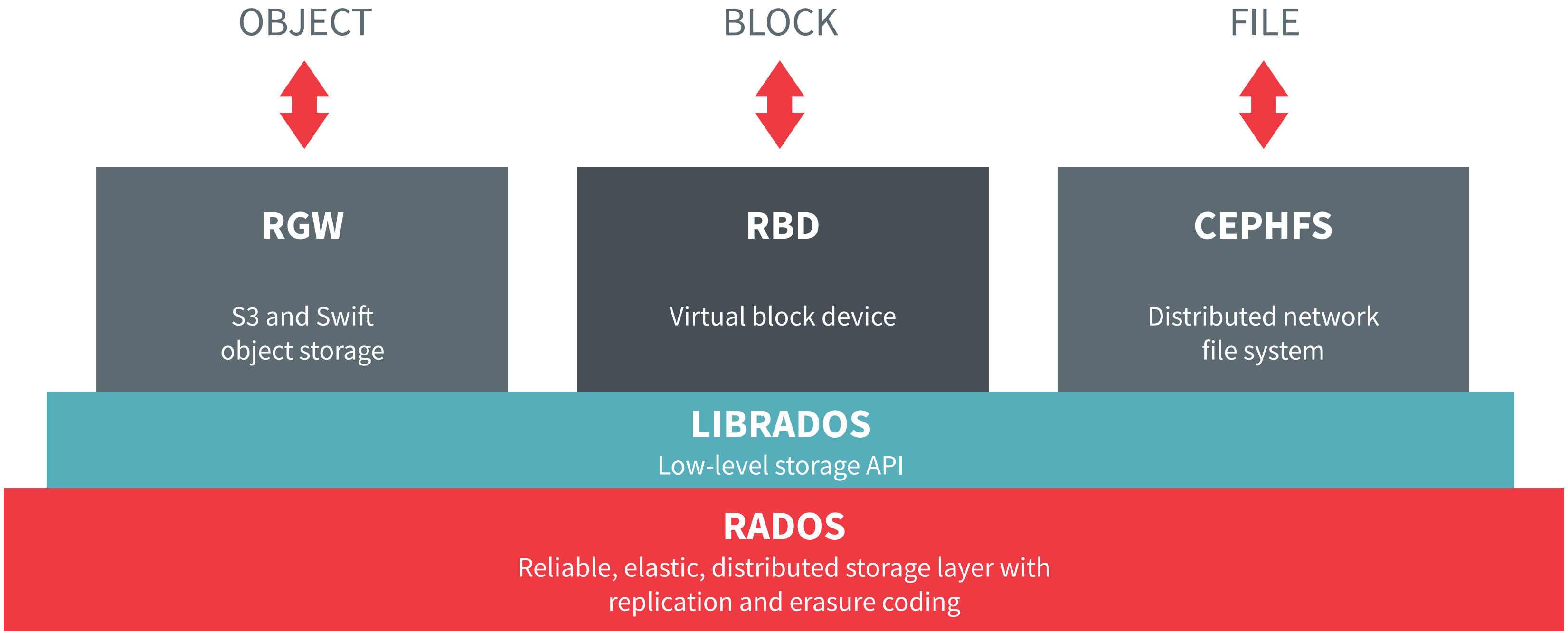
- MDS maintains recursive stats across the file hierarchy
  - File and directory counts
  - File size (summation)
  - Latest **ctime**
- Visible via virtual xattrs
- Recursive bytes as directory size
  - If mounted with ‘rbytes’ option
  - Unfortunately this confuses rsync; off by default
  - Similar to ‘du’, but free

```
$ sudo mount -t ceph 10.1.2.10:/ /mnt/ceph \
-o name=admin,secretfile=secret,rbytes
$ cd /mnt/ceph/some/random/dir
$ getfattr -d -m - .
# file: .
ceph.dir.entries="3"
ceph.dir.files="2"
ceph.dir.subdirs="1"
ceph.dir.rbytes="512000"
ceph.dir.rctime="1474909482.0924860388"
ceph.dir.rentries="17"
ceph.dir.rfiles="16"
ceph.dir.rsubdirs="1"
$ ls -alh
total 12
drwxr-xr-x  3 sage sage 4.5M Jun 25 11:38 ./
drwxr-xr-x 47 sage sage  12G Jun 25 11:38 ../
-rw-r--r--  1 sage sage   2M Jun 25 11:38 bar
drwxr-xr-x  2 sage sage 500K Jun 25 11:38 baz/
-rw-r--r--  1 sage sage   2M Jun 25 11:38 foo
```

# OTHER CEPHFS FEATURES

- Multiple file systems (volumes) per cluster
  - Separate ceph-mds daemons
- xattrs
- File locking (flock and fcntl)
- Quotas
  - On any directory
- Subdirectory mounts + access restrictions
- Multiple storage tiers
  - Directory subtree-based policy
  - Place files in different RADOS pools
  - Adjust file striping strategy
- Lazy IO
  - Optionally relax CephFS-enforced consistency on per-file basis for HPC applications
- Linux kernel client
  - e.g., mount -t ceph $monip:/ /ceph
- ceph-fuse
  - For use on non-Linux hosts (e.g., OS X) or when kernel is out of date
- NFS
  - CephFS plugin for nfs-ganesha FSAL
- CIFS
  - CephFS plugin for Samba VFS
- libcephfs
  - Dynamically link with your application

# COMPLETE STORAGE PLATFORM



# II. Ceph Use-Cases at CERN

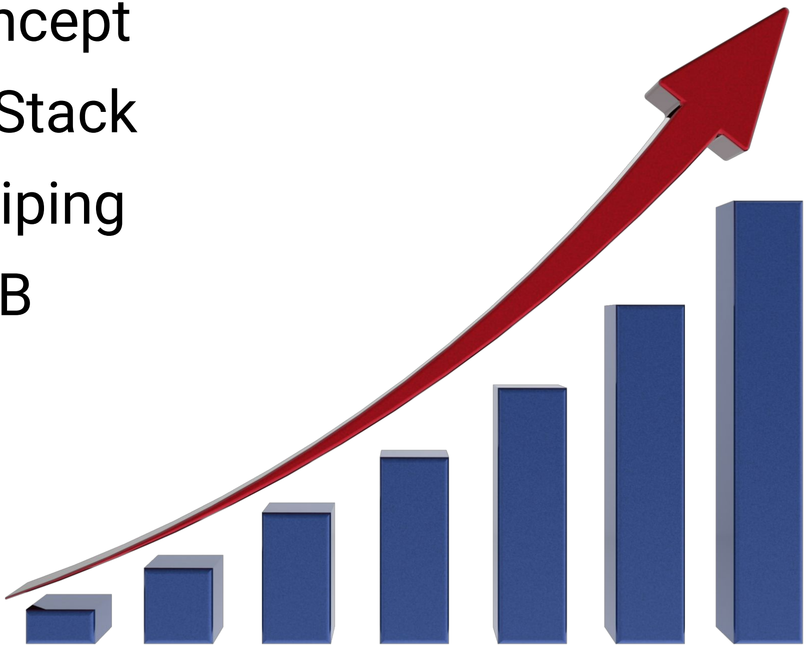
# CERN Computing Infrastructure

- High throughput scientific computing platform:
  - HTCondor batch system: ~250k CPU cores
  - EOS storage system: ~500 petabytes of raw storage
  - CTA tape system for long term archival: ~500 petabytes of tape
- IT infrastructure brings several storage needs:
  - Block Storage and NAS Filers for VMs and Databases
  - Object Storage for web or cloud native applications
  - HPC Scratch areas for MPI clusters
  - “Open Infrastructure"

# CERN IT Open Infrastructure

# Our Ceph History

- March 2013: 300TB proof of concept
- Dec 2013: 3 petabytes for OpenStack
- 2014-15: Erasure coding and striping
- 2016: Upgraded from 3PB to 6PB
- 2017: 8 production clusters
- 2018-19: CephFS and S3
- 2020+: scale out...



CERN

# Current Clusters in Prod (I)

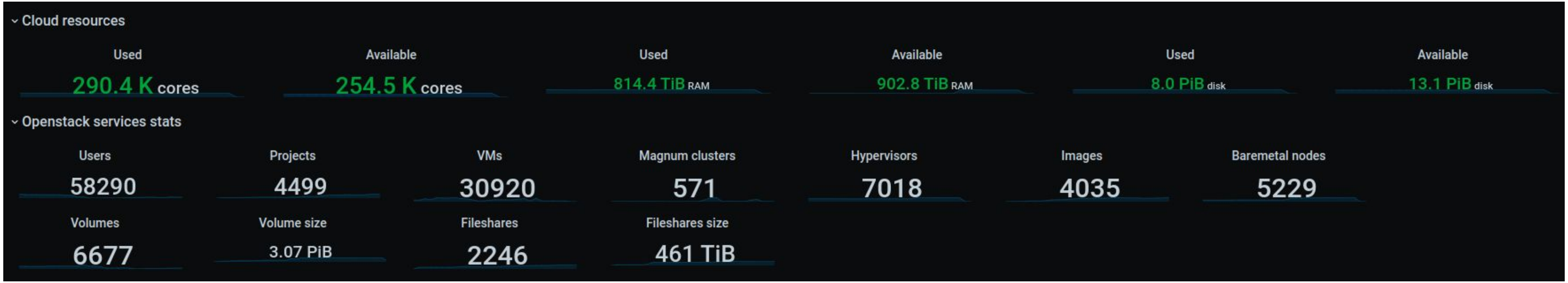
- **Block Storage** for OpenStack
  - Three hdd (w/ssd rocksdb) clusters: 24 petabytes raw (3x replication)
  - Three all-flash clusters: 1.2 petabytes raw (2+2 erasure coding)
  - Integrated to OpenStack as multiple QoS types (IOPS throttles) and availability zones
- **S3 Object Storage**
  - Two clusters in different data centres: 12.5 petabytes raw
  - Data stored in 4+2 erasure coding on HDDs, bucket indices on SSDs
  - Currently independent realms; Working on zonegroup replication now.

# Current Clusters in Prod (II)

- **CephFS**
  - Two general purpose hdd (w/ ssd rocksdb) clusters: 6.3 petabytes raw (3x replication)
  - One general purpose all-flash cluster: 500TB raw (3x replication)
  - Several targeted all-flash clusters: hyperconverged DB tests, groupware, HPC, …
- General experience is that Ceph is **robust and performant**
  - Data remains consistent after infrastructure outages; failure recovery is basically transparent
  - Hardware replacement and flexibility demonstrated across three procurement cycles

# CERN IT OpenStack Cloud

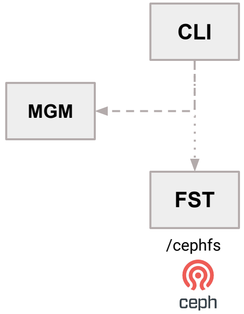
- Since 2013, hosting 90% of CERN's computing resources for scientific and IT needs




openstack®

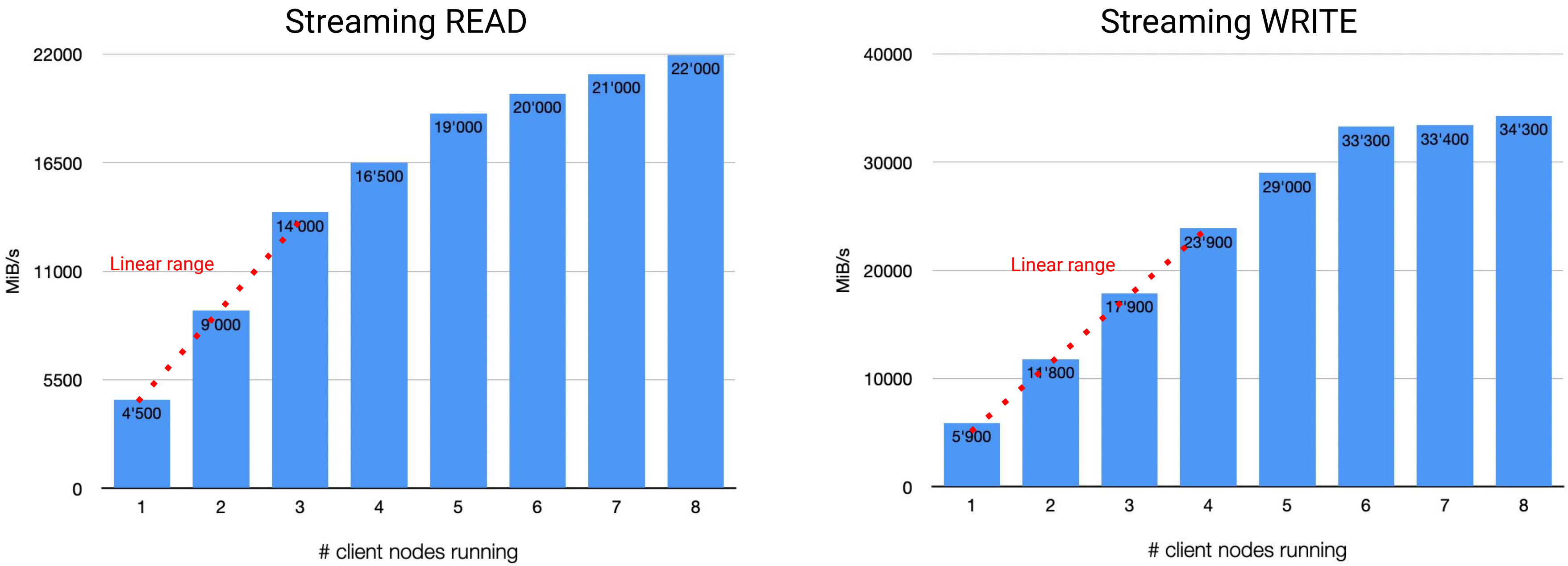
# EOS on CephFS

- EOS storage **developed at CERN for physics** and regular users: **350PB**
- Is it feasible / useful to layer EOS on top of a Ceph backend?
    - Best of both worlds: feature-rich EOS for scientific users + flexible object storage on Ceph
- EOS is clustered storage built upon Xrootd:
    - Files can be replicated or erasure-coded; metadata in “QuarkDB”
    - FST (analogous to the Ceph OSD) normally stores files in a local XFS
        - Files stored using a simple inode hash naming convention
- It’s therefore **straightforward to use CephFS** in the FST
    - Durability is delegated to CephFS
    - EOS configured to store data with a single replica

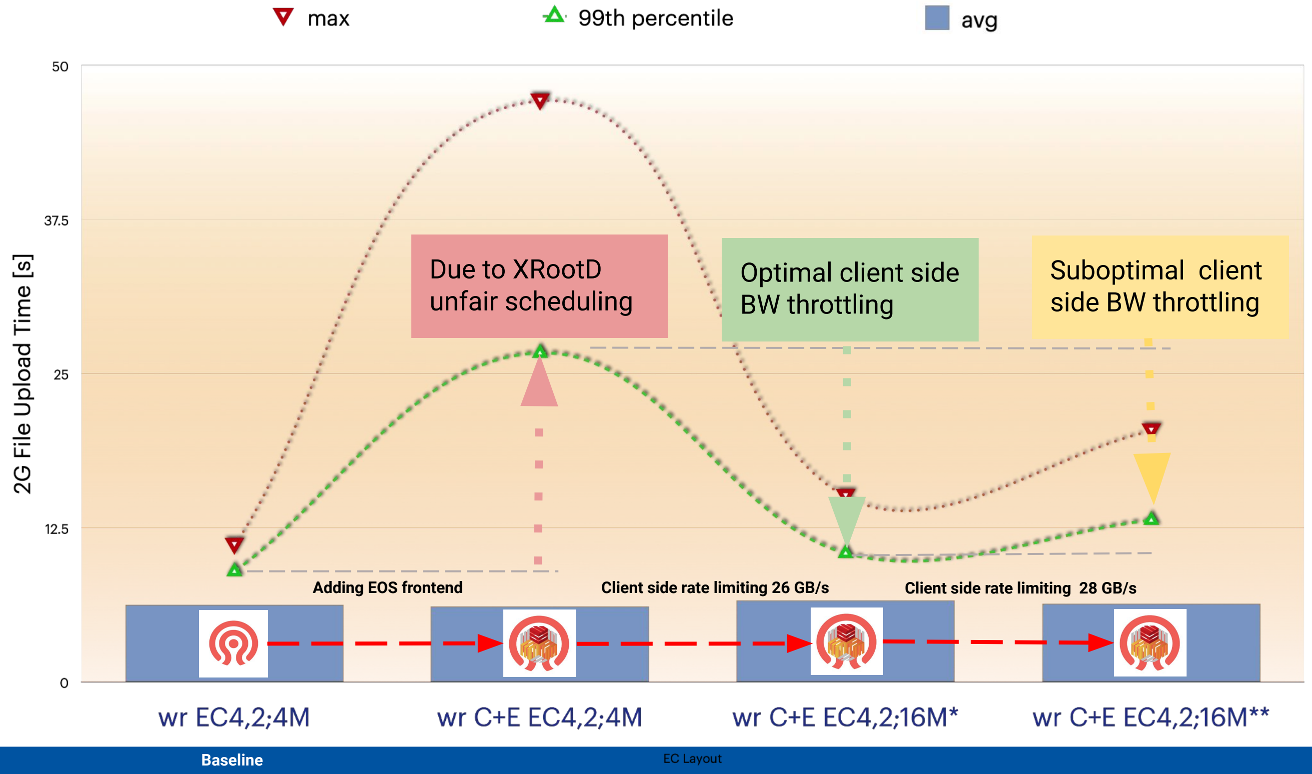



Peters, A.J., van der Ster, D.C. Evaluating CephFS Performance vs. Cost on High-Density Commodity Disk Servers. Comput Softw Big Sci 5, 25 (2021). https://doi.org/10.1007/s41781-021-00071-1

# PoC: CephFS Scalability Measurements



# CephFS+EOS Write Performance Impact?

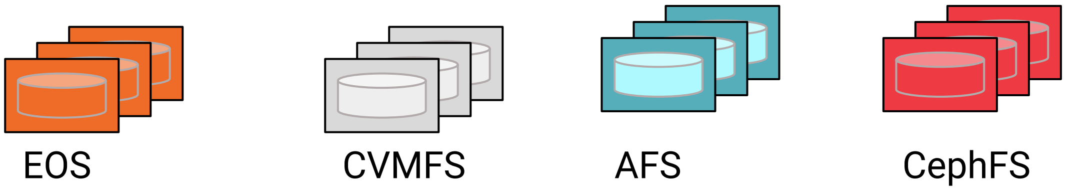



CEPHFS + EOS

# III. CephFS for HPC

# Why use CephFS for HPC?

- At CERN we're already running many network filesystems
  - No desire to introduce yet another (e.g. Lustre)



# Why use CephFS for HPC?

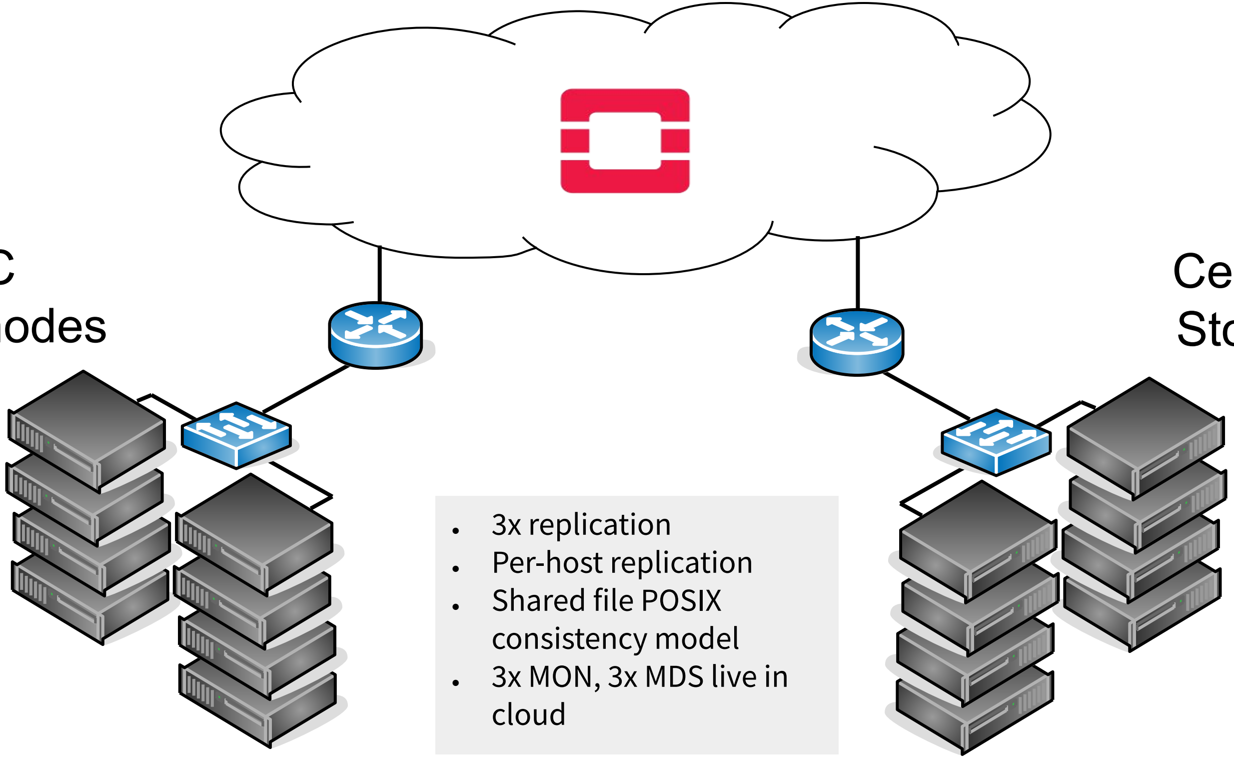
- HPC cluster procurement process optimization
  - We aren’t ordering an HPC cluster from a vendor, it’s 100% DIY HPC + Open Source tech.
  - HW procured as a large order (meant for HTC, HPC, Storage..)
  - Low-latency interconnect added on top

# Why use CephFS for HPC?

- Desire to evaluate CephFS as a multi-purpose filesystem
  - Today: ~ 4 years of experience running CephFS on production for CERN IT's HPC service

HPC Workernodes

CephFS Storage



- 3x replication
- Per-host replication
- Shared file POSIX consistency model
- 3x MON, 3x MDS live in cloud

# Evolution of CephFS as HPC scratch space

- **Shared** CephFS cluster for IT services

BUT…

- **Contention**. I/O-intensive applications affecting other IT services and vice-versa
- CephFS cluster "far" in the network
  - Less resilient to **network issues**
  - Greater I/O **latency**

**ceph-fuse** mounts

BUT…

- Ceph-fuse **not very performant**
- Ceph-fuse issues with **stuck mounts** and stale data after/during network issues

# Evolution of CephFS as HPC scratch space

- **Shared** CephFS cluster for IT services

BUT…
  - I/O-intensive applications affecting other IT services and vice-versa
  - CephFS cluster “far” in the network
    - Less resilient to network issues
    - Greater I/O latency

→ Transitioned to **dedicated** CephFS cluster for increased network failure **resiliency** and **performance**

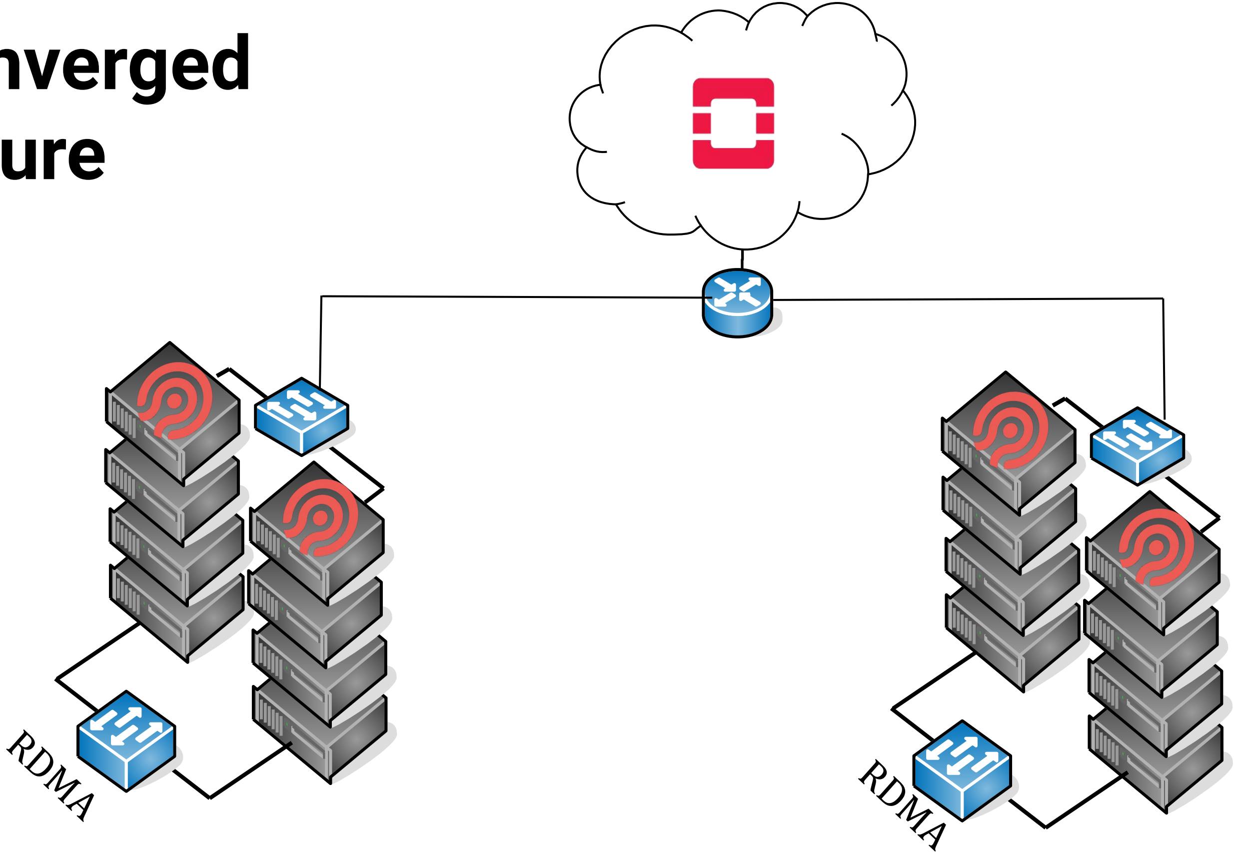
**ceph-fuse** mounts

BUT…
  - Ceph-fuse not very performant
  - Ceph-fuse issues with stuck mounts and stale data after/during network issues

→ Transitioned to **kernel** mounts for greater **performance**, greater **stability**, and much improved **resiliency** to network issues.

# Hyperconverged architecture

Ceph-osd daemons run on HPC compute nodes



# CephFS performance tuning

**Network-locality**: Client/MDS/Disk locality has more than 10x impact on performance

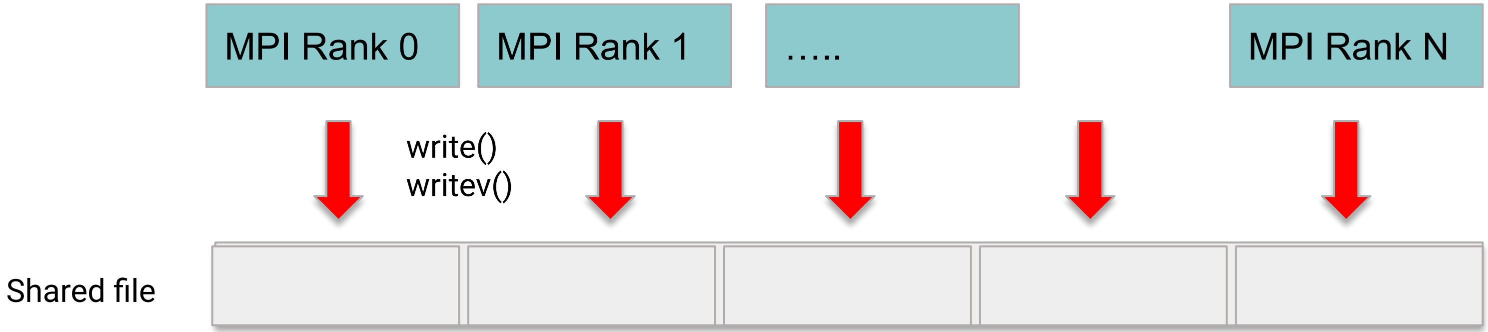
**Replication factor**: Tuning replica count had an impact on write latency.

**Automatic MDS balancing**: Works, but manual pinning can do better if you know the workload

**Lazy I/O**: Much improved performance for single-shared-file collective I/O

# CephFS performance tuning: Lazy I/O

- **Lazy I/O** refers to a mode in which **POSIX semantics are relaxed**
- For shared file collective I/O, coherency is delegated to the application
- Allows **lock-free parallel writes**
- CephFS mode with lazy I/O support added to IOR [https://github.com/hpc/ior]



# Limitations and future plans

- Impact of the Hyperconverged architecture on MPI collectives
  - openQCD is a very tightly coupled HPC application with excellent scalability.
  - Very **sensitive to OS noise**
  - **20%** performance impact from system noise (e.g. Hyperconverged)
- Burst Buffers
  - To significantly **reduce** or remove the **impact** of independent workloads on each other.
- How does a Hyperconverged solution affect day-to-day IT operations?

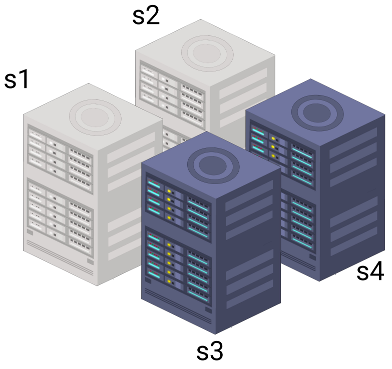
# Impact on automation and IT operations

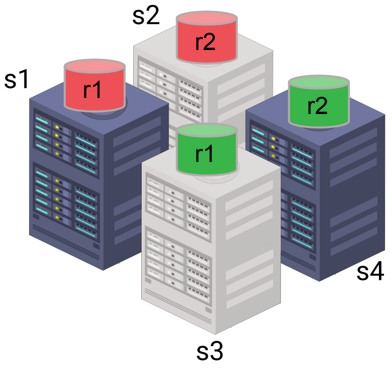
Hyperconverged increases complexity for **transparent operations**

(e.g. kernel reboot campaigns)

Batch System + Distributed Storage System

Drain & shutdown nodes **independently**

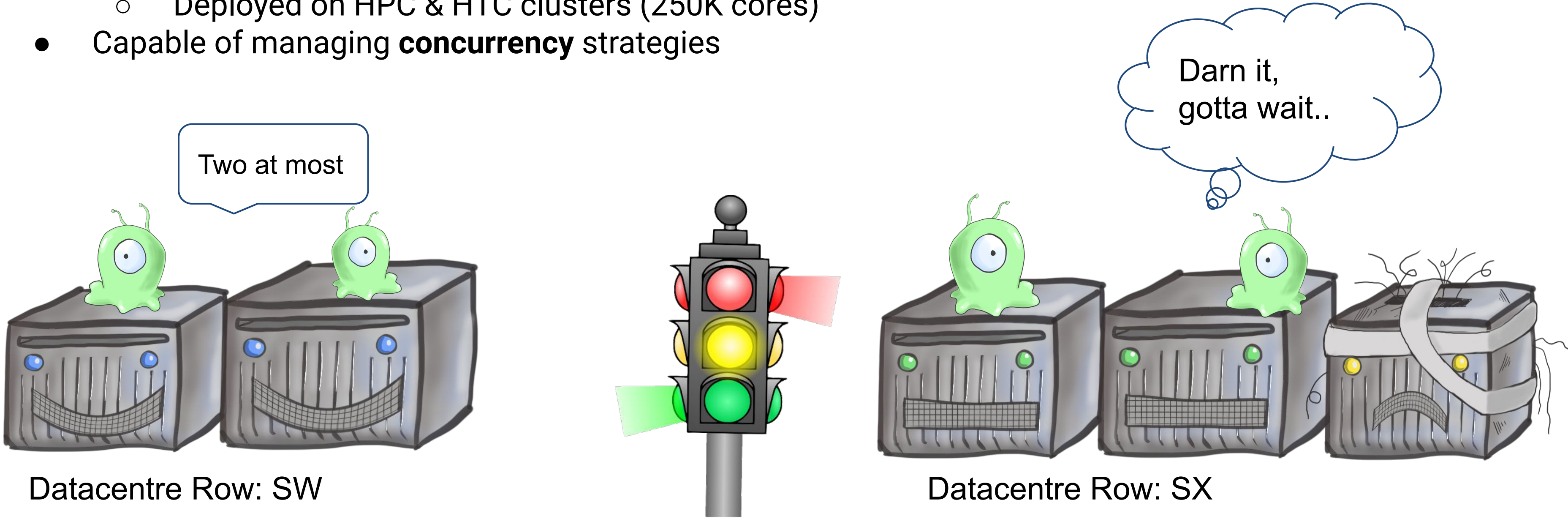



Shutdown nodes according to **data replication** strategy

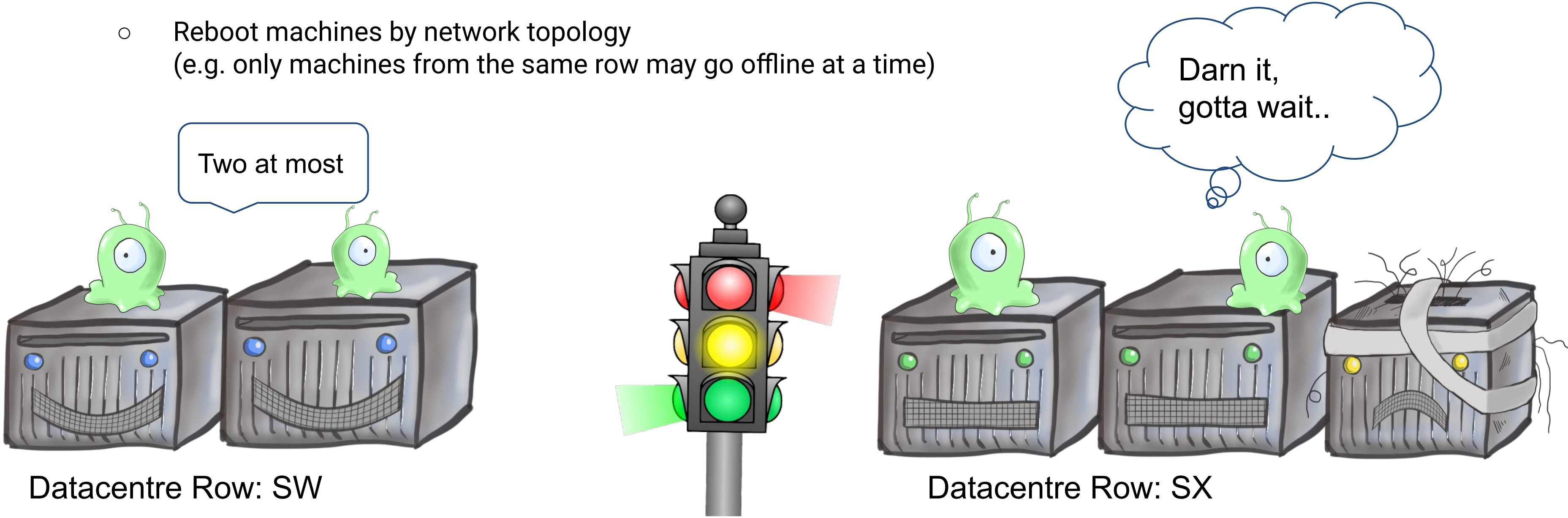
# Impact on automation and IT operations

- **Brainslug** is an **automation tool** written at CERN
- Lightweight daemon running on every node
  - Machine **state manager** (Slurm & HTCondor)
  - Deployed on HPC & HTC clusters (250K cores)
- Capable of managing **concurrency** strategies



# Impact on automation and IT operations

- **Brainslug** is capable of **orchestration** based on user-defined **concurrency strategies**
  - Limit number of nodes draining/offline at a time
    (e.g. drain+reboot 10% at a time)
  - Reboot machines by network topology
    (e.g. only machines from the same row may go offline at a time)



# IIII. Final Words


ceph
cephalocon
2022
July 11-13, 2022 • Portland, OR + Virtual

# Thank you!
# Any Questions?

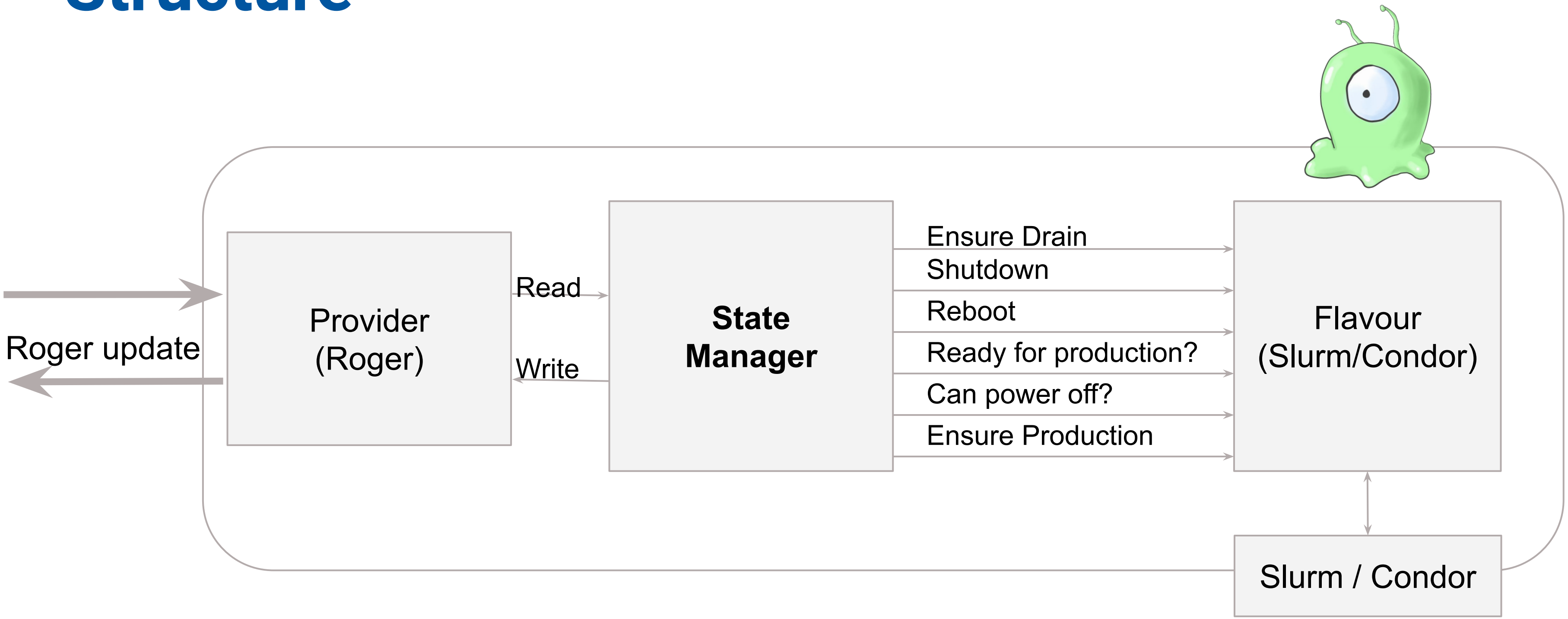
Feel free to get in touch:

daniel.vanderster@cern.ch
pablo.llopis@{gmail.com,cern.ch}

https://ceph.io

# Extra Slides

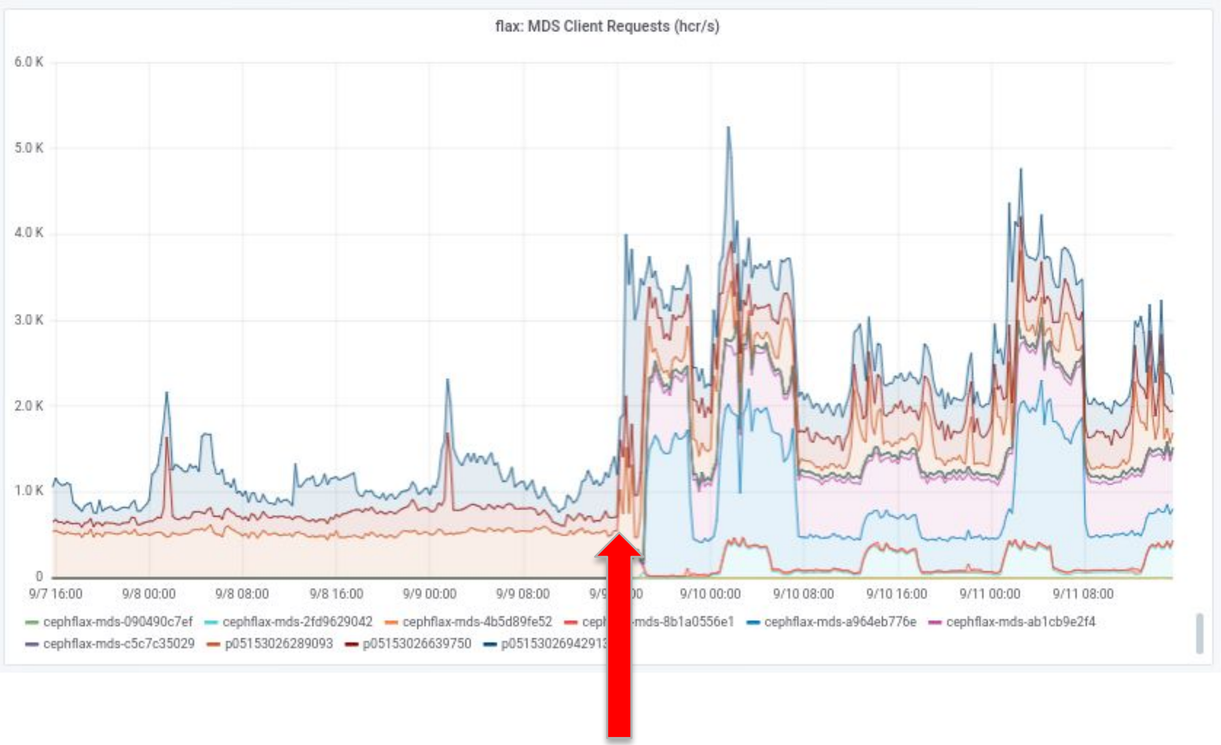
# Structure


Roger update
Provider
(Roger)
Read
Write
State
Manager
Ensure Drain
Shutdown
Reboot
Ready for production?
Can power off?
Ensure Production
Flavour
(Slurm/Condor)
Slurm / Condor

# CephFS Performance

- In previous years we invested in profiling and tuning CephFS for HPC
  - **Automatic MDS balancing**: works, but manual pinning can do better if you know the workload
  - **Keep things local**: Client/MDS/Disk locality has more than 10x impact on performance
  - **LazyIO for parallel IO**: relaxed consistency hints managed by the application
- Tuning for the **IO-500 benchmark** as published at SuperComputing
  - ior: throughput tests for single or multi-file parallel IO
  - mdtest/find: metadata performance tests

# CephFS Scale-Out MDS in Practice




From 3 to 10 active MDS's

# CephFS and IO-500

IO500

| # | information | | | | | | | io500 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | institution | system | storage vendor | filesystem type | client nodes | client total procs | data | score | bw GiB/s | md kIOP/s |
| 1 | University of Cambridge | Data Accelerator | Dell EMC | Lustre | 512 | 8192 | zip | 620.69 | 162.05 | 2377.44 |
| 2 | Oak Ridge National Laboratory | Summit | IBM | Spectrum Scale | 504 | 1008 | zip | 330.56 | 88.20 | 1238.93 |
| 3 | JCAHPC | Oakforest-PACS | DDN | IME | 2048 | 2048 | zip | 275.65 | 492.06 | 154.41 |
| ... | | | | | | | | | | |
| 34 | SUSE | TigerShark | SUSE, Intel, Lenovo | CephFS | 14 | 98 | zip | 8.38 | 3.58 | 19.60 |
| 35 | Clemson University | Palmetto | Dell | BeeGFS | 48 | 48 | zip | 7.64 | 2.93 | 19.88 |
| 36 | CERN | Bytecollider | | CephFS | 64 | 64 | zip | 7.56 | 2.83 | 20.16 |