CEPH

Distributed Storage System

The Ceph Distributed Storage System

- Open-source
- Designed for
  - Commodity hardware
  - Resilience and data safety
  - Scalability
- Popular in Cloud

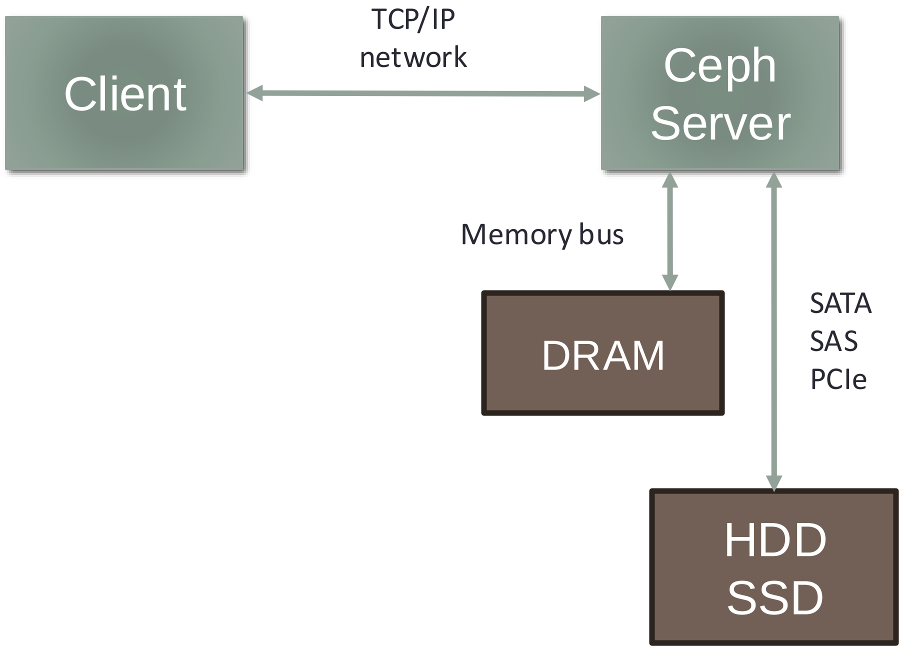
https://ceph.io/en/discover/

https://docs.ceph.com/en/latest/

https://www.youtube.com/watch?v=PmLPbrf-x9g

Hardware Support

- Ceph is software-defined
    - No specific hardware required
- Supports commodity and production hardware
    - HDDs
    - SSDs (SATA/SAS/NVMe)
    - TCP/IP networks
- No DPDK or RDMA support out-of-the-box yet



https://docs.ceph.com/en/latest/start/hardware-recommendations/#data-storage

https://docs.ceph.com/en/latest/rados/configuration/network-config-ref/#general-settings

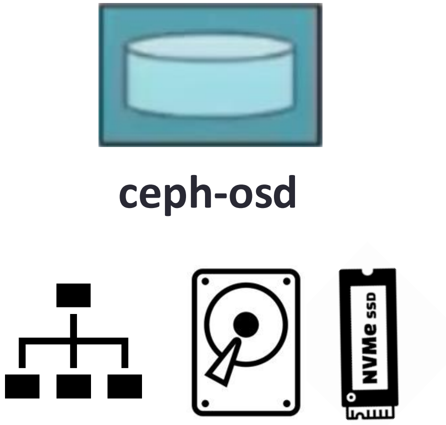
Ceph Architecture

- Ceph Storage Cluster daemons (a.k.a. RADOS)
  - Object Storage Daemon (OSD)
  - Monitor Daemon
  - Manager Daemon
- Other daemons
  - Rados Block Device (RBD)
  - Rados GateWay (RGW) → S3
  - MetaData Server (MDS) → POSIX
- All daemons can be deployed and scaled independently

Object Storage Daemon (OSD) – ceph-osd

- Manages local storage in a node
  - Potentially multiple OSDs per node
- Exploits raw devices
- Stores object data
- Stores metadata index
  - Can exploit fast storage layer if present
- Clients perform I/O directly to OSDs

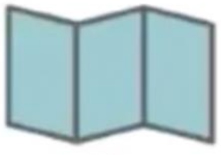
- At least 3 OSDs per system for data safety
- Require 2-4 GiB DRAM each
- Scales up to 10.000s of OSDs



Monitor Daemon – ceph-mon

- Keeps up-to-date map of the cluster
  - OSDs up/down
  - Distribution in nodes, racks, …
- Acts as cluster manager
- Is the authentication authority
- Map consensus with other monitors via Paxos
- 3 to 7 Monitors per system
- Require 32-128 GiB DRAM each

ceph-mon



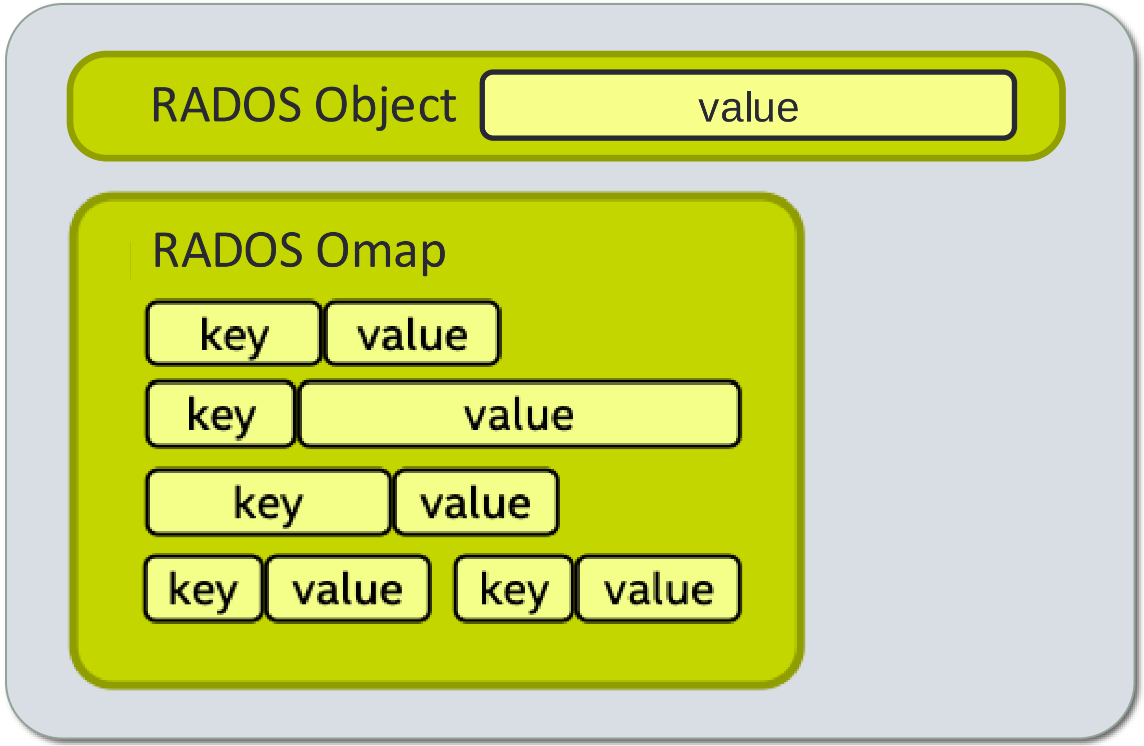
Manager Daemon – ceph-mgr

- Aggregates system metrics
- Exposes system metrics
- 2 Managers per system
- Require 32 GiB DRAM each

ceph-mgr

RADOS object storage API

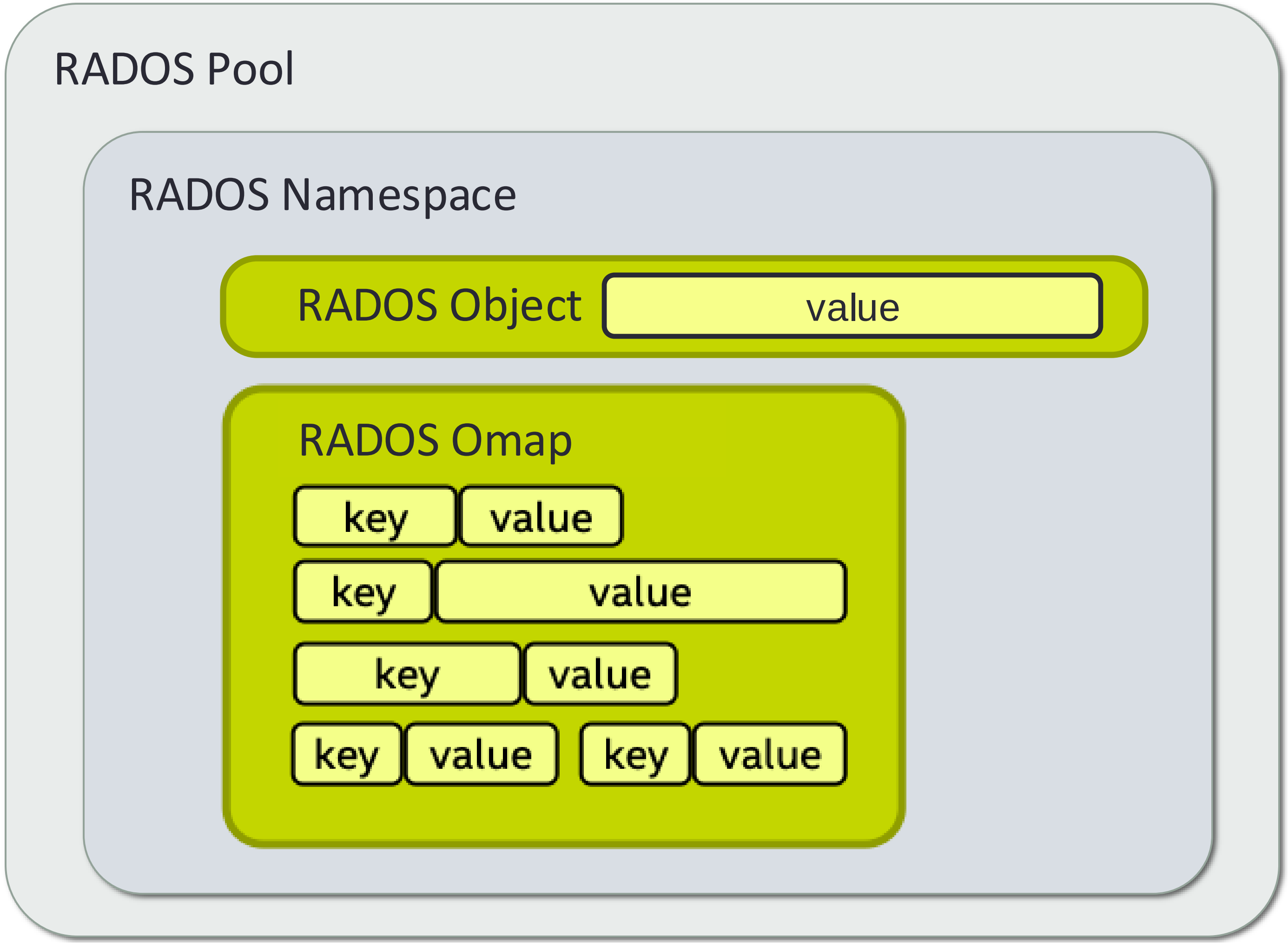
- Clients can interact with the API via librados
- Object
  - Identified by name
  - Can have attributes
  - Regular object
    - stores string of bytes
  - Omap object
    - provides key-value dictionary



https://docs.ceph.com/en/reef/rados/api/librados/

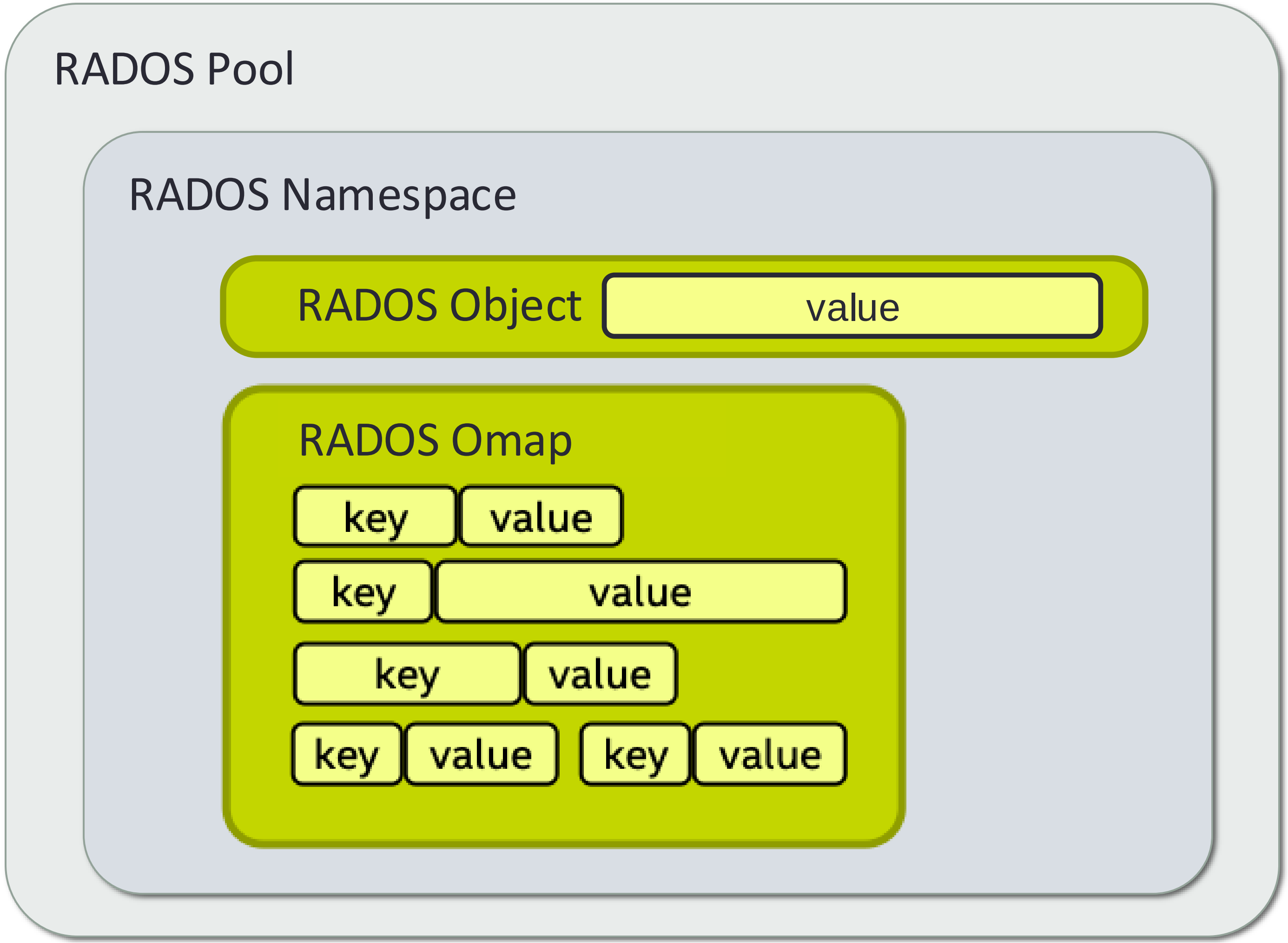
RADOS object storage API

- Pool
  - Partitions object namespace
  - Usually, one pool is created for each type of application
  - Can be bound to specific OSDs
  - Can be configured for
    - Replication
    - Erasure-Coding



RADOS object storage API

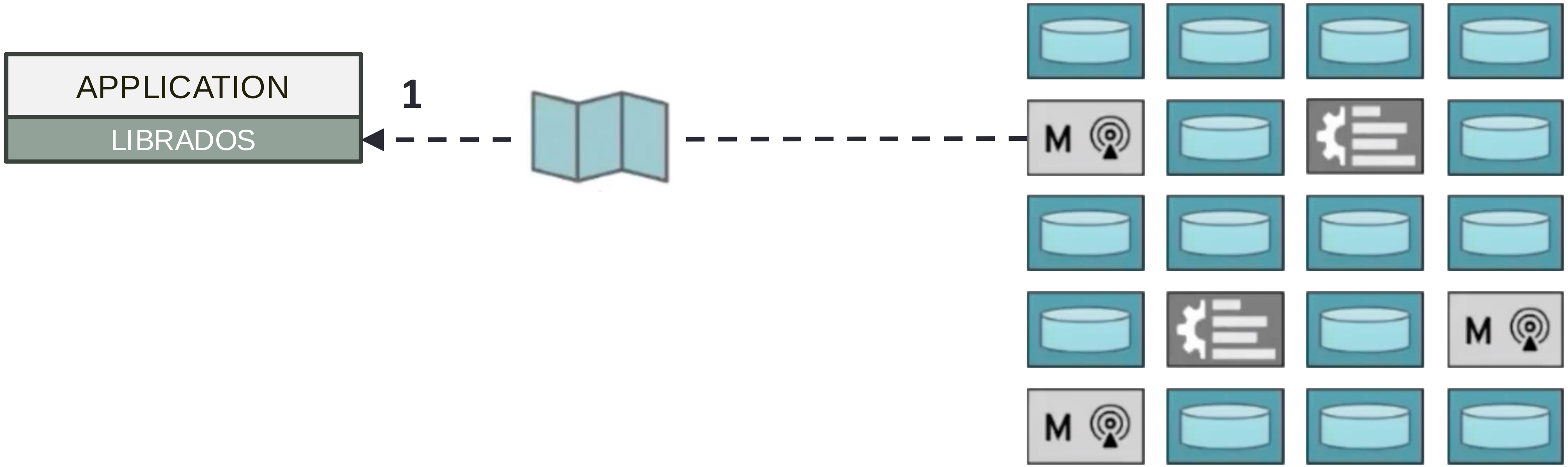
- Namespace
  - Partitions object namespace within a pool
  - Lightweight w.r.t. pool



Algorithmic placement

Algorithmic placement

- 1: retrieve up-to-date cluster map



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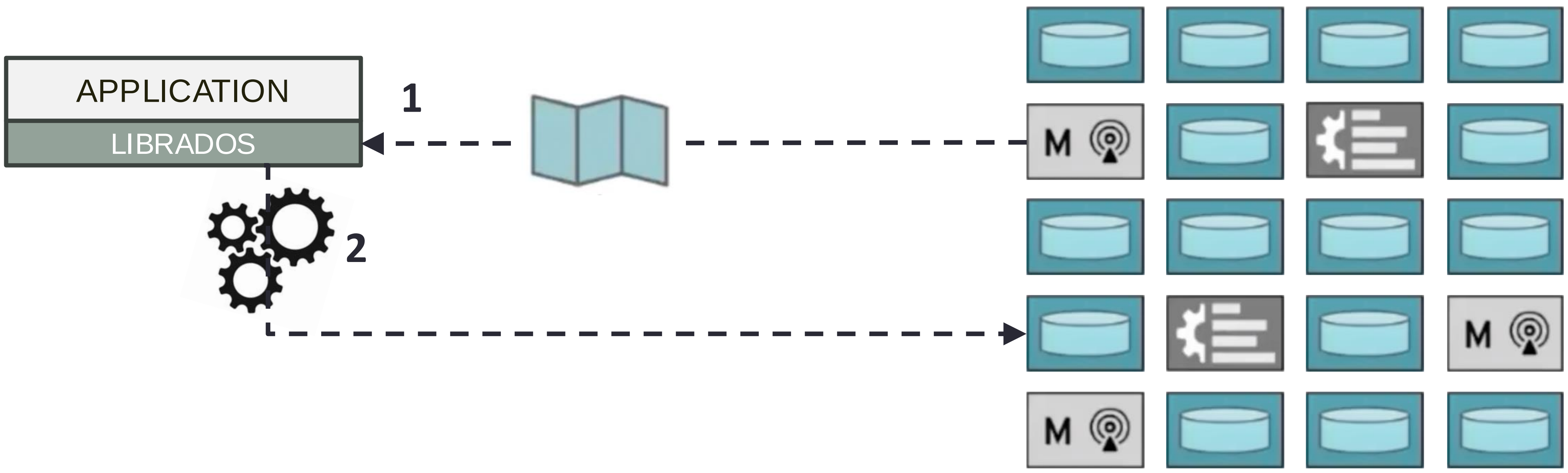
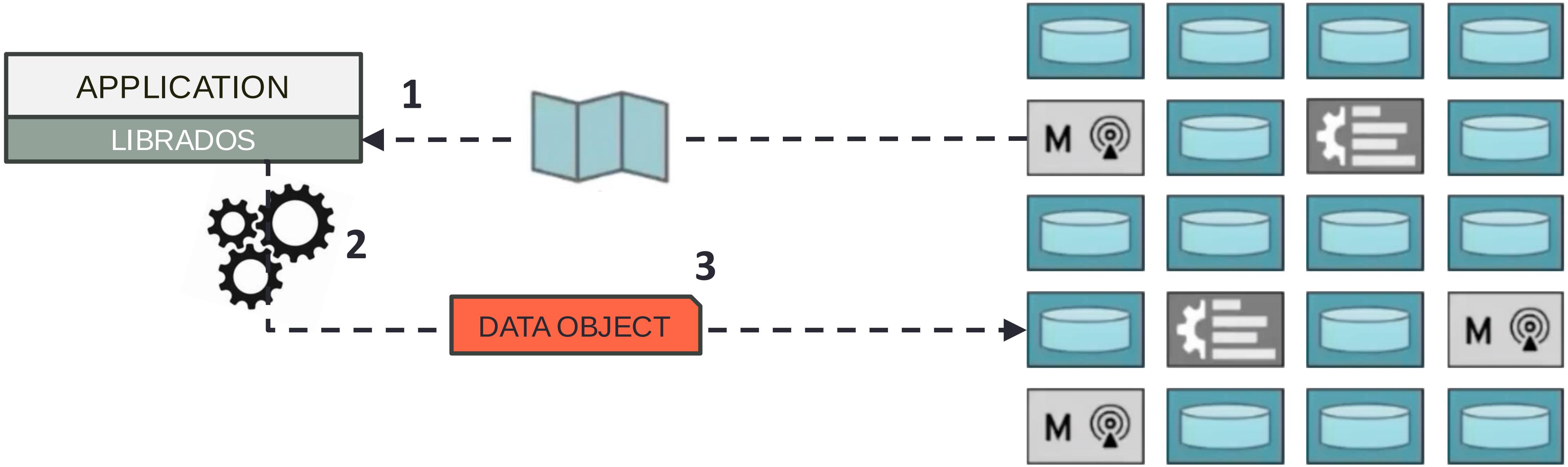
Algorithmic placement

- 1: retrieve up-to-date cluster map
- 2: calculate placement based on object name and map



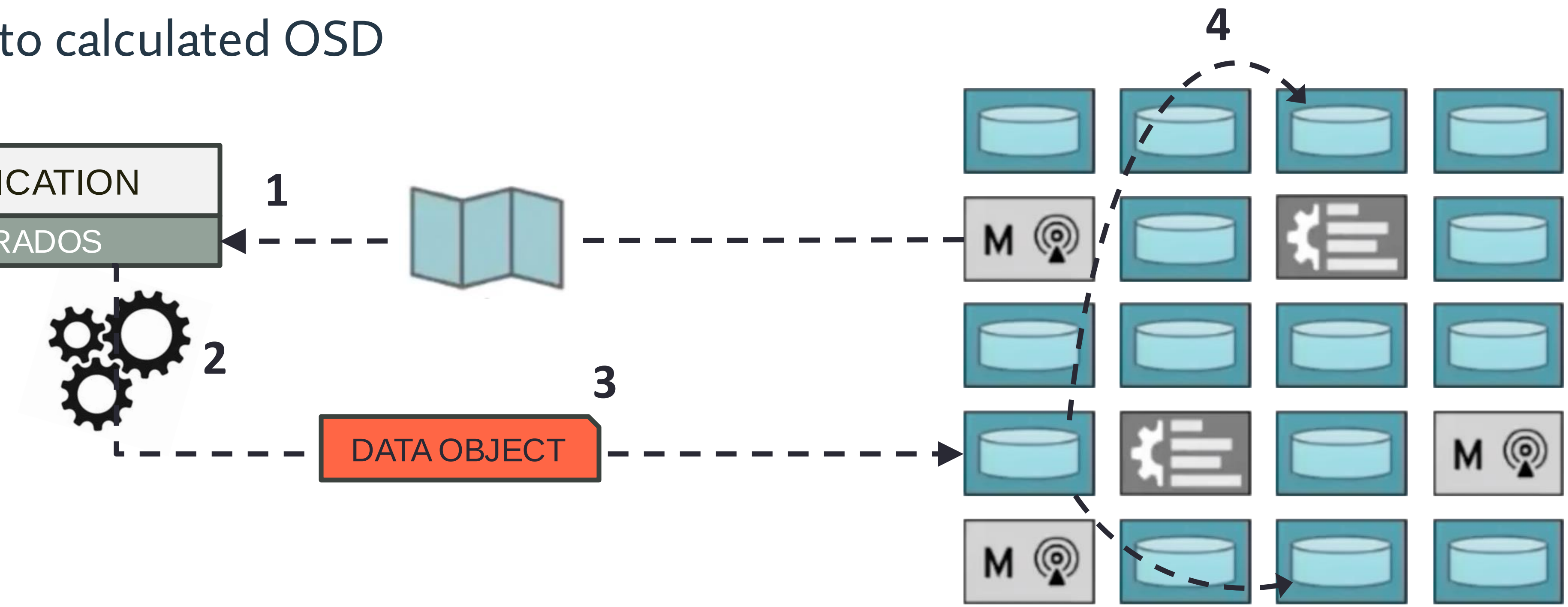
Algorithmic placement

- 1: retrieve up-to-date cluster map
- 2: calculate placement based on object name and map
- 3: write directly to calculated OSD



Algorithmic placement

- 1: retrieve up-to-date cluster map
- 2: calculate placement based on object name and map
- 3: write directly to calculated OSD
- 4: replication



Algorithmic placement

- 1: retrieve up-to-date cluster map
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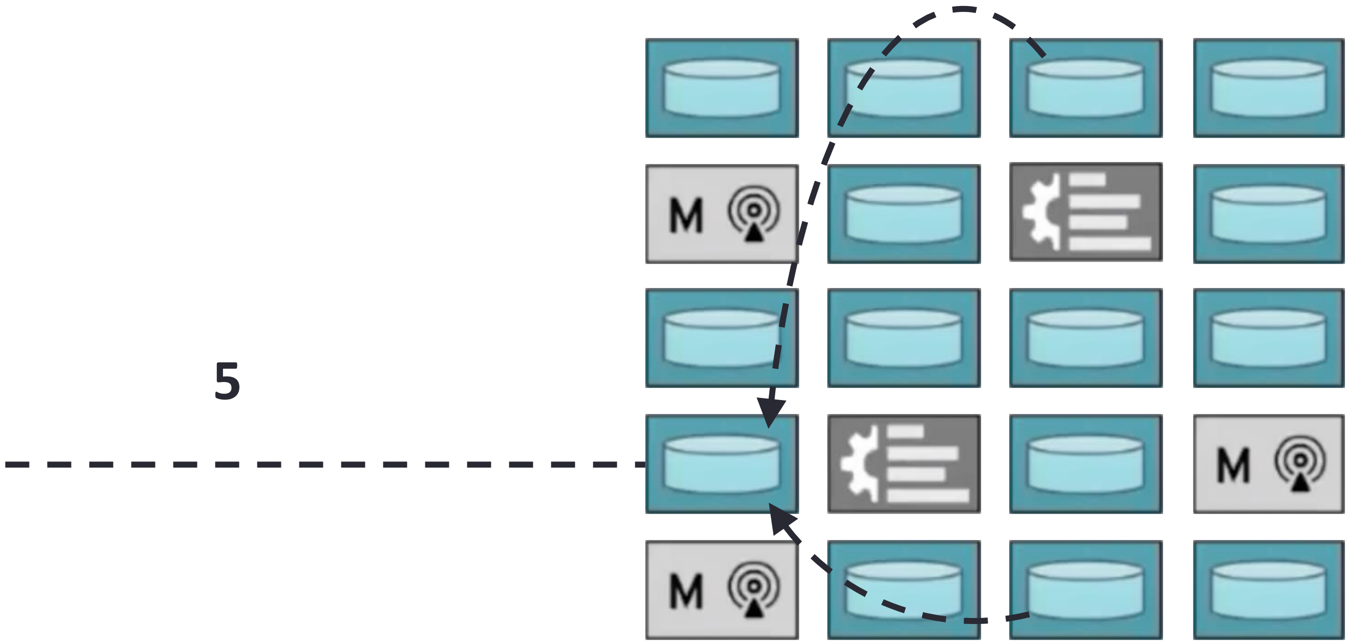
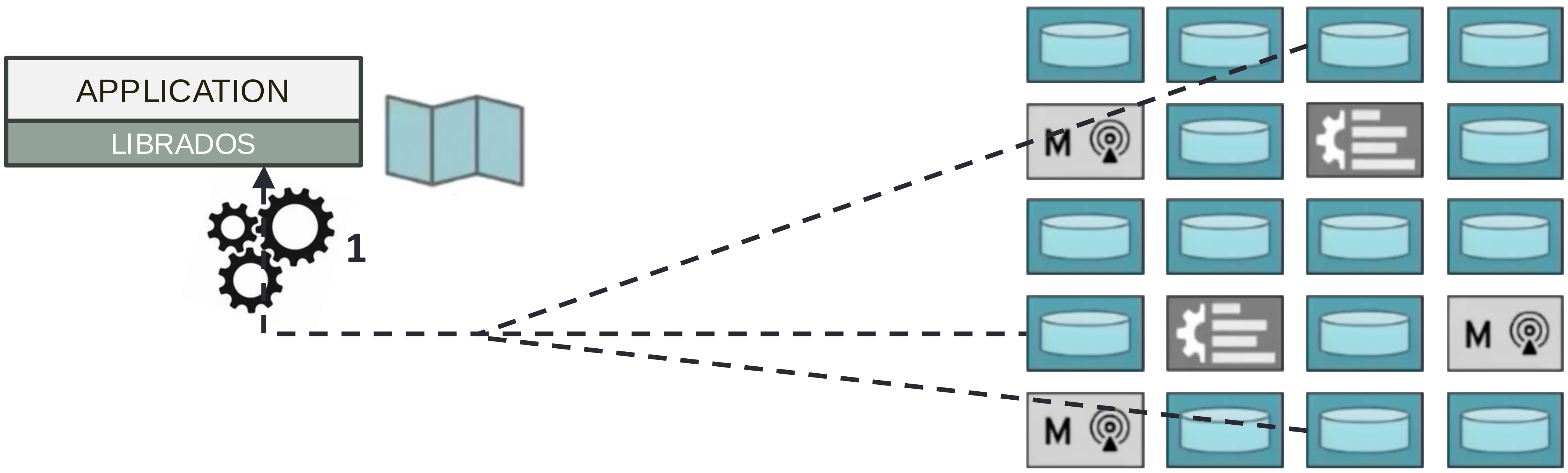


- 4: replication
- 5: return

Algorithmic placement – read

Algorithmic placement – read

- 1: calculate placement based on object name and map



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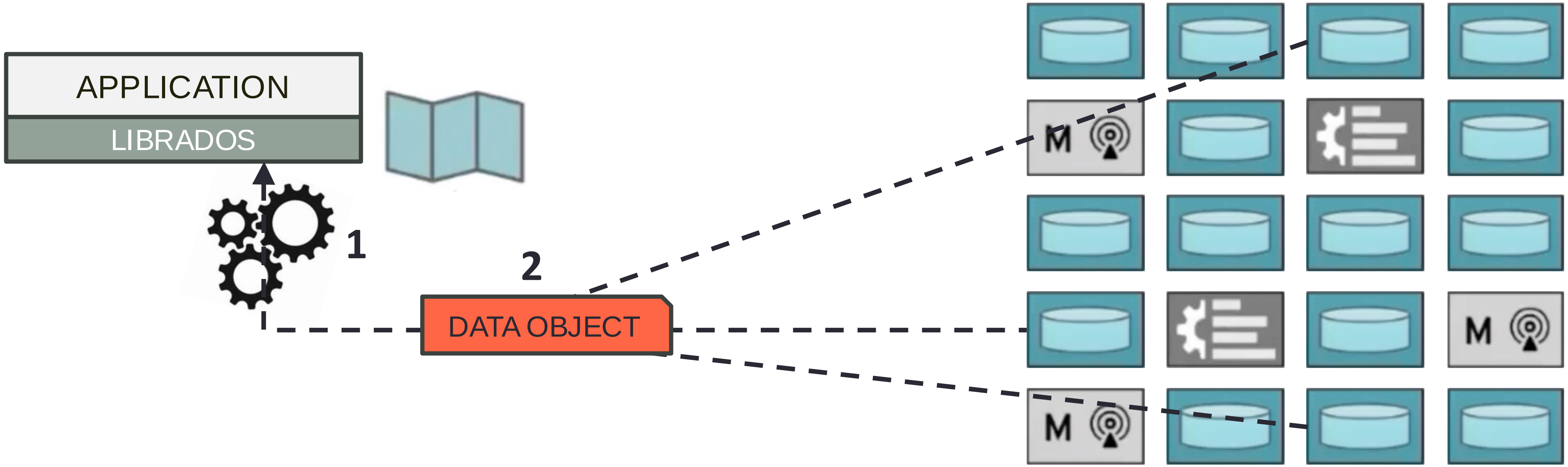
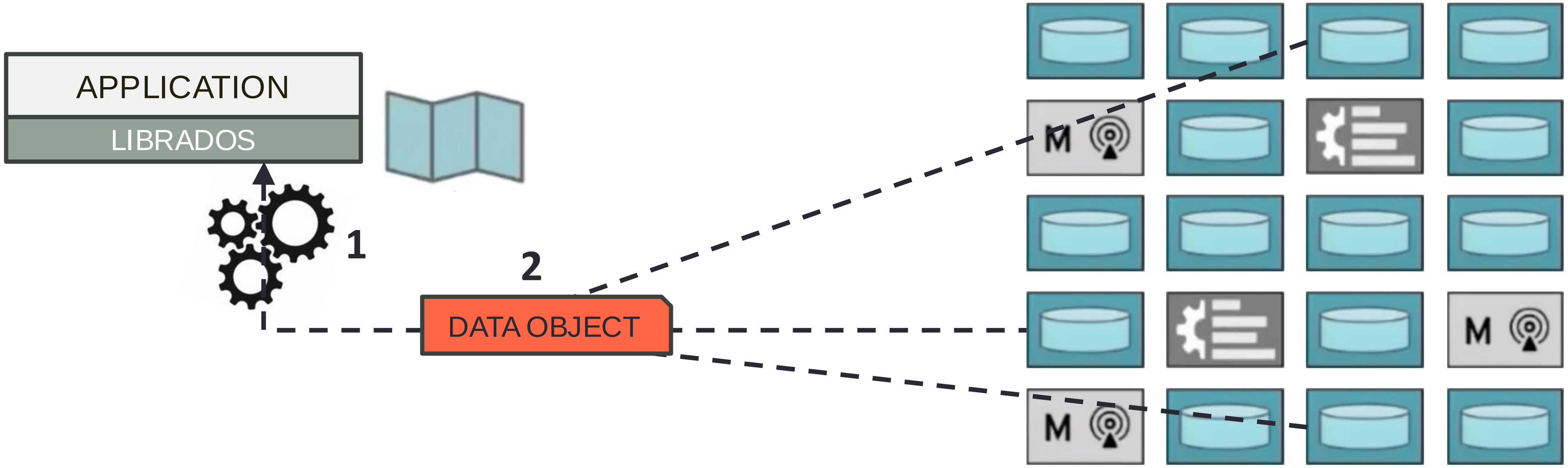
Algorithmic placement – read

- 1: calculate placement based on object name and map
- 2: read object directly from OSDs



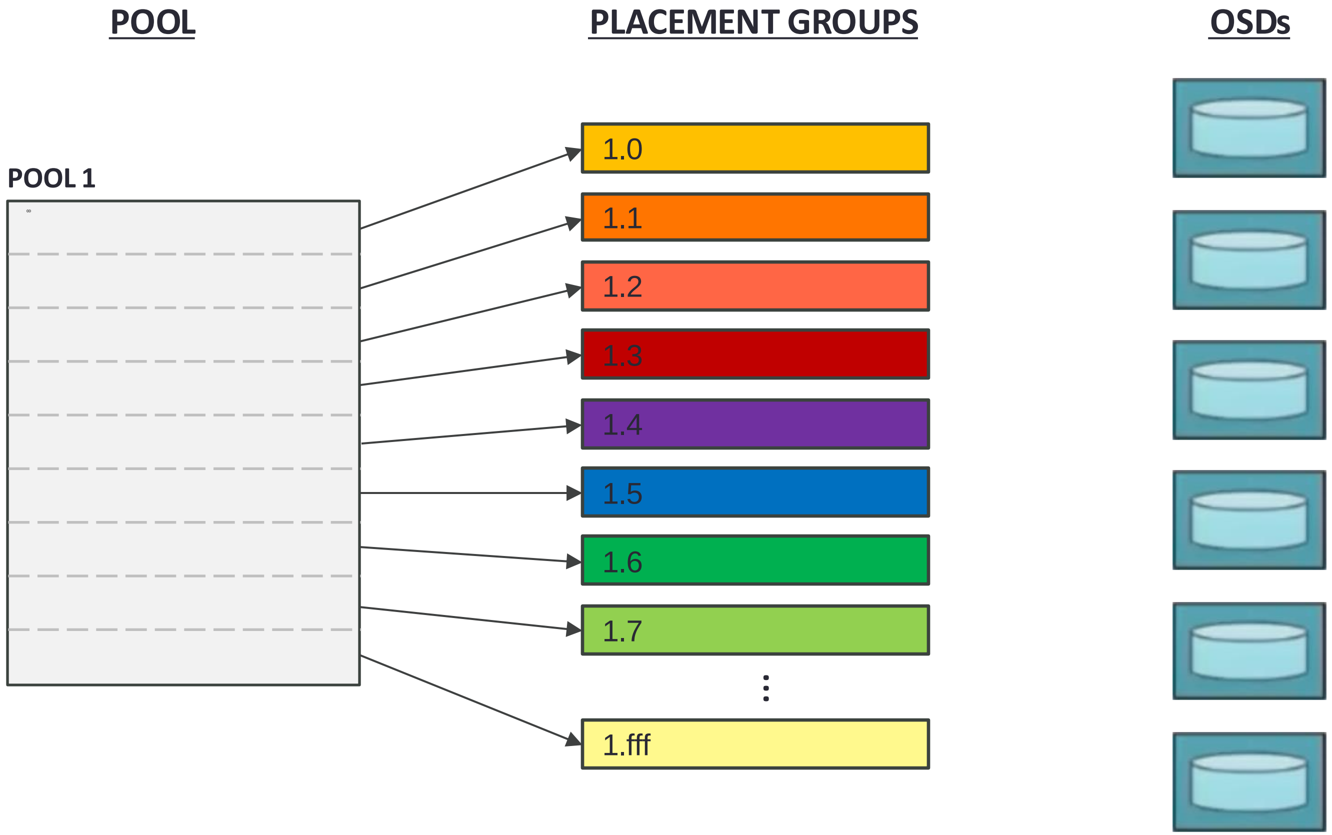
Algorithmic placement

- Algorithmic placement enables scalability
- RADOS’ placement algorithm is deterministic and repeatable – CRUSH
- Failure resilient

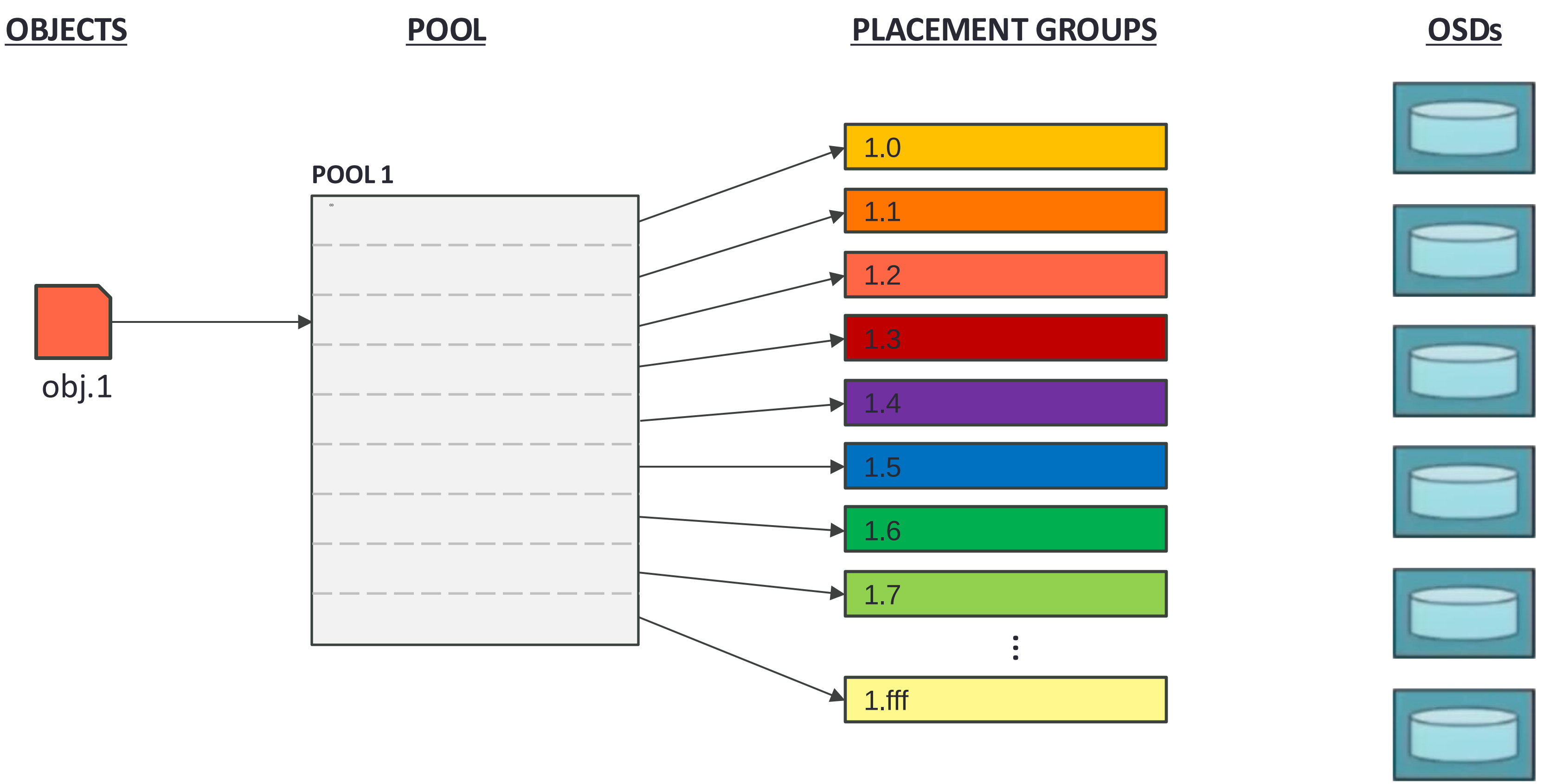


Placement Groups

Placement Groups

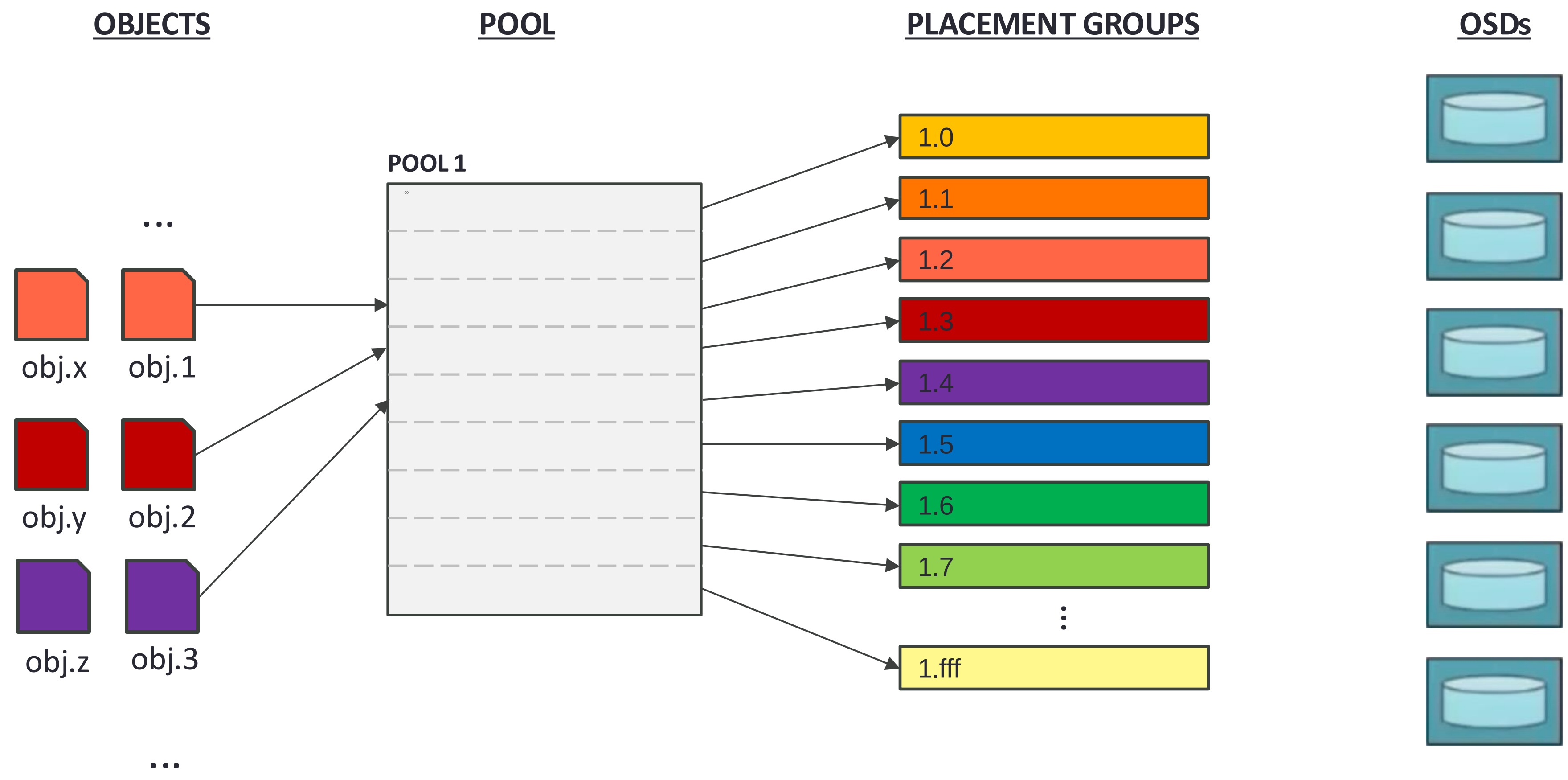


Placement Groups



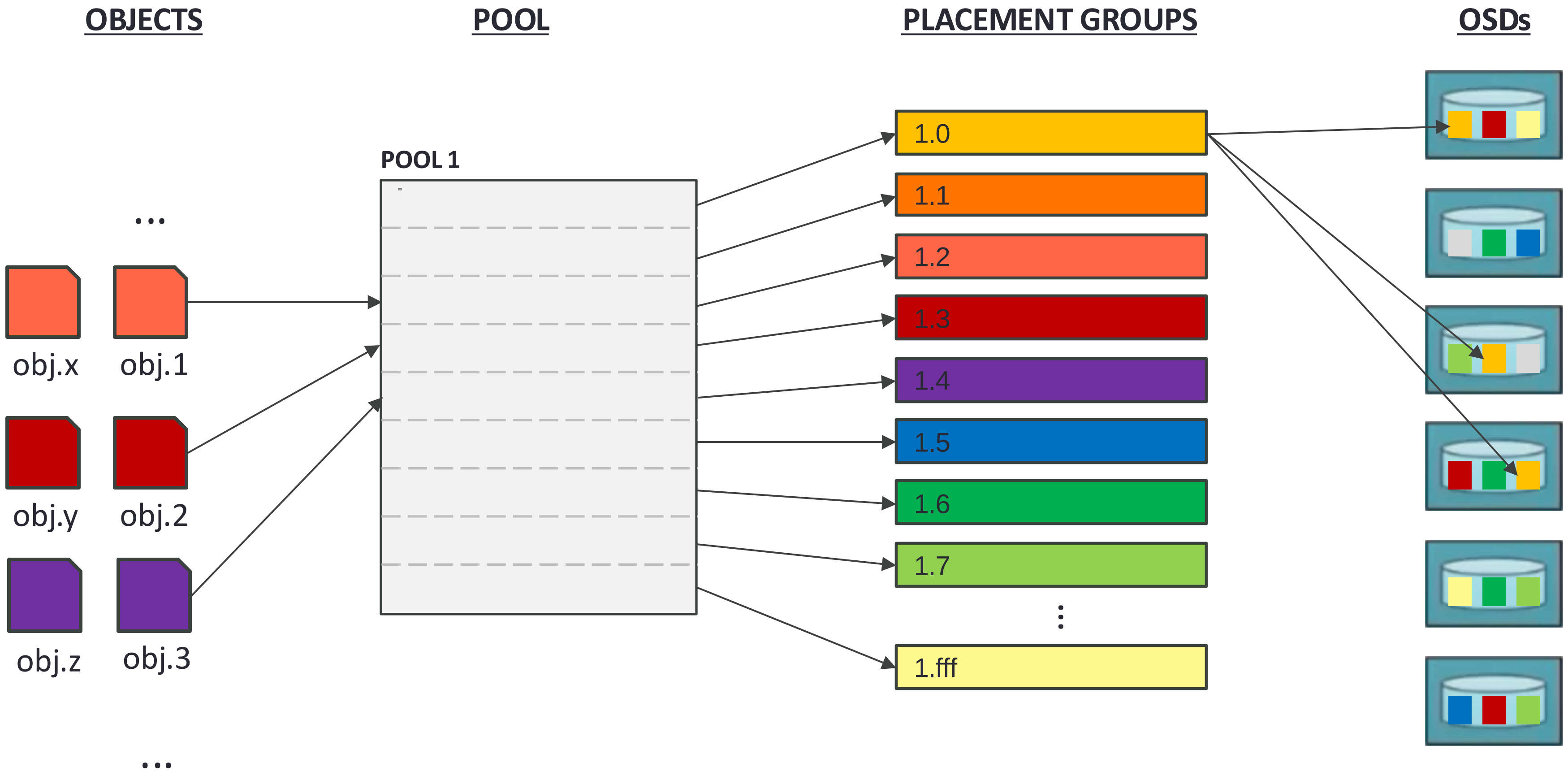
pgid = hash(obj_name) % pg_num
Many GiB of data per PG

Placement Groups



pgid = hash(obj_name) % pg_num
Many GiB of data per PG

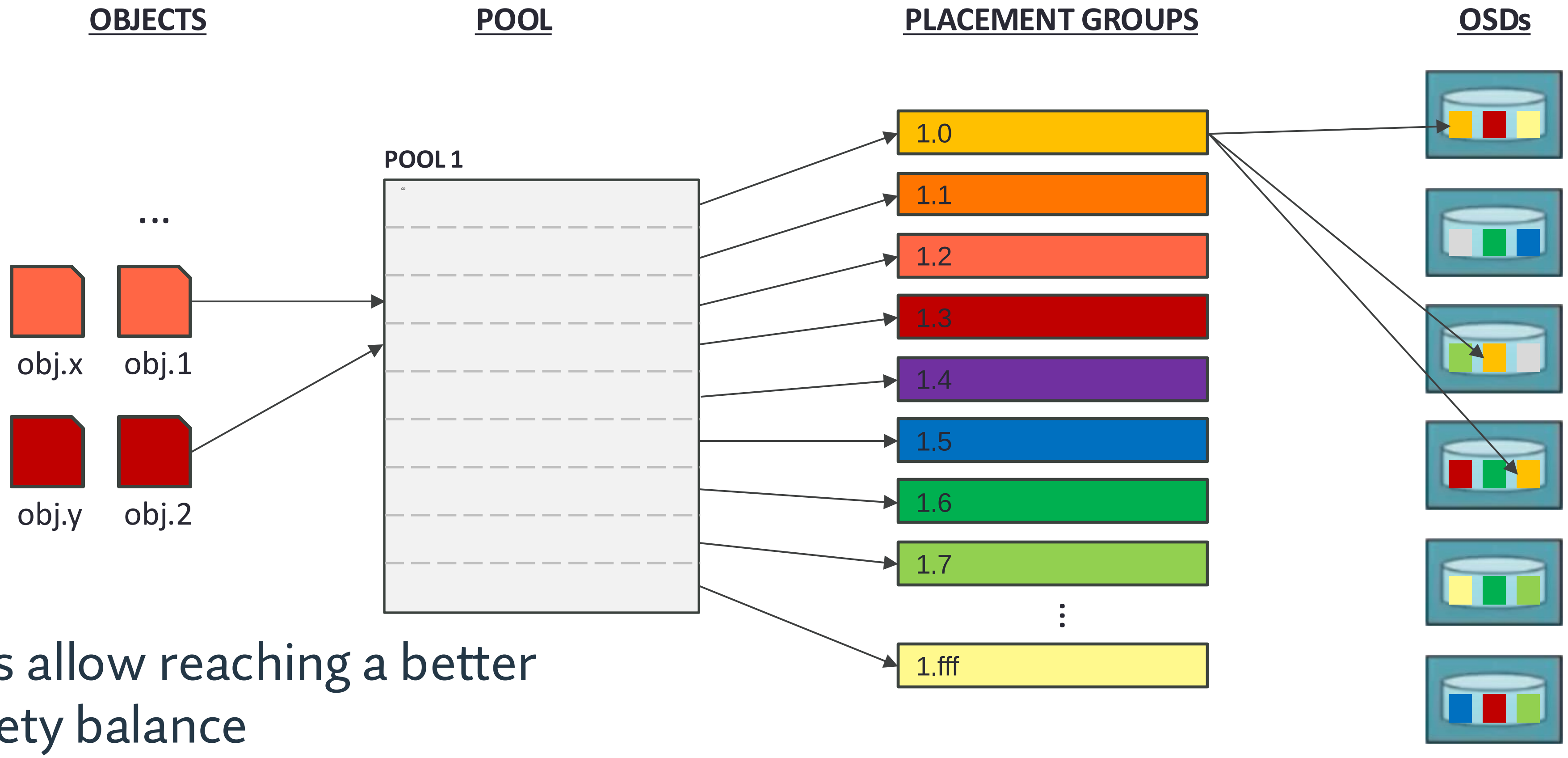
Placement Groups



pgid = hash(obj_name) % pg_num
Many GiB of data per PG

N replicas of each PG
10s of PGs per OSD

Placement Groups



pgid = hash(obj_name) % pg_num
Many GiB of data per PG

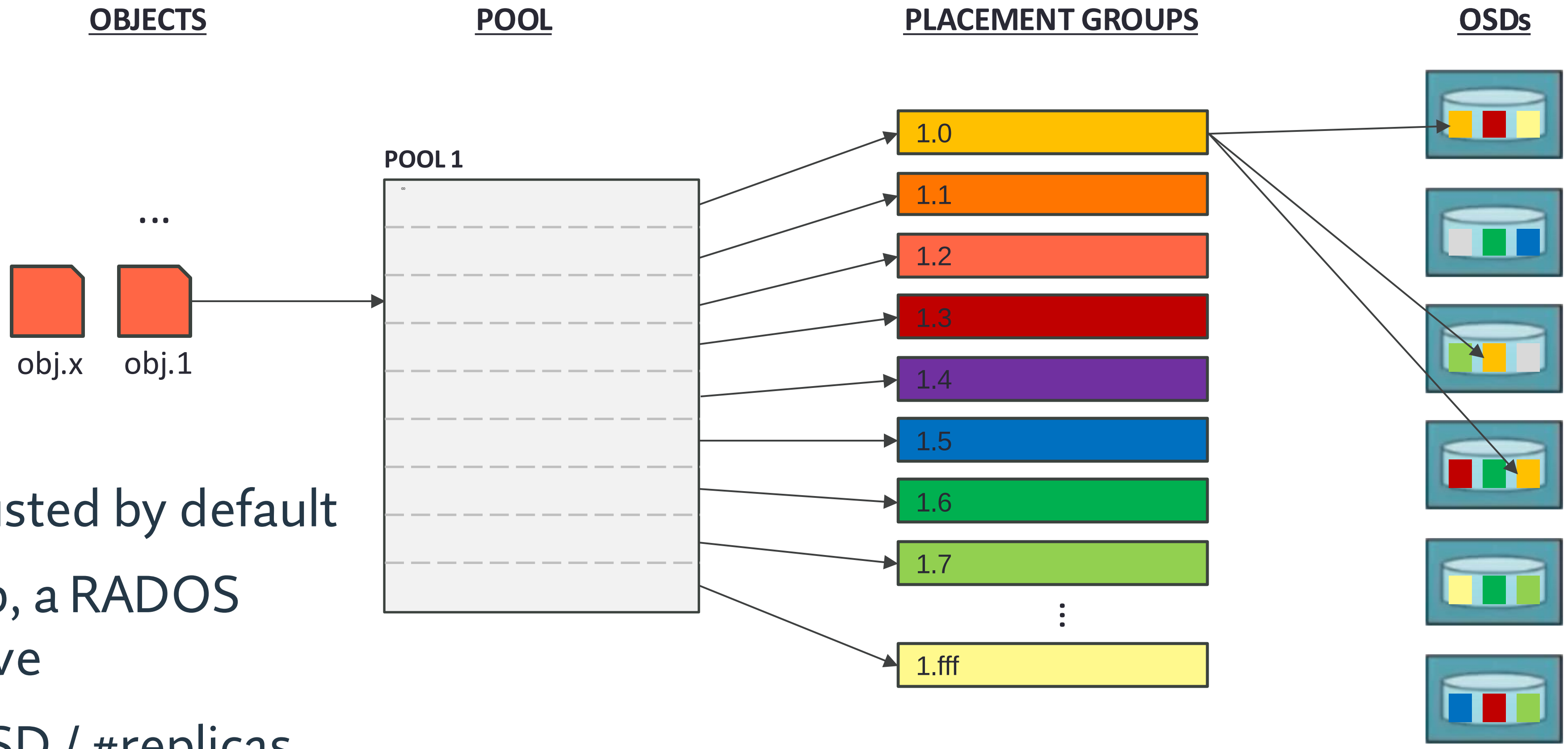
N replicas of each PG
10s of PGs per OSD

- Placement Groups allow reaching a better performance / safety balance

https://www.youtube.com/watch?v=PmLPbrf-x9g

https://ceph.io/assets/pdfs/weil-rados-pdsw07.pdf - section 2

Placement Groups



- PGs are auto-adjusted by default
- As a rule of thumb, a RADOS system should have

  #PG = 100 * #OSD / #replicas

pgid = hash(obj_name) % pg_num
Many GiB of data per PG

N replicas of each PG
10s of PGs per OSD

https://docs.ceph.com/en/latest/rados/operations/pgcalc/

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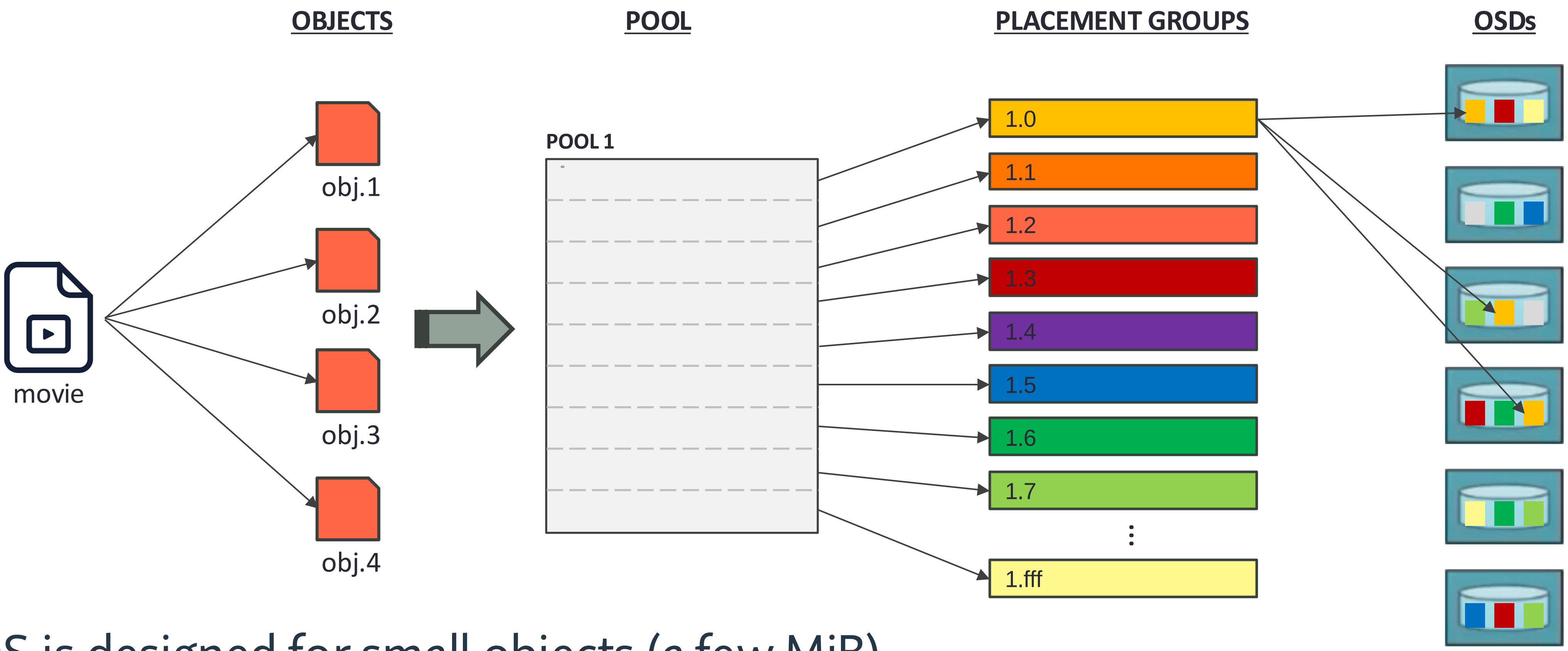
Placement Groups



- RADOS is designed for small objects (a few MiB)

pgid = hash(obj_name) % pg_num
Many GiB of data per PG

N replicas of each PG
10s of PGs per OSD

RADOS consistency and persistency

- Strong consistency guarantees
  - Write-read, read-write, write-write
  - No client-side caching
- Algorithm similar to MVCC
  - Placement calculation
  - Write to primary OSD
  - Replicate to peer OSDs in PG
  - Index object location and return
  - Reader always checks latest index entry on primary OSD

RADOS consistency and persistency

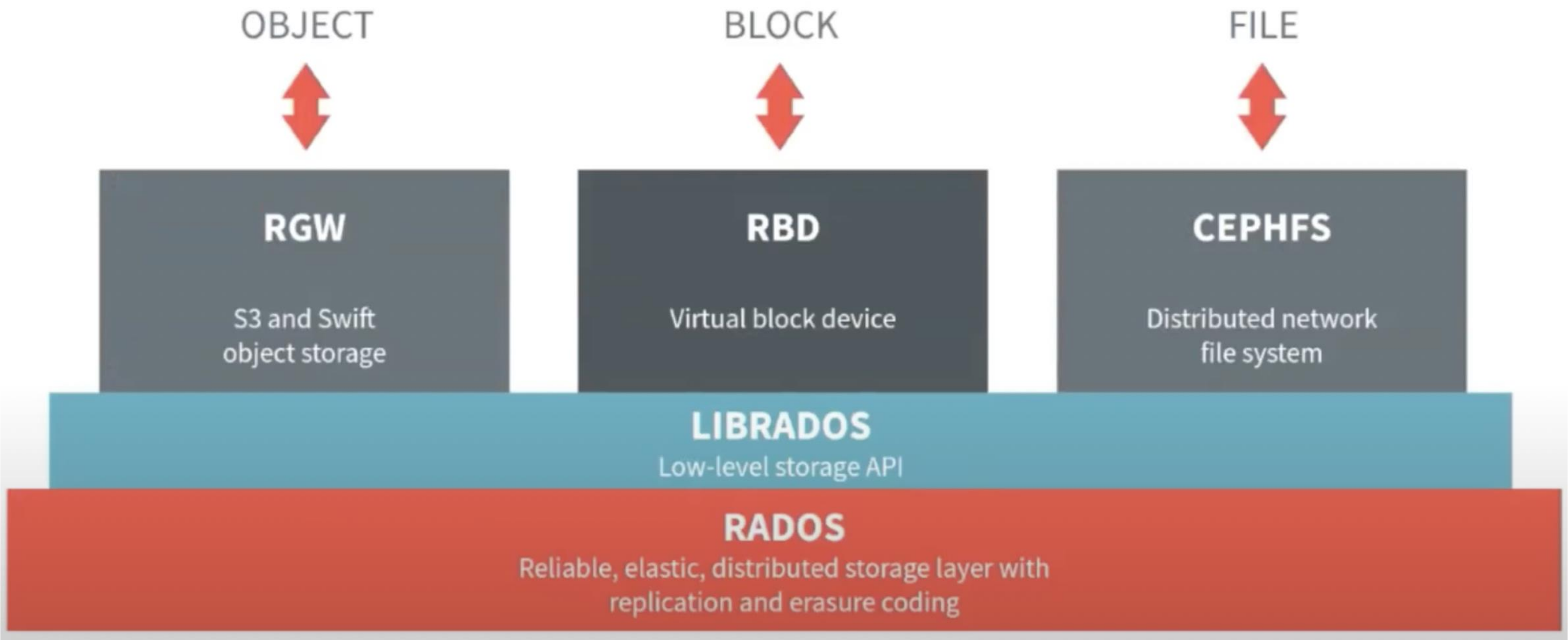
- Immediate persistency
  - Two-step persisting procedure
- Inefficiencies
  - Frequent RPCs to primary OSD
  - Copy on write for partial writes
  - Full transfer to client for partial reads
  - Two-step persistency increases latency

https://ceph.io/assets/pdfs/weil-rados-pdsw07.pdf - section 3

https://docs.ceph.com/en/latest/architecture/#interrupted-full-writes

https://docs.ceph.com/en/latest/dev/osd_internals/erasure_coding/enhancements/#partial-overwrites

Ceph interfaces on RADOS



- RBD and RGW have earned Ceph popularity in Cloud environments
- RGW and CephFS can eliminate the small object constrain in RADOS

https://www.youtube.com/watch?v=PmLPbrf-x9g

RADOS performance

- Designed to scale
- Designed for safety
  - Overhead for RPCs to primary OSDs
  - Overhead for two-phase persistence
  - Partial write/read inefficiencies
- Performance analysis papers

https://sdm.lbl.gov/pdc/pubs/201811_PDSW2018-ObjEval.pdf

https://msstconference.org/MSST-history/2017/Papers/CephObjectStore.pdf

https://www.croit.io/blog/ceph-performance-benchmark-and-optimization

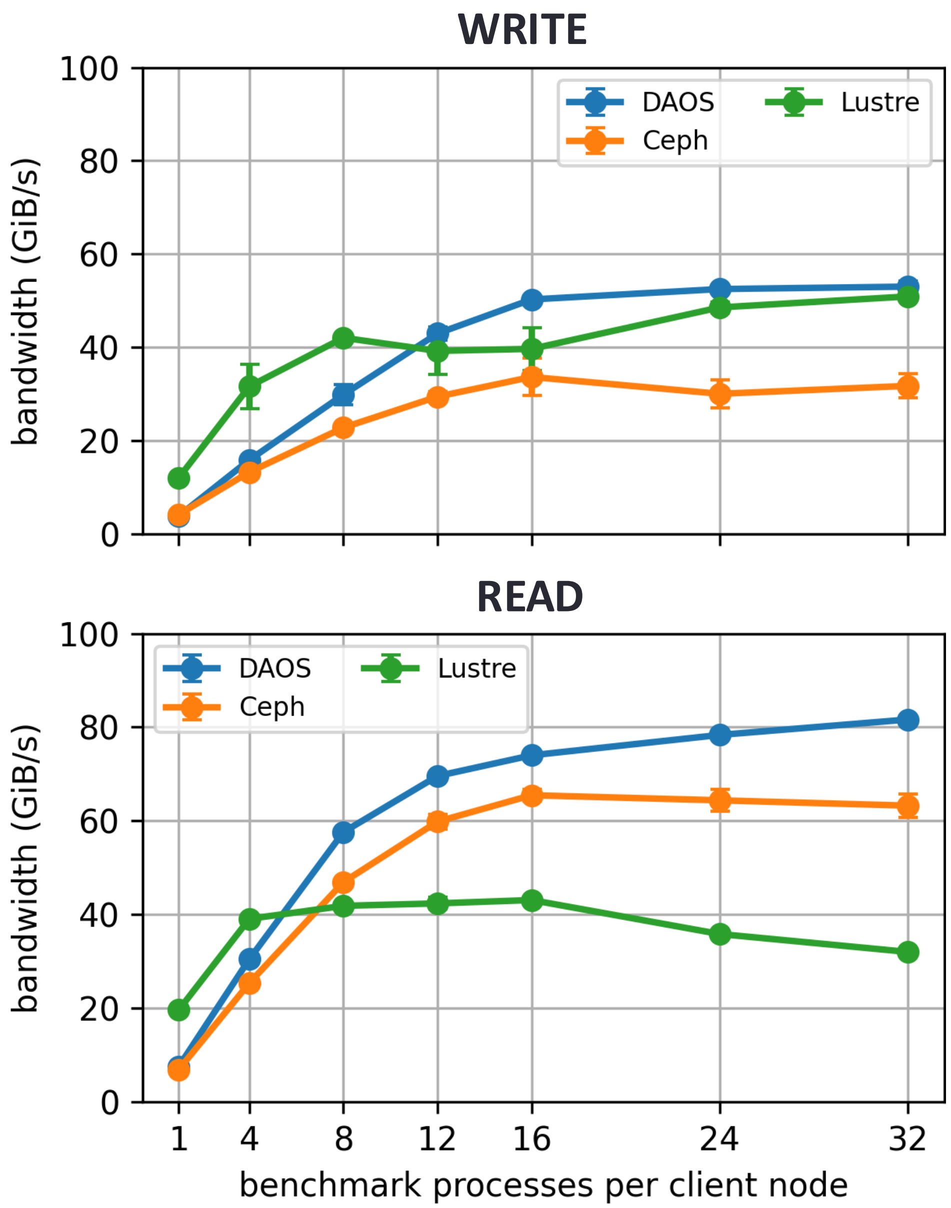
https://ceph.io/en/news/blog/2024/ceph-a-journey-to-1tibps/

https://arxiv.org/pdf/2409.18682

RADOS performance on NVMe

- RADOS/DAOS/Lustre deployments on 16x 6TiB nodes
- I/O benchmark (fdb-hammer) runs on 32 client nodes
- 10000 I/O operations of 1 MiB per process
- No replication or erasure-coding

https://arxiv.org/pdf/2409.18682



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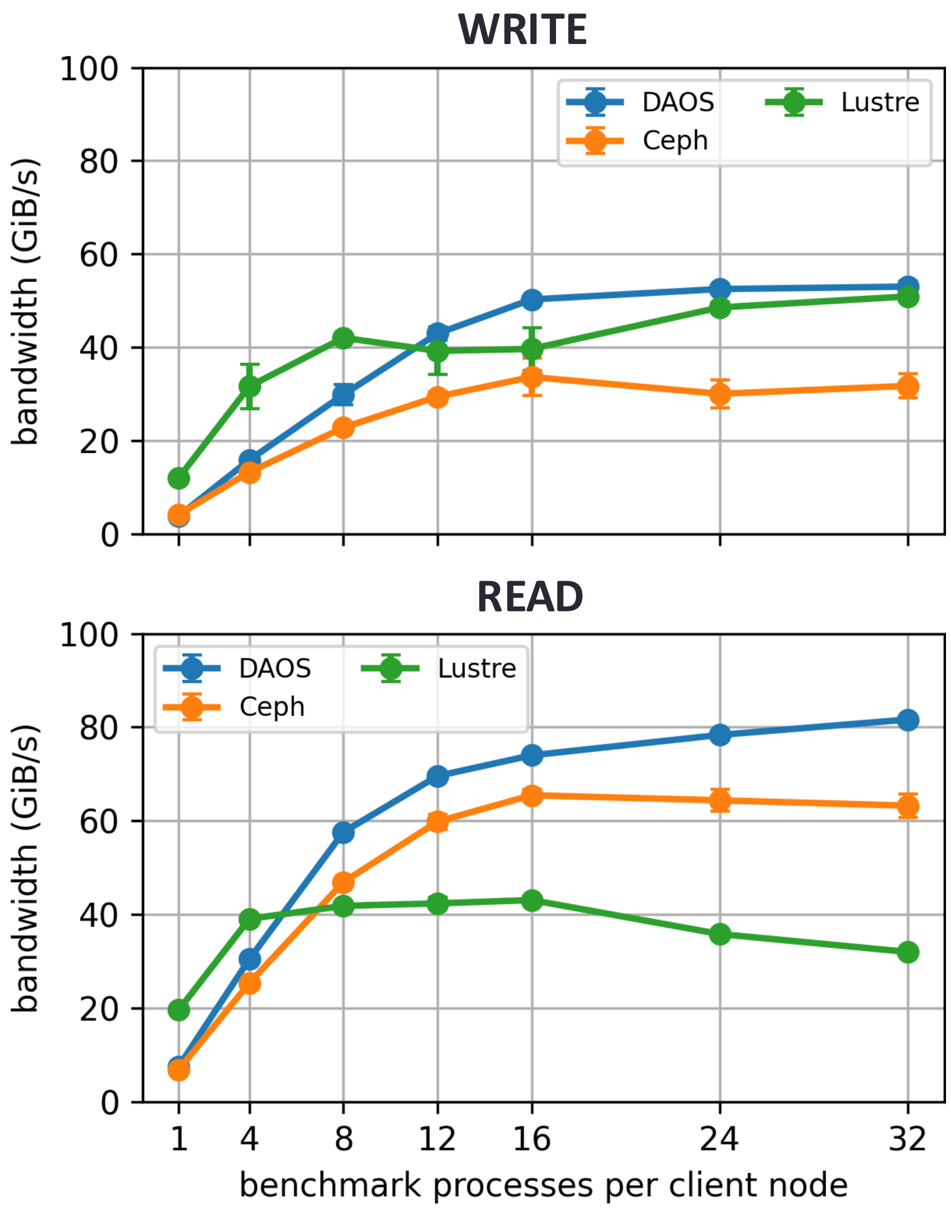
RADOS performance on NVMe

- DAOS reaches close to hardware bandwidths for both write and read
- RADOS performance is lower but decent
- POSIX/Lustre struggles with metadata operations when managing small (1MiB) objects

https://arxiv.org/pdf/2409.18682



RADOS vs DAOS vs Lustre

Feature	RADOS	DAOS	Lustre
Algorithmic placement	Yes	Yes	
Client-side caching	Can do	Can do	Yes
Kernel involved	Can do		Yes
Centralised metadata			Yes
Strictly consistent	Yes	Yes	Yes
Immediately persistent	Yes	Yes	Can do
Provides POSIX files/directories	Can do	Can do	Yes
Provides objects	Yes	Yes	
Provides key-values	Yes	Yes	
Software-level data safety	Yes	Yes	

Feature	RADOS	DAOS	Lustre
High-performance networks		Yes	Yes
Byte-addressable		Yes	
Zero-copying		Yes	
Can exploit fast storage tier	Yes	Yes	Yes
Supports HDDs	Yes		Yes
Can scale to O(10k) nodes	Yes	Yes	Yes
Performs for GiB objects		Yes	Yes
Performs for MiB object	Yes	Yes	
Performs for KiB objects		Yes	

Yes Can do No

Conclusion

- Ceph is an open-source, flexible object storage system designed for commodity hardware
- The multiple interfaces it provides make it a very flexible storage system
- The core interface, librados, provides a rich object storage API including key-value functionality, transactions, and asynchronous IO
- Due to its focus on data safety, it does not perform as well as other HPC storage systems
- Nevertheless, it can perform reasonably well thanks to its algorithmic placement approach and other features such as userspace device usage

librados

- Provides functionality to manipulate all entities in RADOS
  - Daemons, Pools, Objects / Omaps
- Available in many programming languages, including
  - C, C++, Python, Java, PHP, ...
  - The C API is the richest and best documented
  - Ceph distributes the `rados` command-line tool wrapping librados

https://docs.ceph.com/en/reef/rados/api/librados/

(RADOS authentication)

- Users can be created in a RADOS cluster
- Users can be granted permissions
  - To perform management actions
  - To access or manipulate certain pools
- Usually, one user per type of application (e.g. admin, RGW, CephFS, …)
- A Keyring file is generated per user
  - Contains authentication token
  - Is deployed on client nodes usually under `/etc/ceph/ceph.<username>.keyring`

librados – cluster handle

```
int rados_create2(rados_t *pcluster, const char *const clustername,
                  const char *const name, uint64_t flags)
```

- Initialises a `ratos_t` struct given the cluster name and RADOS username to user for subsequent librados calls
- `flags` can be set to `0`

librados – configuration

- The minimum configuration required by librados includes
  - address and port of one ceph-mon (ideally of all ceph-mon)
  - path to keyring file
- Can be specified in different ways
  - Manually item by item via `rados_conf_set()`
  - Via environment variables plus `rados_conf_parse_env()`
  - Via a configuration file plus `rados_conf_read_file()`

librados – configuration

```
int rados_conf_read_file(rados_t cluster, const char *path)
```

- If path is NULL, the following paths are checked:
  - $CEPH_CONF environment variable
  - /etc/ceph/ceph.conf
  - ~/.ceph/config
  - ceph.conf in the current working directory

- If a keyring path is not given in the configuration (“keyring” item), a keyring file with the name `ceph.<username>.keyring` is looked for in the same directories

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librados – cluster connect

`int rados_connect(rados_t cluster)`

- Opens a connection with a RADOS cluster
- If succeeds (`rc == 0`), it must be released with `rados_shutdown()`

`void rados_shutdown(rados_t cluster)`

- Closes an open connection with a RADOS cluster

(RADOS pool create – admin only)

```
ceph osd pool create ${pool_name} ${pg_count} ${pgp_count} replicated
```

- Creates a replicated pool
- Defaults to 3 replicas

```
ceph osd pool set ${pool_name} size ${replica_count}
```

- Sets the replica count for a replicated pool

(RADOS pool create – admin only)

```
ceph osd erasure-code-profile set myprofile k=${k} m=${m} \
  crush-failure-domain=host
```

- Creates an erasure-code profile

```
ceph osd pool create ${pool_name} ${pgc} ${pgpc} erasure [myprofile]
```

- Creates an erasure-coded pool with a given EC profile
- Defaults to 2+2
- Does not support omap objects

librados – pool connect

```
int rados_ioctx_create(rados_t cluster, const char *pool_name,
                       rados_ioctx_t *ioctx)
```

- Initialises an IO context struct for an existing pool
- The rados_ioctx_t allows performing IO operations on a pool
- If succeeds (`rc == 0`), it must be released with `rados_ioctx_destroy()`

```
void rados_ioctx_destroy(rados_ioctx_t io)
```

- Signals librados that an IO context will no longer (and must not) be used
- The iocxt may not be destroyed immediately if it holds active async operations

librados – namespaces

```
void rados_ioctx_set_namespace(rados_ioctx_t io, const char *nspace)
```

- Sets the namespace to use for a given IO context
- nspace can be set to LIBRADOS_ALL_NAMESPACES to list all objects in a pool with `rados_nobjects_list_open()`

librados – I/O APIs

- Synchronous I/O
  - Blocks until operation is complete
  - Provides methods to perform I/O to regular objects
- Transactional API
  - Allows specifying a set of operations to be performed atomically
  - Blocks until transaction is complete
  - Provides methods to perform I/O to regular objects as well as Omaps
- Async API
  - Does not block unless `wait_for_complete()` or `flush()` are called
  - Provides the same I/O features as the transactional API

librados – synchronous I/O

```
int rados_write(rados_ioctx_t io, const char *oid, const char *buf,
                size_t len, uint64_t off)
```

- Write len bytes from buf into the oid object, starting at offset off
- Creates object if n.e.
- Returns 0 on success or a negative value on failure

```
int rados_write_full(rados_ioctx_t io, const char *oid,
                     const char *buf, size_t len)
```

- If the object exists, it is atomically truncated and then written

librados – synchronous I/O

```
int rados_append(rados_ioctx_t io, const char *oid, const char *buf,
                 size_t len)
```

- Append len bytes from buf into the oid object
- Returns 0 on success or a negative value on failure

```
int rados_read(rados_ioctx_t io, const char *oid, char *buf,
               size_t len, uint64_t off)
```

- Read len bytes starting at off from object into buf
- Returns number of read bytes on success or a negative value on failure

librados – synchronous I/O

```
int rados_remove(rados_ioctx_t io, const char *oid)
```

- Delete an object.
- Returns 0 on success or a negative value on failure.

```
int rados_trunc(rados_ioctx_t io, const char *oid, uint64_t size)
```

- Resize an object to size.
- If shrinking, the excess data is deleted. If enlarging, filled with zeros.

librados – transactional I/O

- A single “rados operation” can perform multiple operations on one object atomically
- The whole operation will succeed or fail, and no partial results will be visible
- Operations may be either reads, which can return data, or writes, which cannot
- The effects of writes are applied and visible all at once
  - E.g. an operation that sets an xattr and then checks its value will not see the updated value

create_write_op → write_op_XXX → write_op_YYY → write_op_operate → release_write_op

create_read_op → read_op_XXX → read_op_YYY → read_op_operate → release_read_op

librados – transactional I/O

```
rados_write_op_t rados_create_write_op(void)

void rados_release_write_op(rados_write_op_t write_op)


rados_read_op_t rados_create_read_op(void)

void rados_release_read_op(rados_read_op_t read_op)
```

- Create and release write-type and read-type transactional operations

librados – transactional I/O

```
int rados_write_op_operate(rados_write_op_t write_op,
        rados_ioctx_t io, const char*oid, time_t *mtime, int flags)

int rados_read_op_operate(rados_read_op_t read_op,
        rados_ioctx_t io, const char*oid, int flags)
```

- Execute a "rados operation" on an object

librados – transactional I/O - Omap

```
void rados_write_op_omap_set2(rados_write_op_t write_op,
       char const *const *keys, char const *const *vals,
       const size_t*key_lens, const size_t *val_lens, size_t num)
```

- Insert an array of key-value pairs into an Omap

```
void rados_read_op_omap_get_vals_by_keys2(rados_read_op_t read_op,
        char const *const *keys, size_t num_keys,
        constsize_t *key_lens, rados_omap_iter_t *iter, int *prval)
```

- Query the values associated to a given array of keys
- Returns an iterator with the values
- Any failures are signaled via prval

librados – transactional I/O - Omap

```
unsigned int rados_omap_iter_size(rados_omap_iter_t iter)
```

- Returns number of elements in Omap iterator

```
int rados_omap_get_next2(rados_omap_iter_t iter, char **key,
        char **val, size_t *key_len, size_t *val_len)
```

- Extracts the next key-value pair from an Omap iterator
- If the end of the list has been reached, key=val=NULL, and keylen=vallen=0
- key and val should be copied as rados_omap_get_end() releases them

void rados_omap_get_end(rados_omap_iter_t iter)

Hands-on – Part 1

- Write an MPI application which has each rank <i> write 1 MiB of random data into a new object (one object per rank) with a unique identifier.
  - name the objects as “<username>-rank-<i>”, and place these in a RADOS namespace named “<username>”.
- Have each rank insert the identifier of the object it just wrote into a shared key value (shared among all ranks), where the key is “rank-<i>” and the value is the object identifier.
  - name the key-value as “<username>-index” and place it in the same “<username>” RADOS namespace as the other objects.

Hands-on – Part 1 (continued)

- Compile and run the application on e.g. 4 Slurm compute nodes, and 32 ranks per node.
  - Run `source /opt/intel/setvars.sh` to add mpicc and mpirun to your PATH
  - the librados library headers can be found under /usr/include/rados/
- Write and run a similar application which has each rank deindex and read its corresponding object.

Hands-on – Part 2

- Modify the writer application in Part 1 to have each rank write and index 1000 objects with different identifiers.
- Modify the reader application in Part 2 accordingly.
- Run the writers, measuring the wall-clock time, and then the readers, also measuring the wall-clock time, and calculate the total write and read bandwidths.