Snapshotting Scale-out Storage

Pitfalls and Solutions

Alex Aizman, Nexenta

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Abstract

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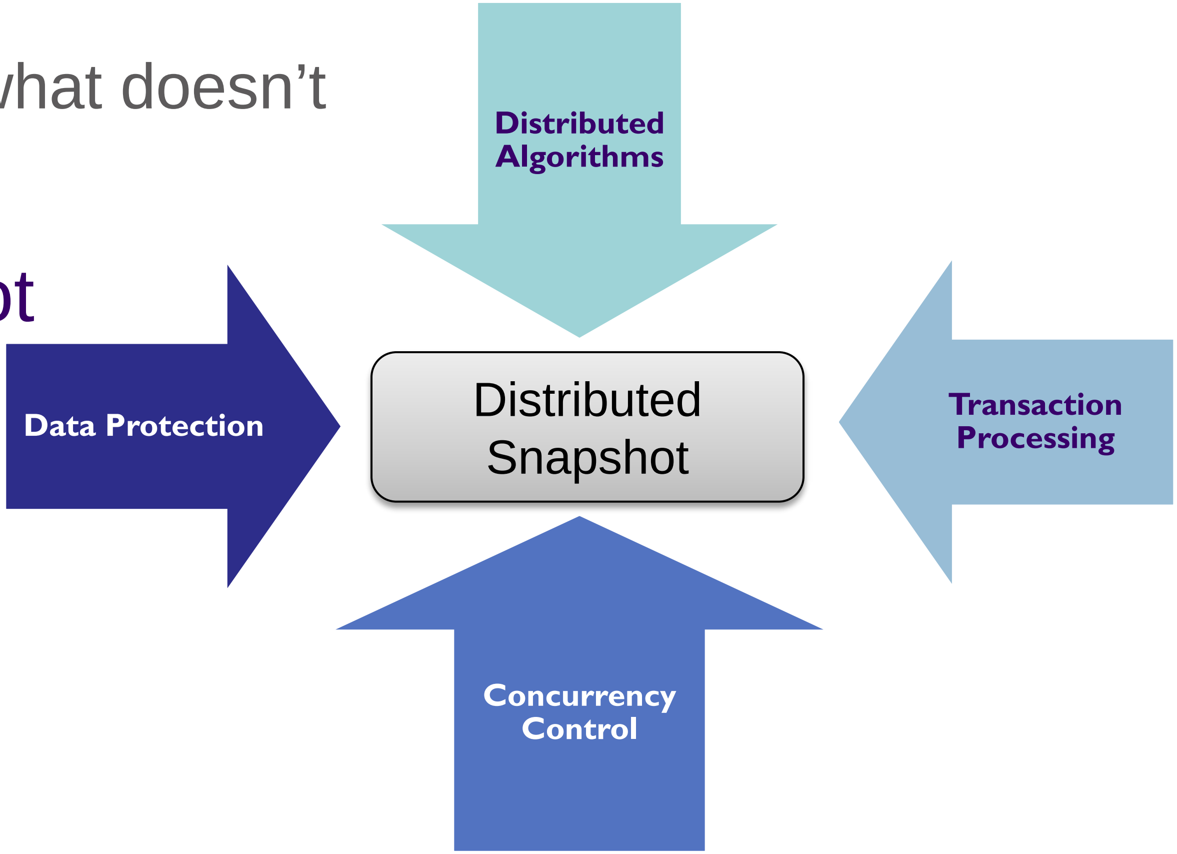
- **Distributed Snapshot: the challenge**
  - One of the toughest technical challenges for the implementors. The best existing distributed storage systems provide partial support or none whatsoever.
- **Distributed Snapshot: the operation**
  - Even for the distributed systems with relaxed consistency models, snapshotting must be a transaction that meets the familiar ACID requirements. Further, the operation must execute concurrently with updates and result in a persistent, immutable, consistent snapshot that can be read and cloned.
  - This presentation examines the topic from a variety of perspectives, and illustrates one possible way to snapshot eventually consistent distributed storage systems.

The seminal 1985 paper by Chandy and Lamport: *Distributed Snapshots: Determining Global States of Distributed Systems*

- "The <snip> algorithm plays the role of a group of photographers observing a panoramic, dynamic scene, such as a sky filled with migrating birds, a scene so vast that it cannot be captured by a single photograph.
- The photographers must take several snapshots and piece the snapshots together to form a picture of the overall scene.
- The snapshots cannot all be taken at precisely the same instant <snip>. Furthermore, the photographers should not disturb the process that is being photographed…"

In this presentation

- Definitions
- Common patterns
  - What works and what doesn't
- Case Studies
- Eventual Snapshot



Definitions

Distributed

Snapshot

must be **Consistent**

Distributed Systems: the great diversity

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- Namespace federated vs striped (sharded)
- Block, Object, Key/Value, SQL, Partial POSIX, Full POSIX
- Specialized (e.g., HDFS) vs general purpose
- Crash-consistent vs not crash-consistent
- Single writer (SWMR) vs MWMR
- Single MDS (metadata server) vs federated metadata vs fully distributed metadata
- Single Initiator vs multiple storage initiators
- Eventually consistent vs stronger consistency levels
- Any combination of the above, and more

For example

- Ceph/RADOS is a
  - General purpose object storage system that is
    - **Fully distributed**
    - **Fault-tolerant**
    - **With distributed metadata**
    - **And concurrent access via multiple storage initiators (librados clients)**
- Distributed snapshotting will be, of course, as diverse as the underlying systems
  - Moreover, highly dependent on specific implementations/tradeoffs

Prerequisites

- [Dynamo: Amazon's Highly Available Key-value Store](#) 2007

Check out SNIA Tutorials:

- The Evolution of File Systems 2012
- Massively Scalable File Storage 2015

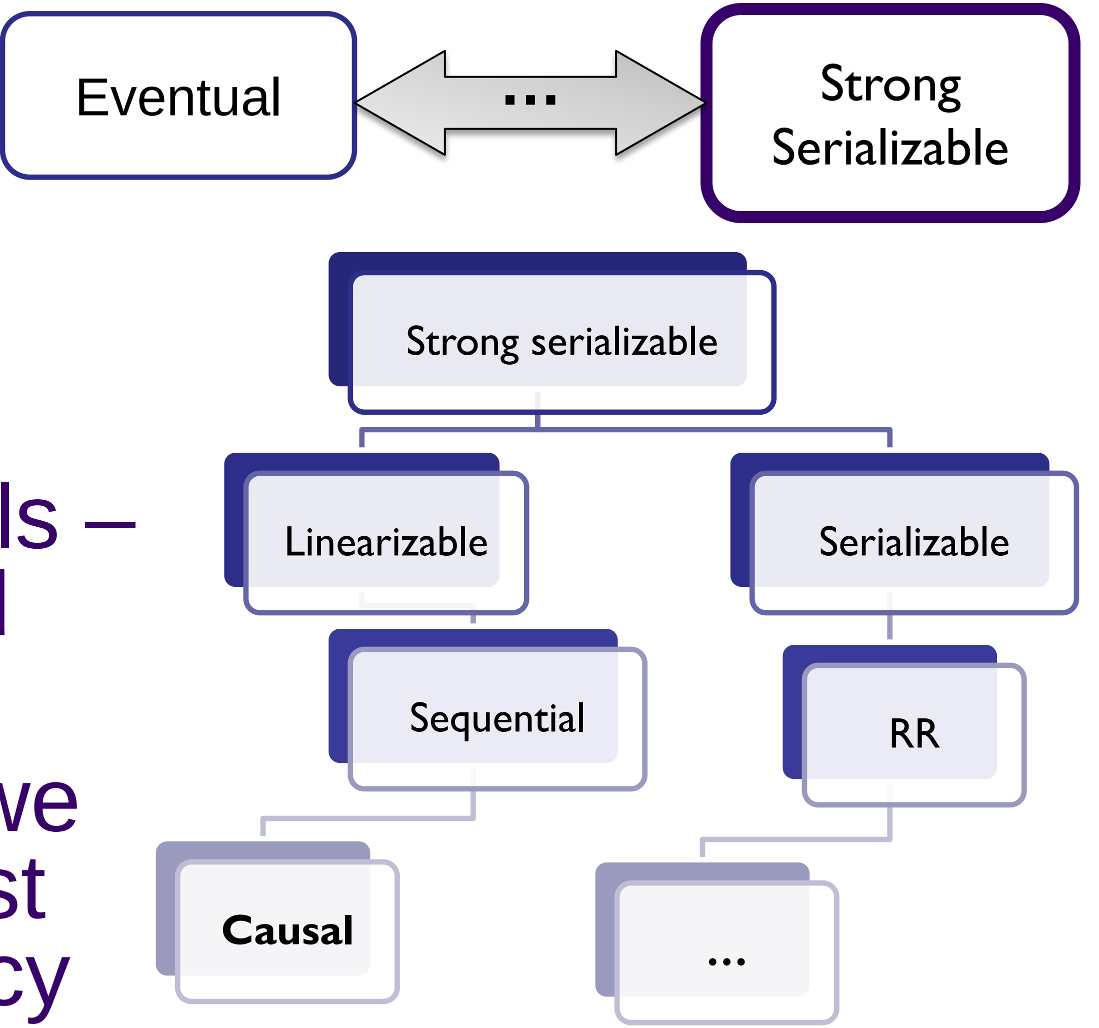
- An Overview of On-Premise File and Object Storage Access Protocols 2016

What is a "snapshot"

- **Snapshot is a read-only consistent dataset referencing a certain subset of persistent data at a given time**
  - Snapshotted data may not necessarily be persistent at the time of snapshotting
- **Local and distributed snapshots vary**
  - In terms of their supported scope, capabilities and internal consistency
- **Scope may be global or tenant, part of hierarchical namespace, a bucket, an object, etc.**
- **Capabilities in turn include:**
  - Copy-on-write (redirect-on-write)
  - Ability to incrementally replicate snapshot "delta"
  - Mount, rollback, clone, rebalance, and more
- **Generally, Data Protection today requires: just-in-time snapshotting and incremental replication**

What is “consistency”

- Snapshot ***is a*** dataset
- Dataset must support a certain *consistency level*
- Consistency levels – the spectrum and the hierarchy:
- For a snapshot, we often want at least causal consistency

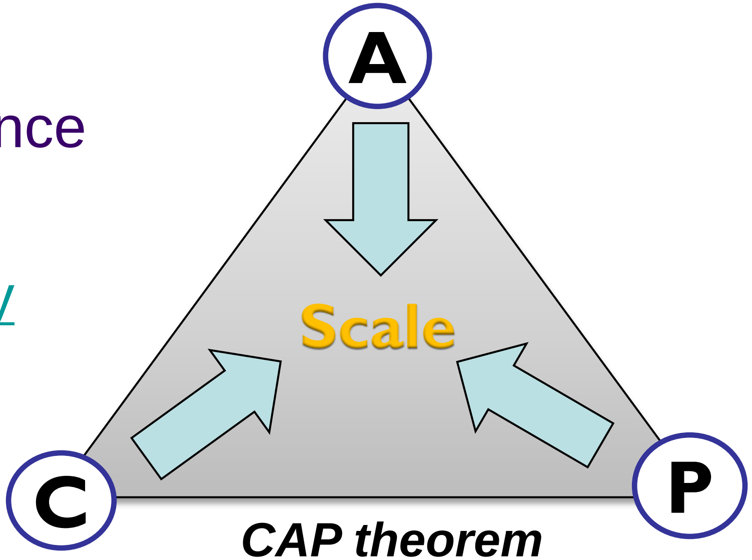


Snapshot Consistency vs Real-Life Scenarios

- **Just-in-time snapshot can be requested at any time, and in parallel with (for instance):**
  - Write operations that have been write-logged but not yet acknowledged back to user
  - Write operations – acknowledged but not yet majority-ACKed
  - Write operations – majority-ACKed but the associated metadata (updating) is still in progress
  - Asynchronous writes – persisted but the file is still open
  - Updates associated with file close and fsync operations – in progress but not finished yet
  - Destroy (or rename) operations – started but not finished yet
  - And more
- **"There is only one hard thing in Computer Science"**

Snapshot Consistency vs CAP theorem

- CAP theorem: distributed system vs **C**onsistency, **A**vailability, **P**artition tolerance
  - Brewer's **conjecture**, followed by:
  - Gilbert and Lynch proof for a narrowly scoped (*linearizable*) consistency
- The broadly accepted fact:
  - A distributed system **cannot** support simultaneously all 3 (three): **C**, **A**, and **P**



CAP theorem

- How do we snapshot a temporarily partitioned cluster?
  - Given that higher scales lead to increased chances of partitioning
- How do we produce a consistent snapshot in the AP system?

Despite all the diversity, here’s what is generally agreed upon today (1 of 2)

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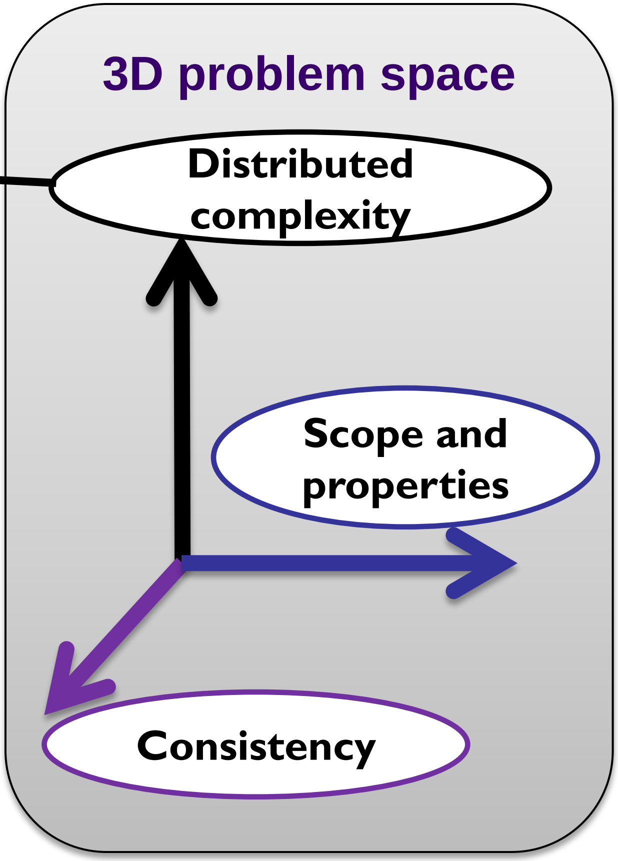
In a distributed system, all components “conspire” to delay, drop and reorder messages



- **Must be consistent and isolated**
  - Can read snapshot in parallel with I/O (*snapshot isolation*)
  - Minimally expected consistency is either causal or the one defined for the (live) dataset that is being snapshotted
- **Must be CoW and immutable**

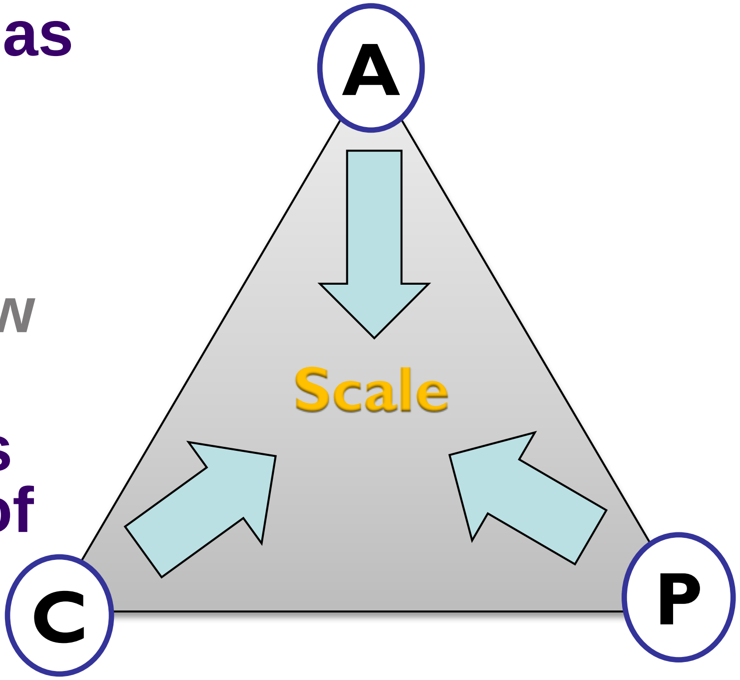
General Consensus (2 of 2)

- **Writeable snapshots are usually called *clones***
- **Distributed snapshot typically consists of local snapshots**
  - Assuming that storage metadata is distributed (central-metadata systems can simply snapshot or clone respective central metadata, case in point: HDFS)
- **Snapshot introduces additional metadata references**
  - Attempt to destroy snapshotted content fails unless the parent (snapshot and/or clone) is destroyed/expired first

Everything else is implementation dependent:
scope and content, capabilities and consistency of the snapshot…

CAP vs Snapshotting Transaction

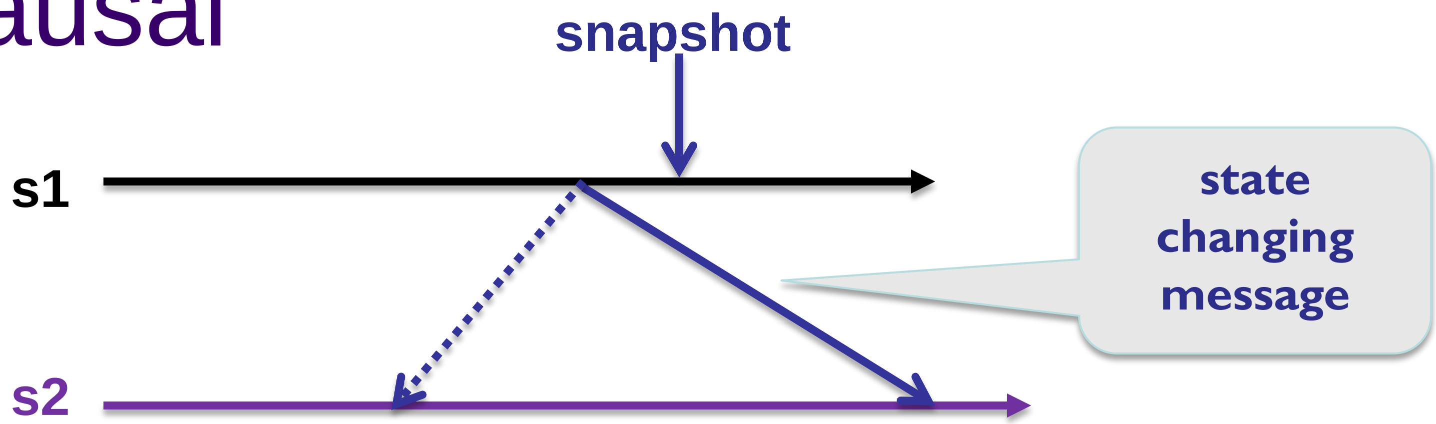
- **CAP theorem: all distributed systems can roughly be classified as CA, CP, and AP**
  - Example of an AP system: eventually consistent object
  - Chances of partitioning will grow with scale
- **Requirement of Availability pushes further down the achievable level of Consistency**
  - Highly Available Transactions: Virtues and Limitations
- **Distributed snapshotting must be transactional**



Common Patterns

The 3 Common Types (1 of 2)

- Point-in-time
- Loosely synchronized
- Causal



The 3 Common Types (2 of 2)

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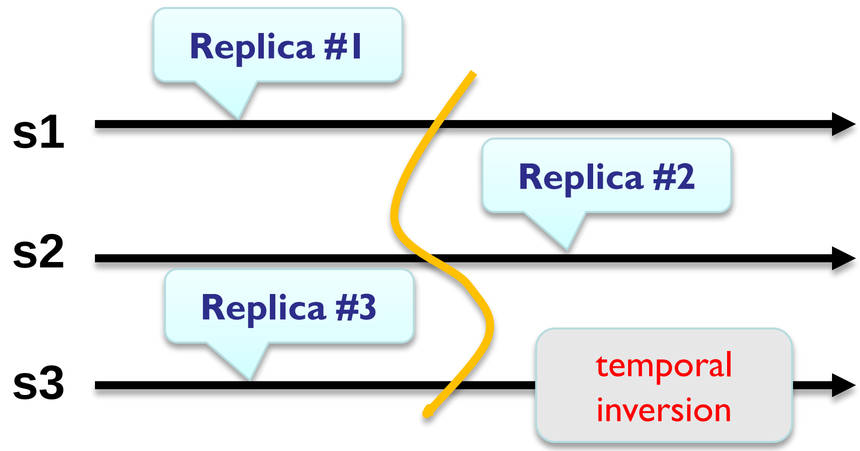
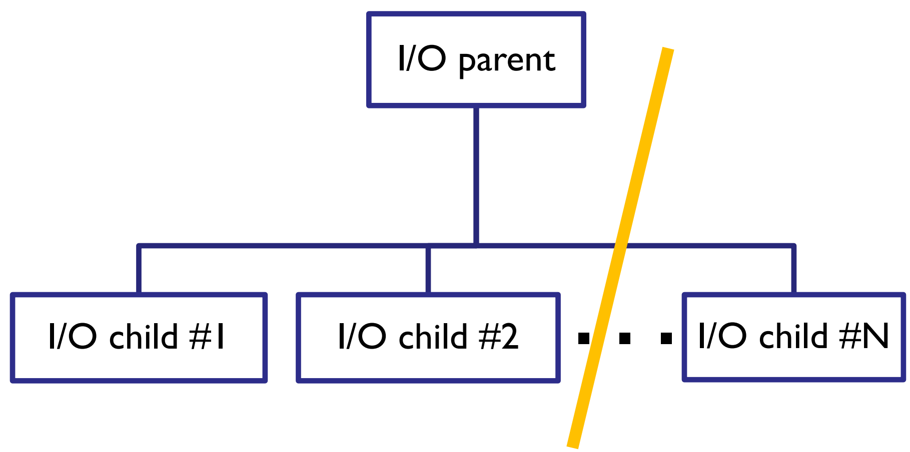
- **Point-in-time**
  - Requires global system time via perfectly synchronized clocks (which is impossible)
  - Or, a single serialization context, not necessarily global or permanent/static (which will hurt performance)
- **Loosely synchronized**
  - Assumes upper bound on clock drift
  - Ti and Tj are considered equal if ABS(Ti – Tj) <= drift
  - Metadata updates delayed until (previous-update + drift)
- **Causal**
  - Snapshot(server-2) must *reflect* Snapshot(server-1)
  - Requires more inter-server messages, more synchronization

The Cut, or when two anomalies meet

- Anomaly type 1: clock drift
  - Solution: global logical time
    - **Time T does not increment as long as there are state-changing events that must be handled by T**
  - Solution: vector clock and variations



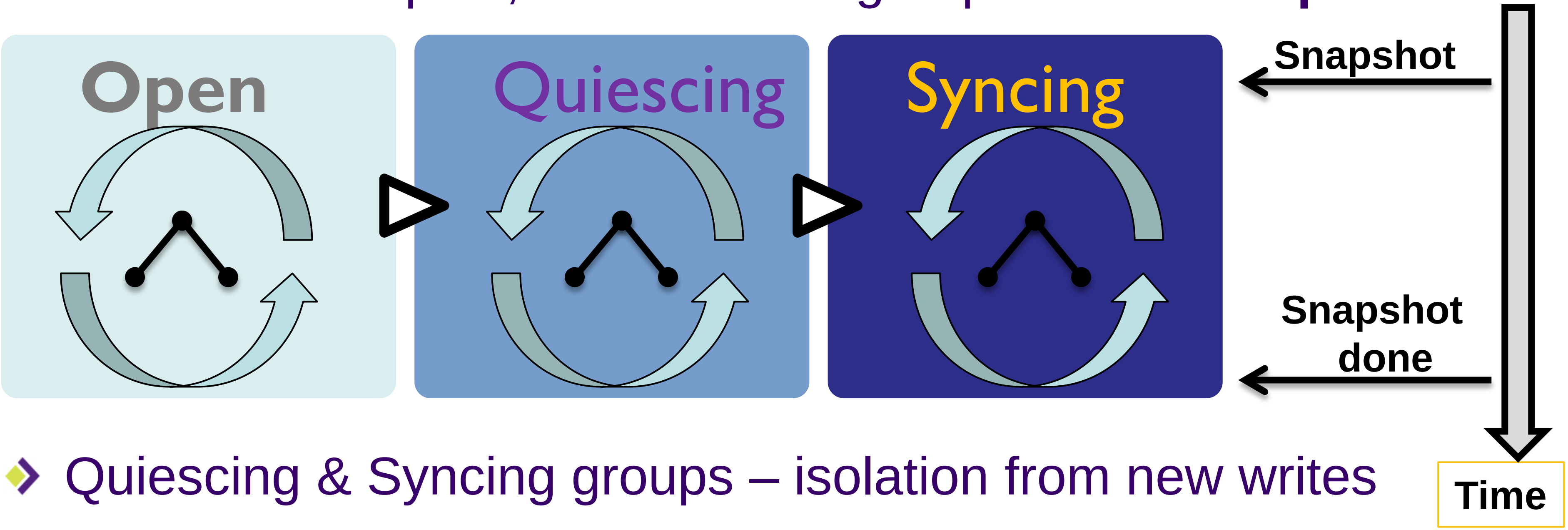
- Anomaly type 2: caused by I/O propagation through pipeline
  - I/Os can multiply and fork, split and join, mutate and even self-cancel
  - Common pattern: I/O parent forking children to execute in parallel



Case Studies

ZFS: transaction group pipeline

- Local FS (but sets user expectations as far as snapshots)
- For each ZFS pool, 3 transaction groups execute **in parallel**:



- Quiescing & Syncing groups – isolation from new writes
- Snapshot can only be created at the end of the Syncing
  - Resulting in a new uberblock (“superblock”) referencing a new consistent set of metadata branches

Ceph snapshots

- http://ceph.com
- Unified distributed object storage system with object (RADOS), block (via RBD), and file (via CephFS)
- Distributed snapshots = work in progress
  1) RADOS http://ceph.com/dev-notes/rados-snapshots/
  2) RBD http://docs.ceph.com/docs/hammer/rbd/rbd-snapshot/
  3) CephFS (jewel) http://docs.ceph.com/docs/jewel/cephfs/early-adopters/
- RBD: recommends to stop I/O before taking a snapshot
- CephFS (jewel): recommends to use a single active MDS and not to use snapshots
- Ceph RADOS introduces "*Snapshot Context*" (librados)
  - Serving as a reference (root) of the snapshotted metadata

HDFS snapshots

- https://hadoop.apache.org/docs/stable
- Distributed storage used by **Hadoop** applications
- Cluster consists of a NameNode (MD) and multiple DataNodes
- Snapshot creation: entry under **.snapshot/** of the snapshotted dir:
  - **<snapshotted-directory>/.snapshot/<snapshot-name>**
- CoW (redirect-on-write):
  - "Modifications are recorded in reverse chronological order"
  - "Snapshot is computed by subtracting the modifications from the current data"
- Notes:
  - Keeping "backward" diffs of the metadata is a fairly unique approach
  - Although easy to implement (and serialize) given a single NameNode
  - Retrieving an old snapshot is going to be (more) time-consuming over time
  - The same applies to destroying older snapshots

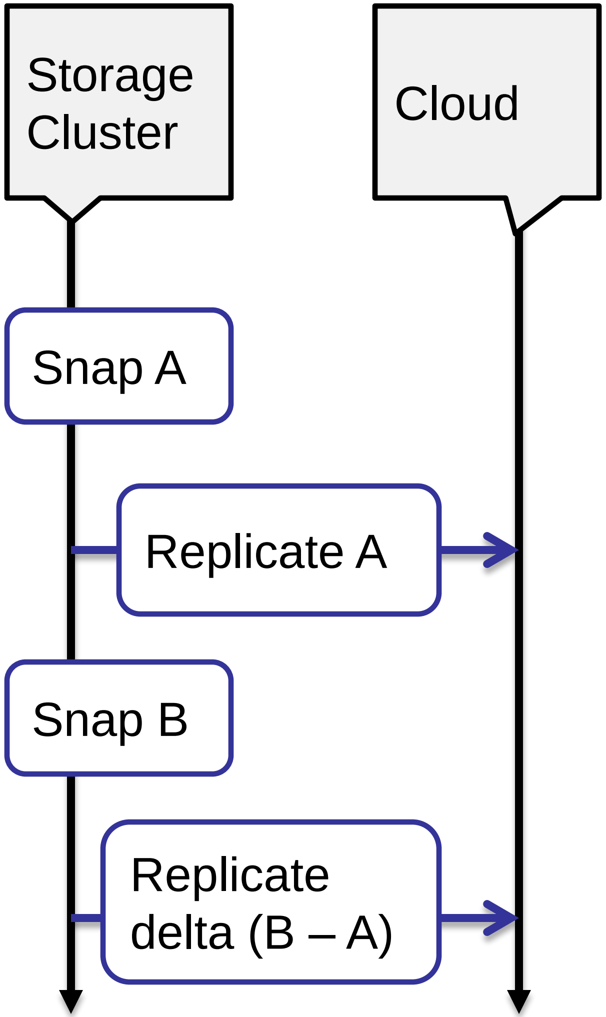
XtreemFS snapshots

- http://www.xtreemfs.org
- Fault-tolerant, distributed, POSIX compliant, relies on local FS
- Excellent white paper on distributed snapshotting:
  - Loosely Time-Synchronized Snapshots in Object-Based File Systems
- XtreemFS metadata: BabuDB (LSM-tree-like local database)
  - https://github.com/xtreemfs/babudb
- Distributed loosely-synchronized snapshot:
  - Consists of local snapshots
  - Serialization via (centralized & replicated) BabuDB metadata transaction
  - Configurable limits on the “fuzziness” of local timestamps
  - Lacking causal consistency
  - New file content (data) snapshot on every close, and never deleted

Eventually Consistent Scale-Out Object Storage

Object Storage vs Snapshots

- **Unlike Ceph RADOS, Amazon S3 (API) and OpenStack Swift do not support self-snapshotting**
  - Both offer block storage snapshots, however (EBS and Cinder volume respectively, the latter – via vendor driver)
- **Object storage is often used to store someone else's snapshots (often, in the Cloud)**
  - DR use case, (incremental) backup and restore, advanced capabilities
- **Cluster-wide snapshots of the object storage itself – not yet a commonly requested feature**
  - Technically, can be done, and will scale (next)



Snapshotting Distributed Object Store: Requirements

- Must be point-in-time
- Must be a fully distributed transaction, with each server contributing a fair share
- Must be consistent
- Must tolerate network partitioning
- May be **unavailable** for a while
  - In the photographic analogy, it takes time to develop the "film"
- The snapshot itself must be a namespace (metadata) object containing Key/Value list of object-versions, sharded as required

Eventual Snapshotting at a glance

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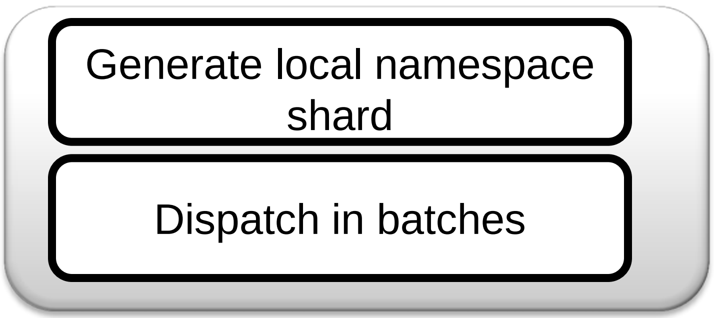
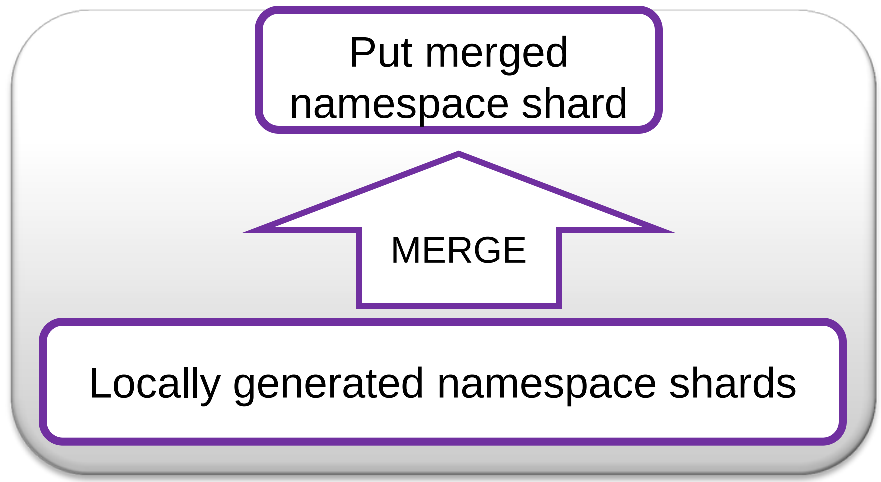
- **Two required primitives**
  - Given Snapshot **Scope**, find whether an object is in the Scope
  - Given Snapshot **Time**, find the *right* object version
- **Map**:



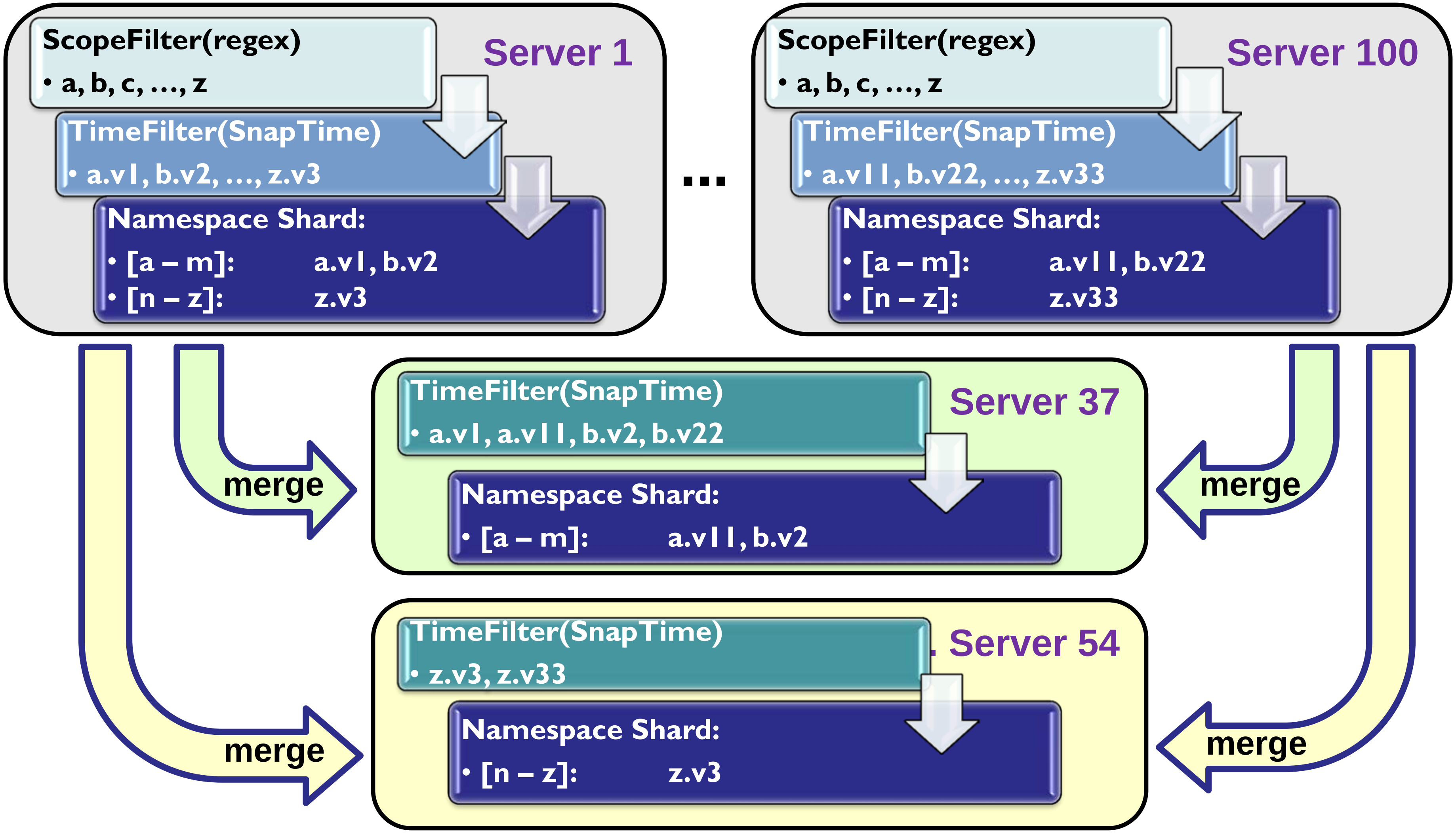


- **Reduce**:
  - **Reconcile multiple versions of the same object**
  - **Put the resulting shards as payloads of the new snapshot object**

Multi-versioned Eventual Consistency: Two Basic Primitives

- Snapshotting an object store boils down to carving out a part of its versioned namespace, and storing it as an object
- Let's illustrate the process with the help of two abstractions:
  - **ScopeFilter(Name, Scope)**
    - **Finds out whether a named object is in the specified scope**
    - Usage #1: **ScopeFilter("/a/b/c", "a/*")** - *will return TRUE*
    - Usage #2: **ScopeFilter(/tenant/bucket/some-name, "*.pdf")**
  - **TimeFilter(Name, Version1, Version2, SnapTime)**
    - **Finds out version(s) of the named object that correspond to the time of the snapshot**
    - **Returns: Version1 | Version2 | Both | None**

Snapshotting 100-node Object Cluster (1 of 3)



Snapshotting 100-node Object Cluster (2 of 3)

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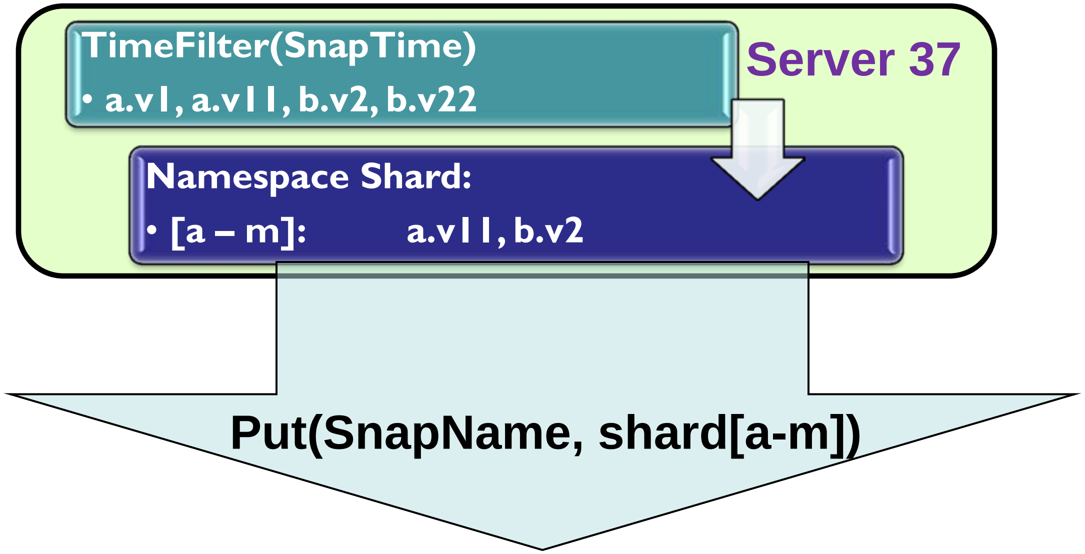
Mapping step:

- Snapshotting job starts processing locally stored namespace shards and local write logs
- Each of the 100 servers (in this example) applies the two filters: ScopeFilter() and TimeFilter()

Reducing step:

- Locally generated namespace shards get distributed internally – for instance, by hashes of their respective names
  - In this example, the targets are: server 37 and server 54
- Each shard includes a sorted KV list of object names and versions
- In the example, the resulting snapshot will contain two namespace shards

Snapshotting 100-node Object Cluster (3 of 3)



- Finally, each of the targets executes an optimized variant of internal Put
- The created snapshot object's payload, in this example, will contain two namespace shards
- Each shard will reference only those versioned objects that are, effectively, snapshotted

Key Takeaways

1. **Distributed snapshotting will *eventually* become a standard checklist item**
2. **Storage systems must be designed from ground up to support snapshotting**
   - **Late addition of the capability may prove to be difficult and costly**
3. **HDFS, Ceph, and other storage systems contribute to usable case studies and learning experience**
4. **Eventually consistent object storage can be snapshotted as illustrated**
   - **To satisfy the requirements stated above as well**

Attribution & Feedback

The SNIA Education Committee thanks the following Individuals for their contributions to this Tutorial.

Authorship History

Alex Aizman, 08/2016

Updates: 09/2016

Additional Contributors

Caitlin Bestler

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