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Erasure Coding for Small Objects in In-Memory Key-Value Storage

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Introduction

- In-memory key-value (KV) stores are widely deployed for scalable, low-latency access
  - Examples: Memcached, Redis, VoltDB, RAMCloud
- Failures are prevalent in distributed storage systems
  - Replication in DRAM?
    - High storage overheads
  - Replication in secondary storage (e.g., HDDs)?
    - High latency to replicas (especially for random I/Os)
  - **Erasure coding**
    - Minimum data redundancy
    - Redundant information is stored entirely in memory for low-latency accesses → fast recovery under stragglers and failures

Erasure Coding

- Divide data to $\boldsymbol{k}$ data chunks
- Encode data chunks to additional $\boldsymbol{n}$-$\boldsymbol{k}$ parity chunks
  - Each collection of n data/parity chunks is called a stripe
- Distribute each stripe to n different nodes
  - Many stripes are stored in large-scale systems

- **Fault tolerance**: any k out of n nodes can recover file data
- Redundancy: $\frac{n}{k}$

Challenges

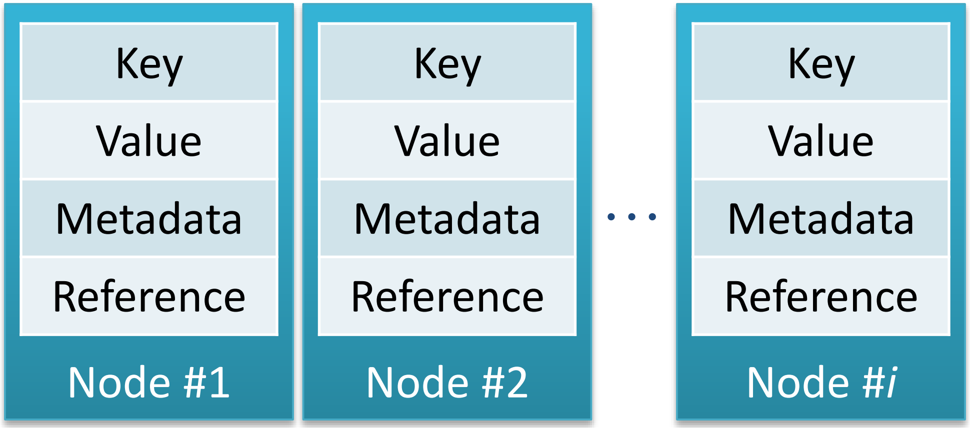
- Erasure coding is expensive in data updates and failure recovery
  - Many solutions in the literature
- Real-life in-memory storage workloads are dominated by **small-size objects**
  - Keys and values can be as small as few bytes (e.g., 2-3 bytes of values) [Atikoglu, Sigmetrics'12]
  - Erasure coding is often used for large objects
- In-memory KV stores issue **decentralized requests** without centralized metadata lookup
  - Need to maintain data consistency when failures happen

Our Contributions

- Build **MemEC**, a high-availability, erasure-coding-based in-memory KV store that aims for
  - Low-latency access
  - Fast recovery (under stragglers/failures)
  - Storage-efficient
- Propose a new **all-encoding** data model
- Ensure graceful transitions between normal mode and degraded mode
- Evaluate MemEC prototype with YCSB workloads

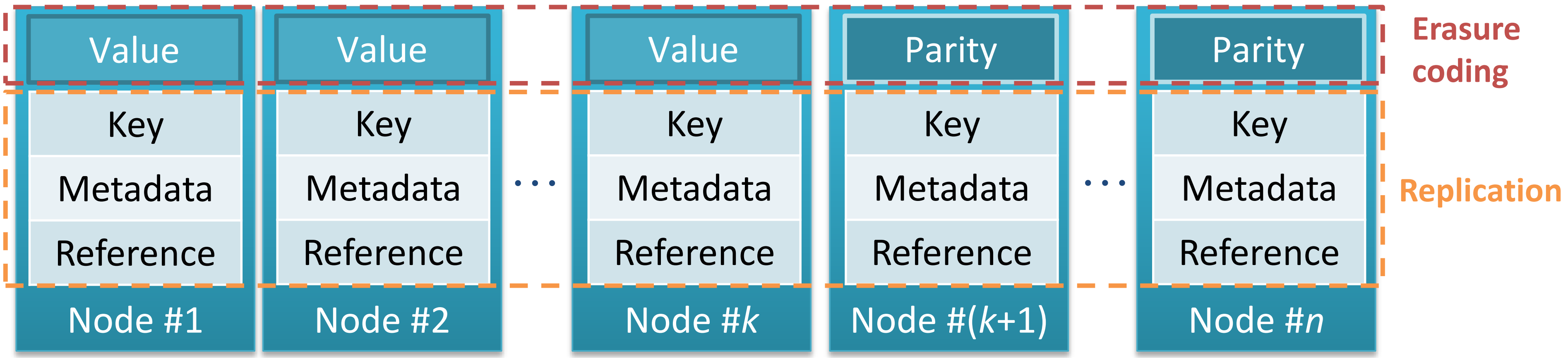
Existing Data Models

- **All-replication**
  - Store multiple replicas for each object in memory
  - Used by many KV stores (e.g., Redis)



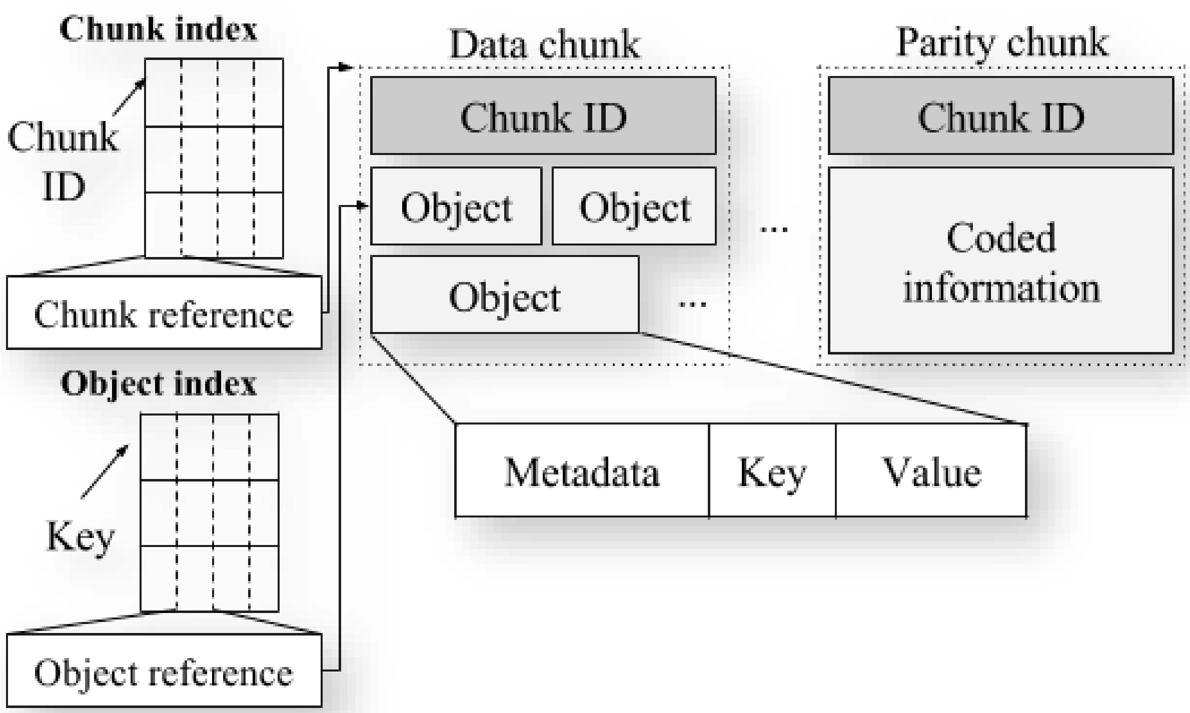
Existing Data Models

- **Hybrid-encoding**
  - Assumption: Value size is sufficiently large
  - Erasure coding to values only
  - Replication for key, metadata, and reference to the object
  - Used by LH*RS [TODS'05], Cocytus [FAST'16]

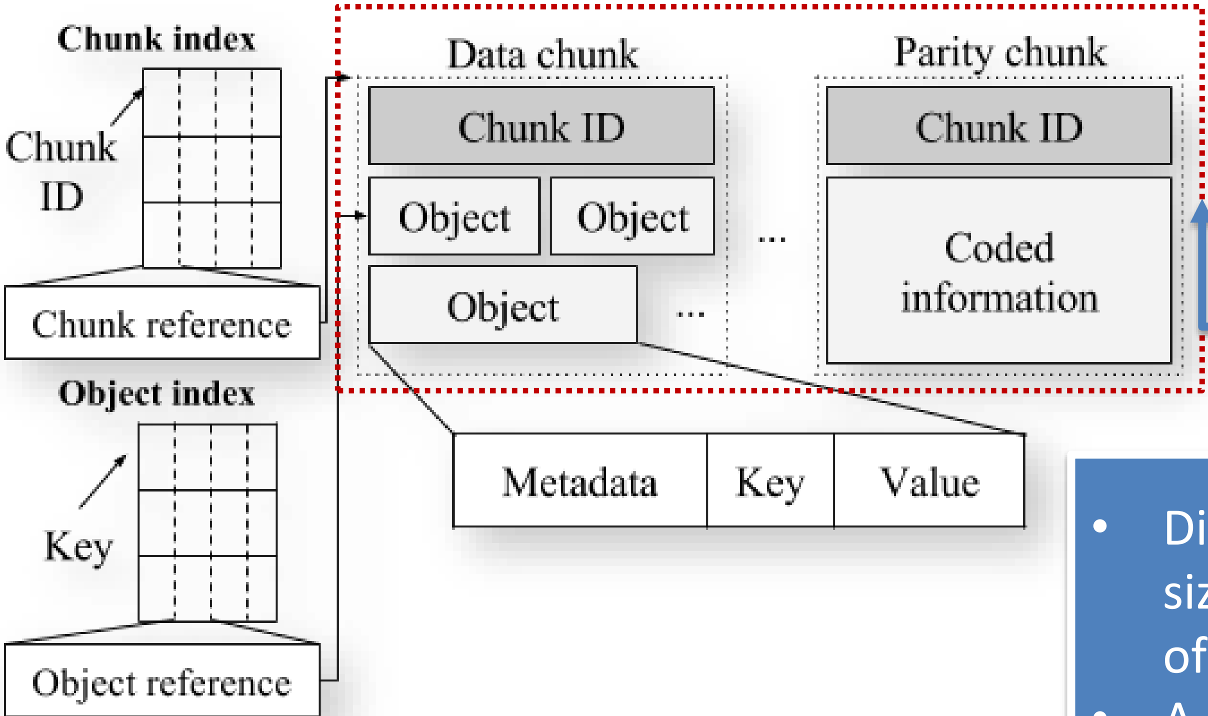


Our data model: All-encoding

- Apply erasure coding to objects in **entirety**
- Design specific index structures to limit storage

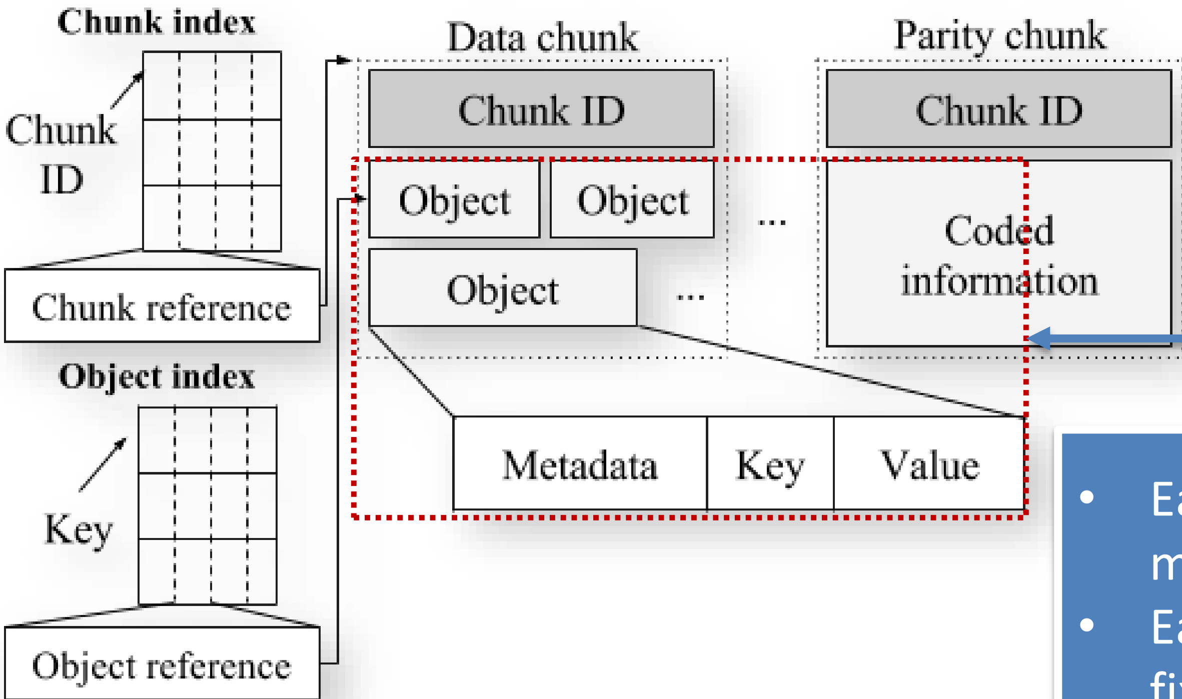


All-encoding: Data Organization



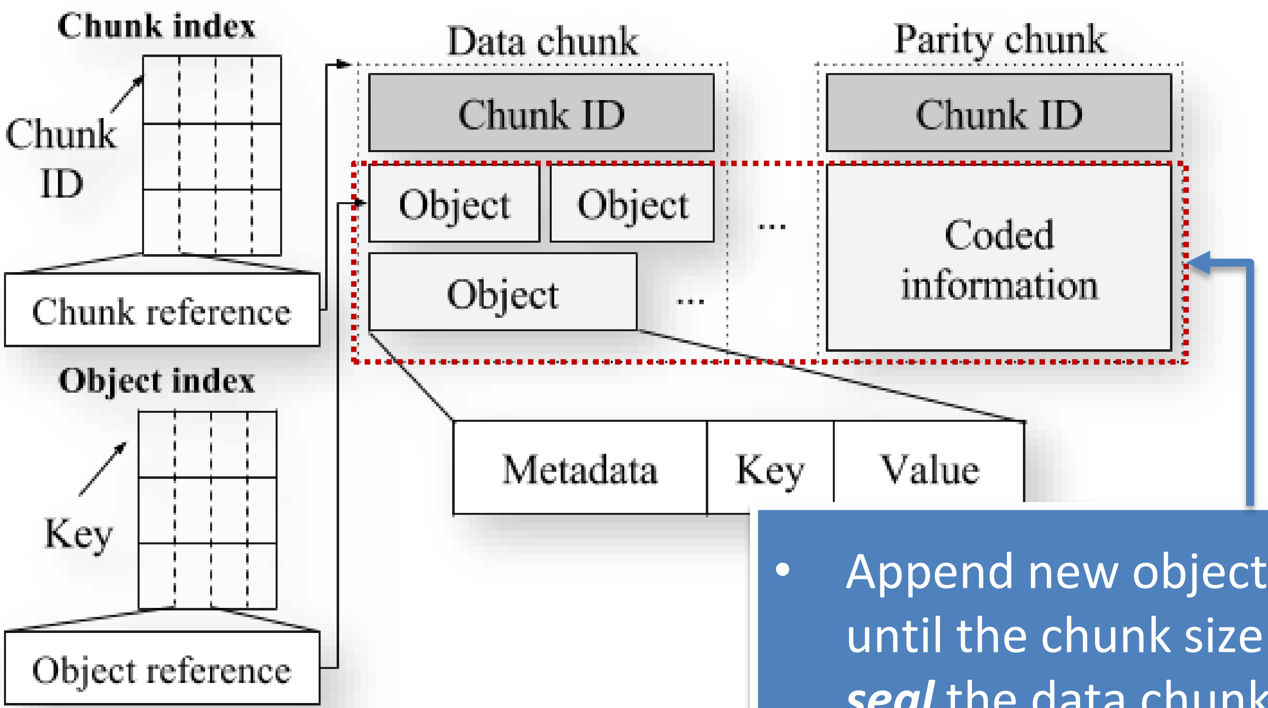
- Divide storage into fixed-size chunks (4 KB) as units of erasure coding
- A unique fixed-size chunk ID (8 bytes) for chunk identification in a server

All-encoding: Data Organization



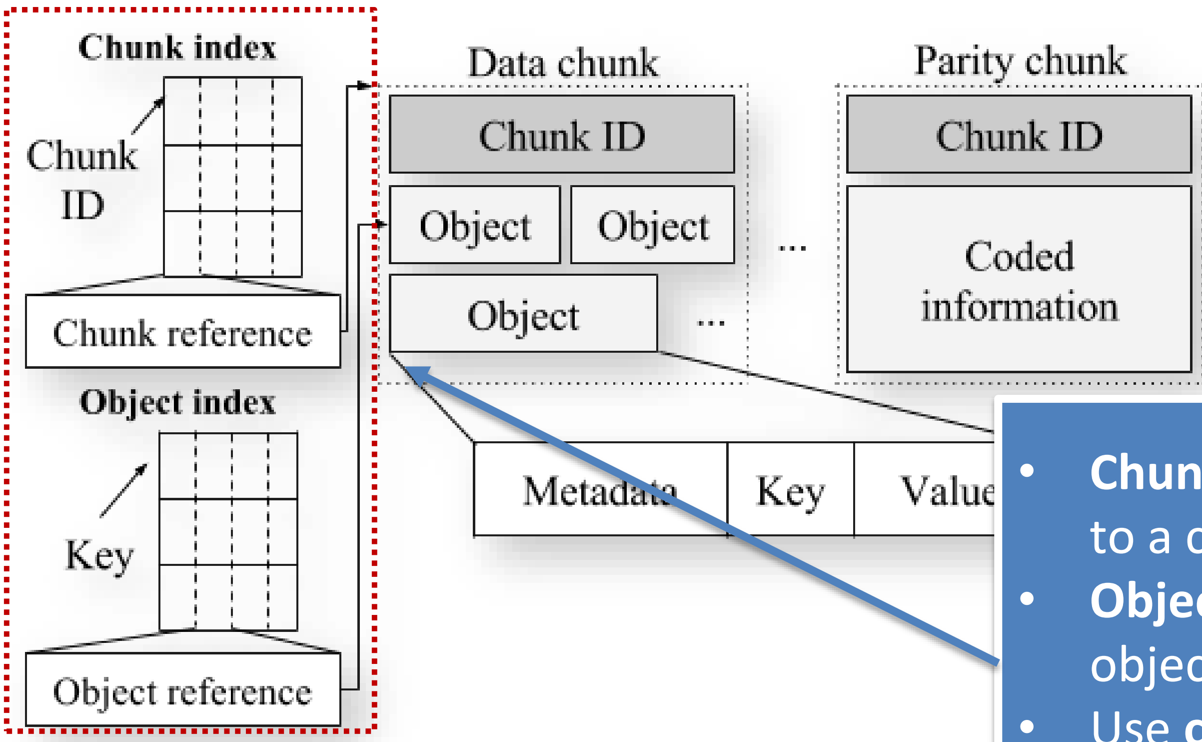
- Each data chunk contains multiple objects
- Each object starts with fixed-size metadata, followed by variable-size key and value

All-encoding: Data Organization



- Append new objects to a data chunk until the chunk size limit is reached, and ***seal*** the data chunk
- Sealed data chunks are encoded to form parity chunks belonging to same stripe

All-encoding: Data Organization

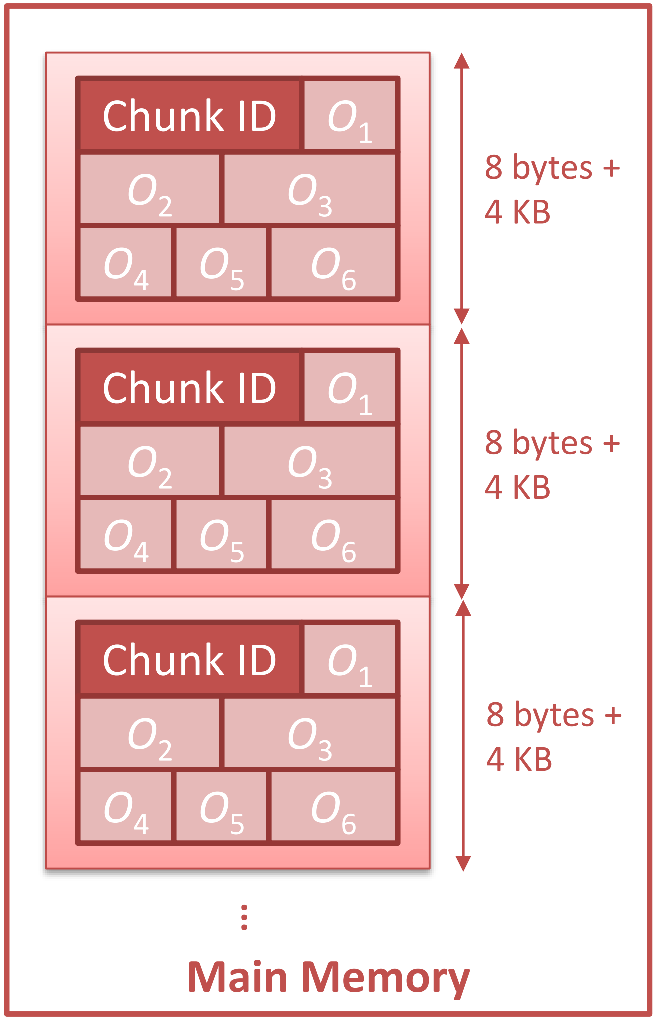


- **Chunk index** maps a chunk ID to a chunk reference
- **Object index** maps a key to an object reference
- Use **cukcoo hashing**
- **No need to keep redundancy for both indexes in memory**

➢ Key-to-chunk mappings are needed for failure recovery, but can be stored in secondary storage

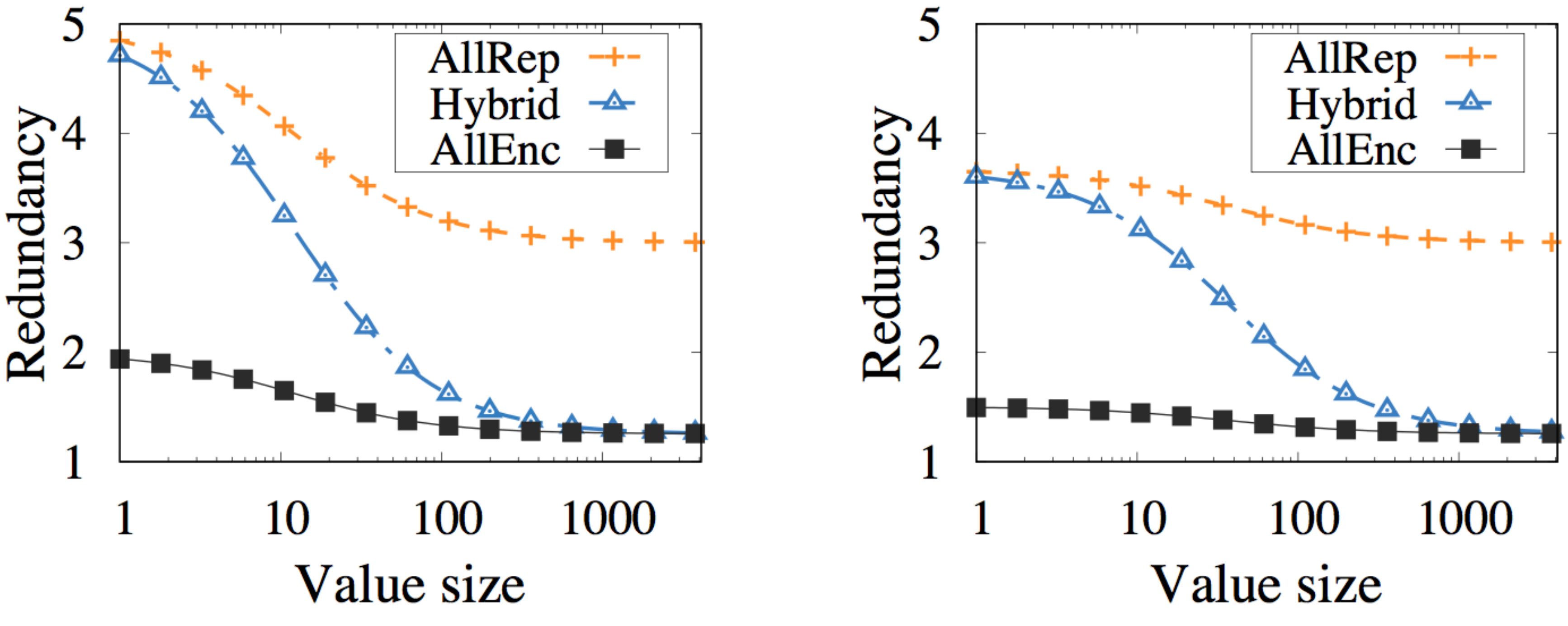
All-encoding: Chunk ID

- Chunk ID has three fields:
  - **Stripe list ID**: identifying the set of *n* data and parity servers for the stripe
    - Determined by hashing a key
  - **Stripe ID**: identifying the stripe
    - Each server increments a local counter when a data chunk is sealed
  - **Chunk position**: from 0 to *n* – 1
- Chunks of the same stripe has the same stripe list ID and same stripe ID



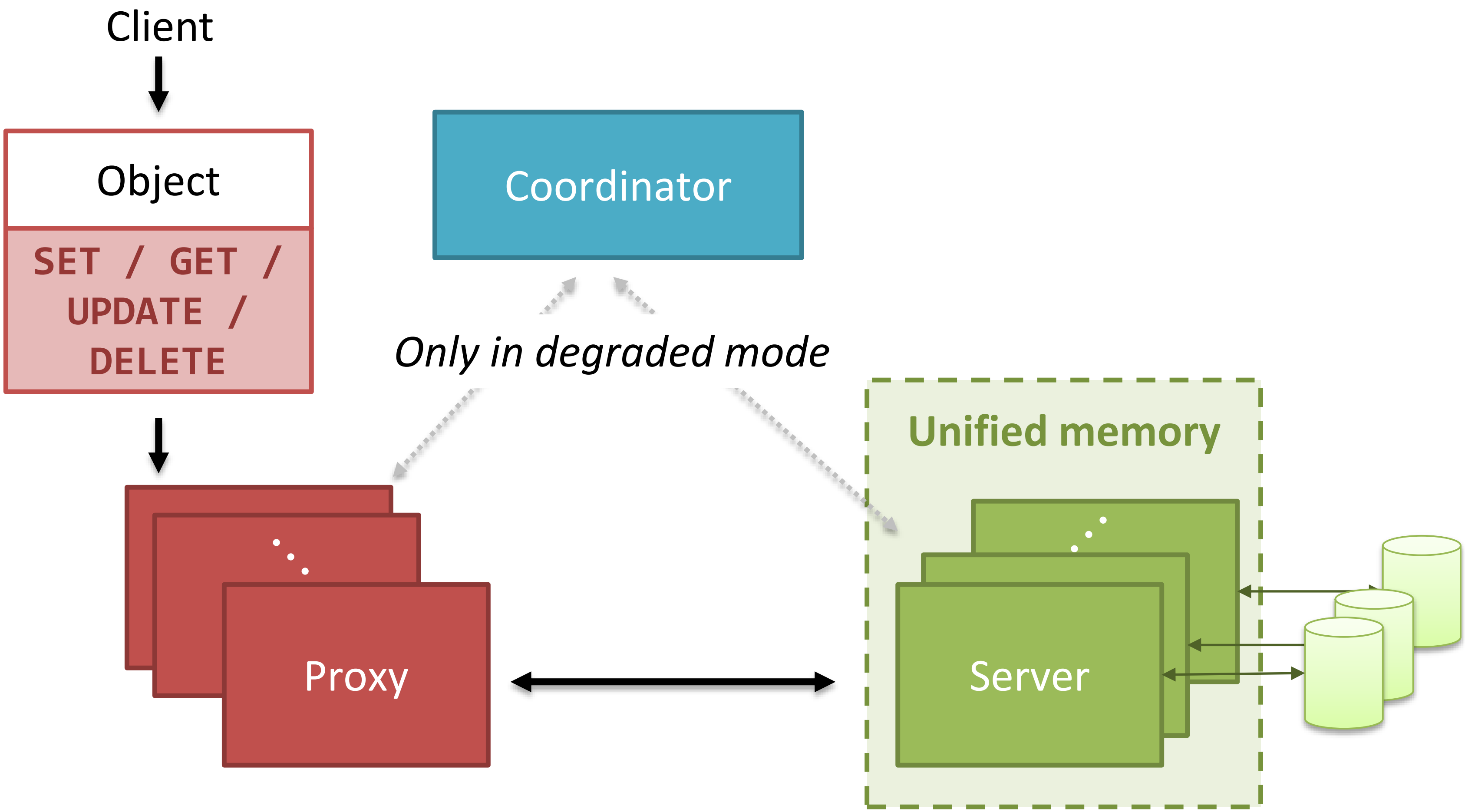
Analysis

➢ All-encoding achieves much lower redundancy



(a) $K = 8, (n, k) = (10, 8)$ (b) $K = 32, (n, k) = (10, 8)$

MemEC Architecture

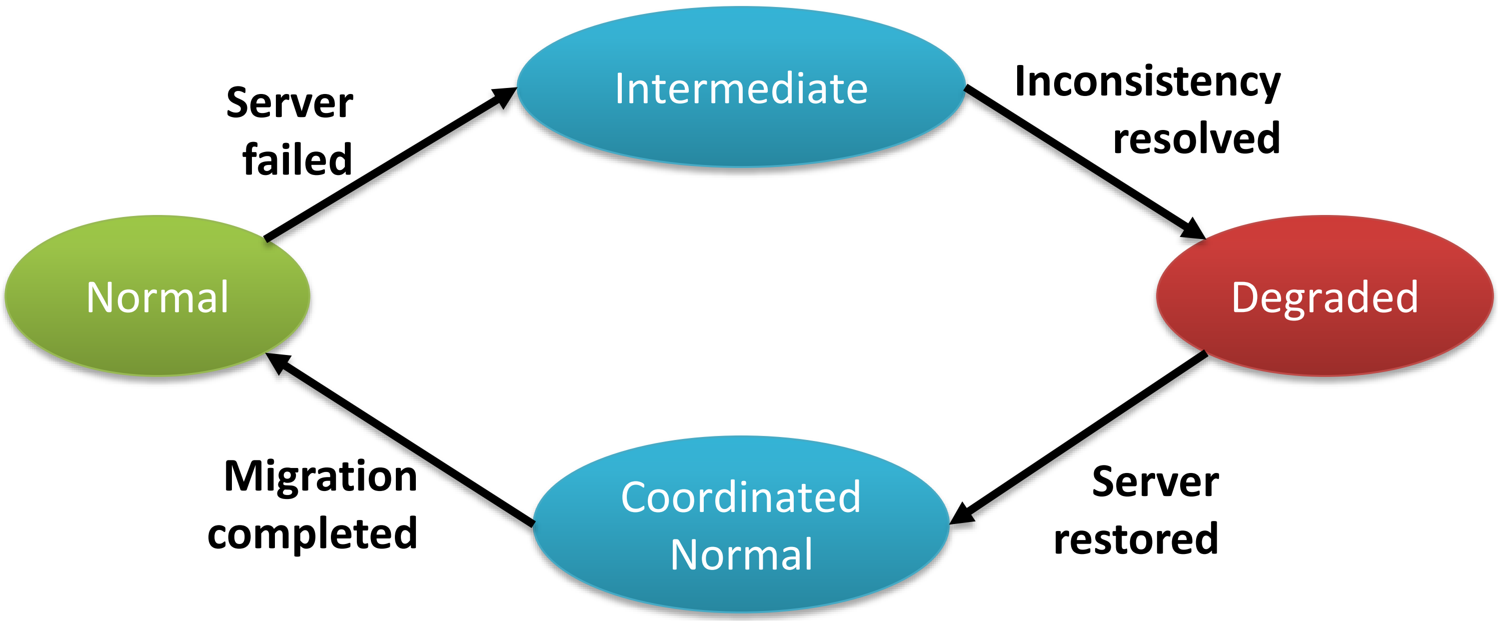


Fault Tolerance

- In normal mode, requests are **decentralized**
  - Coordinator is not on I/O path
- When a server fails, proxies move from decentralized requests to **degraded requests** managed by coordinator
  - Ensure data consistency by reverting any inconsistent changes or replaying incomplete requests
  - Requests that do not involve the failed server remain decentralized
- **Rationale:** normal mode is common case; coordinator is only involved in degraded mode

Server States

- Coordinator maintains a state for each server and instructs all proxies how to communicate with a server



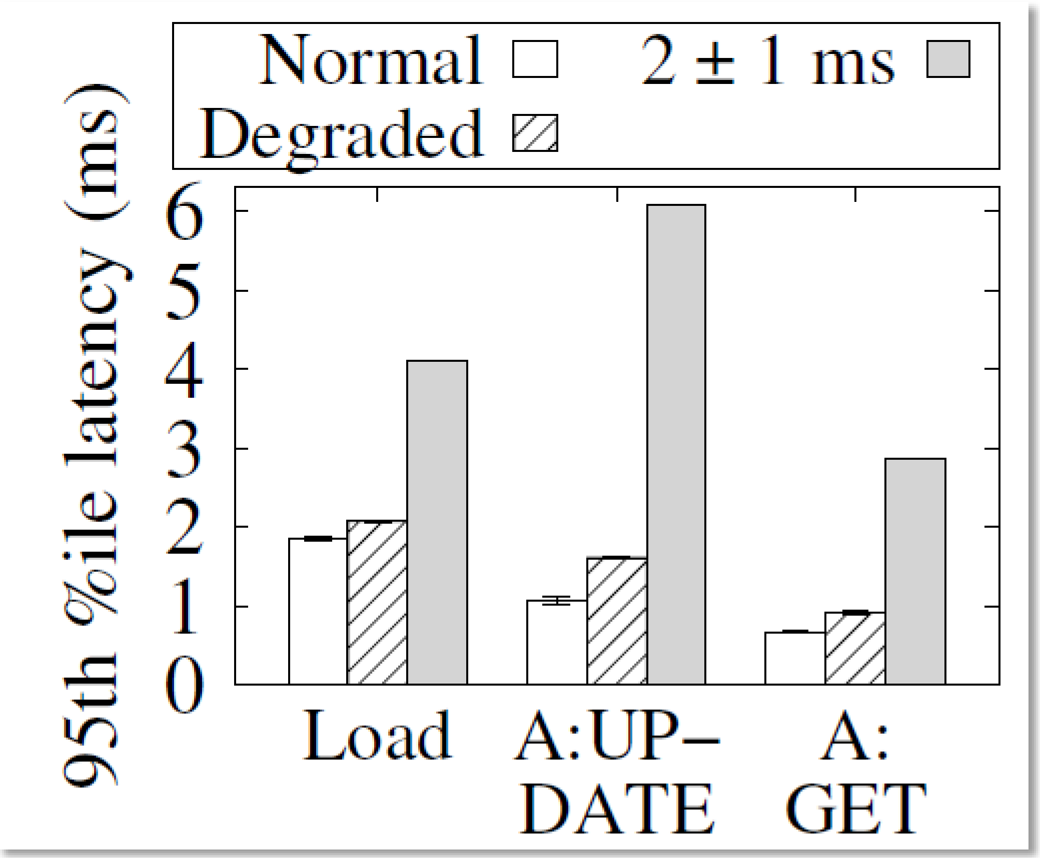
Server States

- All proxies and working servers share the same view of server states
- Two-phase protocol:
  - When coordinator detects a server failure, it notifies all proxies to finish all decentralized requests (intermediate state)
  - Each proxy notifies coordinator when finished
  - Coordinator notifies all proxies to issues degraded requests via coordinator (degraded state)
- Implemented via atomic broadcast

Evaluation

- Testbed under commodity settings:
  - 16 servers
  - 4 proxies
  - 1 coordinator
  - 1 Gbps Ethernet
- YCSB benchmarking (4 instances, 64 threads each)
  - Key size: 24 bytes
  - Value size: 8 bytes and 32 bytes (large values also considered)
  - Do not consider range queries

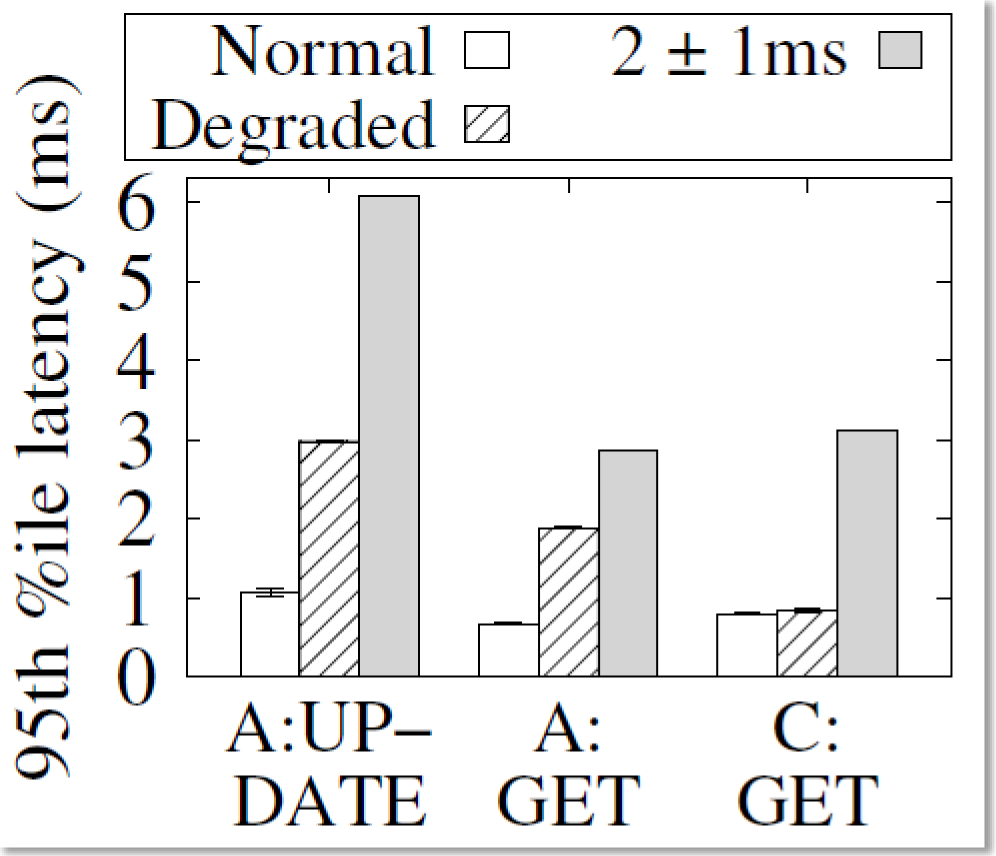
Impact of Transient Failures



Failures occur before load phase:

- Latency of SET in load phase increases by 11.5% with degraded request handing
- For Workload A, latencies of UPDATE and GET increase by 53.3% and 38.2%, resp.

Impact of Transient Failures



Failures occur after load phase:

- Latencies of GET and UPDATE increase by 180.3% and 177.5%, resp.
- Latency of GET in Workload C only increase by 6.69%

State Transition Overhead

State transition		Elapsed time (ms)	
		Single failure	Double failure
$T_{N\to D}$	With req.	4.77 ± 0.79	9.24 ± 0.78
	No req.	1.74 ± 0.09	4.91 ± 0.89
$T_{D\to N}$	With req.	628.5 ± 43.9	667.5 ± 27.2
	No req.	0.91 ± 0.46	1.10 ± 0.19

Average elapsed times of state transitions with 95% confidence

Difference between two elapsed times is mainly caused by **reverting parity updates** of incomplete requests

Elapsed time includes **data migration** from the redirected server to the restored server, so increases a lot

Conclusion

- A case of applying erasure coding to build a high-available in-memory KV store: **MemEC**
  - Enable fast recovery by keeping redundancy entirely in memory
- Two key designs:
  - Support of small objects
  - Graceful transition between decentralized requests in normal mode and coordinated degraded requests in degraded mode
- Prototype and experiments
- Source code: **https://github.com/mtyiu/memec**