Embedded Time Series Storage: A Cookbook

Andrey Pechkurov

About me

- Java (for a long time) and Node.js (for quite a long time) developer
- Node.js core collaborator
- Interests: web, system architecture, distributed systems, performance
- Can be found here:
  - https://twitter.com/AndreyPechkurov
  - https://github.com/puzpuzpuz
  - https://medium.com/@apechkurov

hazelcast IMDG

https://hazelcast.org

- Hazelcast In-Memory Data Grid (IMDG)
- Open-source distributed in-memory object store
- Supports a variety of data structures such as Map, Set, List, and so on
- Implemented in Java
- Supports embedded и standalone modes
- Has client libraries for many languages and platforms

hazelcast IMDG

- Hazelcast IMDG Management Center (MC)
- Monitoring & management application for IMDG clusters
- Supports stand-alone and servlet container deployment
- Self-contained application, i.e. .jar file and Java is everything you need
- Frontend part is built with TypeScript, React and Redux
- Backend part is built with Java, Spring and IMDG Java client

Agenda

- A quick intro
- The problem
- Considered options
- Decisions made
- Results and plans

A quick intro

Terminology

Metric - a numerical value that can be measured at particular time and has a real world meaning. Examples: CPU load, used heap memory. Characterized by name and a set of tags*.

Data point - a metric value measured at the given time. Characterized by metric, timestamp (Unix time) and a value.

* We'll use term "metric" instead of "metric + tags".

Types of metrics

- Gauge (e.g. CPU load, memory consumption)
- Counter (e.g. number of processed operations)
- Histogram (e.g. operation processing latency)

What we mean by "time series"

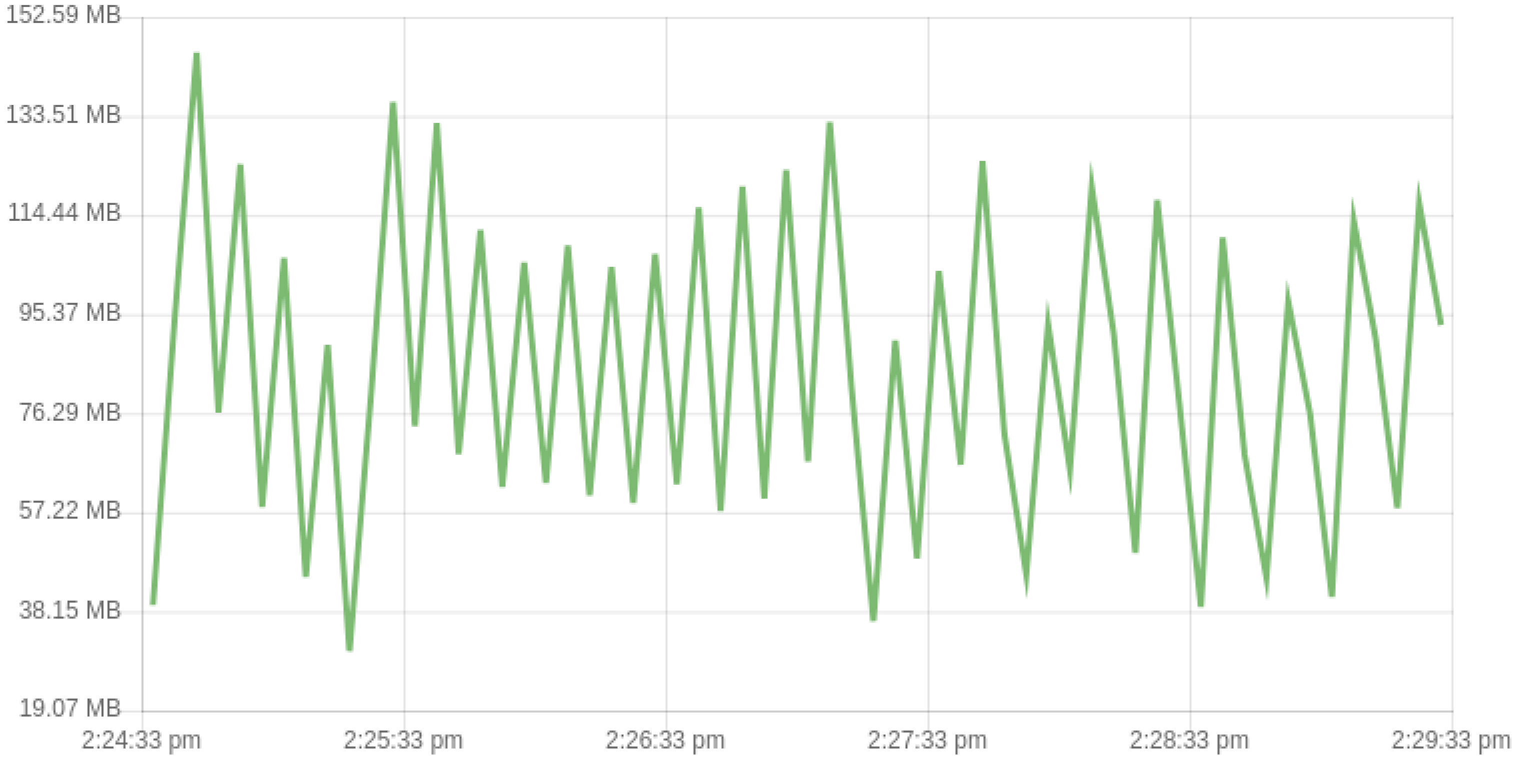
"Time series" (TS) stand for series of metric data points

```
class DataPoint {

    String metric;
    List<Map.Entry<String, String>> tags;
    long time;
    long value;

}
```

Sample data point

metric	tags	time	value
memory.usedHeap	unit=BYTES	1532689094000	136314880

Sample time series



Simple math

```
10 members
6,000 metrics per each
3 sec interval
```

Simple math

10 members
6,000 metrics per each
3 sec interval

20K data points per sec
1,728M data points per day
27.6GB of raw data (time + values)

Summary

Time series data (usually) implies:

- Large data volume
- Writes:
  - Lots of writes
  - Writes involve data points for all metrics or most of them
- Reads:
  - Significantly less reads
  - Reads assume one or several time series over a time range
- Raw and aggregate queries

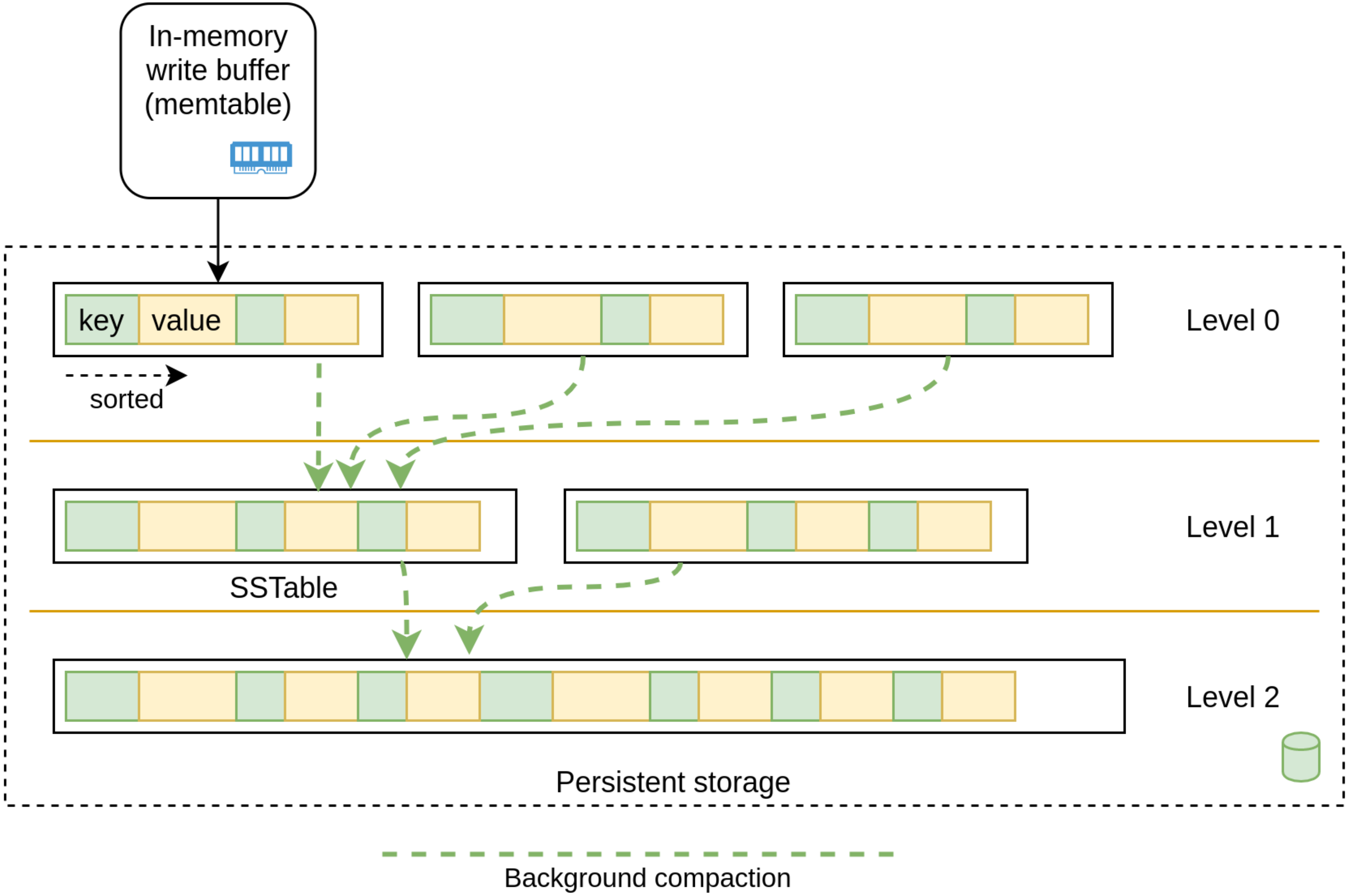
Storage formats

- Column-oriented storage
- Log-structured merge-tree (LSM tree)
- B-tree
- Their variations and combinations

Column-oriented storage

	File 1	File 2	File 3
	time	cpu_load	memory
Row 1	1532689094000	0.32	104857600
	1532689096000	0.51	136314880
	...	...	...
Row N	1532689100000	0.63	137122810
	1532689098000	0.75	158334976

LSM tree


In-memory
write buffer
(memtable)
key
value
sorted
Level 0
Level 1
SSTable
Level 2
Persistent storage
Background compaction

Data compression

- Integer compression
  - Delta encoding
  - Delta-of-delta encoding
  - Simple-8b
  - Run-length encoding
- Floating point compression
  - XOR-based compression
- Type-agnostic compression
  - Dictionary compression
  - Bitmap encoding

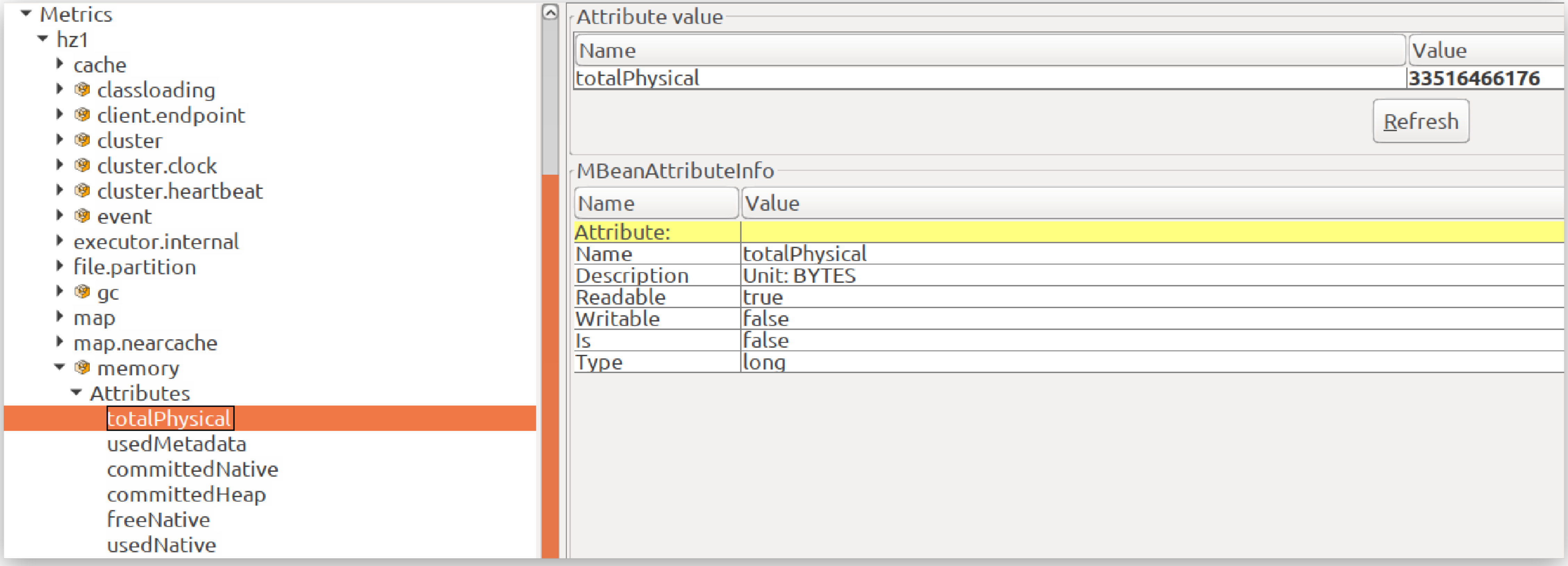
The problem

The problem

- In the past IMDG clusters were reporting their metrics as a large JSON object
- MC was storing collected JSONs into a key-value storage (in-memory and/or JDBM)
- Such approach has some downsides that are critical for us
- Say, it requires changes in many places when we had to add new metrics

The solution

IMDG v4.0+ is capable of reporting collected metrics (probes) to MC in a generic manner



The challenge

- MC has to store those metrics somehow
- Thus, we need a time series database (or, at least, storage)
- Here comes the challenge...

Requirements - must haves

- Embedded time series database or storage
- In-memory and optional persistent modes
- Data compression to achieve low disk footprint in the persistent mode
- Support data retention to avoid running of disk space
- Durability and fault tolerance in the persistent mode

Requirements - nice to haves

- Good write performance (100Ks data points/second on average HW)
- Good enough read performance (10Ks data points/second on average HW)
- Use existing stable SW, when possible

Considered options

TS DBs

- OpenTSDB
- InfluxDB
- TimescaleDB
- Prometheus
- ClickHouse
- and many more

Embedded TS DBs/storages

- Akumuli (C++) - https://akumuli.org
- QuestDB (Java) - https://www.questdb.io

Embedded non-TS DBs/storages

- SQL DBs
  - H2 DB (B-tree)
- Key-value storages
  - H2's MVStore (B-tree)
  - MapDB (HTree, B-tree)
  - RocksDB (LSM tree)

Decisions made

Initial ideas

After initial research and experiments we decided the following:

- Build a TS storage on top of a key-value storage
- Keep the storage API simple

Primitive data layout

key	value
`1532689094000@map.totalGetLatency@name=test-map,unit=MS`	`10234`

Draft API

```java
public interface MetricsStorage {

    void store(Collection<DataPoint> dataPoints);

    DataPointSeries queryRange(Query query);

    Optional<DataPoint> queryLatest(Query query);

}
```

TODO list

1. Choose one of embedded key-value storages
2. Come up with a way to reduce number of persisted entries
3. Think of sufficient data compression for the persisted data

Item 1: embedded key-value storage

After some experiments we picked up two candidates:

- MapDB (Java)
- RocksDB (C++ with JNI bindings)

RocksDB won the battle in the end.

Item 2: number of persisted entries

- We need to group multiple data points into a single entry somehow
- What if we store data points in buckets? Say, each bucket will contain data points within a minute

Bucketed data layout

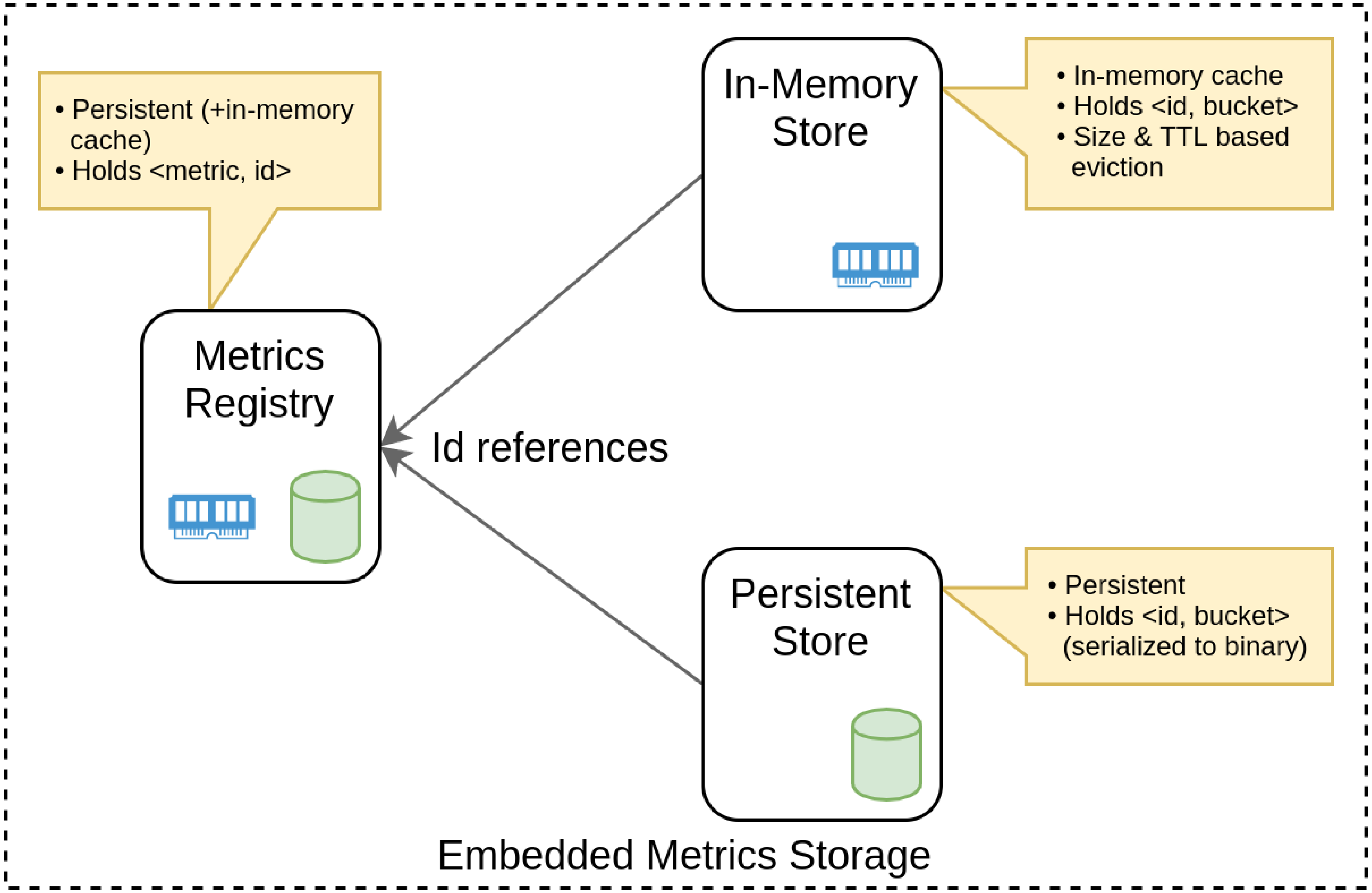
`1532689080000@map.totalGetLatency@name=test-map,unit=MS` `{10234,...,10480}`

`minute start` `new long[60]`

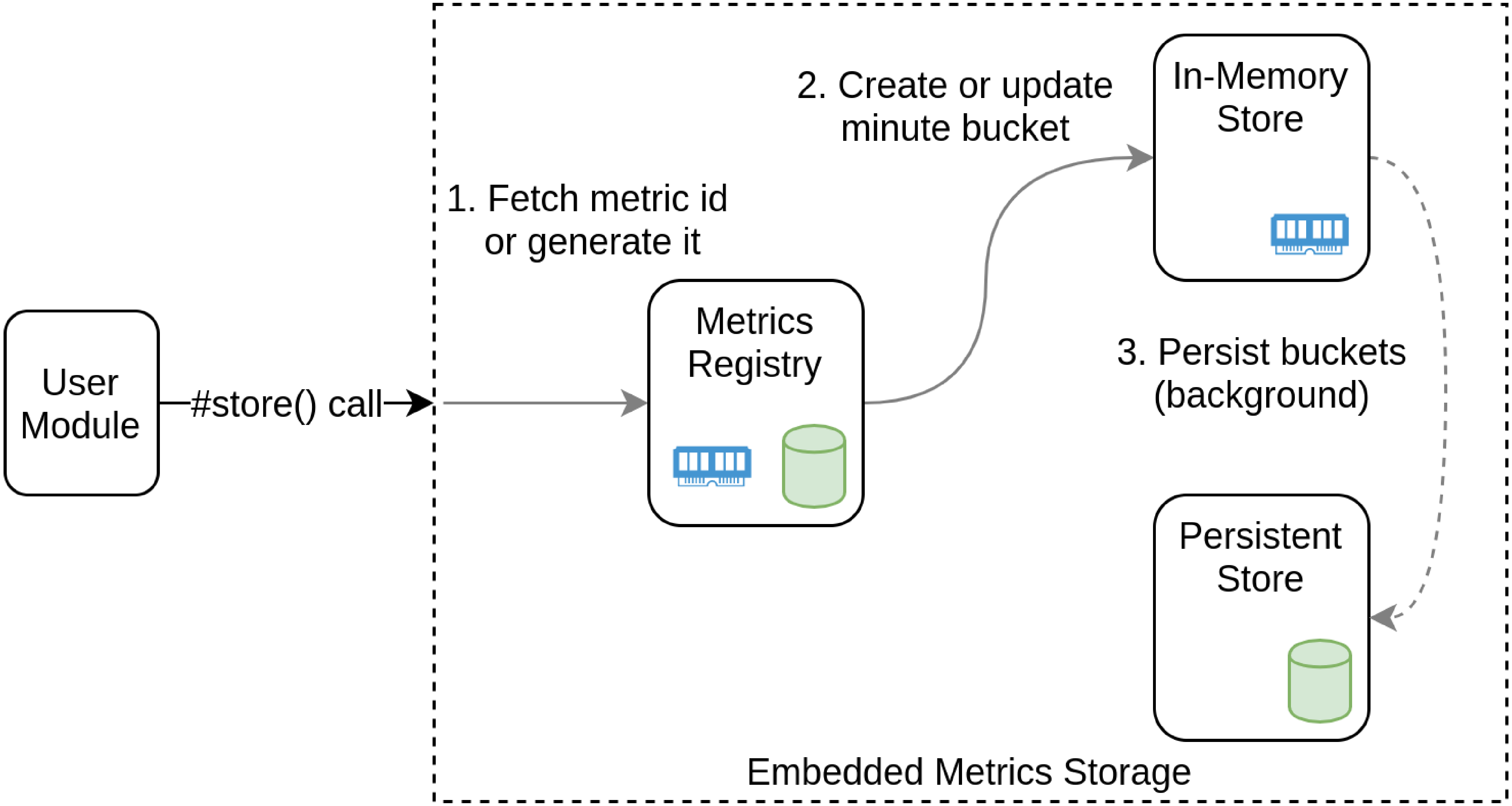
Item 3: data compression

- Keys
  - We could use dictionary compression for metrics
- Values
  - For each minute bucket we could use compression methods for integer numbers, like delta encoding

Overall design

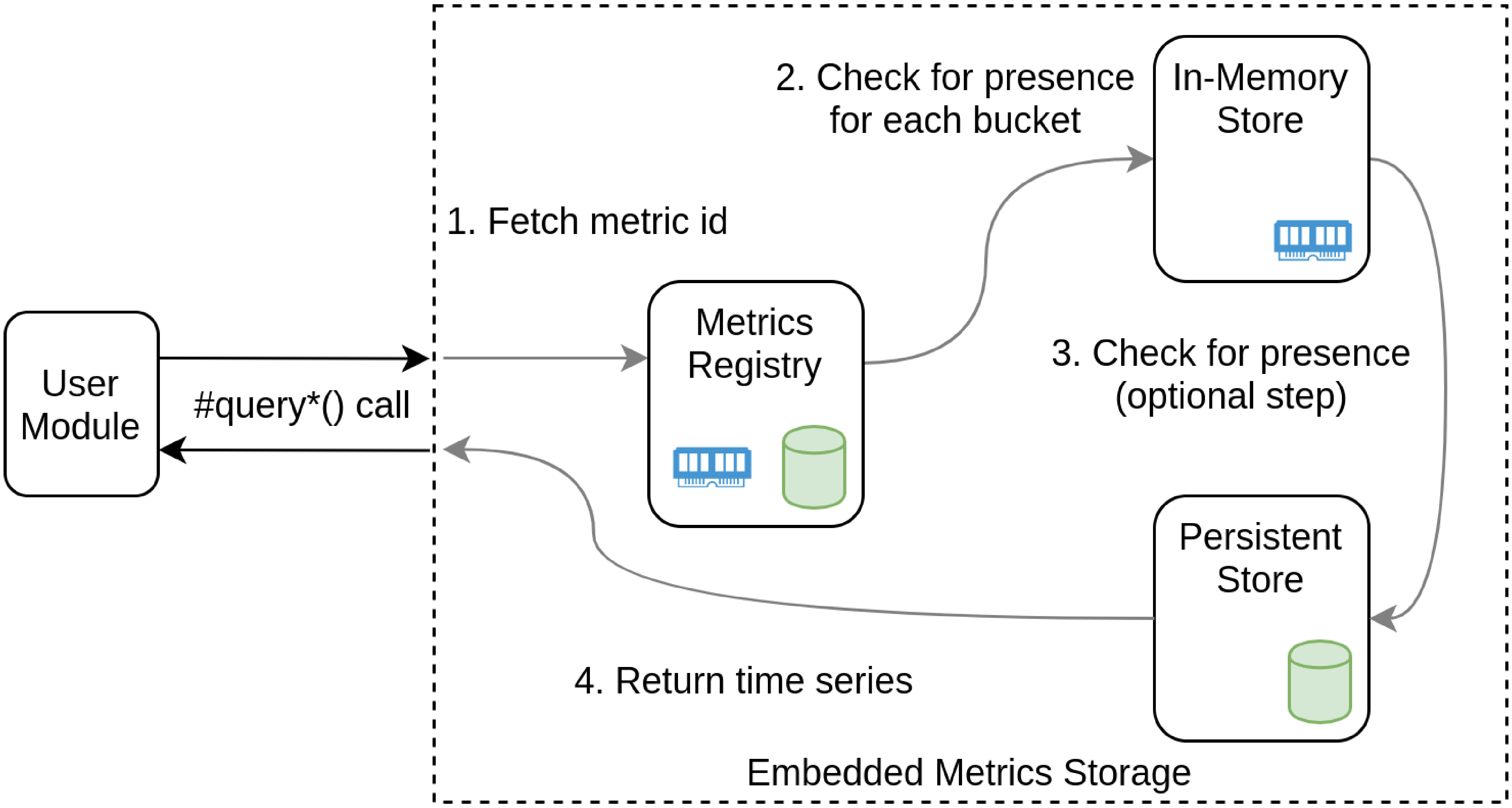


Writes



User Module
#store() call
1. Fetch metric id or generate it
Metrics Registry
2. Create or update minute bucket
In-Memory Store
3. Persist buckets (background)
Persistent Store
Embedded Metrics Storage

Reads



User Module
#query*() call
1. Fetch metric id
Metrics Registry
2. Check for presence for each bucket
In-Memory Store
3. Check for presence (optional step)
Persistent Store
4. Return time series
Embedded Metrics Storage

Metrics Registry

key	value
`map.totalGetLatency@name=test-map,unit=MS`	`42`
metric name + tags	metric id (int)

Data compression: keys

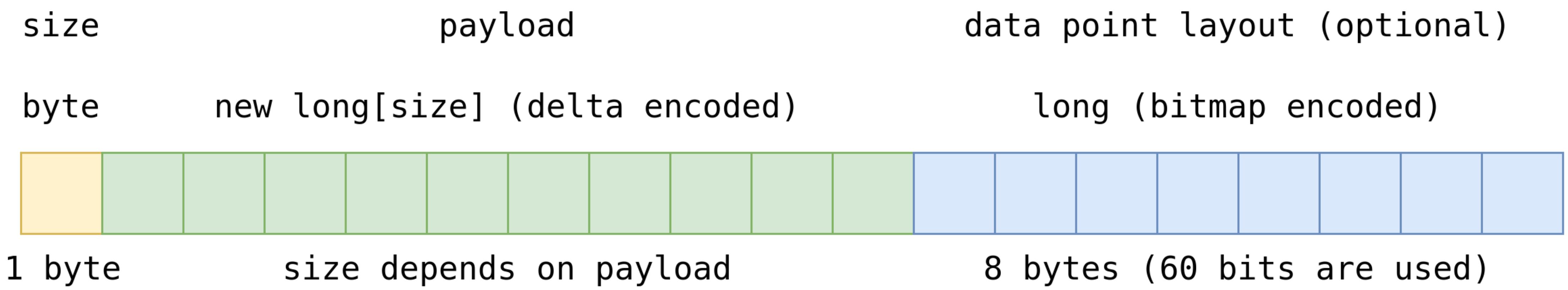
old key format

```
1532689094000@map.totalGetLatency@name=test-map,unit=MS
```

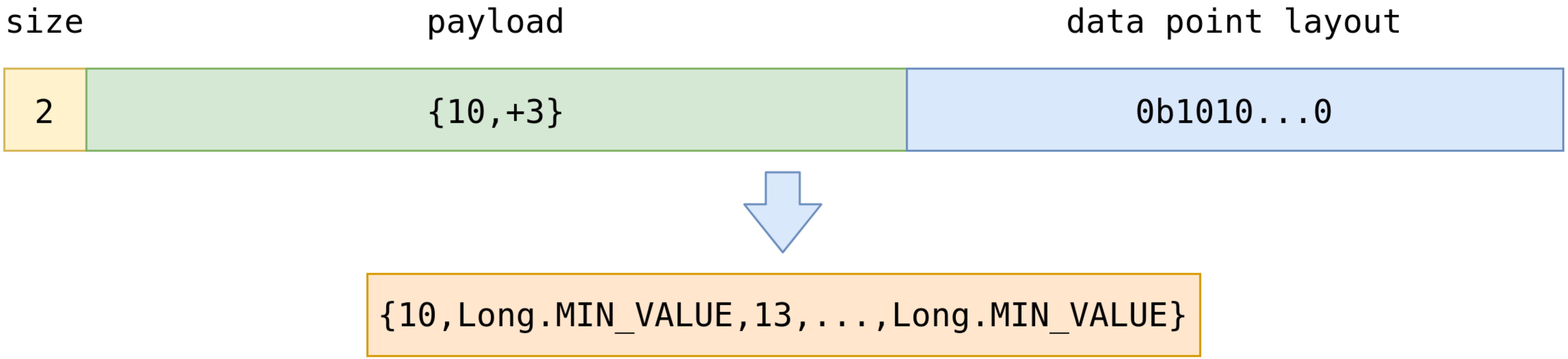
new key format

```
1532689094000@42
```

Data compression: values



Sample compressed value



Value compression efficiency

Scenario	Raw (bytes)	Compressed (bytes)	Ratio
Const `long` (1 sec)	480	12	x40
Const `long` (3 sec)	160	19	x8.4
Inc `long` (3 sec; < `byte`)	160	55	x2.9
Inc `long` (3 sec; < `short`)	160	93	x1.7
Random `long` (3 sec)	160	170	x0.9

Disk cost of each data point

	Cost (bytes)
Raw	16*
Metric Storage	5.25**
Prometheus	3.3
Gorilla	1.37

* Binary size of timestamp + value

** We consider "Inc `long` (3 sec; <`short`)" scenario

Other features

- Data retention
  - Based on per entry time-to-live (TTL) in RocksDB
- Data durability
  - Pending minute buckets are flushed to disk on graceful shutdown
- Aggregation API
  - Built on top of the storage

Design restrictions #1

Problem:

Data point loss when in-memory cache size is insufficient

Potential solution:

Adapt the size dynamically

Design restrictions #2

Problem:

Loss of last minute data on force shutdown

Potential solution:

Additional WAL or flush data on more frequent checkpoints

Design restrictions #3

Problem:

Out of order writes (>1 minute time window)

Potential solution:

Merge buckets during background persistence

Results and plans

Benchmark results

- Scenario:
  - Emulates 10 members, 120K metrics, 3 second interval
  - Random values from 0-1000 range
- Results:
  - Writes* - 400K data point/sec
  - Random minute series reads* - 19K ops/sec

* Results were obtained on a laptop

Further plans

- Add support for additional indexes over metrics
- Implement downsampling
- Expose diagnostics information in runtime
- Perform additional testing and optimization

hazelcast IMDG

Call to action

- You may want to give a try with IMDG and MC: https://hazelcast.org/
- Open source contributions are welcome as well!

Thank you!

Helpful links

- https://docs.hazelcast.org/docs/4.0.1/manual/html-single/index.html#metrics
- https://blog.timescale.com/blog/time-series-compression-algorithms-explained/
- Gorilla: a fast, scalable, in-memory time series database, 2015 - https://dl.acm.org/doi/10.14778/2824032.2824078
- https://github.com/facebook/rocksdb/wiki/Leveled-Compaction
- https://www.mongodb.com/blog/post/time-series-data-and-mongodb-part-2-schema-design-best-practices