> Embedded Time Series Storage: A Cookbook

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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





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 standalone 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 set of tags*.

Data point - a metric value measured at the given time. Characterized by metric, timestamp (Unix time) and 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;
    Map<String, String> tags;
    long time;
    long value;
}
```



Sample data point

metric

tags

time

value

memory.usedHeap

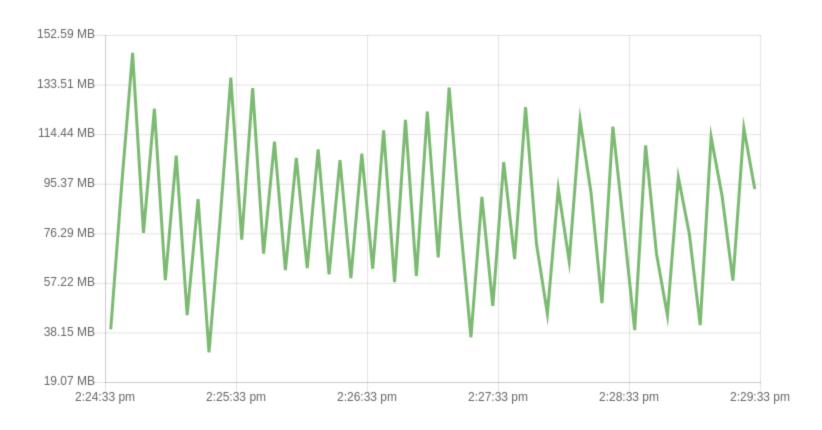
unit=BYTES

1532689094000

136314880



Sample time series





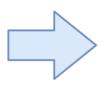
Simple math

```
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
- * See bonus slides



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



* See bonus slides

> The problem

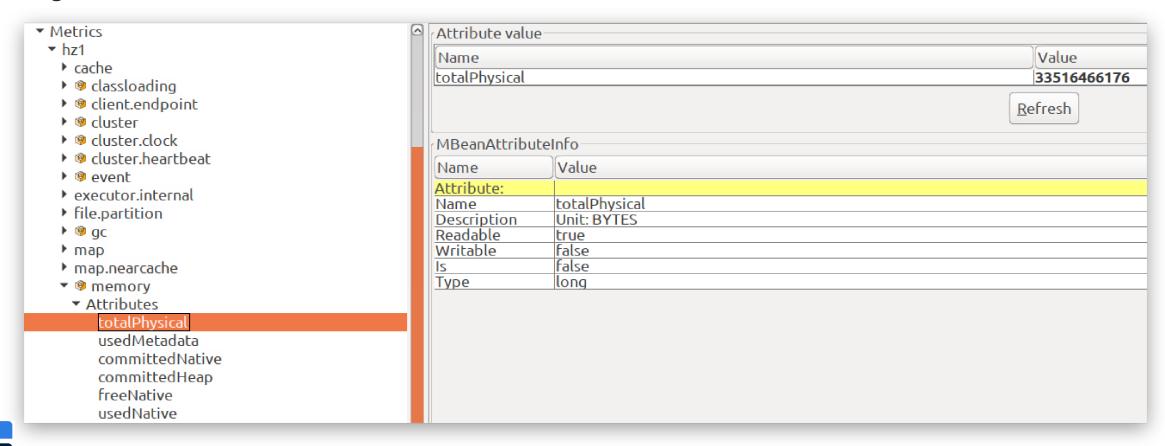
The problem

- 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

- Aggregation API
- 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

```
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]

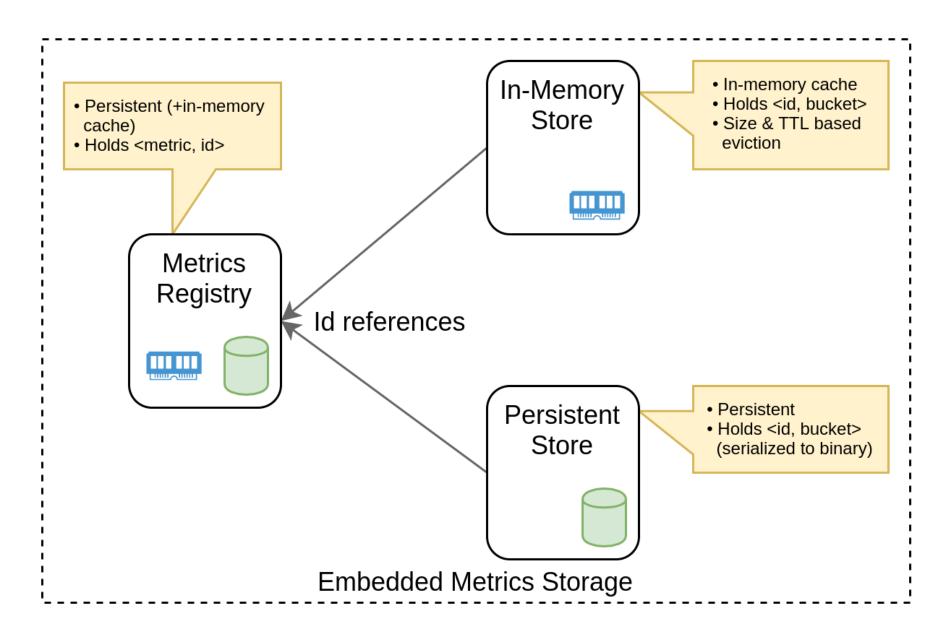


Item 3: data compression

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

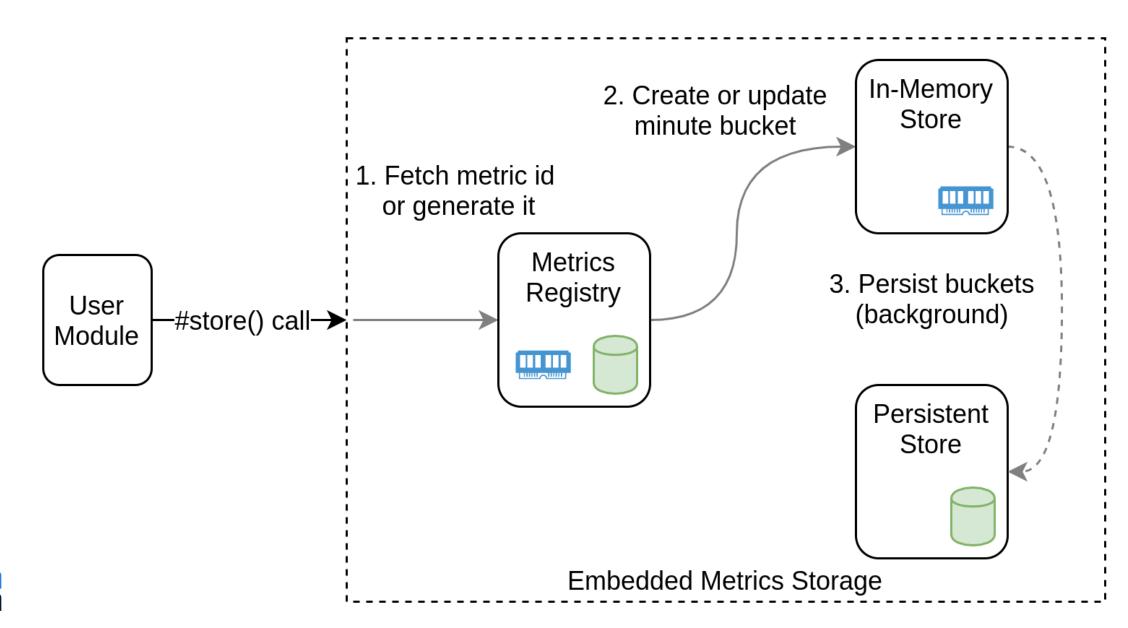


Overall design



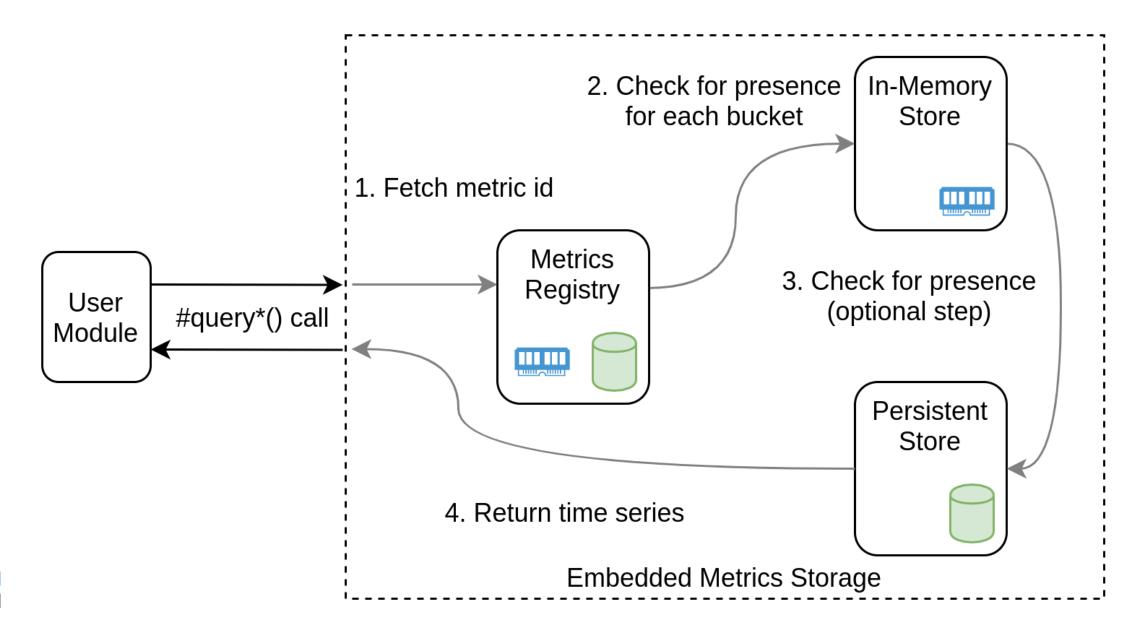


Writes





Reads





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

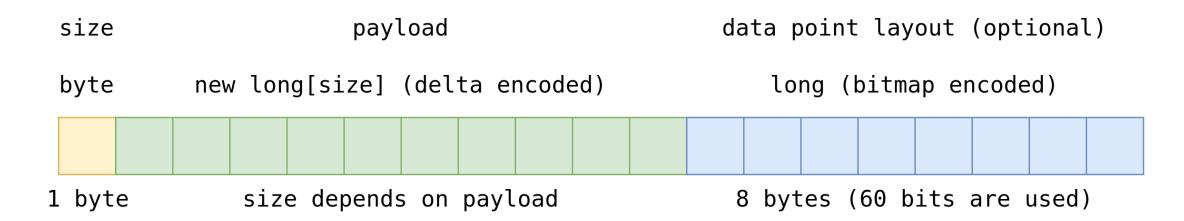


new key format

1532689094000@42



Data compression: values





Sample compressed value

payload data point layout

2 {10,+3} Ob1010...0



{10, Long.MIN_VALUE, 13, ..., Long.MIN_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
<pre>Inc long (3 sec; < byte)</pre>	160	55	x2.9
<pre>Inc long (3 sec; < short)</pre>	160	93	x1.7
Random long (3 sec)	160	170	x0.9



Disk cost of each data point

	Cost (bytes)
Raw	16*
Metrics 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

Simple benchmark

Scenario:

- Emulates 10 members, 120K metrics, 3 second interval
- Random values from 0-1000 range



Benchmark results*

- Write throughput:
 - 400K data point/sec
- Read throughput (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





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-2schema-design-best-practices



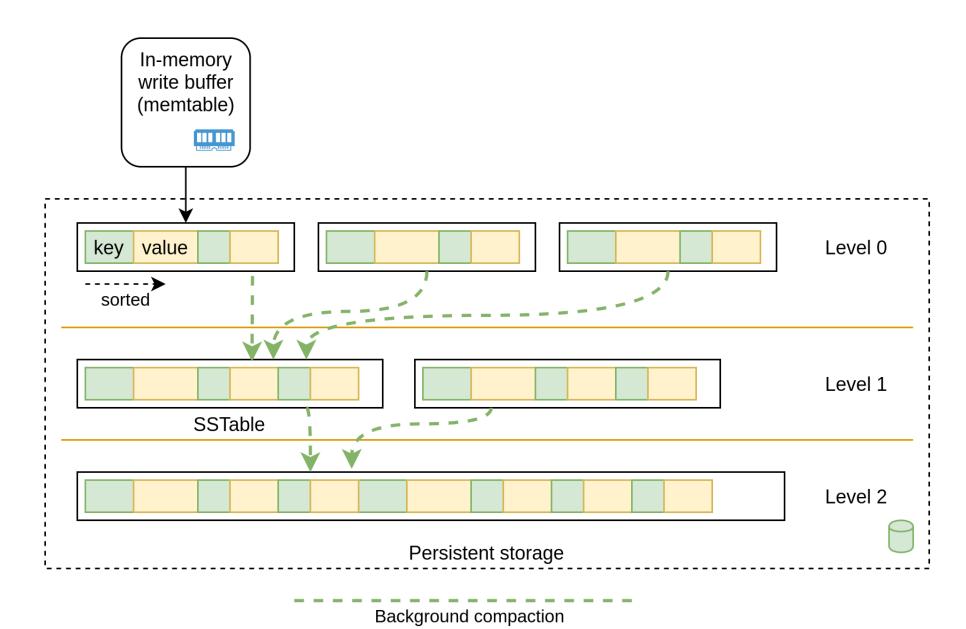


Column-oriented storage

	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	
				•

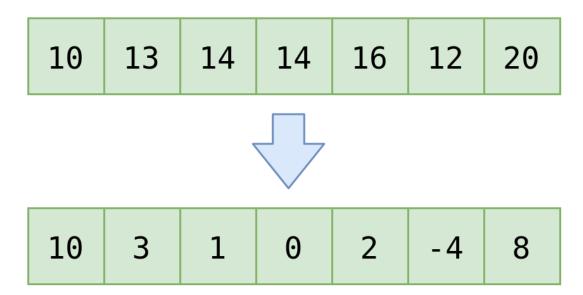


LSM tree



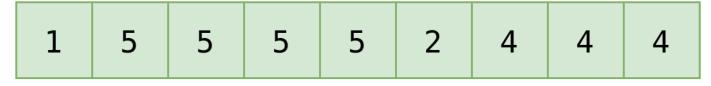


Delta encoding





Run-length encoding

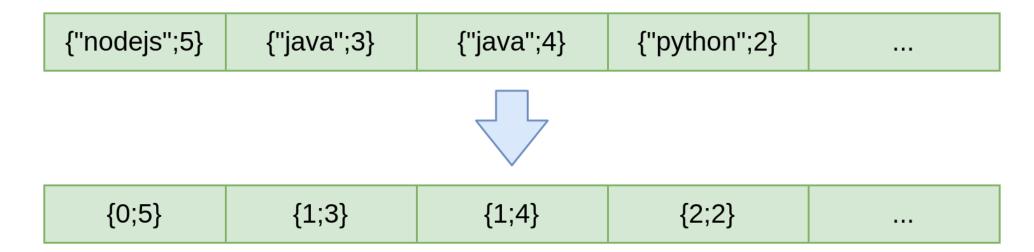




<i>{</i> 1;1 <i>} {</i> 4;5 <i>} {</i> 1;2 <i>} {</i> 3;4 <i>}</i>
--



Dictionary compression



```
dictionary

{
    0: "nodejs",
    1: "java",
    2: "python",
    ...
}
```



Bitmap encoding

City

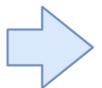
New York

Moscow

Moscow

Istanbul

. . .



New York

Moscow

Istanbul

Bitmap

1	0	0	0	
0	1	1	0	
0	0	0	1	



Row 1

