

# Tezos Context Lima Performance Audit

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## 1 Introduction

The Octez `tezos-context` package maintains an on-disk representation of Tezos blocks. It is implemented using Irmin and the purpose-built Irmin backend `irmin-pack`.

Performance of `tezos-context` is important for overall performance of Octez and previous improvements in `irmin-pack` have led to major performance improvements in Octez.

This report contains an audit of the `irmin-pack` storage backend used by Tezos Octez. We investigate the performance of individual sub-components as well as access patterns used by Tezos.

### 1.1 Overview of `irmin-pack`

Irmin is a content-addressable data store similar to Git. Data is stored in trees where nodes and leaves of the trees are identified by their cryptographic hash. At it's core Irmin is a store of content-addressed objects (nodes and leaves).

`irmin-pack` is a space-optimized Irmin backend inspired by Git packfiles that is currently used in Octez.

Conceptually `irmin-pack` stores content-addressed objects to an append-only file. A persistent datastructure called the index is used to map hashes to positions in the append-only file.

### 1.2 Methodology

If not noted all tests were run on StarLabs Starbook Mk VI with a AMD Ryzen 7 5800U and a PCIe-3 connected 960GiB SSD.

For replays a recording of 100000 blocks starting at block level 2981990 was used.

We use the `fio` tool to simulate disk access patterns and measure performance. A baseline, based on observed access patterns of `irmin-pack` is provided in the section Baseline `fio` job.

## 2 Sub-components

### 2.1 Index

The index is a persistent datastructure that maps the hash of an object to its offset in the append-only pack file.

Since Irmin version 3.0.0 objects in the pack file hold direct references to other objects in the pack file [irmin #1659] this removes the necessity to always query the index when traversing objects. This also allows a smaller index as now only top-level objects (i.e. commits) need to be in the index [irmin #1664]. This is called **minimal** indexing and has allowed considerable performance improvements for the Octez storage layer.

The index datastructure is split into two major parts: the log and the data. The log is a small and bounded structure that holds recently-added bindings. The log is kept in memory after initialization. The data part holds older bindings. When a certain number of bindings are added to the log, the bindings are merged with the bindings in the data part. The datastructure is similar to a two-level Log-structured merge-tree.

The default number of bindings to keep in the log before moving them to the data part in Octez and in `irmin-pack` is set to 2500000.

#### 2.1.1 Archive node

Tezos archive nodes hold the full history since genesis. When using minimal indexing references to at most 2500000 commits/blocks are kept in the log of the index. In July 2022 the Tezos block chain reached that block height. So since at least July 2022 the index of archive nodes will also have a **data** part.

Archive nodes that were bootstrapped before the new minimal indexing strategy was adopted have many more entries in the index:

```
dune exec audits/index/count_bindings.exe -- inputs/archive-node-index/
```

```
Number of bindings in Index: 2036584177
```

Archive nodes bootstrapped before the new minimal indexing strategy was adopted use around 90GiB of space just for the index structure.

### 2.1.2 Rolling and full node

We observe that rolling and full nodes keep a default of 6 cycles which corresponds to about 98304 blocks (16834 blocks per cycle) or, in Irmin terminology, to about 98304 commits.

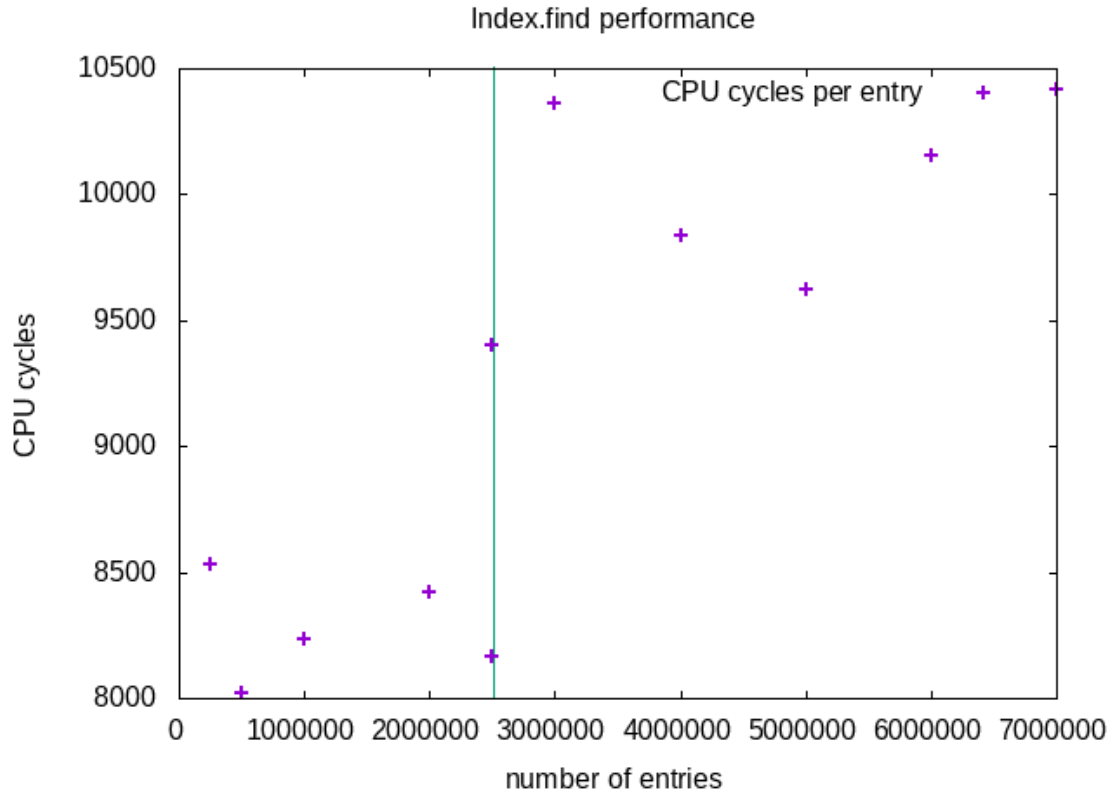
If for every commit a single index entry is maintained, rolling and full nodes will by default never create a data part and every index lookup performed is an in-memory operation.

However, currently entries in the index are never removed. So size of the index is not a function of the history mode and settings of the node, but the time since it was bootstrapped.

### 2.1.3 Find Performance

We measure the performance of index lookups by creating an empty index structure with same parameters as used in Tezos Octez (key size of 30 bytes, value size of 13 bytes and log size of 2500000), adding  $c$  random bindings and performing  $c$  lookups for random bindings. We use the LexiFi/landmarks library to measure performance in CPU cycles (as well as system time).

count	cpu time	sys time	cpu time per entry
250000	2132773826.000000	1.126439	8531.0953
500000	4009158441.000000	2.119049	8018.3169
1000000	8235106179.000000	4.351689	8235.1062
2000000	16838605030.000000	8.893822	8419.3025
2499999	20421445765.000000	10.791509	8168.5816
2500001	23511451504.000000	12.446721	9404.5768
3000000	31077192851.000000	16.442429	10359.064
4000000	39358430251.000000	20.823590	9839.6076
5000000	48122118368.000000	25.448949	9624.4237
6000000	60941841080.000000	32.247097	10156.974
7000000	72898690458.000000	38.564382	10414.099



We note a sharp increase in CPU cycles needed to lookup an entry when the number of bindings jumps over the log size (25000000). The lookup performance stays relatively constant at a higher level for up to 70000000 entries.

#### 2.1.4 Conclusion

With the currently implemented minimal indexing scheme no performance issues are expected when using the default Tezos Octez configurations. No considerable performance degradation is expected up to at least block level 70000000.

For nodes running in history modes `rolling` and `full` a mechanism should be implemented to remove entries for commits that were garbage collected, this would allow the index to remain a purely in-memory structure for such nodes.

Archive nodes that were bootstrapped using non-minimal indexing have a very large index structure. For better disk-usage it is recommended to re-bootstrap these nodes using minimal indexing.

## 2.2 Dict

Irmin stores values in a tree where paths are sequences of strings. In order to de-duplicate commonly occurring path segments, some path segments are stored in an auxiliary persistent structure called the `Dict`.

The `Dict` maintains a mapping from path segments (strings) to integer identifiers. In the Irmin tree the integer identifiers can be used instead of the string path segment. As integer identifiers are in general smaller than the string path segments this results in a more compact on-disk representation.

In `irmin-pack` the `Dict` is limited to 100000 entries that were added on a first-come-first-serve basis. The `Dict` is currently full.

### 2.2.1 Occurrences of Dict elements in store

We count the number of occurrences of path segments that appear in the `Dict` in the store of the Tezos block 3081990.

It seems like the some common path segments are de-duplicated a considerable amount of times:

Path segment	Occurrences in store
4a1cf11667fa0165eac9963333b883a80bcfdfebde09b79bfc740680e986bab6	108903
053f610929e2b6ea458c54dfd8b29716d379c13f5c8fd82d5c793a9e31271743	90893
00d0158265571a474bc6ed02547db51416ab2228327e66332117ea7b587aca94	13912
1ffdaf1cd7574b72f933a9d5e102143f3e4d761a6e51b4019ed821b7b99b097a	2313
04034e4a6228fdb92e8978fb85d9c2d1f79501b0c509f24b0fleede3ca7cb234	1611
10f21b2eacdf858cf9824d29e9c0d09bf666d3d900fbc54b6438f67e63831d4d	1157
2966fdb0cb953d94e959dcee2b2c3238c42bf0d1e0991a5a51609059aaa04080	890
1f33bf814d191cc602888479ef371d13082f19718f63737e685cc76110e323d9	813
02e5f95f2c3a3ccfa5ce71d0f11ad70f4746b8e0f3fe7bcecc63dbc8cfba71d1	731
438c52065d4605460b12d1b9446876a1c922b416103a20d44e994a9fd2b8ed07	477
00642bcad8681caf0f45f195cc1483f8366f155d83e272c9ff93fe3840a61dcb	396
4001852857ca1c5dad1c1275f766fc5208e63c48ba0289127591ffef3c440d53	388
27e1640238d07d569852b3e4fe784f5adce0e6649673ea587aa7389d72b855af	381

However we also note that most entries in the `Dict` do not occur in the store. We count 96394 `Dict` entries that do not occur in the store.

Furthermore, we observe that most entries in the `Dict` are hashes. Commonly used short keywords like `total_bytes`, `missed_endorsement` or `index` are not `Dict` entries.

### 2.2.2 Conclusion

We conclude that the `Dict` is underused. This observation has been previously made. A more efficient use of the `Dict` could lead to a considerably more compact on-disk representation and potential performance improvements. Note that existing `Dict` entries can not be removed and it might be tricky to get a performant `Dict` that is considerably larger. Furthermore, potential performance improvements seem hard to quantify.

We can not recommend any concrete measures for optimizing overall performance with improvements to the `Dict`.

## 3 Audits

### 3.1 IO Activity

In order to measure real disk IO accesses we add some instrumentation to `irmin-pack` that allows us to measure how many bytes are read/written to individual files in how many system calls. In addition we also trace calls to IO reads and writes using the `landmarks` library.

	Read	Write
Bytes in 100000 blocks	59141777410 (56%)	46354750320 (44%)
Bytes per block (mean)	591394.118	463528.962
Number of system calls per block (mean)	9645.864	4.061
Bytes per system call (mean)	61.310642	114141.58
Relative time	13.6%	0.4%
Relative time in I/O	96.5%	3.5%

We observe:

- Total I/O activity in bytes consists of about 56% reads and 44% writes. However, reads take 96.5% of the time <sup>1</sup>.
- Reads are performed in many very small chunks (in mean 61 bytes per system call).

As read performance dominates the overall performance we concentrate on it in the following.

---

<sup>1</sup>We measure this by tracing the `Irmin_pack_unix.Io.Util.really_read` and `Irmin_pack_unix.Io.Util.really_write` functions

### 3.1.1 Baseline fio job

Based on the observations we can create a baseline fio job description that simulates the read access pattern of irmin-pack:

```
[global]
rw=randread
filename=/home/adatario/dev/tclpa/.git/annex/objects/gx/17/SHA256E-s3691765475--13300581

[job1]
ioengine=psync
rw=randread
blocksize_range=50-100
size=591394B
loops=100
```

fio baseline-reads.ini

```
job1: (g=0): rw=randread, bs=(R) 50B-100B, (W) 50B-100B, (T) 50B-100B, ioengine=psync, i
fio-3.35
```

Starting 1 process

```
job1: (groupid=0, jobs=1): err= 0: pid=153129: Thu Jun 15 10:14:00 2023
```

```
read: IOPS=328k, BW=21.0MiB/s (22.1MB/s)(56.4MiB/2681msec)
```

```
clat (nsec): min=210, max=3742.4k, avg=2833.00, stdev=20598.76
```

```
lat (nsec): min=230, max=3743.1k, avg=2858.85, stdev=20605.58
```

```
clat percentiles (nsec):
```

```
| 1.00th=[ 211], 5.00th=[ 221], 10.00th=[ 221], 20.00th=[ 221],
| 30.00th=[ 231], 40.00th=[ 231], 50.00th=[ 231], 60.00th=[ 231],
| 70.00th=[ 241], 80.00th=[ 402], 90.00th=[ 410], 95.00th=[ 676],
| 99.00th=[150528], 99.50th=[158720], 99.90th=[191488], 99.95th=[230400],
| 99.99th=[329728]
```

```
bw ( KiB/s): min=20846, max=21922, per=99.73%, avg=21483.80, stdev=449.08, samples=5
```

```
iops      : min=317386, max=333862, avg=327161.20, stdev=6851.62, samples=5
```

```
lat (nsec) : 250=70.87%, 500=23.40%, 750=1.39%, 1000=1.64%
```

```
lat (usec) : 2=0.93%, 4=0.08%, 10=0.06%, 20=0.01%, 50=0.01%
```

```
lat (usec) : 250=1.59%, 500=0.03%, 750=0.01%, 1000=0.01%
```

```
lat (msec) : 4=0.01%
```

```
cpu      : usr=12.13%, sys=9.74%, ctx=14307, majf=0, minf=10
```

```
IO depths : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
```

```
submit    : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
```

```
complete  : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
```

```
issued rwts: total=879400,0,0,0 short=0,0,0,0 dropped=0,0,0,0
```

```
latency   : target=0, window=0, percentile=100.00%, depth=1
```



Run status group 0 (all jobs):

READ: bw=21.0MiB/s (22.1MB/s), 21.0MiB/s-21.0MiB/s (22.1MB/s-22.1MB/s), io=56.4MiB (5

Disk stats (read/write):

dm-1: ios=14145/0, merge=0/0, ticks=2116/0, in\_queue=2116, util=96.36%, aggrios=1430

dm-0: ios=14301/0, merge=0/0, ticks=2132/0, in\_queue=2132, util=95.57%, aggrios=1430

nvme0n1: ios=14301/0, merge=0/0, ticks=1539/0, in\_queue=1539, util=95.57%

We observe a read band-width of 21.0MiB/s which seems to match our observations.

## 3.2 Compactness of on-disk representation

Having a compact on-disk representation is not only good for disk usage but can also improve overall performance as data can be loaded into memory closer to the processor faster if it is smaller.

We analyze the compactness of the on-disk representation of **irmin-pack** by compressing with the Zstandard compression algorithm. Compact representation have a low compression ratio, whereas less compact representations may admit a more compact representation (for example by compressing with Zstandard).

Store	Uncompressed	Compressed	Compression Ratio
Level 2981990	5108531200	3265930512	1.5641886
Level 3081990	32111902720	10332988078	3.1077073
Single suffix from level 2981990	5101987840	3261700639	1.5642109
Single suffix from level 3081990	3633868800	940228651	3.8648778

There seems to be room to improve the compactness of the on-disk representation.

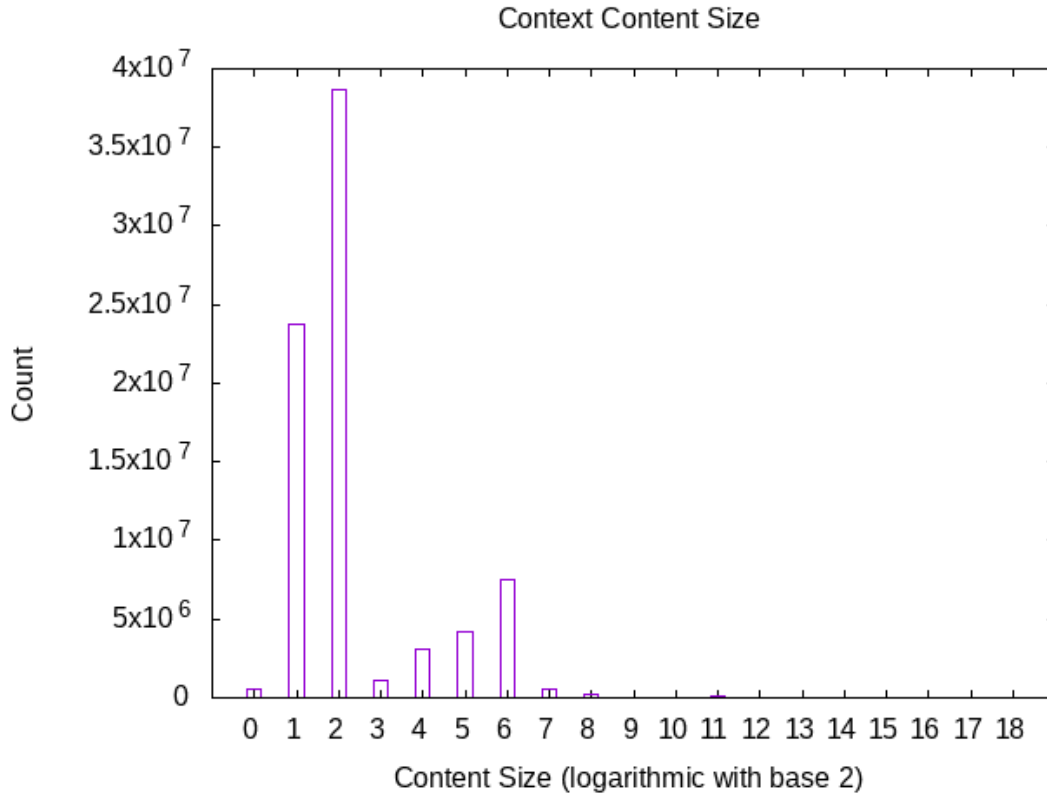
We can not explain the difference in compression rates between the stores of level 2981990 and 3081990.

## 3.3 Context structure and access patterns

### 3.3.1 Content Size distribution

Content Size (logarithmic with base 2)	Count
0	596661
1	23722650
2	38698770

Content Size (logarithmic with base 2)	Count
3	1125580
4	3131048
5	4194650
6	7477058
7	532486
8	194262
9	35410
10	35600
11	71535
12	4289
13	2583
14	260
15	9
16	1
17	3
18	7



We observe that the size of content in the Tezos store is very small.

### 3.3.2 Access Patterns

We perform some audits in order to understand what paths in the Tezos Context are accessed how frequently.

#### 1. Read Operations over 100000 blocks

We analyze the 10000 blocks starting at block level 2981990 and record what paths are accessed by read operations such as `Context.find_tree`, `Context.mem` or `Context.find`:

Path	Read operations *
contracts/global_counter	2121152
big_maps/index/347453/total_bytes	614589
big_maps/index/347455/total_bytes	614589
big_maps/index/347456/total_bytes	614589
big_maps/index/103258/total_bytes	79037
big_maps/index/149768/total_bytes	46549
endorsement_branch	40004
grand_parent_branch	40004
v1/constants	40004
v1/cycle_eras	40004
version	40004
big_maps/index/149787/total_bytes	32835
big_maps/index/149771/total_bytes	29009
big_maps/index/149772/total_bytes	29009
first_level_of_protocol	20002
votes/current_period	20000
big_maps/index/103260/total_bytes	19991
cycle/558/random_seed	16183
cycle/558/selected_stake_distribution	16183

We observe that certain paths are hit very often. The nodes on the commonly accessed paths should be kept in the `irmin-pack` LRU cache and should not incur any disk I/O.

#### 2. Operations in a single block

We also analyze a single block (block level 2981990), breaking down into categories of `mem`, `read`, and `write` operations. Here is the top 15, sorted by `read` and then `mem`.

Path	mem	read	write
contracts/index/0001f46d...63a0/balance	444	888	444

Path	mem	read	write
contracts/index/01e12d94...da00/used_bytes	222	443	222
contracts/index/0001f46d...63a0/delegate	0	443	0
contracts/global_counter	225	224	225
contracts/index/01e12d94...da00/len/storage	222	222	222
contracts/index/0001f46d...63a0/counter	222	222	222
contracts/index/01e12d94...da00/paid_bytes	222	221	222
contracts/index/01e12d94...da00/balance	0	221	0
big_maps/index/347456/total_bytes	111	110	111
big_maps/index/347455/total_bytes	111	110	111
big_maps/index/347453/total_bytes	111	110	111
big_maps/index/149776/contents/af067ef3...5bad/data	6	6	1
contracts/index/00006027...b77a/balance	3	6	3
big_maps/index/149776/contents/af067ef3...5bad/len	0	6	1
contracts/index/0002358c...8636/delegate_desactivation	0	5	2
...			
Total	2363	3892	3180

We note a symmetry in number of `mem` and `write` operations to certain paths.

### 3.4 CPU boundness

We run a replay of 100000 Tezos blocks with three different CPU frequencies:

- 3.40GHz: Run on an Equinix Metal `c3.small.x86` machine with an Intel® Xeon® E-2278G CPU with 8 cores running at 3.40 GHz.
- 2.5GHz: Run on an Equinix Metal `m3.large.x86` machine with an AMD EPYC 7502P CPU with 32 cores running at 2.5 GHz.
- 1.5GHz: Run on an Equinix Metal `m3.large.x86` machine with an AMD EPYC 7502P CPU with 32 cores at 1.5 GHz. The CPU frequency was set using `cpupower frequency-set 1.5GHz`.

CPU Frequency	3.40GHz	2.5GHz	1.5GHz
CPU time elapsed	73m27s	103m26s 141%	194m37s 265%
TZ-transactions per sec	1043.919	741.288 71%	393.969 38%
TZ-operations per sec	6818.645	4841.928 71%	2573.316 38%

This seems to indicate that `irmin-pack` is CPU-bound. Improving CPU efficiency should directly improve overall performance.

### 3.4.1 TODO Slow disk drive

Simulate very slow disk drives and observe performance.

## 4 Potential Improvements

### 4.1 Disable OS page cache

Operating systems implement their own cache mechanism for disk access. This can cause additional CPU cycles which are unnecessary as `irmin-pack.unix` implements it's own cache.

We can disable the operating system to cache blocks by using the `fcntl` system call with `FADV_NOREUSE`. This will prevent the operating system from maintaining blocks in cache, thus saving CPU cycles.

We can tell `fio` to do this with the `fcntl_hint` option:

```
[global]
rw=randread
filename=/home/adatario/dev/tclpa/.git/annex/objects/gx/17/SHA256E-s3691765475--133005811

[job1]
ioengine=psync
rw=randread
blocksize_range=50-100
size=591394B
loops=100
fcntl_hint=noreuse

fio fcntl-noreuse.ini

job1: (g=0): rw=randread, bs=(R) 50B-100B, (W) 50B-100B, (T) 50B-100B, ioengine=psync, i
fio-3.35
Starting 1 process

job1: (groupid=0, jobs=1): err= 0: pid=156889: Thu Jun 15 10:55:44 2023
read: IOPS=432k, BW=27.7MiB/s (29.1MB/s)(56.4MiB/2035msec)
  clat (nsec): min=210, max=3652.8k, avg=2107.02, stdev=18068.27
  lat (nsec): min=230, max=3653.4k, avg=2131.96, stdev=18076.02
  clat percentiles (nsec):
    | 1.00th=[ 211], 5.00th=[ 221], 10.00th=[ 221], 20.00th=[ 221],
    | 30.00th=[ 231], 40.00th=[ 231], 50.00th=[ 231], 60.00th=[ 231],
    | 70.00th=[ 241], 80.00th=[ 402], 90.00th=[ 410], 95.00th=[ 442],
```

```

| 99.00th=[121344], 99.50th=[152576], 99.90th=[224256], 99.95th=[254976],
| 99.99th=[346112]
bw (   KiB/s): min=27723, max=28868, per=99.72%, avg=28298.25, stdev=476.32, samples=4
iops          : min=422174, max=439618, avg=430933.00, stdev=7326.27, samples=4
lat (nsec)    : 250=71.97%, 500=24.01%, 750=1.26%, 1000=0.95%
lat (usec)    : 2=0.51%, 4=0.07%, 10=0.06%, 20=0.01%, 50=0.02%
lat (usec)    : 100=0.02%, 250=1.06%, 500=0.05%, 750=0.01%, 1000=0.01%
lat (msec)    : 4=0.01%
cpu           : usr=12.00%, sys=15.34%, ctx=10101, majf=0, minf=11
IO depths     : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
  submit      : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
  complete    : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
  issued rwts: total=879400,0,0,0 short=0,0,0,0 dropped=0,0,0,0
  latency     : target=0, window=0, percentile=100.00%, depth=1

```

Run status group 0 (all jobs):

```

READ: bw=27.7MiB/s (29.1MB/s), 27.7MiB/s-27.7MiB/s (29.1MB/s-29.1MB/s), io=56.4MiB (5

```

Disk stats (read/write):

```

dm-1: ios=11489/0, merge=0/0, ticks=1868/0, in_queue=1868, util=94.89%, aggrios=1230
dm-0: ios=12303/0, merge=0/0, ticks=2016/0, in_queue=2016, util=94.15%, aggrios=1230
nvme0n1: ios=12303/0, merge=0/0, ticks=1629/0, in_queue=1628, util=94.15%

```

We observe a read bandwidth of 27.7MiB/s. This seems to be a considerable performance improvement (around 30%) that can be implemented fairly easily.

## 4.2 Inline small objects

We note that the size of most content in the Tezos Context Store is very small (see Content Size distribution). These small pieces of content are stored in individual leaf nodes of the tree with their own hash, incurring a large overhead. An optimization would be to inline the small content into the parent node. Preliminary work towards this has already been done (see [mirage/irmin#884](#)).

## 4.3 Optimize tree descent

Access to content in Irmin requires descending a path. Every node on the path needs to be de-referenced, accessed from disk and unpacked individually. The cost for accessing a piece of content is a function of the path size. It might make sense to optimize the tree descent.

### 4.3.1 Flatten Path

Currently Otez uses Irmin with keys that are a list of string (a path). A potential optimization would be to use Irmin with keys that are only strings, i.e. use Irmin as a key-value store instead of a tree-based object storage. This would be a considerable change in how Otez uses Irmin.

The Irmin tree would be reduced to a single Node with many leaf node children. We would need to check if `irmin-pack` can support this. Related work includes the added support for large inodes ([mirage/irmin#807](#)).

### 4.3.2 Path Cache

We note that read accesses to the Tezos Context Store are focused on few paths (see Access Patterns).

The existing LRU cache in `irmin-pack` should prevent re-fetching these paths from the disk, increasing performance considerably. This is done by maintaining a mapping from position in pack file to tree object. When fetching a path, we need to sequentially iterate over the cache until we reach the object. This should be mostly in-memory operations as tree objects are cached. Still this incurs a lot of CPU cycles.

A potential optimization would be use a cache that maintains a mapping from path to tree object. When fetching a path that is cached, only a single lookup would be required to get the final tree object.

## 4.4 Optimize Tezos Storage Functors

Tezos usage of `irmin-pack` goes through the `tezos_context` library but also various storage functors implemented in the `tezos-protocol-015-PtLimaPt.environment`. This is where commonly appearing keywords like `index` or `total_bytes` are defined.

It may be possible that the way these storage functors use `irmin-pack` (indirectly via the `tezos_context` library) could be improved. In particular, it seems like many small files are created with long, nested paths. It may be more efficient to create larger files with shorter paths.

The performance characteristics of `irmin-pack` (and Irmin) seems to be closer to a file-system than a key-value store, whereas the way it is used from Tezos seems to be more like a key-value store.

It would also be interesting to investigate the observed symmetry between `mem` and `write` access as observed in section Operations in a single block.

## 4.5 Decrease system call overhead

Read performance seems to be bad because of the large amount of small reads that are performed with individual system calls. The system call overhead seems to be significant and reducing it should increase performance.

### 4.5.1 Batching Reads

Performance could be improved by batching read operations into larger blocks. For example if we use 4KiB blocks:

```
[global]
rw=randread
filename=/home/adatario/dev/tclpa/.git/annex/objects/gx/17/SHA256E-s3691765475--133005811

[job1]
ioengine=psync
rw=randread
blocksize=4KiB
size=591394B
loops=100

fio batching-reads.ini

job1: (g=0): rw=randread, bs=(R) 4000B-4000B, (W) 4000B-4000B, (T) 4000B-4000B, ioengine=
fio-3.35
Starting 1 process

job1: (groupid=0, jobs=1): err= 0: pid=10702: Fri Jun 16 10:32:29 2023
read: IOPS=8941, BW=34.1MiB/s (35.8MB/s)(56.1MiB/1644msec)
   clat (nsec): min=310, max=3684.8k, avg=110624.46, stdev=91545.42
   lat (nsec): min=330, max=3685.4k, avg=110715.69, stdev=91573.99
  clat percentiles (nsec):
    | 1.00th=[  422],  5.00th=[   628], 10.00th=[   820], 20.00th=[  1256],
    | 30.00th=[  3472], 40.00th=[122368], 50.00th=[134144], 60.00th=[142336],
    | 70.00th=[152576], 80.00th=[164864], 90.00th=[199680], 95.00th=[236544],
    | 99.00th=[317440], 99.50th=[415744], 99.90th=[667648], 99.95th=[700416],
    | 99.99th=[905216]
   bw (  KiB/s): min=32390, max=37875, per=100.00%, avg=34973.67, stdev=2756.26, samples=3
   iops        : min= 8292, max= 9696, avg=8953.33, stdev=705.52, samples=3
  lat (nsec)   : 500=2.02%, 750=6.08%, 1000=6.39%
  lat (usec)   : 2=11.84%, 4=4.03%, 10=1.27%, 20=0.33%, 50=0.01%
  lat (usec)   : 100=0.06%, 250=64.49%, 500=3.18%, 750=0.27%, 1000=0.02%
  lat (msec)   : 4=0.01%
```



```

cpu          : usr=1.58%, sys=7.00%, ctx=10010, majf=0, minf=11
IO depths    : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
  submit     : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
  complete   : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
  issued rwts: total=14700,0,0,0 short=0,0,0,0 dropped=0,0,0,0
  latency    : target=0, window=0, percentile=100.00%, depth=1

```

Run status group 0 (all jobs):

```

  READ: bw=34.1MiB/s (35.8MB/s), 34.1MiB/s-34.1MiB/s (35.8MB/s-35.8MB/s), io=56.1MiB (56.1MB)

```

Disk stats (read/write):

```

  dm-1: ios=8537/0, merge=0/0, ticks=1280/0, in_queue=1280, util=93.46%, aggrrios=10000/0
  dm-0: ios=10000/0, merge=0/0, ticks=1496/0, in_queue=1496, util=93.96%, aggrrios=10000/0
  nvme0n1: ios=10000/0, merge=0/0, ticks=1149/0, in_queue=1149, util=93.90%

```

We observe a read bandwidth of 34.1MiB/s (a 60% performance improvement to the baseline). However, it is not clear how reads could be batched without major re-organization of the on-disk representation.

#### 4.5.2 Memory-mapped reads

Another strategy is to memory-map files for reads. This reduces the amount of system calls drastically as database files are accessible via regular memory access.

However, there are well known issues with memory-mapping files (see [Are You Sure You Want to Use MMAP in Your Database Management System?](#)) that need to be evaluated and weighed in light of potential performance improvements.

### 4.6 Multicore

In order to simulate the potential performance improvement of using multiple cores we use a `fio` job similar to the baseline but instead use `N` cores that in total read the same amount of bytes:

```

[global]
rw=randread
filename=/home/adatario/dev/tclpa/.git/annex/objects/gx/17/SHA256E-s3691765475--13300581
loops=100
group_reporting
thread

[job1]
ioengine=psync

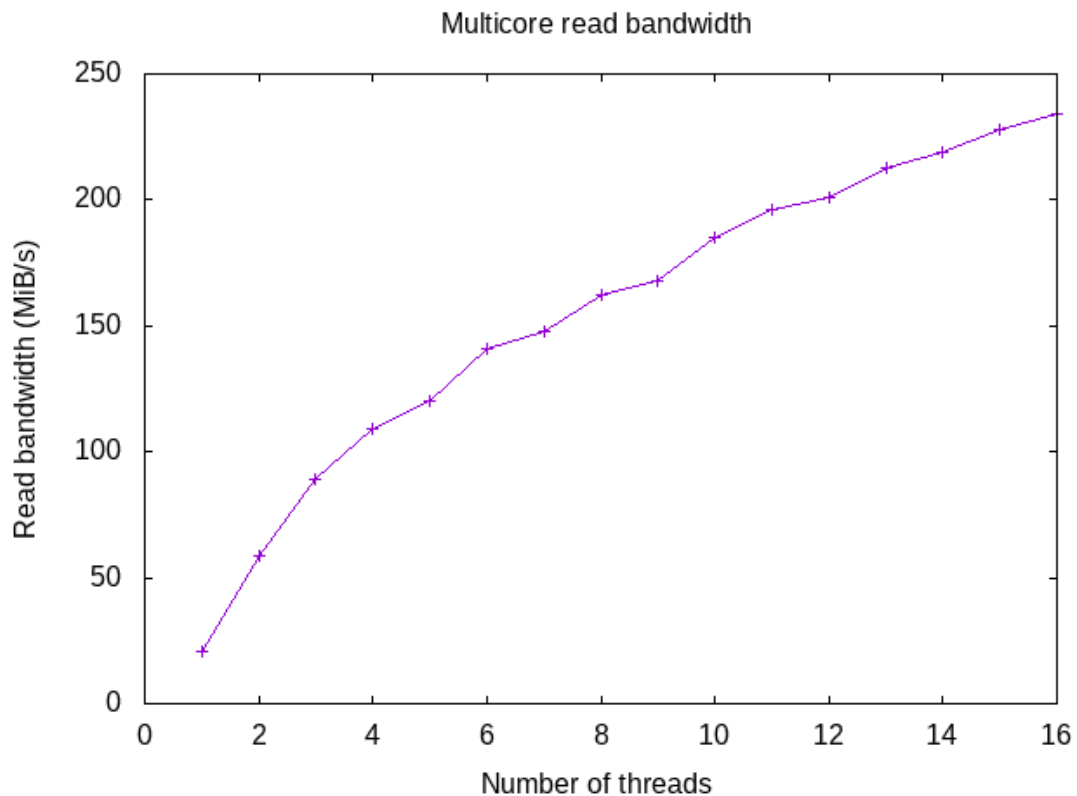
```

```
rw=randread
blocksize_range=50-100
size=591394 / N
numjobs=N
```

Using the options `thread` and `numjobs` we create N threads that randomly read from the file.

We observe following read bandwidths:

Number of Threads	Read bandwidth (MiB/s)
1	21
2	58.8
3	89.4
4	109
5	120
6	141
7	148
8	162
9	168
10	185
11	196
12	201
13	213
14	219
15	228
16	234



Increasing the number of threads/CPU cores utilized seems to lead to considerable performance improvements.

Note however, that we simulate  $N$  independent threads. In `irmin-pack`, and Irmin in general, reads may need to be sequential as they descend a tree by de-referencing nodes individually.

## 4.7 Modern hardware and asynchronous I/O

Modern PCIe-attached solid-state drives (SSDs) offer high throughput and large capacity at low cost. They are exposed to the system using the same block-based APIs as traditional disks or SSDs attached via serial buses. However, in order to utilize the full performance of modern hardware, the way I/O operations are performed needs to be changed.

In order to illustrate the capabilities of modern hardware we run `fio` using the Linux `io_uring` API. This allows asynchronous I/O operations. We also increase size of the blocks read from a few bytes to 64KiB. This increases latency for individual reads, but allows much higher bandwidth.

```

[global]
rw=randread
filename=/home/adatario/dev/tclpa/.git/annex/objects/gx/17/SHA256E-s3691765475--13300581
loops=100
group_reporting
thread

[job1]
ioengine=io_uring
iodepth=16
rw=randread
blocksize=64KiB
size=100MiB
numjobs=8

fio read-io_uring.ini

job1: (g=0): rw=randread, bs=(R) 62.5KiB-62.5KiB, (W) 62.5KiB-62.5KiB, (T) 62.5KiB-62.5KiB
...
fio-3.33
Starting 8 threads

job1: (groupid=0, jobs=8): err= 0: pid=44365: Fri May 19 14:25:25 2023
read: IOPS=147k, BW=8955MiB/s (9390MB/s)(74.5GiB/8517msec)
  slat (nsec): min=290, max=9700.4k, avg=9392.25, stdev=73806.67
  clat (nsec): min=130, max=23784k, avg=767189.99, stdev=1005905.48
    lat (usec): min=4, max=23786, avg=776.58, stdev=1007.13
      clat percentiles (usec):
        | 1.00th=[ 17], 5.00th=[ 30], 10.00th=[ 43], 20.00th=[ 62],
        | 30.00th=[ 83], 40.00th=[ 125], 50.00th=[ 215], 60.00th=[ 400],
        | 70.00th=[ 914], 80.00th=[ 1795], 90.00th=[ 2278], 95.00th=[ 2606],
        | 99.00th=[ 3884], 99.50th=[ 4490], 99.90th=[ 6390], 99.95th=[ 7439],
        | 99.99th=[10028]
      bw ( MiB/s): min= 7688, max=10172, per=100.00%, avg=9047.06, stdev=83.12, samples=129
      iops       : min=125968, max=166674, avg=148226.72, stdev=1361.83, samples=129
      lat (nsec)  : 250=0.01%, 500=0.01%, 750=0.01%, 1000=0.01%
      lat (usec)  : 2=0.01%, 4=0.02%, 10=0.10%, 20=1.72%, 50=11.80%
      lat (usec)  : 100=21.71%, 250=17.36%, 500=10.21%, 750=4.71%, 1000=3.36%
      lat (msec)  : 2=12.41%, 4=15.67%, 10=0.88%, 20=0.01%, 50=0.01%
      cpu         : usr=2.68%, sys=14.62%, ctx=559563, majf=0, minf=0
      IO depths   : 1=0.1%, 2=0.1%, 4=0.3%, 8=0.5%, 16=99.0%, 32=0.0%, >=64=0.0%
        submit    : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
        complete   : 0=0.0%, 4=99.9%, 8=0.0%, 16=0.1%, 32=0.0%, 64=0.0%, >=64=0.0%
        issued rwts: total=1249600,0,0,0 short=0,0,0,0 dropped=0,0,0,0

```

```
latency    : target=0, window=0, percentile=100.00%, depth=16
```

Run status group 0 (all jobs):

```
READ: bw=8955MiB/s (9390MB/s), 8955MiB/s-8955MiB/s (9390MB/s-9390MB/s), io=74.5GiB (8
```

Disk stats (read/write):

```
dm-1: ios=345735/95, merge=0/0, ticks=597292/4, in_queue=597296, util=98.72%, aggr
```

```
dm-0: ios=349972/95, merge=0/0, ticks=599656/4, in_queue=599660, util=98.56%, aggr
```

```
nvme0n1: ios=349972/87, merge=0/8, ticks=542294/6, in_queue=542303, util=97.77%
```

We observe a read bandwidth of about 8955MiB/s this is an improvement of more than 40000% compared to the baseline. Note that this is pure I/O read bandwidth without any data management.

On-going research is investigating how the performance of such hardware can be used in database systems (see LeanStore: In-Memory Data Management Beyond Main Memory). We note that the main ingredients for doing this in the OCaml ecosystem are present or are being actively worked on: OCaml 5 with Multicore support and Algebraic Effects as well as the eio library. The question seems to be: What Are You Waiting For? Use Coroutines for Asynchronous I/O to Hide I/O Latencies and Maximize the Read Bandwidth!

## 5 Conclusion

In this report we have identified storage performance bottlenecks of Irmin and `irmin-pack` as used by Octez and propose potential improvements.

A selection of proposed improvements is provided in the following table:

Description	Potential improvement <sup>2</sup>	Effort	On-disk format
Disable OS page cache	30%	Low	No change
Path Cache	-	Medium	No change
Inline small objects	-	High	Change
General CPU efficiency improvments	-	High	Potential change
More compact on-disk representation	-	High	Change
Optimize Tezos Storage Functors	-	High	No change
Multicore	700%	Very high	No change
Asynchronous I/O	40000%	Epic	Change

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<sup>2</sup>On raw I/O bandwidth