Where did my memory go?

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PostgreSQL relies on the OS for memory

In most cases 'the OS' will be Linux.

Linux memory usage can be seen in many ways.

A common way is: /proc/meminfo

```
[vagrant@pg15 ~]$ cat /proc/meminfo
MemTotal:        1856020 kB
MemFree:         1471340 kB
MemAvailable:    1555788 kB
Buffers:            4204 kB
Cached:           203252 kB
SwapCached:            0 kB
Active:            60820 kB
Inactive:         215696 kB
Active(anon):        784 kB
Inactive(anon):    76888 kB
Active(file):      60036 kB
Inactive(file):   138808 kB
Unevictable:           0 kB
Mlocked:               0 kB
SwapTotal:       2154492 kB
SwapFree:        2154492 kB
Dirty:                32 kB
Writeback:             0 kB
AnonPages:         69064 kB
Mapped:            93892 kB
Shmem:              8612 kB
KReclaimable:      33040 kB
Slab:              68128 kB
SReclaimable:      33040 kB
SUnreclaim:        35088 kB
KernelStack:        2224 kB
PageTables:         5856 kB
NFS_Unstable:          0 kB
Bounce:                0 kB
WritebackTmp:          0 kB
CommitLimit:     3082500 kB
Committed_AS:     324464 kB
VmallocTotal:   34359738367 kB
VmallocUsed:           0 kB
VmallocChunk:          0 kB
Percpu:              992 kB
HardwareCorrupted:     0 kB
AnonHugePages:     14336 kB
ShmemHugePages:        0 kB
ShmemPmdMapped:        0 kB
FileHugePages:         0 kB
FilePmdMapped:         0 kB
HugePages_Total:       0
HugePages_Free:        0
HugePages_Rsvd:        0
HugePages_Surp:        0
Hugepagesize:       2048 kB
Hugetlb:               0 kB
DirectMap4k:       90048 kB
DirectMap2M:     2007040 kB
```

PostgreSQL relies on the OS for memory

Problem: lots of entries.

/proc/meminfo is a motley gathering of memory related statistics.

Multiple views: (in)active, file/anon, memory/swap, hugepages (pages!), virtual, etc.

```
[vagrant@pg15 ~]$ cat /proc/meminfo
MemTotal:        1856020 kB
MemFree:         1471340 kB
MemAvailable:    1555788 kB
Buffers:            4204 kB
Cached:           203252 kB
SwapCached:            0 kB
Active:            60820 kB
Inactive:         215696 kB
Active(anon):        784 kB
Inactive(anon):    76888 kB
Active(file):      60036 kB
Inactive(file):   138808 kB
Unevictable:           0 kB
Mlocked:               0 kB
SwapTotal:       2154492 kB
SwapFree:        2154492 kB
Dirty:                32 kB
Writeback:             0 kB
AnonPages:         69064 kB
Mapped:            93892 kB
Shmem:              8612 kB
KReclaimable:      33040 kB
Slab:              68128 kB
SReclaimable:      33040 kB
SUnreclaim:        35088 kB
KernelStack:        2224 kB
PageTables:         5856 kB
NFS_Unstable:          0 kB
Bounce:                0 kB
WritebackTmp:          0 kB
CommitLimit:     3082500 kB
Committed_AS:     324464 kB
VmallocTotal:   34359738367 kB
VmallocUsed:           0 kB
VmallocChunk:          0 kB
Percpu:              992 kB
HardwareCorrupted:     0 kB
AnonHugePages:     14336 kB
ShmemHugePages:        0 kB
ShmemPmdMapped:        0 kB
FileHugePages:         0 kB
FilePmdMapped:         0 kB
HugePages_Total:       0
HugePages_Free:        0
HugePages_Rsvd:        0
HugePages_Surp:        0
Hugepagesize:       2048 kB
Hugetlb:               0 kB
DirectMap4k:       90048 kB
DirectMap2M:     2007040 kB
```

Linux allows memory oversubscription

Setting: `vm.overcommit_memory`

Default: 0 (heuristic overcommit) -> OOM killer.

Best: 2 (don't overcommit) -> Error on memory allocation (single backend).

Test!

Linux - meminfo - Memory hierarchy v1.0

Virtual Memory (not a statistic)

- MemTotal
  - MemFree
  - Slab
  - PageTables
  - KernelStack
  - SwapCached
  - AnonPages
  - Cached
    - Mapped
      - Shmem (SysV /dev/zero mmapped)
    - Dirty
- SwapTotal
  - SwapFree

Linux - meminfo - Memory hierarchy v1.0

Virtual Memory (not a statistic)

MemTotal

MemFree

Slab

PageTables

KernelStack

SwapCached

AnonPages

Cached

Mapped

Shmem (SysV /dev/zero mmapped)

Dirty

SwapTotal

SwapFree

Linux - meminfo - Memory hierarchy v1.0

Virtual Memory (not a statistic)

MemTotal

MemFree

Slab

PageTables

KernelStack

SwapCached

AnonPages

Cached

Mapped

Shmem (SysV /dev/zero mmapped)

Dirty

SwapTotal

SwapFree

Linux - meminfo - Memory hierarchy v1.0

Virtual Memory (not a statistic)

MemTotal

MemFree

Slab

PageTables

KernelStack

SwapCached

AnonPages

Cached

Mapped

Shmem (SysV /dev/zero mmapped)

Dirty

SwapTotal

SwapFree

Linux - meminfo - Memory hierarchy v1.0

Linux - meminfo - Memory hierarchy v1.0

Virtual Memory (not a statistic)

MemTotal

MemFree

Slab

PageTables

KernelStack

SwapCached

AnonPages

Cached

Mapped

Shmem (SysV /dev/zero mmapped -- ??)

Dirty

SwapTotal

SwapFree

Linux - meminfo - Memory hierarchy v1.0

Virtual Memory (not a statistic)

MemTotal

MemFree

Slab

PageTables

KernelStack

SwapCached

AnonPages

Cached

Mapped

Shmem (SysV /dev/zero mmapped)

Dirty

SwapTotal

SwapFree

Linux - meminfo - Memory hierarchy v1.0

Virtual Memory (not a statistic)

MemTotal

MemFree

Slab

PageTables

KernelStack

SwapCached

AnonPages

Cached

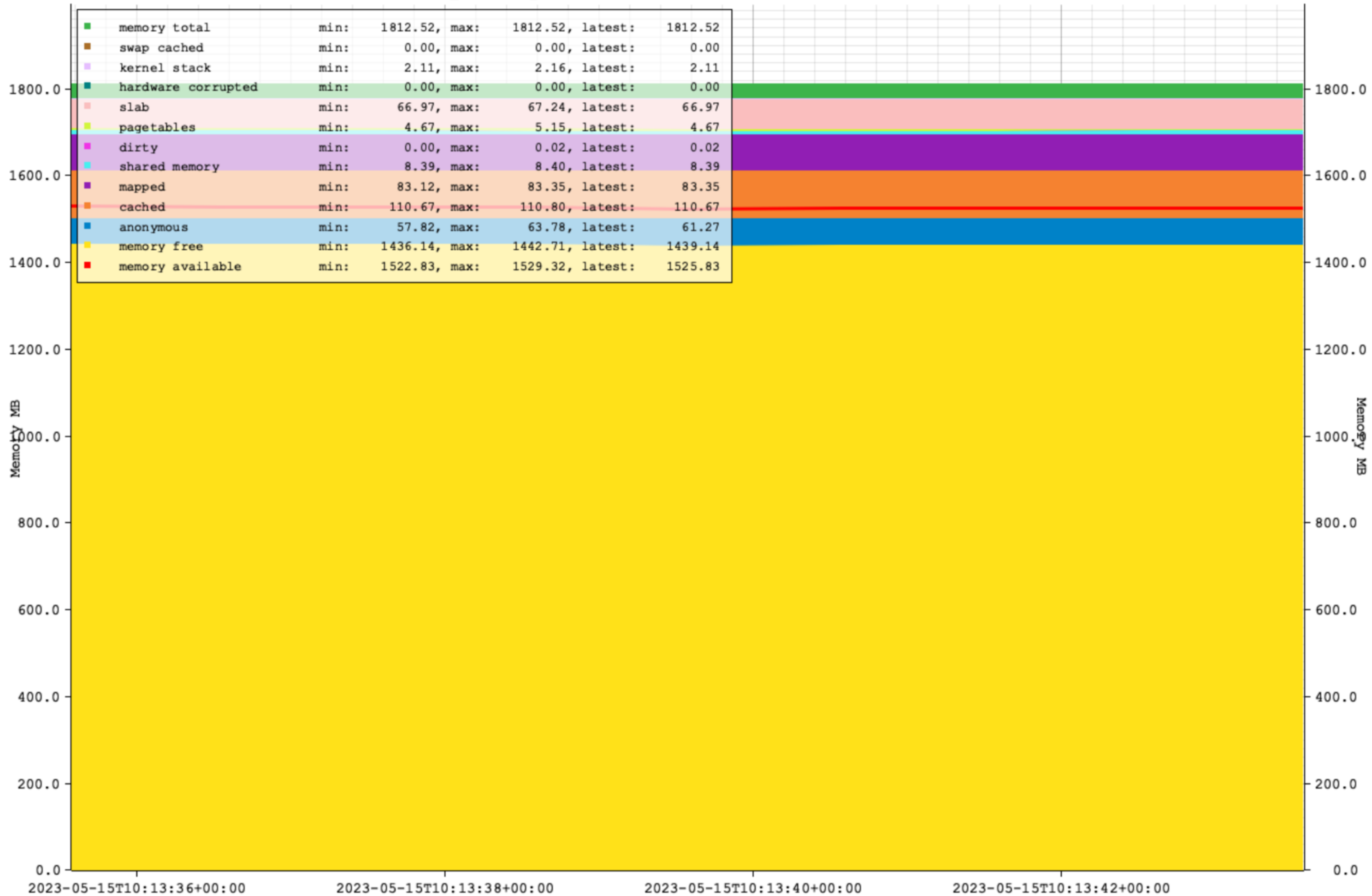
Mapped

Shmem (SysV /dev/zero mmapped)

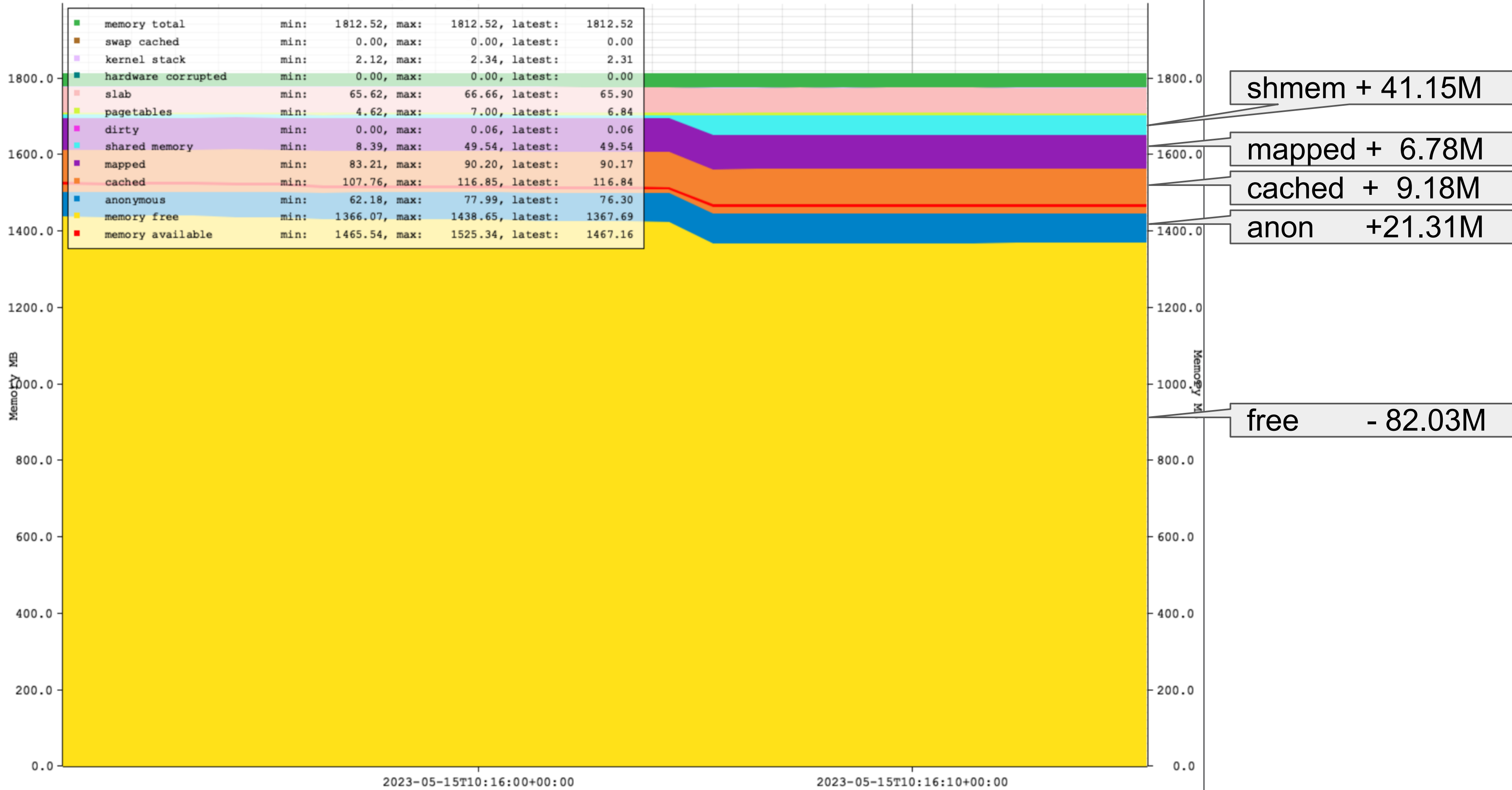
Dirty

SwapTotal

SwapFree



Memory usage: 192.168.66.100:9300:metrics
memory total min: 1812.52, max: 1812.52, latest: 1812.52
swap cached min: 0.00, max: 0.00, latest: 0.00
kernel stack min: 2.11, max: 2.16, latest: 2.11
hardware corrupted min: 0.00, max: 0.00, latest: 0.00
slab min: 66.97, max: 67.24, latest: 66.97
pagetables min: 4.67, max: 5.15, latest: 4.67
dirty min: 0.00, max: 0.02, latest: 0.02
shared memory min: 8.39, max: 8.40, latest: 8.39
mapped min: 83.12, max: 83.35, latest: 83.35
cached min: 110.67, max: 110.80, latest: 110.67
anonymous min: 57.82, max: 63.78, latest: 61.27
memory free min: 1436.14, max: 1442.71, latest: 1439.14
memory available min: 1522.83, max: 1529.32, latest: 1525.83
Memory MB
2023-05-15T10:13:36+00:00
2023-05-15T10:13:38+00:00
2023-05-15T10:13:40+00:00
2023-05-15T10:13:42+00:00



Memory usage: 192.168.66.100:9300:metrics
memory total min: 1812.52, max: 1812.52, latest: 1812.52
swap cached min: 0.00, max: 0.00, latest: 0.00
kernel stack min: 2.12, max: 2.34, latest: 2.31
hardware corrupted min: 0.00, max: 0.00, latest: 0.00
slab min: 65.62, max: 66.66, latest: 65.90
pagetables min: 4.62, max: 7.00, latest: 6.84
dirty min: 0.00, max: 0.06, latest: 0.06
shared memory min: 8.39, max: 49.54, latest: 49.54
mapped min: 83.21, max: 90.20, latest: 90.17
cached min: 107.76, max: 116.85, latest: 116.84
anonymous min: 62.18, max: 77.99, latest: 76.30
memory free min: 1366.07, max: 1438.65, latest: 1367.69
memory available min: 1465.54, max: 1525.34, latest: 1467.16
Memory MB
2023-05-15T10:16:00+00:00
2023-05-15T10:16:10+00:00
shmem + 41.15M
mapped + 6.78M
cached + 9.18M
anon +21.31M
free - 82.03M

The shared memory segment from 'smaps':

```
7f5187787000-7f51ca8d3000 rw-s 00000000 00:01 33813                      /dev/zero (deleted)
Size:            1099056 kB
KernelPageSize:        4 kB
MMUPageSize:           4 kB
Rss:               41012 kB
Pss:               26659 kB
Shared_Clean:          0 kB
Shared_Dirty:      25540 kB
Private_Clean:         0 kB
Private_Dirty:     15472 kB
Referenced:        41012 kB
Anonymous:             0 kB
LazyFree:              0 kB
AnonHugePages:         0 kB
ShmemPmdMapped:        0 kB
FilePmdMapped:         0 kB
Shared_Hugetlb:        0 kB
Private_Hugetlb:       0 kB
Swap:                  0 kB
SwapPss:               0 kB
Locked:                0 kB
THPeligible:    0
VmFlags: rd wr sh mr mw me ms sd
```

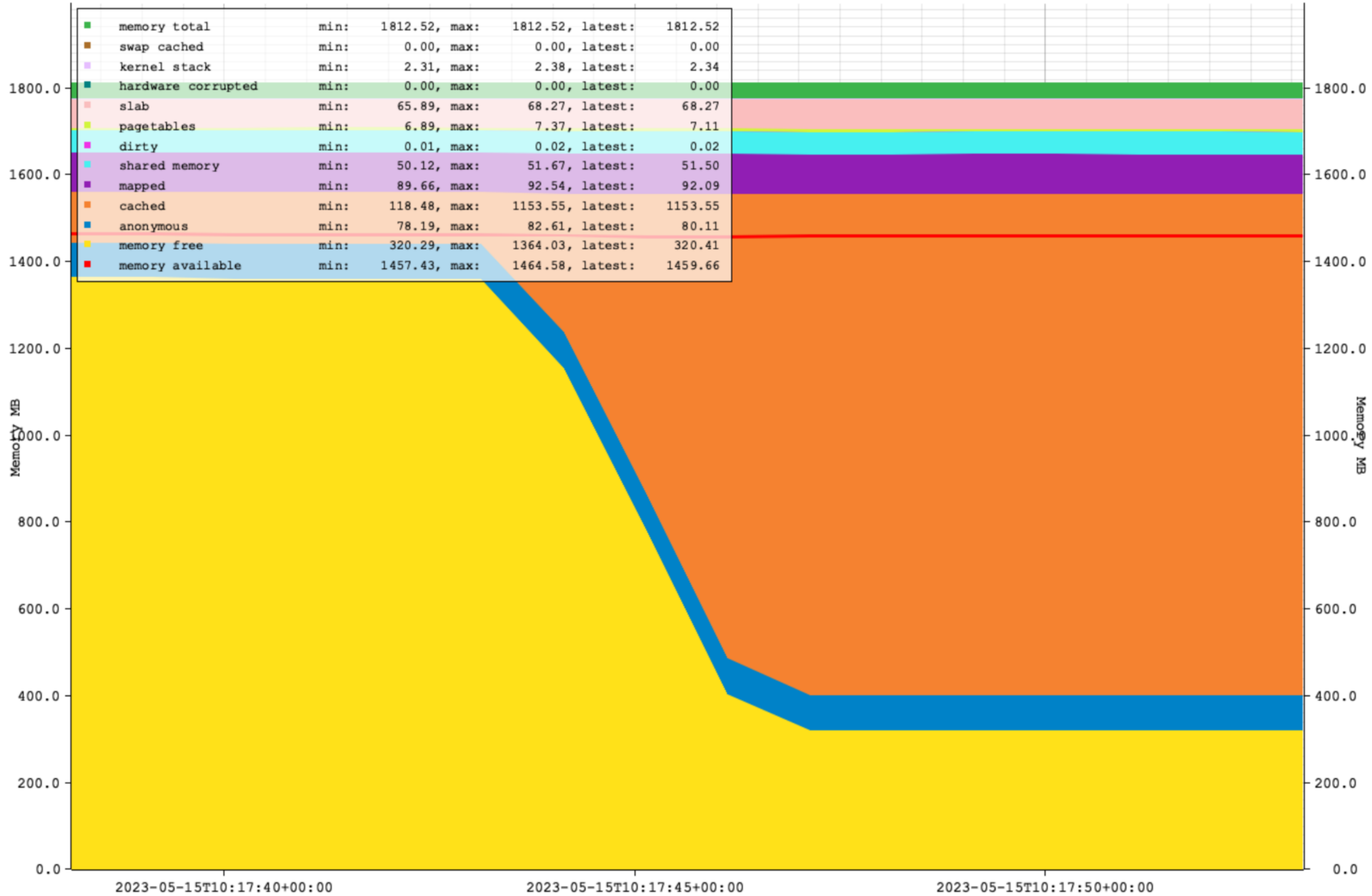
Let's test!

```
-- precreated table:
create table t( id int primary key, f1 text);
insert into t select id, repeat('x',16384) from generate_series(1,4500000) id;

-- table size
postgres=# \dt+ t
                                   List of relations
 Schema | Name | Type  |  Owner   | Persistence | Access method |  Size   | Description
--------+------+-------+----------+-------------+---------------+---------+-------------
 public | t    | table | postgres | permanent   | heap          | 1034 MB |
-- index size
postgres=# \di+ t_pkey
                                       List of relations
 Schema |  Name  | Type  |  Owner   | Table | Persistence | Access method | Size  | Description
--------+--------+-------+----------+-------+-------------+---------------+-------+-------------
 public | t_pkey | index | postgres | t     | permanent   | btree         | 96 MB |
```

1. Force seq scan

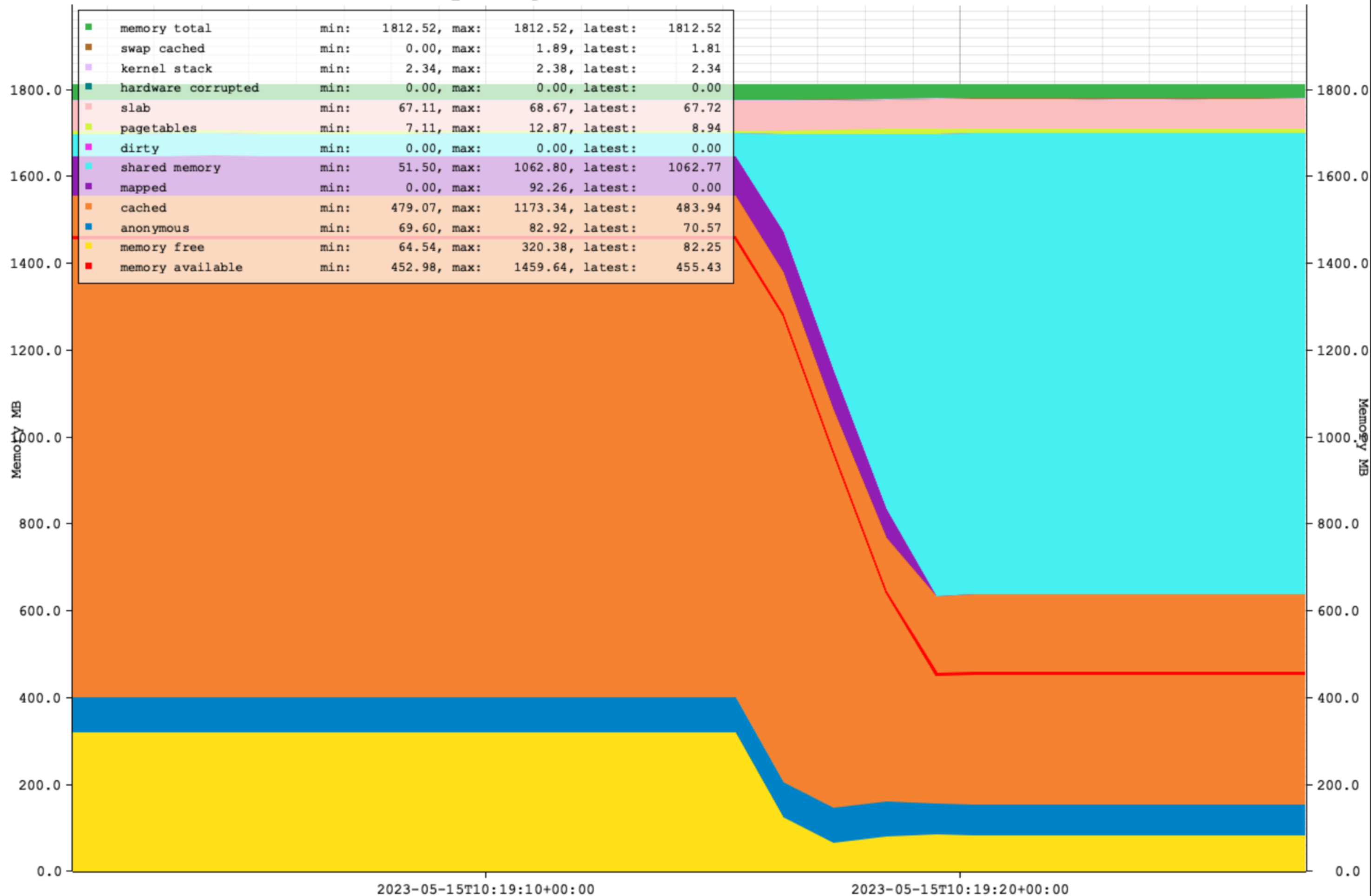
```
explain analyze select count(f1) from t;
                                                                 QUERY PLAN
------------------------------------------------------------------------------------------------
 Finalize Aggregate  (cost=156790.72..156790.73 rows=1 width=8) (actual time=2395.054..2403.280 rows=1 loo
   ->  Gather  (cost=156790.50..156790.71 rows=2 width=8) (actual time=2394.649..2403.272 rows=3 loops=1)
         Workers Planned: 2
         Workers Launched: 2
         ->  Partial Aggregate  (cost=155790.50..155790.51 rows=1 width=8) (actual time=2367.083..2367.08
               ->  Parallel Seq Scan on t  (cost=0.00..151103.00 rows=1875000 width=200) (actual time=0.6
 Planning Time: 7.306 ms
 Execution Time: 2403.614 ms
(8 rows)
```



Memory usage: 192.168.66.100:9300:metrics
memory total min: 1812.52, max: 1812.52, latest: 1812.52
swap cached min: 0.00, max: 0.00, latest: 0.00
kernel stack min: 2.31, max: 2.38, latest: 2.34
hardware corrupted min: 0.00, max: 0.00, latest: 0.00
slab min: 65.89, max: 68.27, latest: 68.27
pagetables min: 6.89, max: 7.37, latest: 7.11
dirty min: 0.01, max: 0.02, latest: 0.02
shared memory min: 50.12, max: 51.67, latest: 51.50
mapped min: 89.66, max: 92.54, latest: 92.09
cached min: 118.48, max: 1153.55, latest: 1153.55
anonymous min: 78.19, max: 82.61, latest: 80.11
memory free min: 320.29, max: 1364.03, latest: 320.41
memory available min: 1457.43, max: 1464.58, latest: 1459.66
Memory MB
2023-05-15T10:17:40+00:00
2023-05-15T10:17:45+00:00
2023-05-15T10:17:50+00:00

2. Force index scan

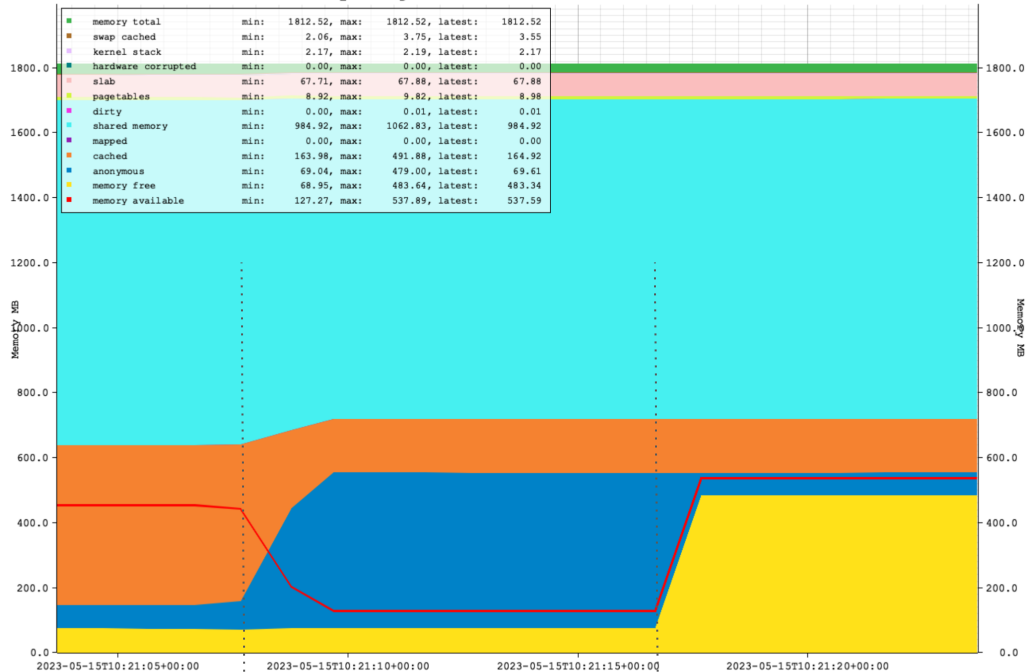
```
set enable_seqscan=off;
explain analyze select count(f1) from t where id > 0;
                                                          QUERY PLAN
-------------------------------------------------------------------------------------------------------
 Index Scan using t_pkey on t  (cost=0.43..260474.43 rows=4500000 width=204) (actual time=0.036..4414.006
   Index Cond: (id > 0)
 Planning Time: 6.661 ms
 Execution Time: 4716.215 ms
(4 rows)
```



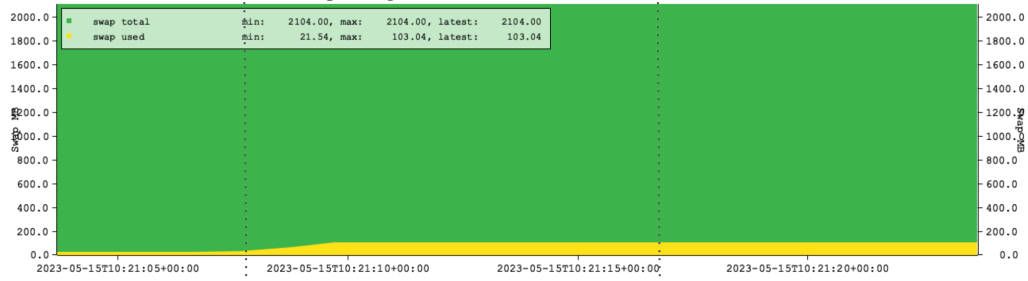
Memory usage: 192.168.66.100:9300:metrics
memory total min: 1812.52, max: 1812.52, latest: 1812.52
swap cached min: 0.00, max: 1.89, latest: 1.81
kernel stack min: 2.34, max: 2.38, latest: 2.34
hardware corrupted min: 0.00, max: 0.00, latest: 0.00
slab min: 67.11, max: 68.67, latest: 67.72
pagetables min: 7.11, max: 12.87, latest: 8.94
dirty min: 0.00, max: 0.00, latest: 0.00
shared memory min: 51.50, max: 1062.80, latest: 1062.77
mapped min: 0.00, max: 92.26, latest: 0.00
cached min: 479.07, max: 1173.34, latest: 483.94
anonymous min: 69.60, max: 82.92, latest: 70.57
memory free min: 64.54, max: 320.38, latest: 82.25
memory available min: 452.98, max: 1459.64, latest: 455.43
Memory MB
2023-05-15T10:19:10+00:00
2023-05-15T10:19:20+00:00

2. Force backend allocation

```
set my.count to 409600;
set my.size to 1020;
do
$$
  declare
    text_array text[];
    counter    int:= current_setting('my.count',true);
    size       int:= current_setting('my.size',true);
    size_read  varchar;
  begin
    raise info 'Pid: %', pg_backend_pid();
    raise info 'Array element size: %, count: %', size, counter;
    for count in 1..counter loop
      text_array[count]:=repeat('x',size);
    end loop;
    raise info 'done!';
    select pg_size_pretty(sum(total_bytes)) into size_read from pg_backend_memory_contexts;
    raise info 'size now: %', size_read;
    perform pg_sleep(60);
  end
$$;
```



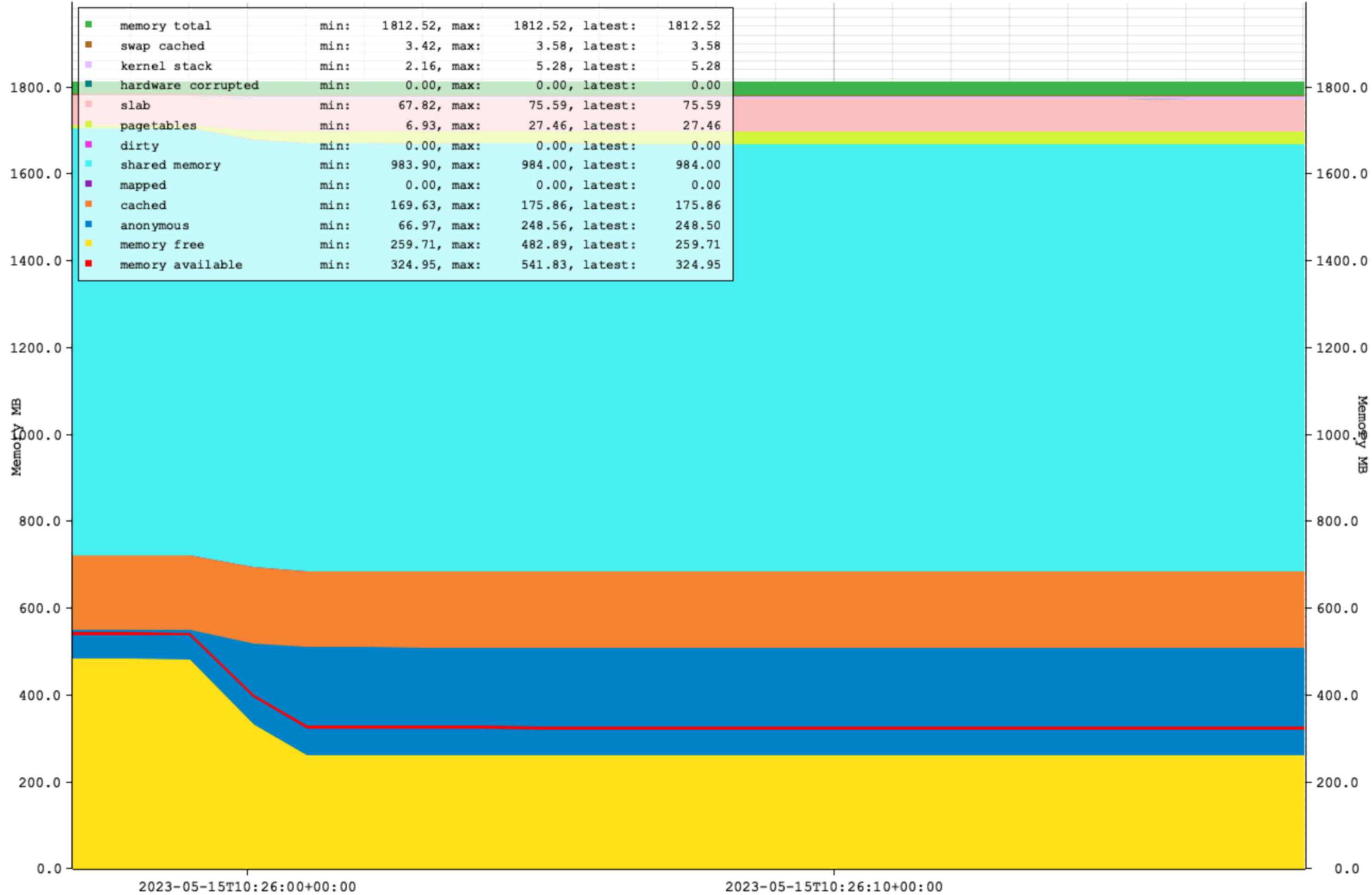
Memory usage: 192.168.66.100:9300:metrics
memory total min: 1812.52, max: 1812.52, latest: 1812.52
swap cached min: 2.06, max: 3.75, latest: 3.55
kernel stack min: 2.17, max: 2.19, latest: 2.17
hardware corrupted min: 0.00, max: 0.00, latest: 0.00
slab min: 67.71, max: 67.88, latest: 67.88
pagetables min: 8.92, max: 9.82, latest: 8.98
dirty min: 0.00, max: 0.01, latest: 0.01
shared memory min: 984.92, max: 1062.83, latest: 984.92
mapped min: 0.00, max: 0.00, latest: 0.00
cached min: 163.98, max: 491.88, latest: 164.92
anonymous min: 69.04, max: 479.00, latest: 69.61
memory free min: 68.95, max: 483.64, latest: 483.34
memory available min: 127.27, max: 537.89, latest: 537.59
Memory MB
2023-05-15T10:21:05+00:00
2023-05-15T10:21:10+00:00
2023-05-15T10:21:15+00:00
2023-05-15T10:21:20+00:00



Swap usage: 192.168.66.100:9300:metrics
swap total min: 2104.00, max: 2104.00, latest: 2104.00
swap used min: 21.54, max: 103.04, latest: 103.04
Swap MB
2023-05-15T10:21:05+00:00
2023-05-15T10:21:10+00:00
2023-05-15T10:21:15+00:00
2023-05-15T10:21:20+00:00

3.a Lots of backends -- idle

```
for T in $(seq 1 100); do
    psql -c "select pg_sleep(60)" &
done
```



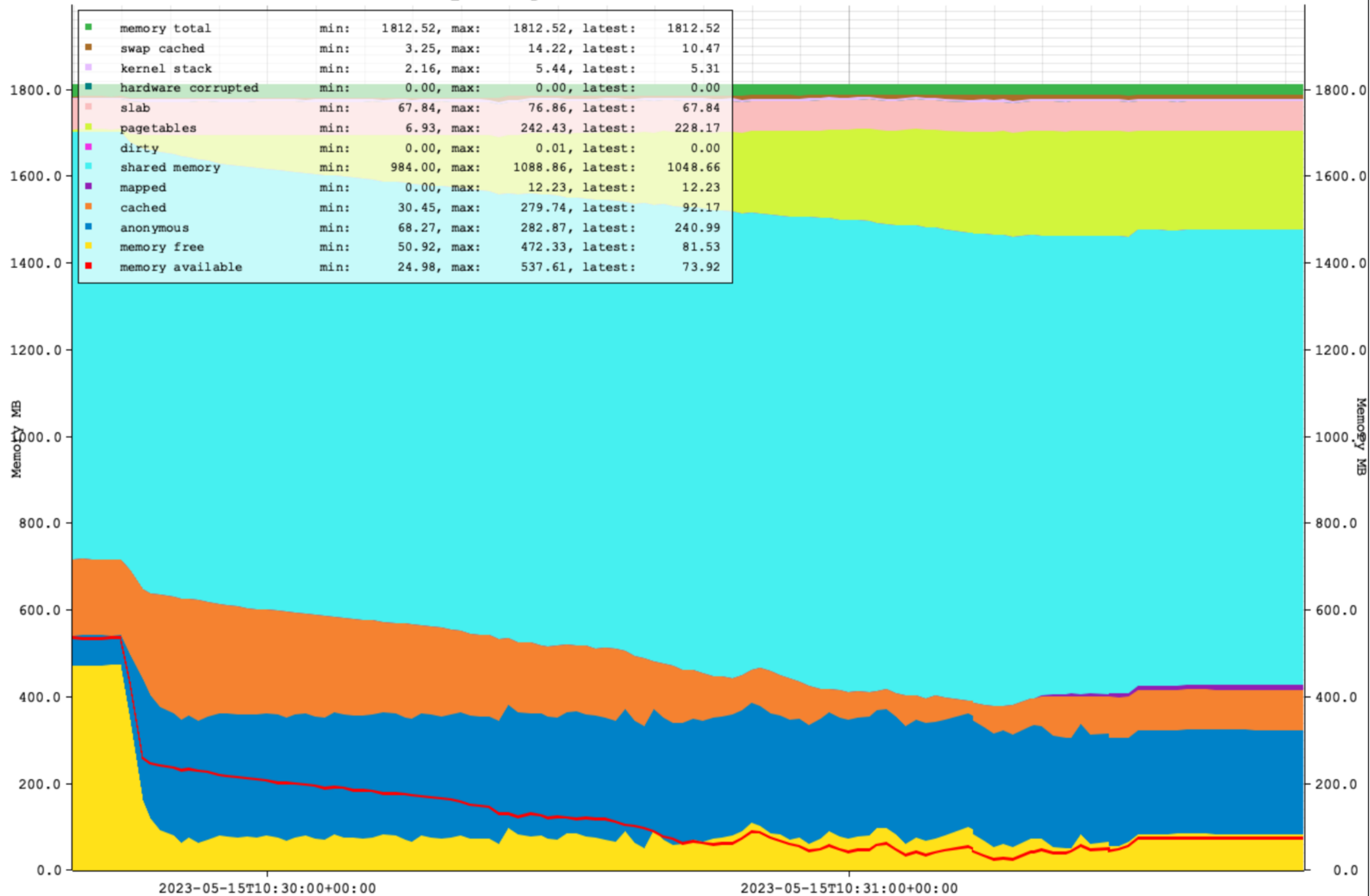
Memory usage: 192.168.66.100:9300:metrics
memory total min: 1812.52, max: 1812.52, latest: 1812.52
swap cached min: 3.42, max: 3.58, latest: 3.58
kernel stack min: 2.16, max: 5.28, latest: 5.28
hardware corrupted min: 0.00, max: 0.00, latest: 0.00
slab min: 67.82, max: 75.59, latest: 75.59
pagetables min: 6.93, max: 27.46, latest: 27.46
dirty min: 0.00, max: 0.00, latest: 0.00
shared memory min: 983.90, max: 984.00, latest: 984.00
mapped min: 0.00, max: 0.00, latest: 0.00
cached min: 169.63, max: 175.86, latest: 175.86
anonymous min: 66.97, max: 248.56, latest: 248.50
memory free min: 259.71, max: 482.89, latest: 259.71
memory available min: 324.95, max: 541.83, latest: 324.95
Memory MB
2023-05-15T10:26:00+00:00
2023-05-15T10:26:10+00:00

3.a Lots of backends -- idle

```
postgres=# select pg_size_pretty(sum(total_bytes)) from pg_backend_memory_contexts;
 pg_size_pretty
----------------
 1862 kB
```

3.b Lots of backends -- just doing simple things

```
for T in $(seq 1 100); do
    psql -c "set enable_seqscan=off; select count(f1) from t where id > 0; select pg_sleep(60)" &
done
```



Memory usage: 192.168.66.100:9300:metrics
memory total min: 1812.52, max: 1812.52, latest: 1812.52
swap cached min: 3.25, max: 14.22, latest: 10.47
kernel stack min: 2.16, max: 5.44, latest: 5.31
hardware corrupted min: 0.00, max: 0.00, latest: 0.00
slab min: 67.84, max: 76.86, latest: 67.84
pagetables min: 6.93, max: 242.43, latest: 228.17
dirty min: 0.00, max: 0.01, latest: 0.00
shared memory min: 984.00, max: 1088.86, latest: 1048.66
mapped min: 0.00, max: 12.23, latest: 12.23
cached min: 30.45, max: 279.74, latest: 92.17
anonymous min: 68.27, max: 282.87, latest: 240.99
memory free min: 50.92, max: 472.33, latest: 81.53
memory available min: 24.98, max: 537.61, latest: 73.92
Memory MB
2023-05-15T10:30:00+00:00
2023-05-15T10:31:00+00:00

4. Large backend allocations

Here is an oddity I found that could be very confusing.

In order to show this:

- I restart the server to decrease allocated shared memory.
- This allows anonymous allocations to be the majority of memory allocated.
- I run the PLpgSQL array allocation procedure with different settings:

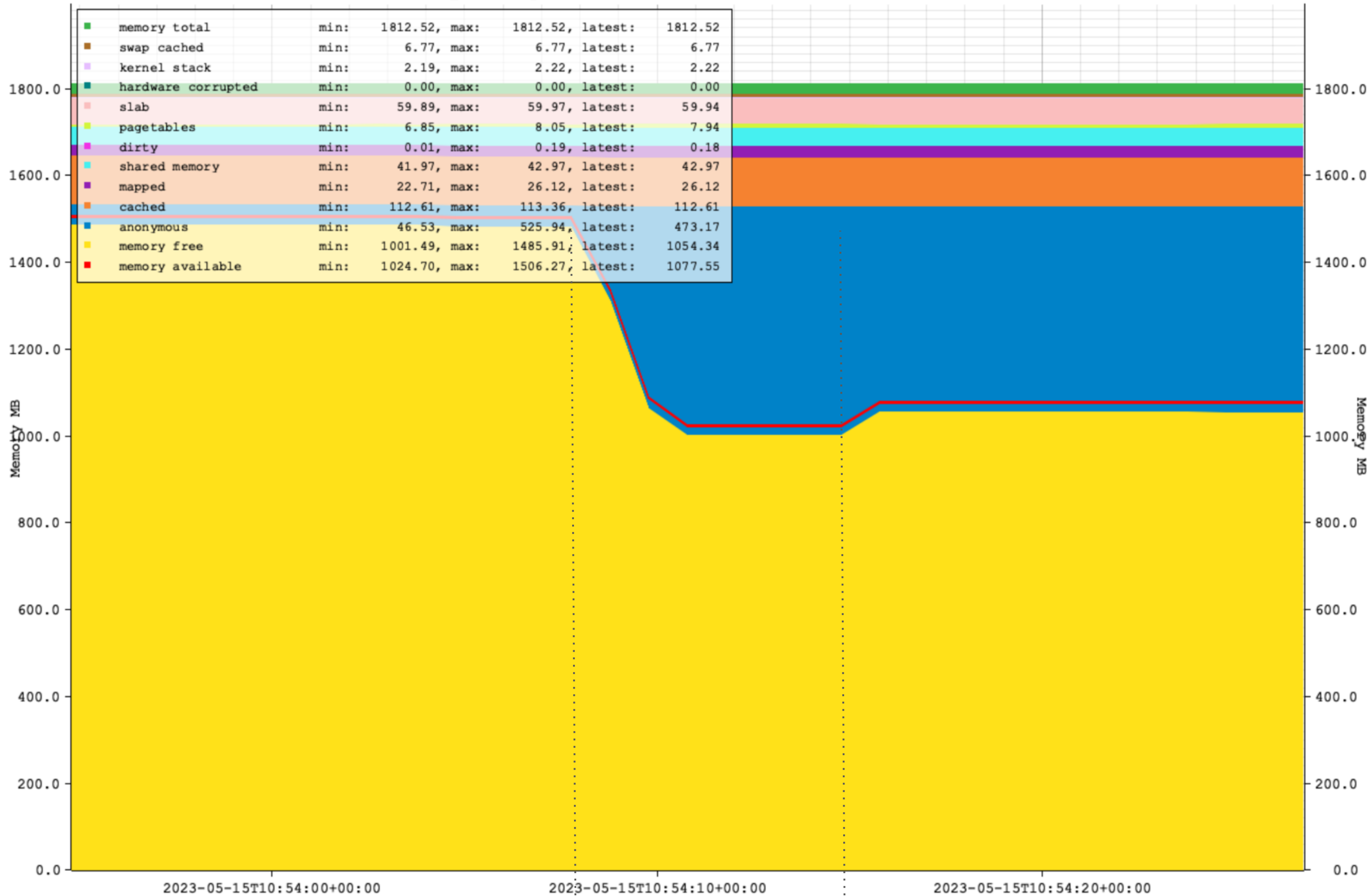
4. Large backend allocations

```
select pg_size_pretty(sum(total_bytes)) from pg_backend_memory_contexts;
set my.count to 3000;
set my.size to 166666;
do
$$
  declare
    text_array text[];
    counter    int:= current_setting('my.count',true);
    size       int:= current_setting('my.size',true);
    size_read  varchar;
  begin
    raise info 'Pid: %', pg_backend_pid();
    raise info 'Array element size: %, count: %', size, counter;
    for count in 1..counter loop
      text_array[count]:=repeat('x',size);
    end loop;
    raise info 'done!';
    select pg_size_pretty(sum(total_bytes)) into size_read from pg_backend_memory_contexts;
    raise info 'size now: %', size_read;
    perform pg_sleep(5);
  end
$$;
select pg_size_pretty(sum(total_bytes)) from pg_backend_memory_contexts;
```

4. Large backend allocations

```
postgres=# \i alloc_x.sql
 pg_size_pretty
----------------
 1755 kB
(1 row)

SET
SET
psql:alloc_x.sql:56: INFO:  Pid: 8646
psql:alloc_x.sql:56: INFO:  Array element size: 166666, count: 3000
psql:alloc_x.sql:56: INFO:  done!
psql:alloc_x.sql:56: INFO:  size now: 479 MB
DO
 pg_size_pretty
----------------
 1774 kB
(1 row)
```



Memory usage: 192.168.66.100:9300:metrics
memory total min: 1812.52, max: 1812.52, latest: 1812.52
swap cached min: 6.77, max: 6.77, latest: 6.77
kernel stack min: 2.19, max: 2.22, latest: 2.22
hardware corrupted min: 0.00, max: 0.00, latest: 0.00
slab min: 59.89, max: 59.97, latest: 59.94
pagetables min: 6.85, max: 8.05, latest: 7.94
dirty min: 0.01, max: 0.19, latest: 0.18
shared memory min: 41.97, max: 42.97, latest: 42.97
mapped min: 22.71, max: 26.12, latest: 26.12
cached min: 112.61, max: 113.36, latest: 112.61
anonymous min: 46.53, max: 525.94, latest: 473.17
memory free min: 1001.49, max: 1485.91, latest: 1054.34
memory available min: 1024.70, max: 1506.27, latest: 1077.55
Memory MB
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
1400.0
1600.0
1800.0
2023-05-15T10:54:00+00:00
2023-05-15T10:54:10+00:00
2023-05-15T10:54:20+00:00

4. Large backend allocations – short explanation

Anonymous allocations in PostgreSQL are performed by `palloc()`.
Palloc is a PostgreSQL abstraction, and calls the OS-level `malloc()` call.

malloc() is not a system call. It is a **library** to manage allocations in an address space.

So it's a memory management software layer between PostgreSQL and the OS.

It keeps allocated chunks around/cached 'in case you need it'.

- Small enough allocations are hardly visible/influencing.
- Very large allocations will get freed.
- Medium to large allocations are cached and can be significant.

Malloc resources

Malloc internals: https://sourceware.org/glibc/wiki/MallocInternals

Azeria heap exploitation part 1 (intro): https://azeria-labs.com/heap-exploitation-part-1-understanding-the-glibc-heap-im

Azeria heap exploitation part 2 (free): https://azeria-labs.com/heap-exploitation-part-2-glibc-heap-free-bins/

Conclusion

- Memory statistics in linux require interpretation and calculation.
    - I am not sure mine is 100% correct, but it seems to give a reasonable impression.
    - Any updates or corrections are welcome!

- Memory allocations in linux are lazy allocated.
    - And therefore PostgreSQL allocations are lazy allocated too.
    - Notably the buffer cache; anything else in the backend is even more dynamic.

- For architects and testers:
    - This means you need to build quite sophisticated test cases with real life data to be realistic.
    - Too simple test cases mean you actually/probably test a different scenario.

Conclusion

- Free memory != usable memory.
  - Look at available memory.
  - Too much free memory consistently reported likely means not using all memory.

- Main common PostgreSQL allocations:
  - Shared memory (== mapped memory == cached memory): buffer cache.
  - Anonymous memory: backend memory allocation.

- PostgreSQL is exhaustively documented to be needing OS cache.
  - Actual cache == cached - shared memory - mapped memory - dirty pages
  - Do you leave memory for OS caching?
    - If not: this will make query latency fluctuate a lot for seemingly identical situations.

Conclusion

- Large seq scans will only use 256k of buffers as ring.
  - Large means > 25% of set buffer cache size.
- Backends require a low amount of memory.
  - But need to build a pagetables to access buffer cache.
  - Any actual work requiring backend memory allocation comes on top.
  - Therefore: be very reserved about the number of backends.
- Malloc can play memory tricks.
  - For small allocations this is probably as good as invisible.
  - For 'medium' allocations this might play up.
  - I am not sure how often this plays up, but it's hard to spot if you're unaware.

Conclusion

- dsar (which created the memory graphs):
  - https://github.com/fritshoogland-yugabyte/dsar
  - Any requests are welcome!