Is it me, or the GIL?

Christoph Heer
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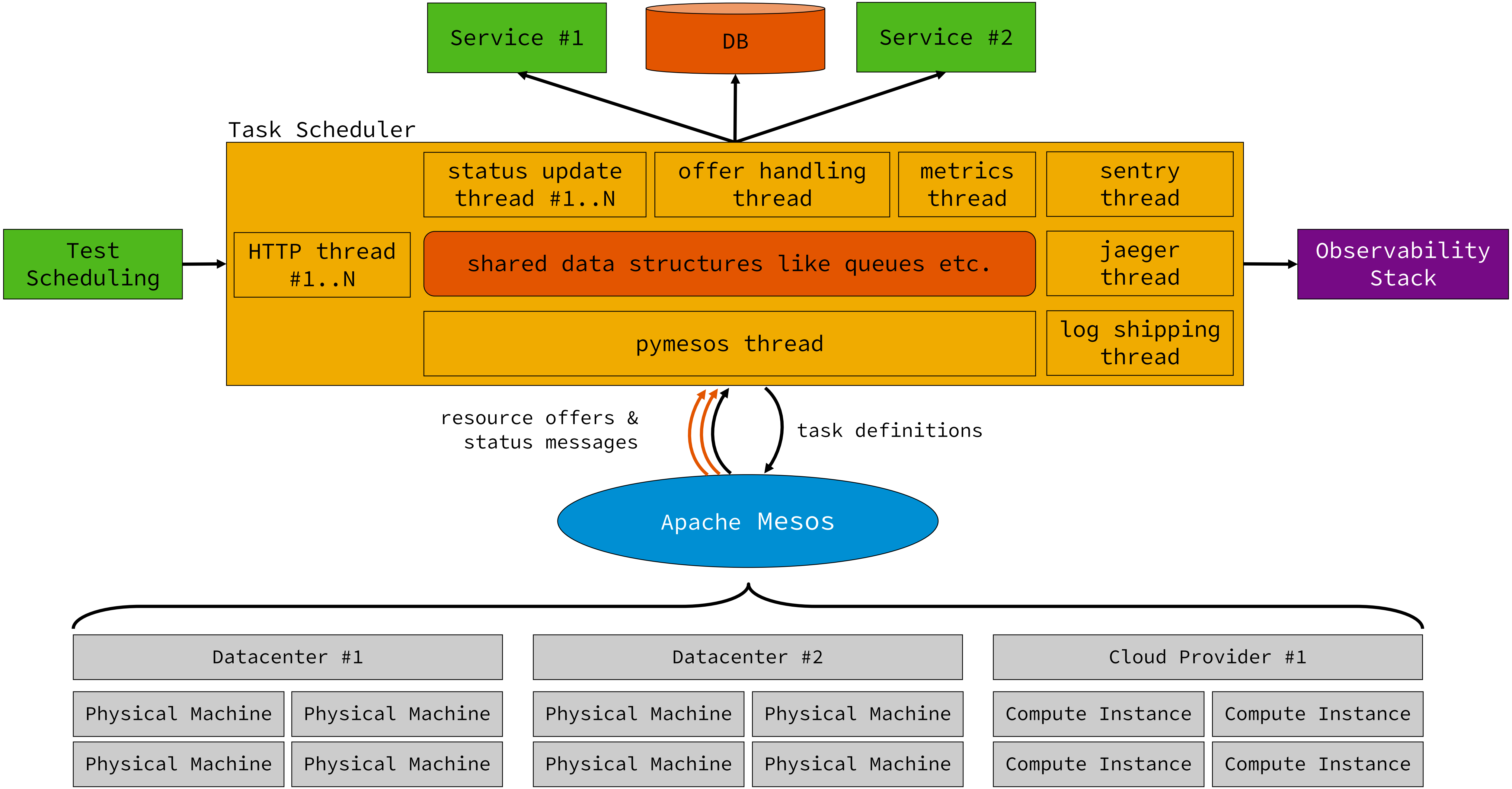
Background

- Quality assurance for SAP HANA
- Automated testing of ~800 commits per day
- Mainly testing with physical hardware: ~1600 machines, 610 TB RAM (256 GB – 8TB)
- Development of optimized tools and services


Service #1
DB
Service #2
Task Scheduler
status update thread #1..N
offer handling thread
metrics thread
sentry thread
Test Scheduling
HTTP thread #1..N
shared data structures like queues etc.
jaeger thread
Observability Stack
pymesos thread
log shipping thread
resource offers & status messages
task definitions
Apache Mesos
Datacenter #1
Datacenter #2
Cloud Provider #1
Physical Machine
Physical Machine
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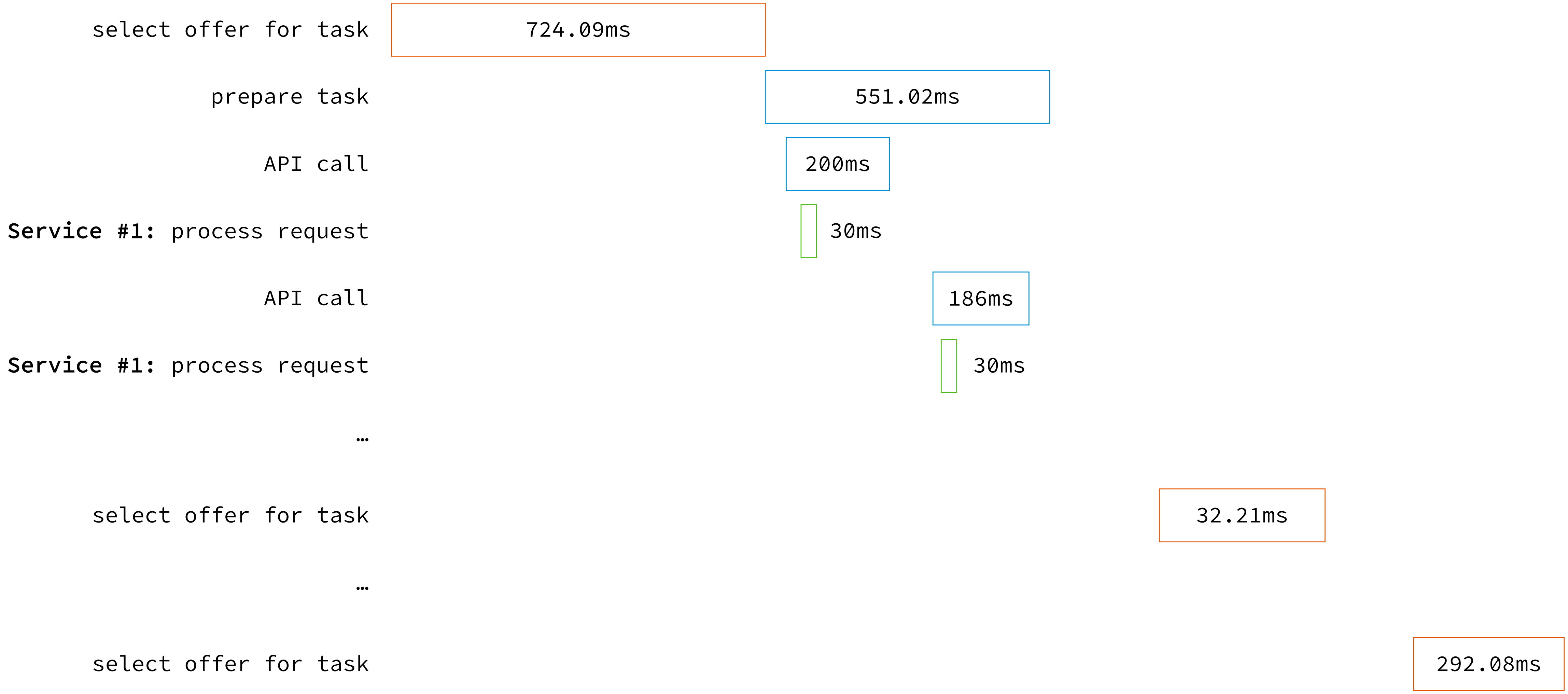
Compute Instance
Compute Instance
Compute Instance
Compute Instance

Inspect offer handling thread



Inspect offer handling thread

select offer for task 724.09ms

prepare task 551.02ms

API call 200ms

Service #1: process request 30ms

API call 186ms

Service #1: process request 30ms

…

select offer for task 32.21ms

…

select offer for task 292.08ms

Observations

- Different function runtimes

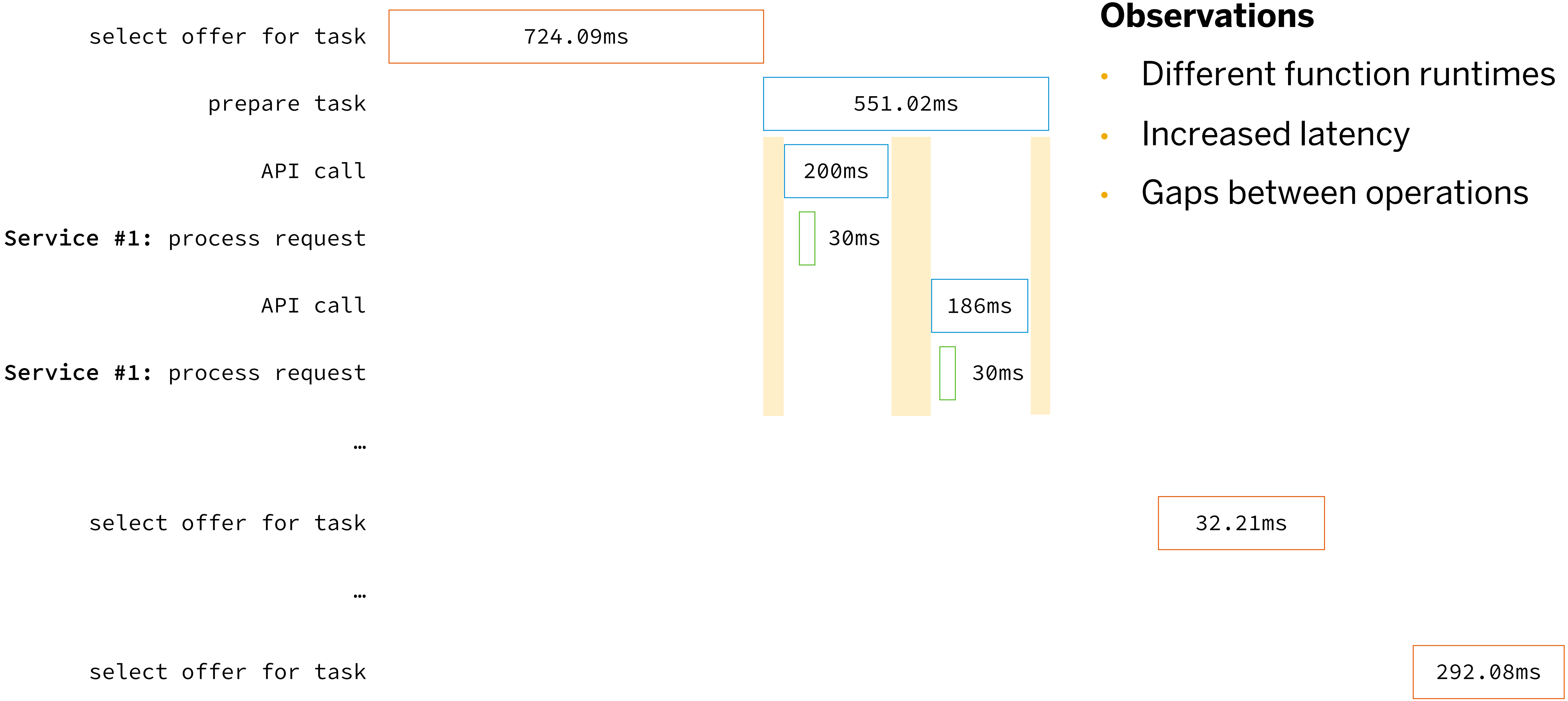
Inspect offer handling thread

select offer for task	724.09ms
prepare task	551.02ms
API call	200ms
Service #1: process request	30ms
API call	186ms
Service #1: process request	30ms
…	
select offer for task	32.21ms
…	
select offer for task	292.08ms

Observations

- Different function runtimes
- Increased latency

Inspect offer handling thread



Observations

- Different function runtimes
- Increased latency
- Gaps between operations

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…

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Observations

- Different function runtimes
- Increased latency
- Gaps between operations

Assumption: Thread released GIL multiple times and had to wait for re-acquire

Mitigate GIL contention

Python’s ecosystem offers various ways:

- multithreading => asyncio
- multithreading => multiprocessing (+ asyncio)
- CPU-intensive functions => Cython without the GIL
- Python => $faster language
- …

But, Rewriting and major refactoring are expensive

- Verify the assumption and measure GIL contention
- Decide about solution based on collected metrics instead of intuition

Look at the GIL

```
$ python3.7
Python 3.7.1 (default, Oct 22 2018, 13:16:18) [GCC] on linux
Type "help", "copyright", "credits" or "license" for more information.
>>> import sys
>>> sys.get_gil_stats()
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
AttributeError: module 'sys' has no attribute 'get_gil_stats’
```

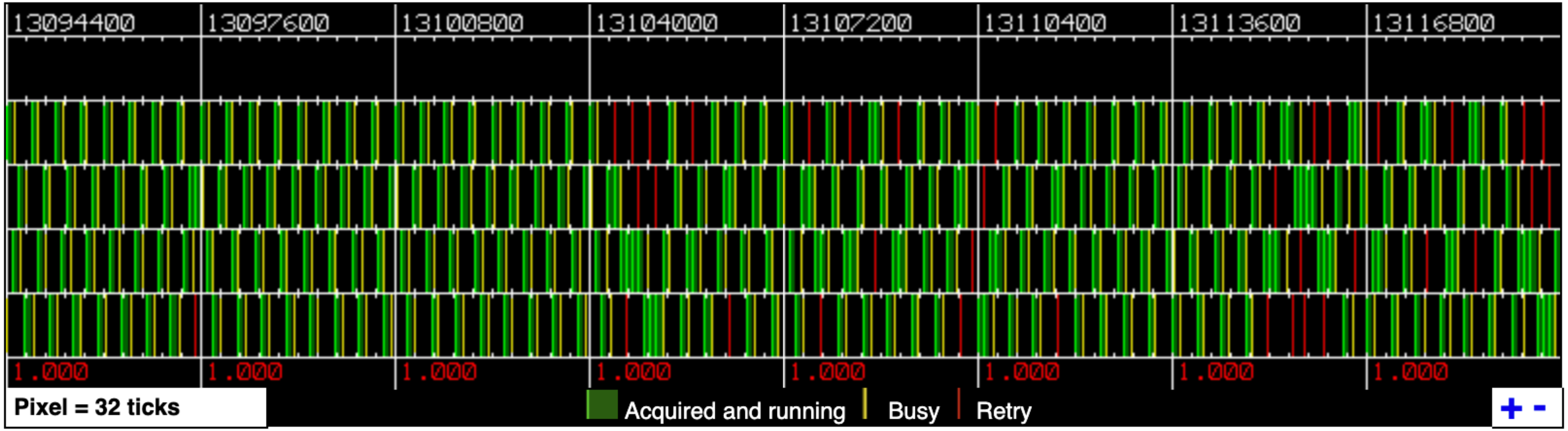
Wish list

- Provides metrics about GIL contention
  - wait time
  - hold time
- Additional context
  - Thread identifier/name
  - Python/C-Function
  - Trace/Request Id
- Usable for productive environments
  - Low overhead
  - Dynamically attachable to running Python processes
- Integration into existing observability stack

Related work and instrumentation approaches

A [Zoomable Interactive Python Thread Visualization]() by Dave Beazley

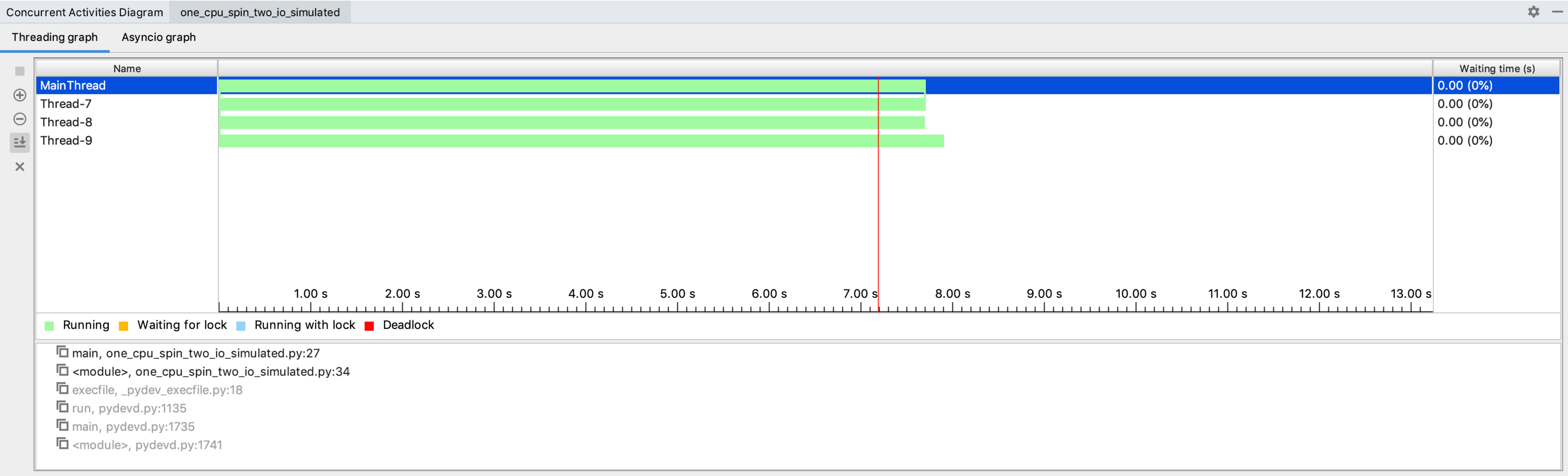
- Understanding the Python GIL (PyCon 2010)
- Adjustments in CPython 2.6 to store events about the GIL



Related work and instrumentation approaches

Thread Concurrency Visualization by PyCharm

- Visualizes and reveals locking issues but omits GIL



Related work and instrumentation approaches

gil_load by Chris Billington

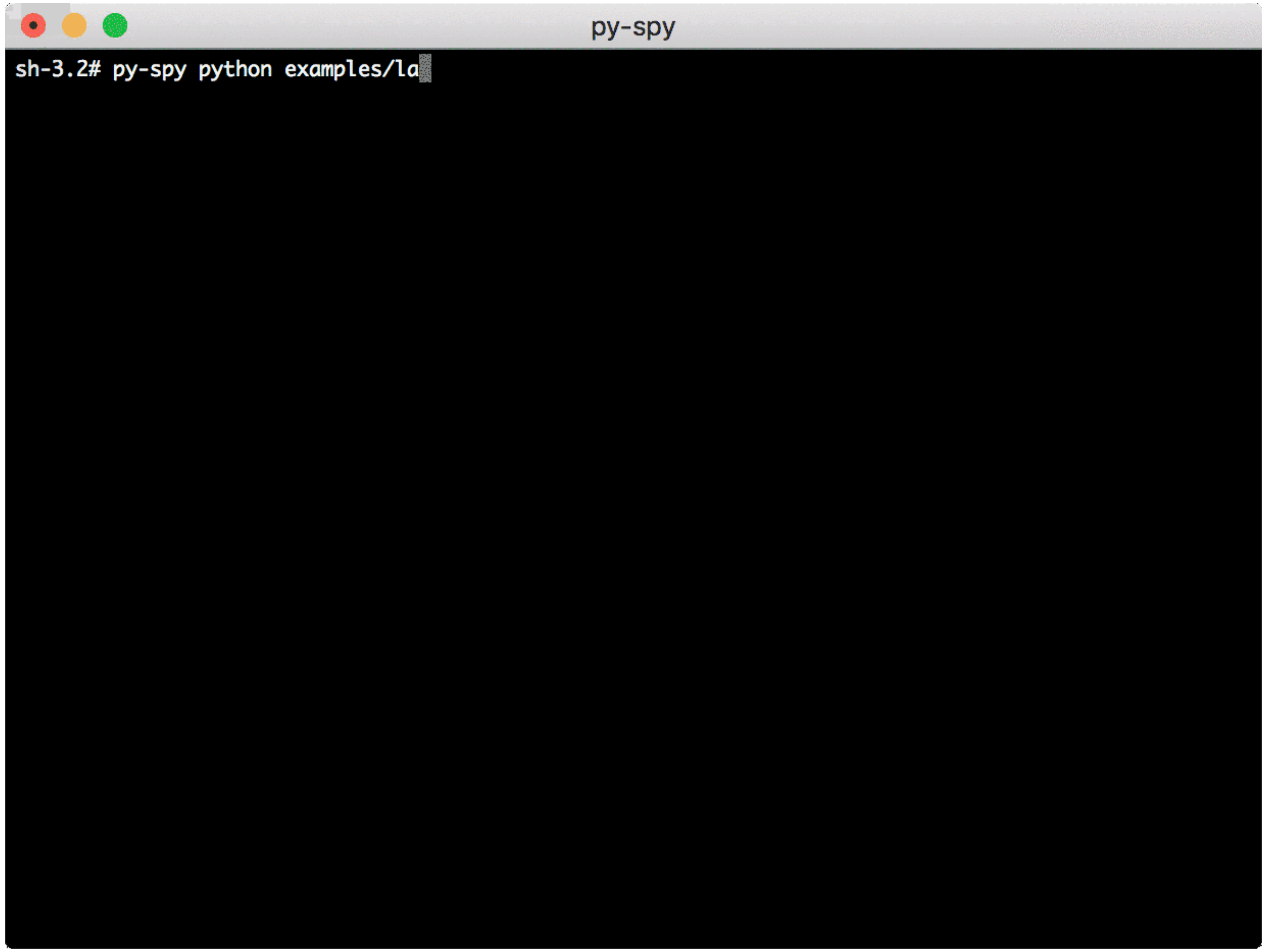
- Statistical profiler based on sampling states of all python threads every 50ms
- Installable python package (not Python 3.7 compatible yet)

```
$ python example_two.py
[2019-06-21 23:23:20]  GIL load: 1.00 (1.00, 1.00, 1.00)
[2019-06-21 23:23:21]  GIL load: 1.00 (1.00, 1.00, 1.00)
[2019-06-21 23:23:23]  GIL load: 1.00 (1.00, 1.00, 1.00)
[2019-06-21 23:23:23]  GIL load: 1.00 (1.00, 1.00, 1.00)
[2019-06-21 23:23:25]  GIL load: 1.00 (1.00, 1.00, 1.00)
[2019-06-21 23:23:26]  GIL load: 1.00 (1.00, 1.00, 1.00)
[2019-06-21 23:23:27]  GIL load: 1.00 (1.00, 1.00, 1.00)
```

Related work and instrumentation approaches

py-spy by Ben Frederickson

- Promising sampling profiler in Rust for Python applications
- Includes GIL utilization metric but no breakdown into usage per thread



“There is no magic GIL performance analysis tool”

a sad Python developer

Creating a tool that reveals the GIL

- Base: SystemTap
- Analyze Linux applications by attaching handlers to events
- CPython 3.6 introduced DTrace/SystemTap support & markers
  - `function__entry`
  - `function__return`
  - Great documentation: [Instrumenting CPython with DTrace and SystemTap]
- Pre-build Linux packages often compiled without: `--with-dtrace`
- No GIL related markers

Adding SystemTap markers about the GIL

```
diff --git a/Python/ceval_gil.h b/Python/ceval_gil.h
index ef5189068e..aecd3c99aa 100644
@@ static void drop_gil(PyThreadState *tstate)
     MUTEX_LOCK(_PyRuntime.ceval.gil.mutex);
     _Py_atomic_store_relaxed(&_PyRuntime.ceval.gil.locked, 0);
+    if (PyDTrace_GIL_DROP_ENABLED())
+        PyDTrace_GIL_DROP(PyThread_get_thread_ident());
+
     COND_SIGNAL(_PyRuntime.ceval.gil.cond);
     MUTEX_UNLOCK(_PyRuntime.ceval.gil.mutex);

@@ static void take_gil(PyThreadState *tstate)
     if (tstate == NULL)
         Py_FatalError("take_gil: NULL tstate");

+    if (PyDTrace_GIL_CLAIM_ENABLED())
+        PyDTrace_GIL_CLAIM(PyThread_get_thread_ident());
+
     err = errno;
     MUTEX_LOCK(_PyRuntime.ceval.gil.mutex);
```

Only thread identifiers as argument as there is currently no C API for accessing user-defined thread name

Measure time between GIL markers

```
probe process("libpython3.7m.so.1.0").mark("gil_claim") {
    last_timestamp[$arg1] = gettimeofday_ns();
}

probe process("libpython3.7m.so.1.0").mark("gil_acquired") {
    wait_time_ns = gettimeofday_ns() - last_timestamp[$arg1];
    gil_wait_aggregate[$arg1] <<< wait_time_ns;
    last_timestamp[$arg1] = gettimeofday_ns();
}

probe process("libpython3.7m.so.1.0").mark("gil_drop") {
    hold_time_ns = gettimeofday_ns() - last_timestamp[$arg1];
    gil_hold_aggregate[$arg1] <<< hold_time_ns;
}
```

- Attach probes (event handlers) to GIL markers
- Calculate timing of transitions
  - claim - acquired - drop
- Store measurements in SystemTap statistical aggregate type per thread

Produce summary of collected data

```
probe begin {println("Start tracing of Python GIL probes")}

probe end {
    println("Terminate tracing")
    println("Summary (all time measurements in ns)")
    foreach (thread in gil_wait_aggregate) {
        printf("Python Thread %d\n", thread)
        printf(
            "Aggregated GIL wait time: %d\n",
            @sum(gil_wait_aggregate[thread])
        )
        printf(
            "Aggregated GIL hold time: %d\n",
            @sum(gil_hold_aggregate[thread])
        )
        printf("GIL wait latency\n")
        println(@hist_log(gil_wait_aggregate[thread]))
        printf("GIL hold time\n")
        println(@hist_log(gil_hold_aggregate[thread]))
    }
}
```

- Handlers for start and end of tracing session
- Report GIL wait and hold time as sum and histogram

Experiment 1: Process with 2 IO-bound threads

```python
def io_work(n=150):
    while n > 0:
        n -= 1
        time.sleep(0.1)

def main():
    io1 = Thread(name='io1', target=io_work)
    io2 = Thread(name='io2', target=io_work)

    io1.start()
    io2.start()
    io1.join()
    io2.join()
```

```
Summary (all time measurements in ns)
Python Thread 140604373862144         # MainThread
Aggregated GIL wait time: 1102539     #  1.10ms
Aggregated GIL hold time: 27794967    # 27.79ms

Python Thread 140604351805184         # io1
Aggregated GIL wait time: 452269      #  0.45ms
Aggregated GIL hold time: 1490119     #  1.49ms

Python Thread 140604343412480         # io2
Aggregated GIL wait time: 462690      #  0.46ms
Aggregated GIL hold time: 1382457     #  1.38ms
```

```
App. runtime:  15064.3ms
GIL Hold time:     29.7ms 0.20% of runtime
GIL Wait time:      1.9ms 0.01% of runtime
```

Experiment 2: CPU-bound thread

```python
def io_work(n=150):
    while n > 0:
        n -= 1
        time.sleep(0.1)

def cpu_spin():
    while True:
        pass

def main():
    io1 = Thread(name='io1', target=io_work)
    io2 = Thread(name='io2', target=io_work)
    cpu1 = Thread(
        name='cpu1', target=cpu_spin, daemon=True
    )

    ...
```

```
Summary (all time measurements in ns)
Python Thread 140347214374656         # MainThread
Aggregated GIL wait time: 45613707    #    45.61ms
Aggregated GIL hold time: 28039210    #    28.04ms

Python Thread 140347192317696         # io1
Aggregated GIL wait time: 760017132   #   760.02ms
Aggregated GIL hold time: 2109572     #     2.11ms

Python Thread 140347116091136         # io2
Aggregated GIL wait time: 770118858   #   770.01ms
Aggregated GIL hold time: 1504611     #     1.50ms

Python Thread 140347107698432         # cpu1
Aggregated GIL wait time: 3816216     #     3.81ms
Aggregated GIL hold time: 15790884948 # 15790.88ms
```

```
App. runtime:   15822ms
GIL hold time: 15821ms 99.99% of runtime
GIL wait time:  1578ms   9.97% of runtime
```

Experiment 2: GIL wait latency for IO threads

```
Python Thread 140347192317696 # io1
GIL wait latency
   value |-------------------------------------------------- count
     512 |                                                    0
    1024 |                                                    0
    2048 |                                                    1
    4096 |                                                    0
    8192 |                                                    0
         ~
 1048576 |                                                    0
 2097152 |                                                    0
 4194304 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ 150
 8388608 |                                                    0
16777216 |                                                    0
```

```
Python Thread 140347116091136 # io2
GIL wait latency
   value |-------------------------------------------------- count
     512 |                                                    0
    1024 |                                                    0
    2048 |                                                    1
    4096 |                                                    0
    8192 |                                                    0
         ~
 1048576 |                                                    0
 2097152 |                                                    0
 4194304 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@   149
 8388608 |                                                    1
16777216 |                                                    0
33554432 |                                                    0
```

Stable wait latency between 4 – 8ms

```
GIL hold time
  value |--------------------------------
   1024 |
   2048 |
   4096 |@@@@@@@@@@@@@@
   8192 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
  16384 |
  32768 |                                                   2
  65536 |                                                   2
 131072 |                                                   0
 262144 |                                                   1
```

```
--------------------------------- count
                                    0
                                    0
                                   34
@@@@@@@@@@@@@@@@@@@@@             115
  16384 |                           0
  32768 |                           1
  65536 |                           1
```

Experiment 2: Evaluation

- GIL contention affects overall application performance
  - Additional 5ms latency on each GIL acquire attempt after one blocking IO operation

```
>>> import sys
>>> sys.getswitchinterval()
0.005
```

- `switchinterval` defines the grace period before a waiting thread requests GIL drop
- GIL-holding thread may keep the GIL longer due to
  - long-running bytecode operation
  - external C function

Analyze production application with SystemTap

- **Plan**
  - Deploy container with customized CPython and SystemTap
  - Attach to process
  - Get clear and precise insides about GIL contention

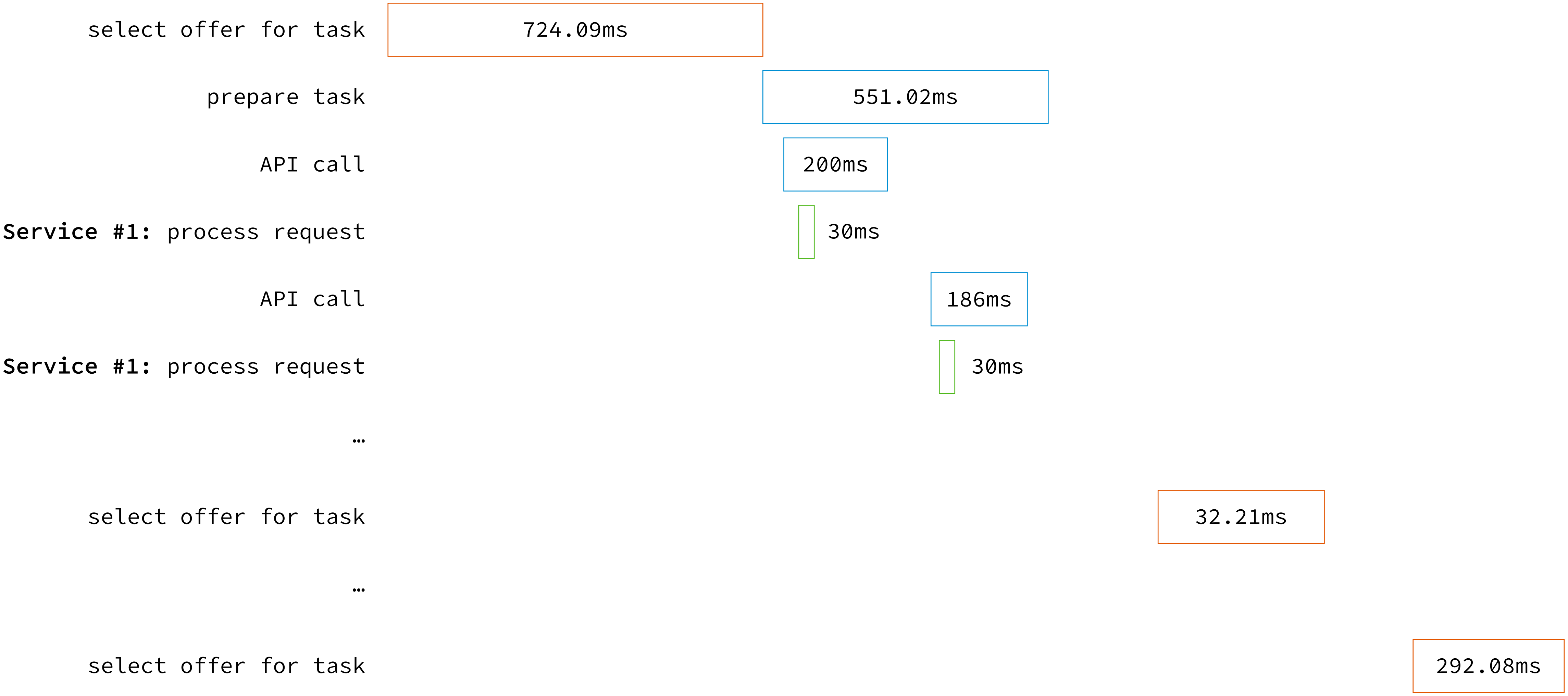
- **Relativity**
  - Deploy container with customized CPython
  - Install SystemTap on host with kernel sources, compiler toolchain etc.
  - Copy libpython3.7m.so.1.0 from container into host filesystem
  - Attach to process = Load custom kernel extension with your systemtap handlers
  - Get huge text file with report

Result: Analysis of productive task scheduler

```
Observation period:   120091.89ms
GIL hold time:        105680.91ms   88.00% of timeframe
GIL wait time:        352997.64ms  293.94% of timeframe
```

- **Proved, our application suffers from GIL contention**
- More questions:
  - Are there threads that hold the GIL longer than 5ms?
  - If yes, which functions are so expensive?
  - Is it possible to identify time-based patterns with higher contention?
- **Problem: With 31 threads the text report isn't well understandable**

Timelines are easier to understand



Replace text report with some colorful charts

Collect and store data with SystemTap

↓

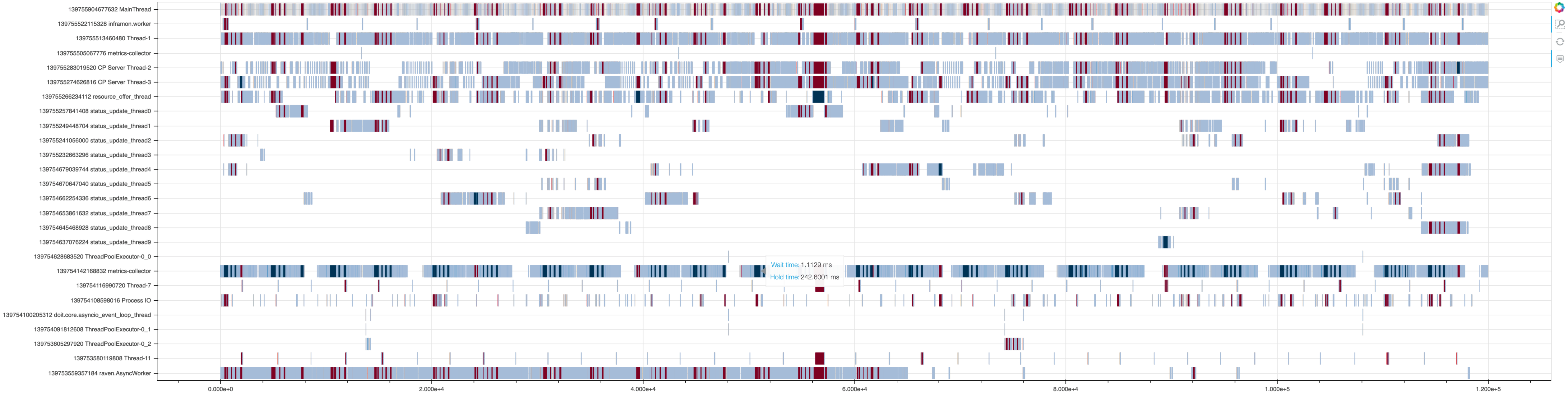
Load data into Jupyter notebook

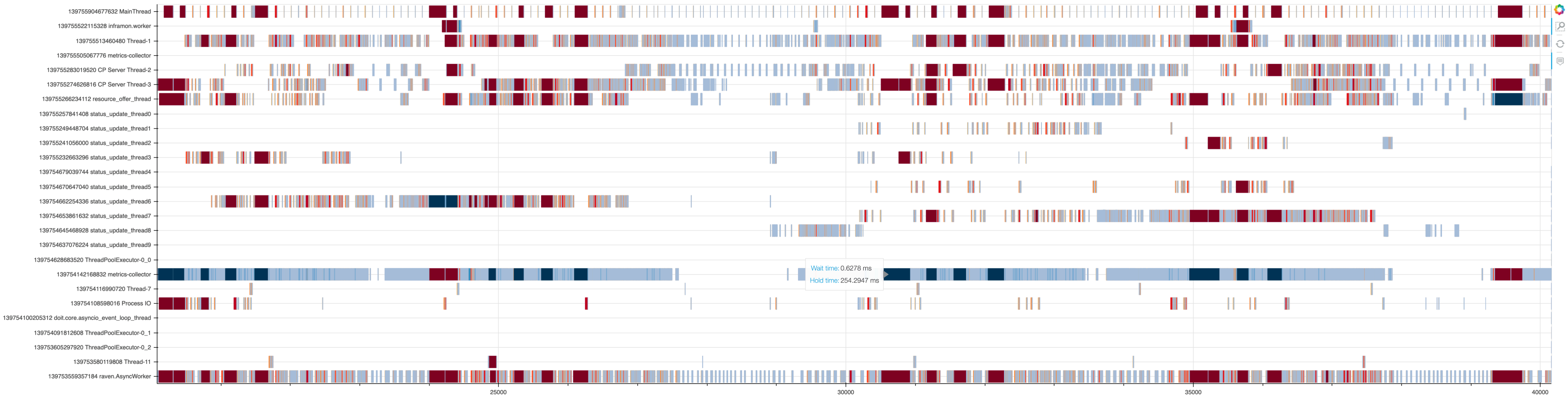
↓

Transform data

↓

Visualize data with Bokeh


139755904677632 MainThread
139755522115328 inframon.worker
139755513460480 Thread-1
139755505067776 metrics-collector
139755283019520 CP Server Thread-2
139755274626816 CP Server Thread-3
139755266234112 resource_offer_thread
139755257841408 status_update_thread0
139755249448704 status_update_thread1
139755241056000 status_update_thread2
139755232663296 status_update_thread3
139754679039744 status_update_thread4
139754670647040 status_update_thread5
139754662254336 status_update_thread6
139754653861632 status_update_thread7
139754645468928 status_update_thread8
139754637076224 status_update_thread9
139754628683520 ThreadPoolExecutor-0_0
139754142168832 metrics-collector
139754116990720 Thread-7
139754108598016 Process IO
139754100205312 doit.core.asyncio_event_loop_thread
139754091812608 ThreadPoolExecutor-0_1
139753605297920 ThreadPoolExecutor-0_2
139753580119808 Thread-11
139753559357184 raven.AsyncWorker
Wait time: 1.1129 ms
Hold time: 242.6001 ms
0.000e+0
2.000e+4
4.000e+4
6.000e+4
8.000e+4
1.000e+5
1.200e+5



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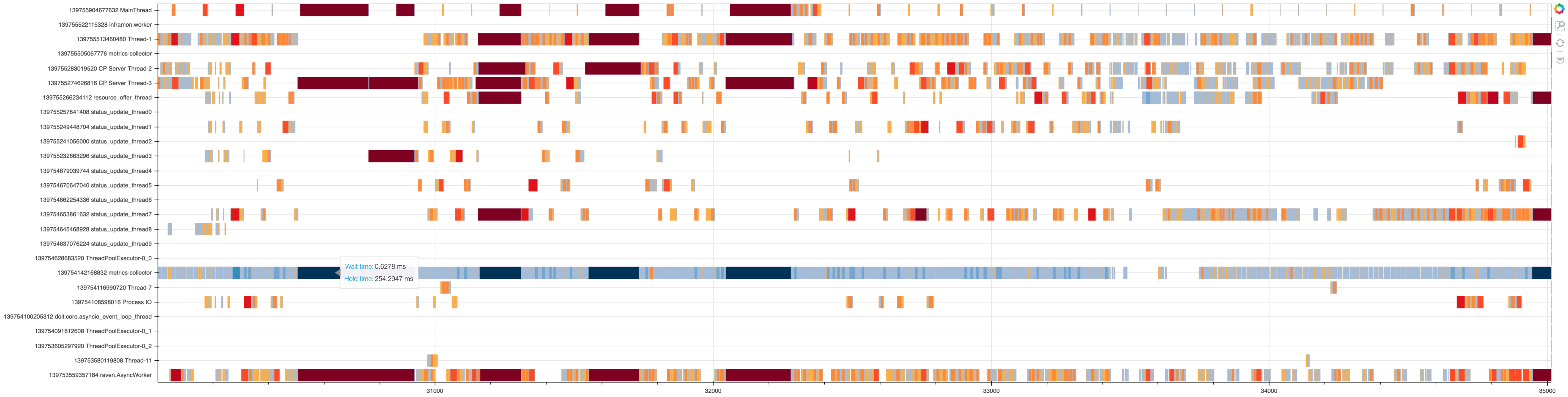
139753605297920 ThreadPoolExecutor-0_2
139753580119808 Thread-11
139753559357184 raven.AsyncWorker
Wait time: 0.6278 ms
Hold time: 254.2947 ms
25000
30000
35000
40000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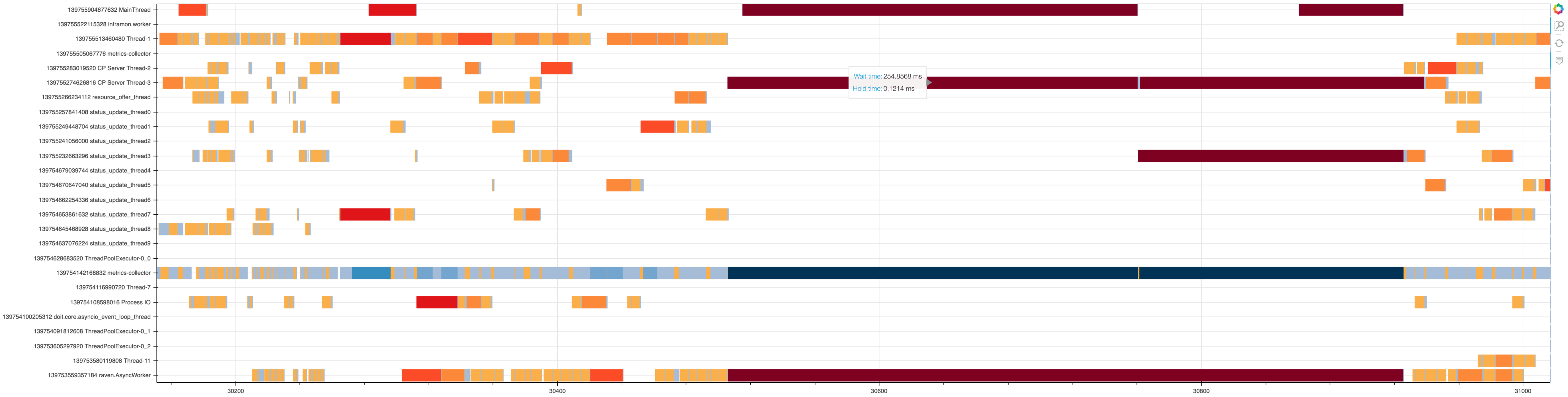
Wait time: 0.6278 ms
Hold time: 254.2947 ms
31000
32000
33000
34000
35000



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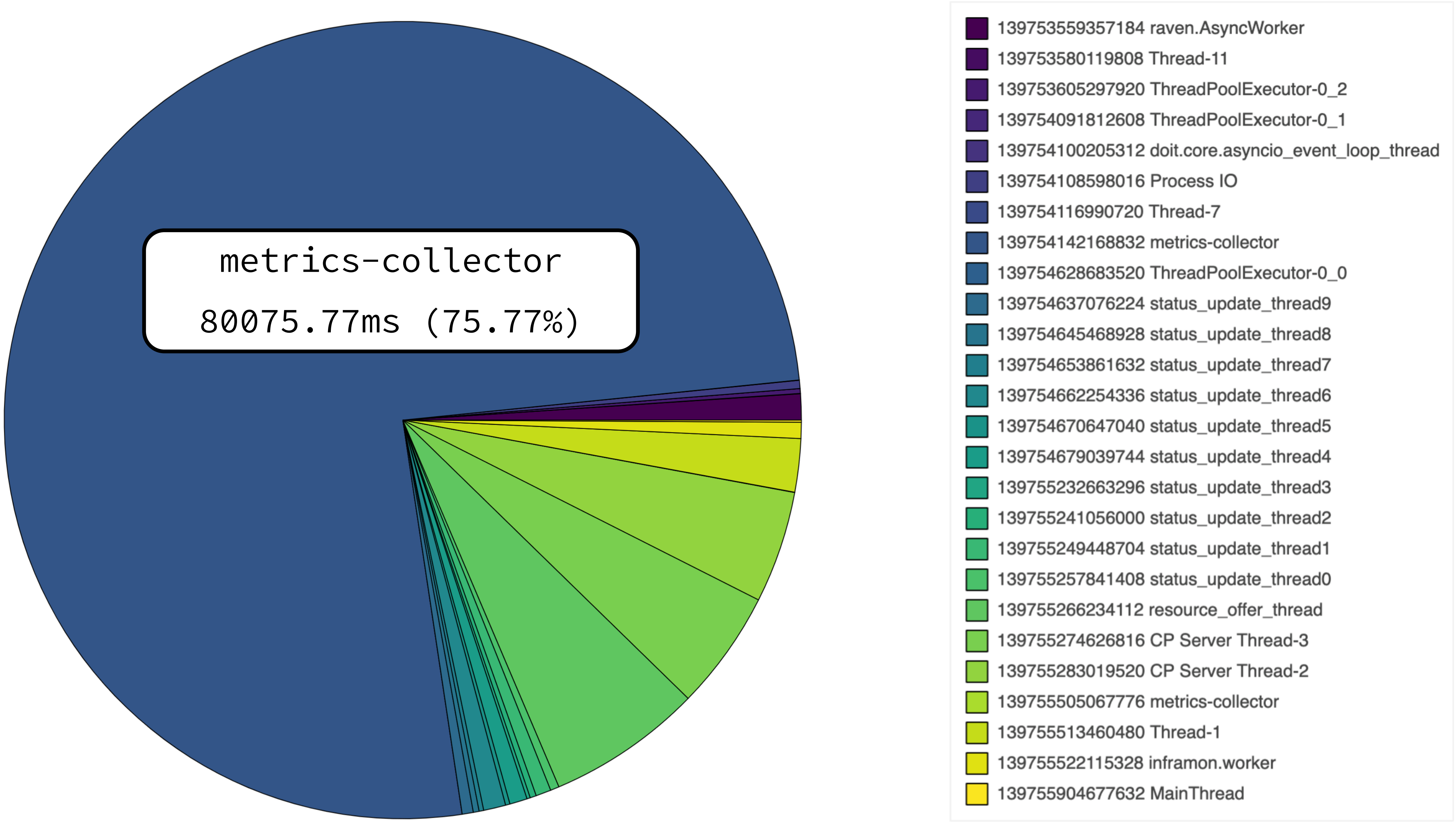
139754091812608 ThreadPoolExecutor-0_1
139753605297920 ThreadPoolExecutor-0_2
139753580119808 Thread-11
139753559357184 raven.AsyncWorker
Wait time: 254.8568 ms
Hold time: 0.1214 ms
30200
30400
30600
30800
31000

Distribution of GIL hold time



Fixing our GIL contention

- Started replacing of an expensive C-Extension that doesn’t release the GIL
- Increased sleep time of metrics-collector thread from 10sec to 120sec

```
Before:
Observation period:   120091.89ms
GIL hold time:        105680.91ms   88.00% of timeframe
GIL wait time:        352997.64ms  293.94% of timeframe

After:
Observation period: 300112.84ms
GIL hold time:      130806.91ms     43.59% of timeframe
GIL wait time:      240568.60ms     80.16% of timeframe
```

- **Without major refactoring the system is now able to utilize all available resources**
- Collected data will helps us to decide about coming architectural changes

Many additional ideas

- Bring toolset (systemtap script & visualization) in a public usable state
- Enhance CPython for data collection with SystemTap
  - Integrate GIL markers into CPython
  - C API for thread names
- Maybe collect and provide GIL metrics directly with CPython
  - sys.get_gil_stats()
  - Easier integration into existing observability tooling like distributed tracing
  - No need to compile custom kernel extensions in your productive environment
- **If you are also interested in that area, let's talk!**

Thank you.

Christoph Heer

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THE BEST RUN

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