Red Hat

# Introduction to low-level profiling and tracing

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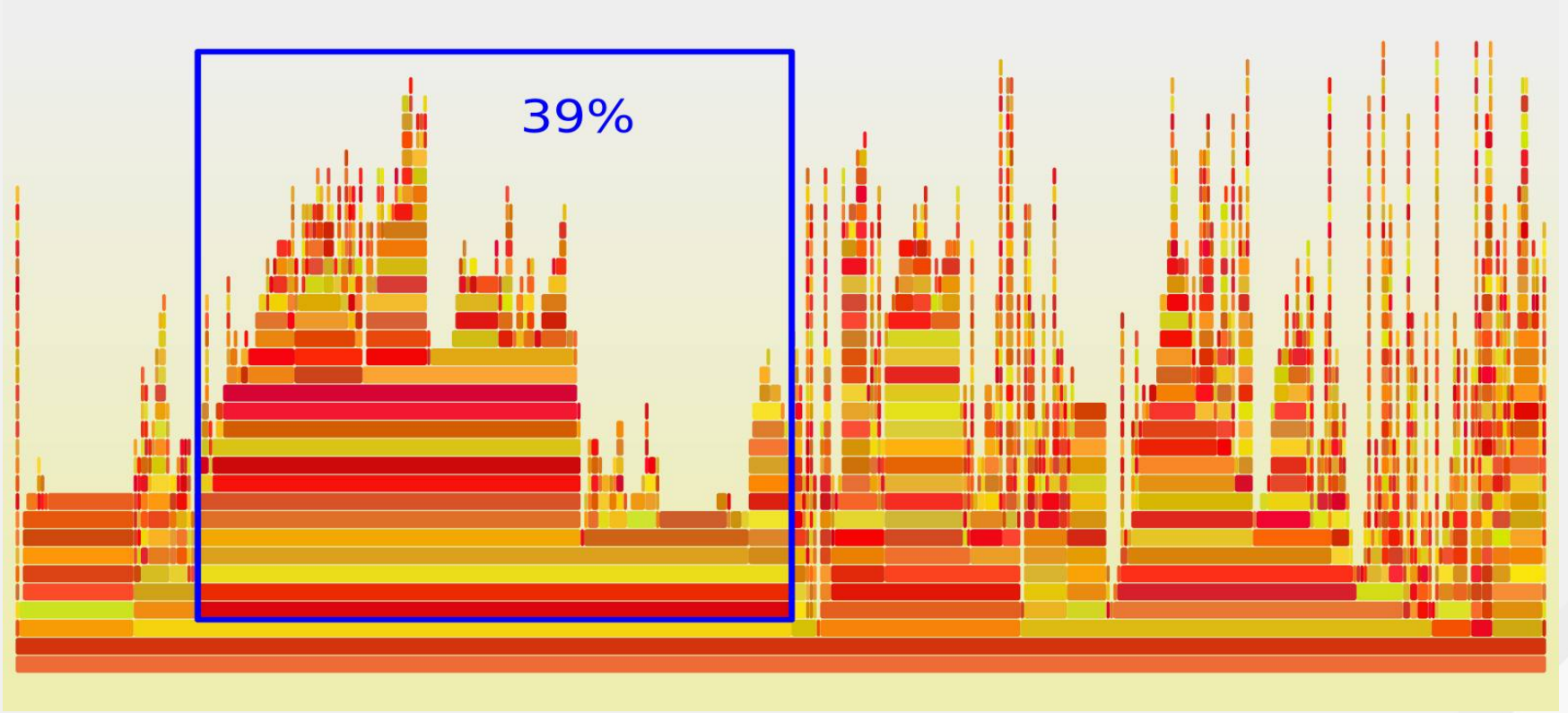
Our systems block every 5 minutes.
We are loosing money. Fix it!

# Is it me, or the GIL?

Christoph Heer
EuroPython 2019

# requests.get('https://www.python.org')



# 2 ½ use case for tracing tools

# Who am I?

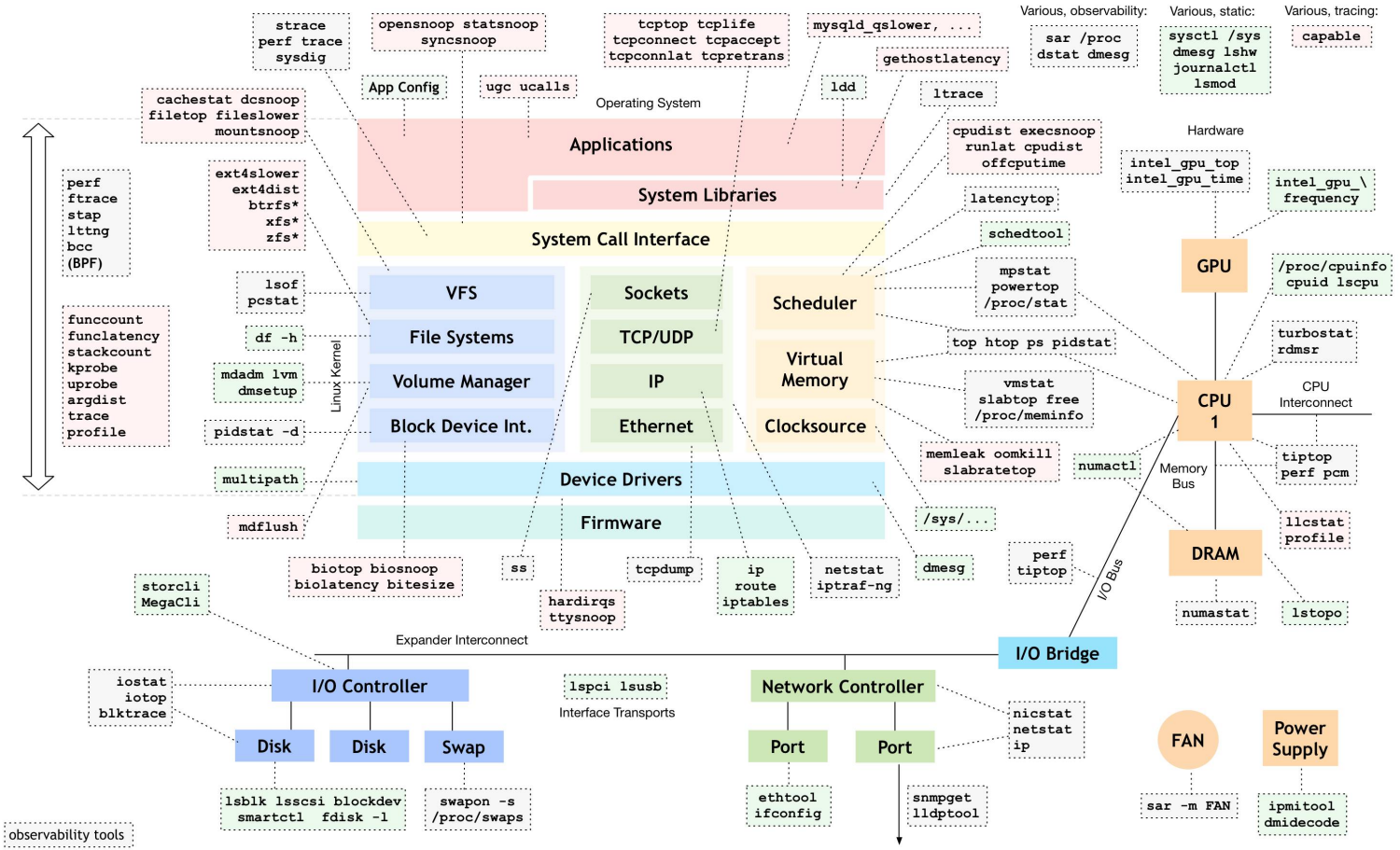
- from Hamburg/Germany
- Python and C developer
- Python core contributor since 2008
  - maintainer of ssl and hashlib module
  - Python security team

# Professional life


- Principal Software Engineer at Red Hat
- Security Engineering
  - FreeIPA Identity Management
  - Dogtag PKI

# Agenda
# &
# Goals

# Linux Performance Tools

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# Agenda

- introduction
- ptrace (strace, ltrace)
- kernel & hardware tracing tools
- Summary
- ~ 5 minutes Q&A

# Special thanks

- Brendan Gregg (Netflix)
- Victor Stinner (CPython, Red Hat)
  https://vstinner.readthedocs.io/benchmark.html
- Dmitry Levin (strace)
  ”Modern Strace”, DevConf.CZ 2019
- Michal Sekletár (Red Hat)
  ”Tracing Tools for Systems Engineers”, DevConf.CZ 2019

# Introduction

# Terminology

## Debugging – The process of identifying and removing bugs.

- active, expensive, intrusive, slow-down
  - deploy new version
  - attach debugger

## Tracing – observing and monitoring behavior

- passive, non-intrusive, and fast*

## Profiling – gathering and analyzing metrics

- byproduct of tracing with counting and timing

# Methodology

## Application level tracing

- debug builds
- performance logs (MySQL Slow Query Log, PHP xdebug)
- trace hooks (Python: `sys.settrace()`)

## User space tracing

- LD_PRELOAD, ptrace

## Kernel space tracing

- ftrace, eBPF, systemtap, LTTng, ...

## Hardware tracing

- hardware performance counter, PMU, ...

# Prerequisites

- installation of extra packages
- permissions
  - root or special group
  - CAP_SYS_PTRACE, CAP_SYS_ADMIN, CAP_SYS_MODULE
- recent Kernel (BCC, eBPF)
- debug symbols
  dnf debuginfo-install package, apt install package-dbg
- compiler/linker flags (-g, -fno-omit-framepointer, BIND_LAZY)
- disable secure boot (stap)

**Kernel Live Patching or dynamic modules**

“Lies, damned lies,
and statistics”

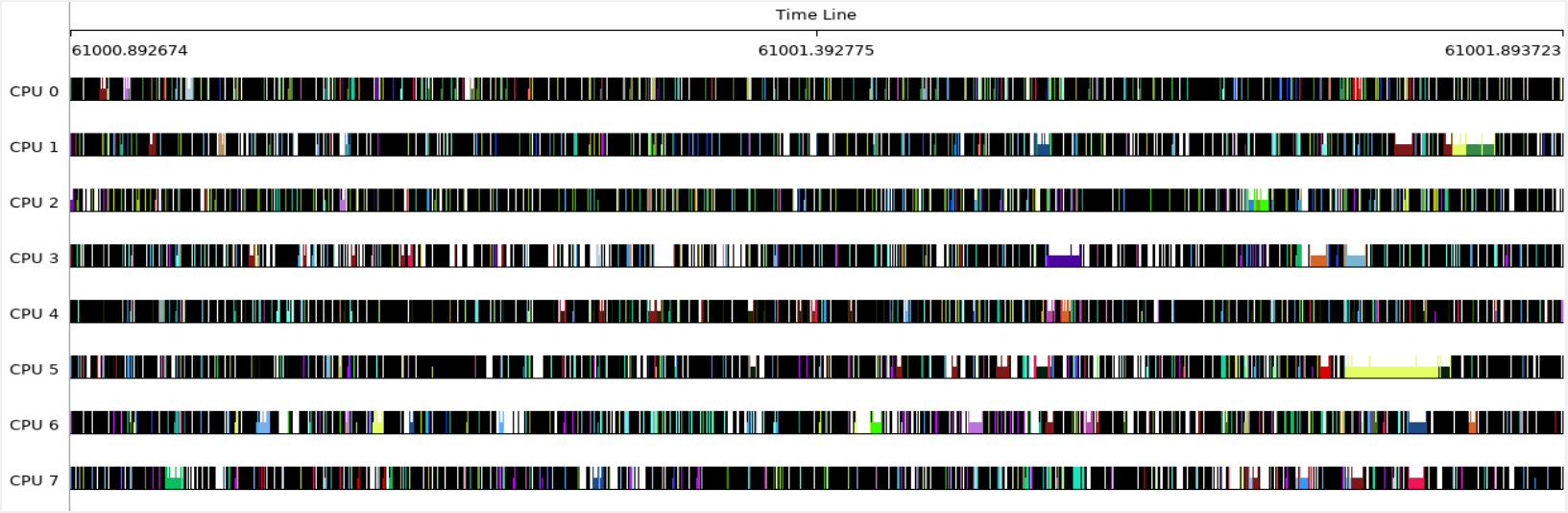
”Wer misst, misst Mist.”

# benchmarks / statistics

- average, median, standard deviation, **percentile**
- observational error
  - systematic error
  - random error
- systemic bias, cognitive bias (human factor)
- misleading presentation (Vatican City has 2.27 popes / $km^2$)
- sampling profiler: quantization error, Nyquist–Shannon theorem

“Producing Wrong Data Without Doing Anything Obviously Wrong!”
(Mytkowicz, Diwan, Hauswirth, Sweeney)

# Computers are noisy




- CPU power states (P-states, C-states, TurboBoost, thermal throttling)
- caches (L1 CPU, file system, JIT warm-up, DNS/HTTP)
- hardware IRQs, Address Space Layout Randomization (ASLR)

https://vstinner.readthedocs.io/benchmark.html

# env vars, path length, hostname, username

```
Benchmark without Python virtual environment

% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 28.78    0.000438           0      1440           read
 27.33    0.000416           1       440        25 stat
  9.72    0.000148           1       144           mmap
...
  0.79    0.000012           1        11           munmap

Benchmark inside a virtual environment

% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 57.12    0.099023           2     61471           munmap
 41.87    0.072580           1     61618           mmap
  0.23    0.000395           1       465        27 stat
```

- https://mail.python.org/pipermail/python-dev/2019-February/156522.html
- https://homes.cs.washington.edu/~bornholt/post/performance-evaluation.html

# Let's profile

```
import time

start = time.time()

with open('/etc/os-release') as f:
    lines = f.readlines()

print(time.time() - start)
```

# Examples

- shell
  - cat
- Python
  - open + read file
  - HTTPS request with requests

# ptrace

# ptrace

- process trace syscall
- introduced in Unix Version 6 (~1985)
- user-space tracing
- used by debuggers and code analysis tools
  - gdb
  - strace
  - ltrace
  - code coverage
  - ...

# ltrace – A library call tracer

```
$ ltrace -e 'SSL_CTX*@*' \
    python3 -c 'import requests; requests.get("https://www.python.org")'
_ssl.cpython-37m-x86_64-linux-gnu.so->SSL_CTX_new(0x7fa4a1a77120, 0, 0, 0)                                  = 0x55636123a100
_ssl.cpython-37m-x86_64-linux-gnu.so->SSL_CTX_get_verify_callback(0x55636123a100, -2, 0x7fa4a1acd5e0, 0x7fa4a1acd5f8)   = 0
_ssl.cpython-37m-x86_64-linux-gnu.so->SSL_CTX_set_verify(0x55636123a100, 0, 0, 0x7fa4a1acd5f8)                  = 0
_ssl.cpython-37m-x86_64-linux-gnu.so->SSL_CTX_set_options(0x55636123a100, 0x82420054, 0, 0x7fa4a1acd5f8)     = 0x82520054
_ssl.cpython-37m-x86_64-linux-gnu.so->SSL_CTX_ctrl(0x55636123a100, 33, 16, 0)                                 = 20
_ssl.cpython-37m-x86_64-linux-gnu.so->SSL_CTX_set_session_id_context(0x55636123a100, 0x7fa4af500494, 7, 0)             = 1
...
_ssl.cpython-37m-x86_64-linux-gnu.so->SSL_CTX_free(0x55636123a100, 0x7fa4af4b1e10, -3, 0x7fa4a12734c8)                 = 0
```

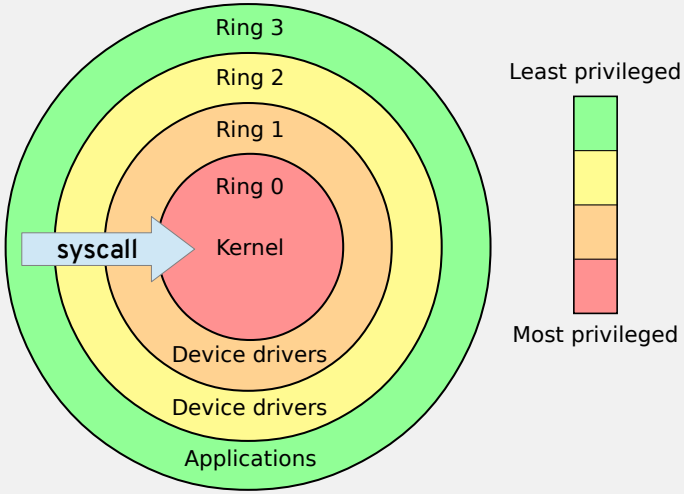
# ltrace – count memory allocations

```
>>> import os, time, requests
>>> os.getpid()
6504
# attach ltrace
>>> start = time.time(); r = requests.get("https://www.python.org"); print(time.time() - start)
# without ltrace: 0.566 sec
# with ltrace:    3.396 sec
```

```
$ ltrace -e 'malloc+free+realloc@*' -c -p 6504
% time     seconds  usecs/call     calls      function
------ ----------- ----------- --------- --------------------
 53.49    1.104804          37     29796 free
 45.78    0.945565          37     25523 malloc
  0.73    0.015069          48       309 realloc
------ ----------- ----------- --------- --------------------
100.00    2.065438                 55628 total
```

# strace – trace system calls and signals

- Paul Kranenburg in 1991
- Dmitry Levin (current maintainer)




Hertzsprung at English Wikipedia [CC BY-SA 3.0]

# strace “open” syscall

```
$ strace -e open cat /etc/os-release >/dev/null
+++ exited with 0 +++
$ man 2 open
...
The open() system call opens the file specified by pathname.
```

```
$ strace -c cat /etc/os-release >/dev/null
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 31,40    0,000591         590         1           execve
 13,51    0,000254          28         9           mmap
  8,67    0,000163          40         4           mprotect
  7,20    0,000135          22         6           read
  6,95    0,000131          32         4           openat
  6,36    0,000120          19         6           close
  6,21    0,000117          29         4           brk
  ...
------ ----------- ----------- --------- --------- ----------------
100.00    0,001882                    49         2 total
```

# syscall ABI / API

- open
  - x86_64 glibc <= 2.25: open
  - x86_64 glibc >= 2.26: openat
  - riscv: openat

```
$ strace -e '/^open(at)?$'
```

- stat
  - fstat, fstat64, fstatat64, lstat, lstat64, newfstatat, oldfstat, oldlstat, oldstat, stat, stat64, statx

```
$ strace -e %%stat
```

%%stat = %stat + %lstat + %fstat + statx

# strace “openat” syscall

```
$ strace -e openat cat /etc/os-release >/dev/null
openat(AT_FDCWD, "/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
openat(AT_FDCWD, "/lib64/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
openat(AT_FDCWD, "/usr/lib/locale/locale-archive", O_RDONLY|O_CLOEXEC) = 3
openat(AT_FDCWD, "/etc/os-release", O_RDONLY) = 3
+++ exited with 0 +++
```

```
$ strace -P /etc/os-release cat /etc/os-release >/dev/null
strace: Requested path '/etc/os-release' resolved into '/usr/lib/os.release.d/os-release-fedora'
openat(AT_FDCWD, "/etc/os-release", O_RDONLY) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=693, ...}) = 0
fadvise64(3, 0, 0, POSIX_FADV_SEQUENTIAL) = 0
read(3, "NAME=Fedora\nVERSION=\"29 (Twenty "..., 131072) = 693
read(3, "", 131072)                     = 0
close(3)                                = 0
+++ exited with 0 +++
```

# strace options

- filter class examples
  - %file: syscall that take a file name as argument
  - %desc: file descriptor related syscalls
  - %net: network related syscalls
- arguments
  - -P: path filter
  - -y: print path associated with file descriptor
  - -yy: print protocol information (e.g. ip:port)
  - -t/-tt/-ttt: time stamp
  - -T: time spent
  - -k: caller stack trace

# strace: requests.get(...)

```
$ strace -e %file -p 6504
...
stat("/etc/resolv.conf", {st_mode=S_IFREG|0644, st_size=300, ...}) = 0
openat(AT_FDCWD, "/etc/hosts", O_RDONLY|O_CLOEXEC) = 3
openat(AT_FDCWD, "/etc/crypto-policies/back-ends/openssl.config", O_RDONLY) = 4
openat(AT_FDCWD, "/etc/ssl/cacert.pem", O_RDONLY) = -1 ENOENT (No such file or directory)
```

```
$ strace -e %net -p 6504
socket(AF_INET, SOCK_DGRAM|SOCK_CLOEXEC|SOCK_NONBLOCK, IPPROTO_IP) = 3
connect(3, {sa_family=AF_INET, sin_port=htons(53), sin_addr=inet_addr("10.38.5.26")}, 16) = 0
sendto(3, "\323\300\1\0\0\1\0\0\0\0\0\0\3www\6python\3org\0\0\1\0\1", 32, MSG_NOSIGNAL, NULL, 0) = 32
recvfrom(3, "\323\300\201\200\0\1\0\2\0\0\0\0\3www\6python\3org\0\0\1\0\1"..., 2048, 0,
{sa_family=AF_INET, sin_port=htons(53), sin_addr=inet_addr("10.38.5.26")}, [28->16]) = 93

socket(AF_INET, SOCK_STREAM|SOCK_CLOEXEC, IPPROTO_TCP) = 3
setsockopt(3, SOL_TCP, TCP_NODELAY, [1], 4) = 0
connect(3, {sa_family=AF_INET, sin_port=htons(443), sin_addr=inet_addr("151.101.36.223")}, 16) = 0
getsockopt(3, SOL_SOCKET, SO_TYPE, [1], [4]) = 0
getpeername(3, {sa_family=AF_INET, sin_port=htons(443), sin_addr=inet_addr("151.101.36.223")}, [16]) = 0
```

# syscall tampering

```
$ strace -e inject=socket:error=EMFILE -p 6504
>>> requests.get("https://www.python.org/en")
Traceback (most recent call last):
   ...
socket.gaierror: [Errno -2] Name or service not known
$ strace -e inject=socket:error=EMFILE:when=2+ -p 6504
Traceback (most recent call last):
...
  File "/usr/lib64/python3.7/socket.py", line 151, in __init__
    _socket.socket.__init__(self, family, type, proto, fileno)
OSError: [Errno 24] Too many open files
```

```
$ dd if=/dev/zero of=/dev/null bs=1M count=10
10485760 bytes (10 MB, 10 MiB) copied, 0,00328225 s, 3,2 GB/s
$ strace -e inject=write:delay_exit=100000 -o /dev/null \
    dd if=/dev/zero of=/dev/null bs=1M count=10
10485760 bytes (10 MB, 10 MiB) copied, 1,10699 s, 9,5 MB/s
```

# syscall tampering

```
$ strace -P /tmp/foo -e inject=unlinkat:retval=0 \
    rm /tmp/foo
newfstatat(AT_FDCWD, "/tmp/foo", {st_mode=S_IFREG|0664, st_size=0, ...}, AT_SYMLINK_NOFOLLOW) = 0
newfstatat(AT_FDCWD, "/tmp/foo", {st_mode=S_IFREG|0664, st_size=0, ...}, AT_SYMLINK_NOFOLLOW) = 0
faccessat(AT_FDCWD, "/tmp/foo", W_OK)   = 0
unlinkat(AT_FDCWD, "/tmp/foo", 0)       = 0 (INJECTED)
+++ exited with 0 +++
$ ls /tmp/foo
/tmp/foo
```

# Verdict

- ✔ easy to use
- ✔ powerful tool for quick hacks
- ✔ no extra privileges
- ✗ slow
- ✗ limit view (user-space only)
- ✗ ltrace incompatible with optimizations

```
$ ltrace ls >/dev/null
+++ exited (status 0) +++
$ scanelf -a /bin/ls
 TYPE    PAX   PERM ENDIAN STK/REL/PTL TEXTREL RPATH BIND FILE
ET_DYN  PeMRxS 0755 LE     RW- R-- RW- -       -     NOW /bin/ls
```

# Low-level tracing

What is the Kernel doing?

What is my hardware doing?

# Low-level tracing

- Trace inside the Kernel
  - file system
  - hardware drivers
- Profile hardware
  - CPU cache
  - memory / MMU
- efficient user-space tracing
  - single process
  - system-wide
- learn how Kernel space and hardware works

# Data sources

- kprobes
- uprobes
- events
  - perf_event (HPC, PMU, page faults, TLB, ...)
  - clock
  - Kernel TRACE_EVENT, DEFINE_EVENT
- user defined
  - dtrace probe / USDT (Userland Statically Defined Tracing)
  - lttng-ust

# kprobes / uprobes

Kernel probes

- (almost) all internal Kernel functions
- /proc/kallsyms

User-space probes

- (almost) all functions in binaries
  - applications
  - shared libraries

# perf_event & metrics

```
$ perf list
  branch-instructions OR branches                    [Hardware event]
  branch-misses                                      [Hardware event]
  bus-cycles                                         [Hardware event]
  ...
  alignment-faults                                   [Software event]
  bpf-output                                         [Software event]
  context-switches OR cs                             [Software event]
  cpu-clock                                          [Software event]
  cpu-migrations OR migrations                       [Software event]
  ...
  L1-dcache-load-misses                              [Hardware cache event]
  L1-dcache-loads                                    [Hardware cache event]
  L1-dcache-stores                                   [Hardware cache event]
  L1-icache-load-misses                              [Hardware cache event]
  ...
  power/energy-cores/                                [Kernel PMU event]
  power/energy-gpu/                                  [Kernel PMU event]
  power/energy-pkg/                                  [Kernel PMU event]
  power/energy-psys/                                 [Kernel PMU event]
  ...
floating point:
  fp_arith_inst_retired.128b_packed_double
       [Number of SSE/AVX computational 128-bit packed double precision floating-point instructions ...]
   ...
Summary:
  CLKS
       [Per-thread actual clocks when the logical processor is active. This is called 'Clockticks' in VTune]
  CPI
       [Cycles Per Instruction (threaded)]
```

# Kernel trace events

```
# find /sys/kernel/debug/tracing/events -name format | wc -l
1897
```

```
# trace-cmd record -e 'cfg80211:cfg80211_inform_bss_frame' -e 'cfg80211:cfg80211_get_bss'
# trace-cmd report
...
  irq/140-iwlwifi-1834  [002] 91697.995389: cfg80211_inform_bss_frame: phy0, band: 1, freq:
5180(scan_width: 0) signal: -6600, tsb:132269768490547, detect_tsf:0, tsf_bssid: 00:00:00:00:00:00
    kworker/u16:3-23176 [004] 91697.995468: cfg80211_inform_bss_frame: phy0, band: 1, freq:
5180(scan_width: 0) signal: -6600, tsb:132269768490547, detect_tsf:0, tsf_bssid: 00:00:00:00:00:00
  irq/140-iwlwifi-1834  [002] 91698.002485:  cfg80211_inform_bss_frame: phy0, band: 1, freq:
5180(scan_width: 0) signal: -6700, tsb:132269775585563, detect_tsf:0, tsf_bssid: 00:00:00:00:00:00
   wpa_supplicant-2320  [000] 91698.198168: cfg80211_get_bss:     phy0, band: 1, freq: 5180,
08:96:d7:XX:XX:XX, buf: 0x73, bss_type: 0, privacy: 2
   wpa_supplicant-2320  [000] 91698.216052: cfg80211_get_bss:     phy0, band: 1, freq: 5180,
08:96:d7:XX:XX:XX, buf: 0x73, bss_type: 0, privacy: 2
```

# Advanced Tools

# Advanced tools

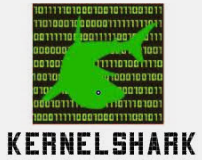
- ftrace (tracefs)
- perf
- BCC / eBPF tools
- SystemTap
- more tools
  - LTTng
  - dtrace
  - VTune
  - SysDig
  - ...

# DTrace

- Sun Microsystems (2005) for Solaris
- DTrace markers
- operating systems
  - Linux (2017)
  - Windows (2018)
  - macOS
  - FreeBSD
  - NetBSD

# ftrace – Function Tracer

- by Steven Rostedt (2008)
- tracefs `/sys/kernel/debug/tracing`
- ring buffer / pipes
- GCC profiling, live patching, trampolines
- foundation for Live Kernel Patching
- frontends
  - busybox / shell (cat, echo)
  - trace-cmd
  - KernelShark
  - perf



# trace-cmd: NFS open (simplified)

```
# trace-cmd record -p function_graph -l 'nfs_*' -c python3 python_open.py
# trace-cmd report
...
     <...>-56879 [006] 8398345.057032: funcgraph_entry:                   |  nfs_permission() {
     <...>-56879 [006] 8398345.057032: funcgraph_entry:       0.065 us   |    nfs_do_access();
     <...>-56879 [006] 8398345.057033: funcgraph_entry:                   |    nfs_do_access() {
     <...>-56879 [006] 8398345.057034: funcgraph_entry:       0.912 us   |      nfs_alloc_fattr();
     <...>-56879 [006] 8398345.057947: funcgraph_entry:                   |      nfs_refresh_inode() {
     <...>-56879 [006] 8398345.057950: funcgraph_entry:                   |        nfs_refresh_inode.part.27() {
     <...>-56879 [006] 8398345.057951: funcgraph_entry:                   |          nfs_refresh_inode_locked() {
     <...>-56879 [006] 8398345.057952: funcgraph_entry:                   |            nfs_update_inode() {
     <...>-56879 [006] 8398345.057952: funcgraph_entry:       0.190 us   |              nfs_file_has_writers();
     <...>-56879 [006] 8398345.057954: funcgraph_entry:       0.235 us   |              nfs_set_cache_invalid();
     <...>-56879 [006] 8398345.057955: funcgraph_exit:        3.089 us   |            }
     <...>-56879 [006] 8398345.057955: funcgraph_exit:        4.106 us   |          }
     <...>-56879 [006] 8398345.057955: funcgraph_exit:        4.830 us   |        }
     <...>-56879 [006] 8398345.057964: funcgraph_exit:      + 14.691 us  |      }
     <...>-56879 [006] 8398345.057964: funcgraph_entry:       0.053 us   |      nfs_access_set_mask();
     <...>-56879 [006] 8398345.057966: funcgraph_entry:       2.621 us   |      nfs_access_add_cache();
     <...>-56879 [006] 8398345.057970: funcgraph_exit:      ! 936.572 us |    }
     <...>-56879 [006] 8398345.057970: funcgraph_exit:      ! 937.907 us |  }
```

# trace-cmd: NFS open call stack

```
# trace-cmd record -p function --func-stack -l nfs_permission -c python3 python_open.py
# trace-cmd report
           <...>-56912 [006] 8398623.394239: function:             nfs_permission
           <...>-56912 [006] 8398623.394605: kernel_stack:         <stack trace>
=> nfs_permission (ffffffffc075d415)
=> inode_permission (ffffffffba2bb34e)
=> link_path_walk.part.49 (ffffffffba2bf172)
=> path_lookupat.isra.53 (ffffffffba2bfbc3)
=> filename_lookup.part.67 (ffffffffba2c18c0)
=> vfs_statx (ffffffffba2b5683)
=> __do_sys_newstat (ffffffffba2b5c29)
=> do_syscall_64 (ffffffffba00418b)
=> entry_SYSCALL_64_after_hwframe (ffffffffbaa00088)
...
           <...>-56912 [006] 8398623.396069: function:             nfs_permission
           <...>-56912 [006] 8398623.396093: kernel_stack:         <stack trace>
=> nfs_permission (ffffffffc075d415)
=> inode_permission (ffffffffba2bb34e)
=> link_path_walk.part.49 (ffffffffba2bf172)
=> path_openat (ffffffffba2bfdef)
=> do_filp_open (ffffffffba2c26e3)
=> do_sys_open (ffffffffba2ada36)
=> do_syscall_64 (ffffffffba00418b)
=> entry_SYSCALL_64_after_hwframe (ffffffffbaa00088)
```

# perf – Performance analysis tools for Linux

- Linux Kernel (2009)
- perf_event_open() syscall
  - perf counters (HPC, SPC)
  - kprobes, uprobes, trace points
  - LBR (Last Branch Records) sampling on recent Intel CPUs
- low-overhead sampling with callgraph
- wide range analysis from CPU instructions to Python, Java, NodeJS…
- `perf` command
  - privileged and unprivileged
  - ncurse user interface

# perf stat

```
# perf stat -d make -j
        208.784,16 msec task-clock                #    2,599 CPUs utilized
           156.385      context-switches          #  749,028 M/sec
             7.964      cpu-migrations            #   38,145 M/sec
         3.774.260      page-faults               # 18077,343 M/sec
   611.151.444.573      cycles                    # 2927194,826 GHz                    (62,51%)
   620.124.617.748      instructions              #    1,01  insn per cycle          (75,02%)
   134.224.550.386      branches                  # 642887148,373 M/sec                (75,02%)
     4.022.428.040      branch-misses             #    3,00% of all branches         (75,00%)
   170.553.275.660      L1-dcache-loads           # 816888629,684 M/sec                (75,00%)
    10.332.035.249      L1-dcache-load-misses     #    6,06% of all L1-dcache hits    (74,99%)
     2.288.155.928      LLC-loads                 # 10959440,992 M/sec                 (49,98%)
       477.323.105      LLC-load-misses           #   20,86% of all LL-cache hits     (50,01%)

      80,335503652 seconds time elapsed
     185,163504000 seconds user
      18,416851000 seconds sys
```

```
# perf stat -M Turbo_Utilization make -j
   599.287.742.470      cpu_clk_unhalted.thread   #      1,7 Turbo_Utilization
   354.672.677.325      cpu_clk_unhalted.ref_tsc

Intel i5-8265U 1.60GHz / 3.90GHz
```

# perf probe

```
$ sudo perf probe -x /lib64/libc.so.6 --add malloc --add realloc --add free
Added new events:
  probe_libc:malloc    (on malloc in /usr/lib64/libc-2.28.so)
  probe_libc:malloc_1  (on malloc in /usr/lib64/libc-2.28.so)
  probe_libc:realloc   (on realloc in /usr/lib64/libc-2.28.so)
  probe_libc:realloc_1 (on realloc in /usr/lib64/libc-2.28.so)
  probe_libc:free      (on free in /usr/lib64/libc-2.28.so)
  probe_libc:free_1    (on free in /usr/lib64/libc-2.28.so)
```

```
$ sudo perf stat -e 'probe_libc:malloc*' -e 'probe_libc:free*' -e 'probe_libc:realloc*' -p 18154
            25.540      probe_libc:malloc_1
                 0      probe_libc:malloc
                 0      probe_libc:free
            29.948      probe_libc:free_1
                 0      probe_libc:realloc
               309      probe_libc:realloc_1
```

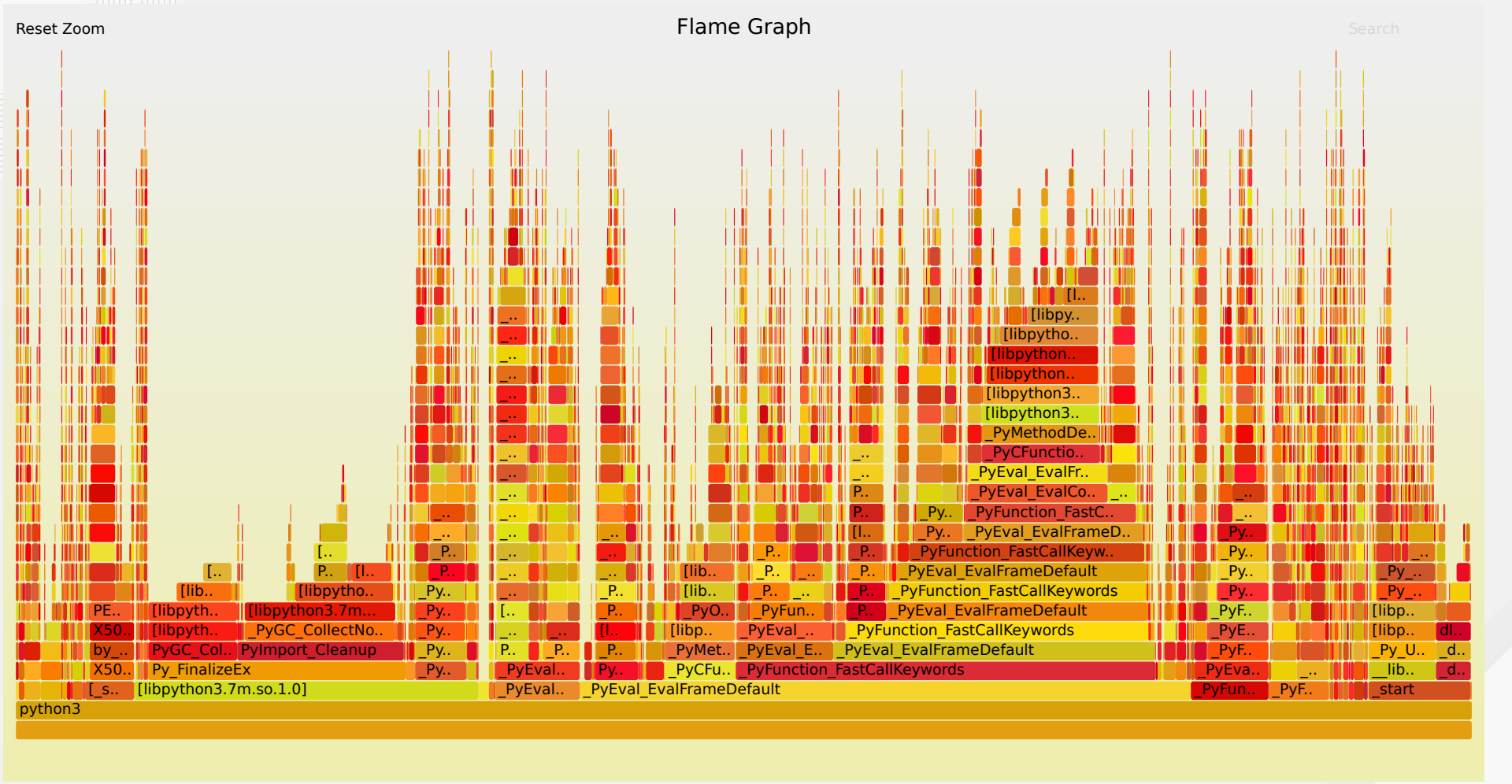
plain 0.566 sec
ltrace 3.396 sec
perf 0.705 sec

# perf record / report

```
$ perf record -Fmax --call-graph lbr \
      python3 -c "import requests; requests.get('https://www.python.org')"
```

```
$ perf report
$ perf annotate
```

```
$ perf script | stackcollapse-perf.pl  > out.perf-folded-full
$ flamegraph.pl out.perf-folded-full > perf-calls-full.svg
```


Reset Zoom
Flame Graph
Search
[l..
[libpy..
[libpytho..
[libpython..
[libpython..
[libpython3..
[libpython3..
_PyMethodDe..
_PyCFunctio..
_PyEval_EvalFr..
_PyEval_EvalCo..
_PyFunction_FastC..
_PyEval_EvalFrameD..
_PyFunction_FastCallKeyw..
_PyEval_EvalFrameDefault
_PyFunction_FastCallKeywords
_PyEval_EvalFrameDefault
_PyFunction_FastCallKeywords
_PyEval_EvalFrameDefault
_PyEval_EvalFrameDefault
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[libpytho..
PE..
[libpyth..
[libpython3.7m...
X50..
[libpyth..
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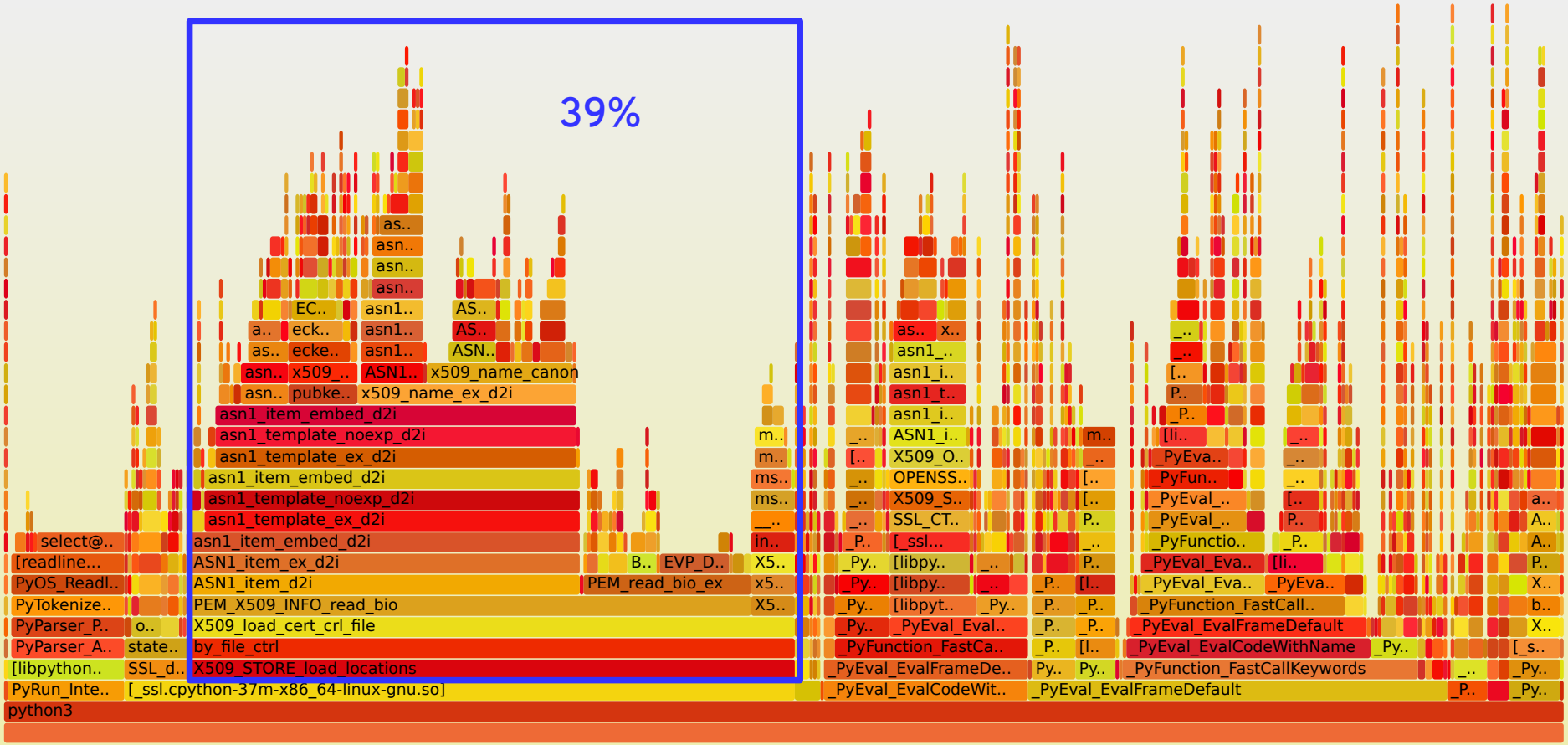
by_..
PyGC_Col..
PyImport_Cleanup
X50..
Py_FinalizeEx
[_s..
[libpython3.7m.so.1.0]
_PyO..
_PyFun..
[libp..
_PyEval_...
_PyMet..
_PyEval_E..
_PyCFu..
_PyFun..
_PyEva..
_PyFun..
_PyF..
_start
__lib..
_Py_U..
dl..
_d..

# perf record / report (2)

```
$ python3
>>> import os, requests
>>> os.getpid()
19414
>>> requests.get('https://www.python.org')
<Response [200]>
```

```
$ perf record -Fmax --call-graph lbr -p 19414
^C[ perf record: Woken up 1 times to write data ]
$ perf script | stackcollapse-perf.pl  > out.perf-folded-partial
$ flamegraph.pl out.perf-folded-partial > perf-calls-partial.svg
```


Reset Zoom
Flame Graph
Search
39%
python3
[libpython..
PyRun_Inte..
[_ssl.cpython-37m-x86_64-linux-gnu.so]
PyParser_A..
state..
SSL_d..
by_file_ctrl
X509_STORE_load_locations
PyParser_P..
o..
X509_load_cert_crl_file
PyTokenize..
PEM_X509_INFO_read_bio
PyOS_Readl..
ASN1_item_d2i
[readline...
ASN1_item_ex_d2i
select@..
asn1_item_embed_d2i
asn1_template_noexp_d2i
asn1_template_ex_d2i
asn1_item_embed_d2i
asn1_template_noexp_d2i
asn1_template_ex_d2i
asn1_item_embed_d2i
asn1_template_ex_d2i
x509_name_ex_d2i
x509_name_canon
asn1..
x509_..
pubke..
ecke..
eck..
EC..
a..
as..
asn..
ASN1..
asn1..
AS..
ASN..
B..
EVP_D..
PEM_read_bio_ex
X5..
x5..
in..
ms..
m..
__..
_..
_Py..
_P..
[libpyt..
[libpy..
[ssl...
SSL_CT..
OPENSS..
X509_O..
ASN1_i..
asn1_t..
asn1_..
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_PyFun..
_PyEval_..
_PyEval_Eva..
_PyFunctio..
_PyEval_EvalFrameDefault
_PyEval_EvalCodeWithName
_PyFunction_FastCallKeywords
_PyFunction_FastCall..
_PyEval_EvalFrameDe..
_PyEval_EvalCodeWit..
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Search

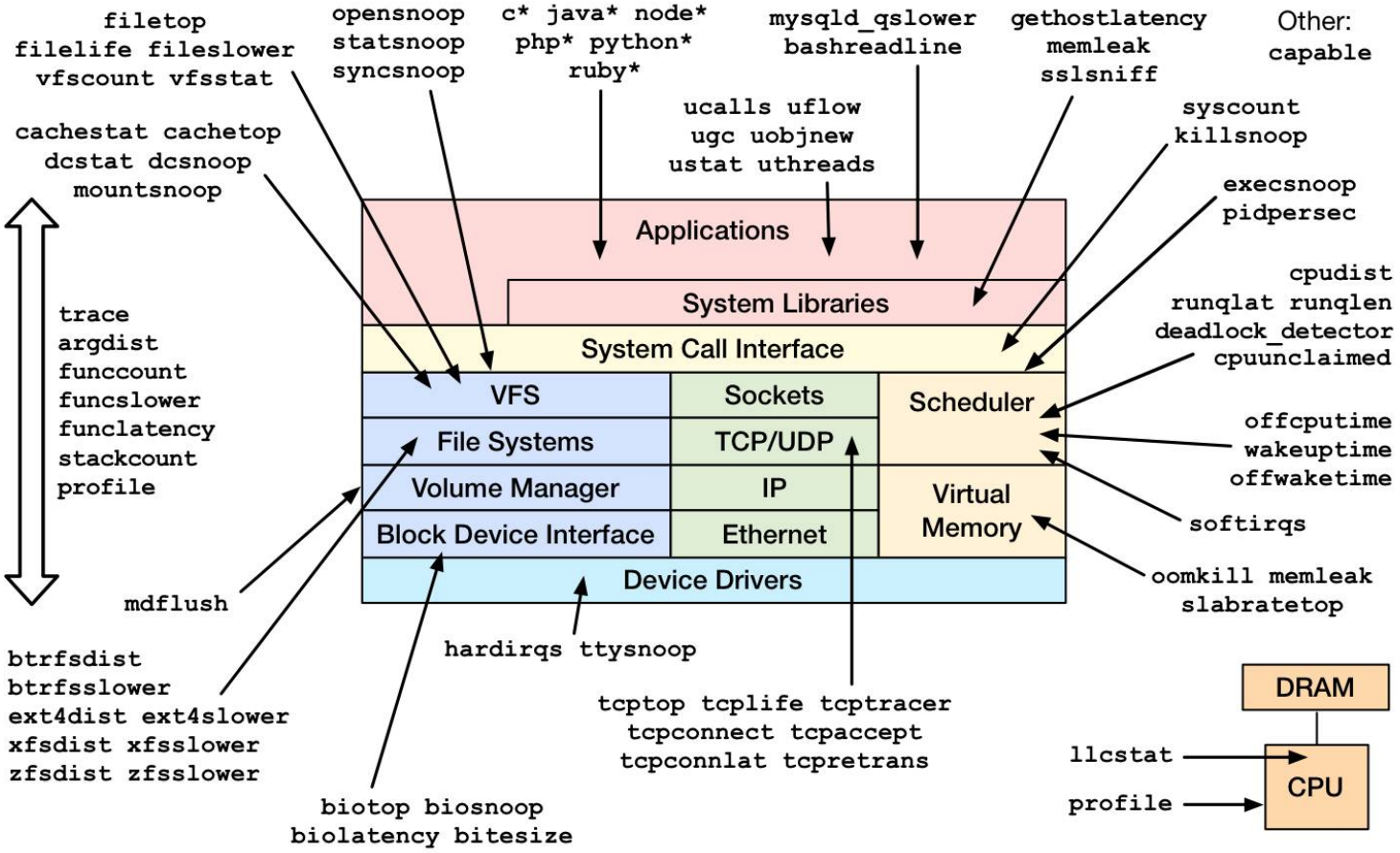
# Advanced Analysis in Kernel space

# BCC – BPF Compiler Collection

A toolkit for creating efficient kernel tracing and manipulation programs.

- Run tracing code in Kernel space
- extended BPF (Berkeley Packet Filters)
  - eBPF JIT 2014
  - Usable Kernel 4.12 - 4.15, 2017
- C with Python and LUA frontends
- rich set of existing tools

# Linux bcc/BPF Tracing Tools




https://github.com/iovisor/bcc#tools 2017

# BCC: ext4slow, tcpconnect

## Slow ext4fs operations

```
# ./ext4slower 1
Tracing ext4 operations slower than 1 ms
TIME     COMM           PID    T BYTES   OFF_KB   LAT(ms) FILENAME
18:44:18 bash           4573   R 128     0           6.45 balooctl
18:44:19 IndexedDB #198 4571   S 0       0           8.90 583651055lp.sqlite-wal
18:44:21 IndexedDB #198 4571   S 0       0          10.02 583651055lp.sqlite-wal
18:44:21 IndexedDB #198 4571   S 0       0           3.90 583651055lp.sqlite
18:44:43 mozStorage #5  4571   W 24      288         6.10 cookies.sqlite-wal
```

## TCP connections for user id 1000

```
# ./tcpconnect -u 1000
PID    COMM         IP SADDR            DADDR            DPORT
4874   Chrome_IOThr 4  192.168.7.168    107.170.8.46     80
4874   Chrome_IOThr 4  192.168.7.168    107.170.8.46     443
4874   Chrome_IOThr 4  192.168.7.168    107.170.8.46     443
4874   Chrome_IOThr 4  192.168.7.168    107.170.8.46     443
4874   Chrome_IOThr 4  192.168.7.168    107.170.8.46     443
4874   Chrome_IOThr 4  192.168.7.168    107.170.8.46     443
```

# BCC: sslsniff

```
>>> requests.get("https://ep2019.europython.eu/", headers={'Accept-Encoding': 'identity'})
```

```
# ./sslsniff -p18888
FUNC         TIME(s)            COMM             PID    LEN
WRITE/SEND   0.000000000        python3          18888  146
----- DATA -----
GET / HTTP/1.1
Host: ep2019.europython.eu
User-Agent: python-requests/2.20.0
Accept-Encoding: identity
Accept: */*
Connection: keep-alive
----- END DATA -----

READ/RECV    0.159023041        python3          18888  8192
----- DATA -----
HTTP/1.1 200 OK
Server: nginx
Date: Sun, 07 Jul 2019 19:18:46 GMT
Content-Type: text/html; charset=utf-8
Content-Length: 33617
Connection: keep-alive
X-Frame-Options: SAMEORIGIN
ETag: "c35dc4fdb282b799d8d77703a7553424"
Vary: Accept-Language, Cookie
Content-Language: en
Set-Cookie: django_language=en; expires=Mon, 06-Jul-2020 19:18:46 GMT; Max-Age=31536000; Path=/
```

# BPFtrace

https://github.com/iovisor/bpftrace

```
$ sudo bpftrace -e \
    'tracepoint:syscalls:sys_enter_openat { printf("%s(%d) %s\n", comm, pid, str(args->filename)); }'
irqbalance(1329) /proc/interrupts
```

```
>>> requests.get("https://ep2019.europython.eu/")
$ sudo bpftrace -e 'uprobe:/lib64/libc.so.6:malloc / comm == "python3" / { @bytes = hist(arg0); }'
@bytes:
[1]                 171 |                                                    |
[2, 4)              661 |@@@                                                 |
[4, 8)              356 |@                                                   |
[8, 16)            1699 |@@@@@@@@                                            |
[16, 32)           7929 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@           |
[32, 64)          10513 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@|
[64, 128)          1574 |@@@@@@@                                             |
[128, 256)          609 |@@@                                                 |
[256, 512)         1006 |@@@@                                                |
[512, 1K)           608 |@@@                                                 |
[1K, 2K)            362 |@                                                   |
[2K, 4K)             57 |                                                    |
[4K, 8K)             10 |                                                    |
[8K, 16K)            12 |                                                    |
[16K, 32K)           13 |                                                    |
[32K, 64K)            2 |                                                    |
[64K, 128K)           1 |                                                    |
```

# SystemTap


- Initial release 2005
- `stap`
- Scripting Language for dynamic instrumentation
  - Kernel module
  - DynInst
  - eBPF (extended Berkeley Packet Filter) programs
- additional features:
  - USDT / DTrace probes (Userland Statically Defined Tracing)
  - Cross-VM instrumentation
  - Prometheus

# USDT (dtrace / systemtap)

```
$ stap -l 'process("/usr/lib64/libpython3.7m*").mark("*")'
process("/usr/lib64/libpython3.7m.so.1.0").mark("function__entry")
process("/usr/lib64/libpython3.7m.so.1.0").mark("function__return")
process("/usr/lib64/libpython3.7m.so.1.0").mark("gc__done")
process("/usr/lib64/libpython3.7m.so.1.0").mark("gc__start")
process("/usr/lib64/libpython3.7m.so.1.0").mark("import__find__load__done")
process("/usr/lib64/libpython3.7m.so.1.0").mark("import__find__load__start")
process("/usr/lib64/libpython3.7m.so.1.0").mark("line")
```

```
$ stap -l 'process.provider("php").mark("*")' -c /usr/bin/php
process("/usr/bin/php").provider("php").mark("compile__file__entry")
process("/usr/bin/php").provider("php").mark("compile__file__return")
process("/usr/bin/php").provider("php").mark("error")
process("/usr/bin/php").provider("php").mark("exception__caught")
process("/usr/bin/php").provider("php").mark("exception__thrown")
process("/usr/bin/php").provider("php").mark("execute__entry")
process("/usr/bin/php").provider("php").mark("execute__return")
process("/usr/bin/php").provider("php").mark("function__entry")
process("/usr/bin/php").provider("php").mark("function__return")
process("/usr/bin/php").provider("php").mark("request__shutdown")
process("/usr/bin/php").provider("php").mark("request__startup")
```

```
$ stap -l 'process("/usr/lib/jvm/java*/jre/lib/amd64/server/libjvm.so").mark("*")' | wc -l
521
```

# Tracing with stap

```
$ sudo stap python-import.stp -c "python3 -c pass"
Pass 1: parsed user script and 496 library scripts ...
Pass 2: analyzed script: 2 probes, 4 functions, 4 embeds, 2 globals ...
Pass 3: translated to C into "/tmp/stapz4MP9b/stap_d6d27027af93310fa02967b0e5910963_5289_src.c" ...
Pass 4: compiled C into "stap_d6d27027af93310fa02967b0e5910963_5289.ko" ...
Pass 5: starting run.
ERROR: Couldn't insert module '/tmp/stapz4MP9b/stap_d6d27027af93310fa02967b0e5910963_5289.ko': Operation
not permitted
$ dmesg
[335808.816759] Lockdown: staprun: Loading of unsigned module is restricted; see man kernel_lockdown.7
```

```
$ sudo systemctl reboot --firmware-setup
```

# Trace Python imports

```
global depths = 0;
global timing

probe process("python3").library("libpython3.7m.so.1.0").mark("import__find__load__start") {
    modname = user_string($arg1);
    now = local_clock_ns()
    timing[tid(), depths] = now
    printf("%*s* Importing '%s' ...\n", 2*depths, "", modname);
    depths++;
}

probe process("python3").library("libpython3.7m.so.1.0").mark("import__find__load__done") {
    modname = user_string($arg1);
    found = $arg2;
    depths--;
    now = local_clock_ns()
    dur = now - timing[tid(), depths]
    if (found)
        printf("%*s+ Imported  '%s' in %ldus\n", 2*depths, "", modname, dur/1000);
    else
        printf("%*s- Failed    '%s' in %ldus\n", 2*depths, "", modname, dur/1000);
}
```

# Trace Python imports

```
$ sudo stap python-import.stp -c "python3 -c pass"
* Importing 'zipimport' ...
+ Imported  'zipimport' in 125us
...
* Importing 'encodings' ...
  * Importing 'codecs' ...
    * Importing '_codecs' ...
    + Imported  '_codecs' in 187us
  + Imported  'codecs' in 1273us
  * Importing 'encodings.aliases' ...
  + Imported  'encodings.aliases' in 836us
+ Imported  'encodings' in 3263us
...
* Importing 'site' ...
  ...
  * Importing 'sitecustomize' ...
  - Failed    'sitecustomize' in 149us
  * Importing 'usercustomize' ...
  - Failed    'usercustomize' in 144us
+ Imported  'site' in 28946us
```

# Verdict

- ✔ extremely detailed information
- ✔ fast, efficient
- ✔ apps, system-wide, hardware events
- ✔ wide range from pre-build tools to custom code
- ✗ extremely detailed information
- ✗ learning curve
- ✗ turn your 64 core server into a Commodore C64

# Summary

# In my humble opinion

- strace, bpftrace: Swiss Army Knife for simple tasks
- bcc: pre-build tools
- perf: benchmarking and hot-spot profiling
- SystemTap: dynamic languages (Python)
- ftrace: tracing on old Kernels
- future: eBFP

# Resources

- Brendan Gregg http://www.brendangregg.com/
- eBPF
- IOVisor Project https://www.iovisor.org/
- Sergey Klyaus: “Dynamic Tracing with DTrace & SystemTap”
  https://myaut.github.io/dtrace-stap-book/
- SystemTap beginners guide
  https://sourceware.org/systemtap/SystemTap_Beginners_Guide/
- Eben Freeman, PyBay16: Python Tracing Superpowers
  https://speakerdeck.com/emfree/python-tracing-superpowers-with-systems-tools
- Slides: https://speakerdeck.com/tiran/

# Questions?

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Red Hat

# THANK YOU

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