Linux Trace Tools

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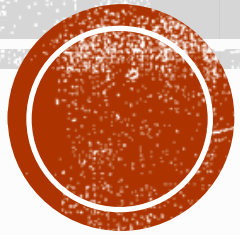
HTTP://OLIVERYANG.NET



AGENDA

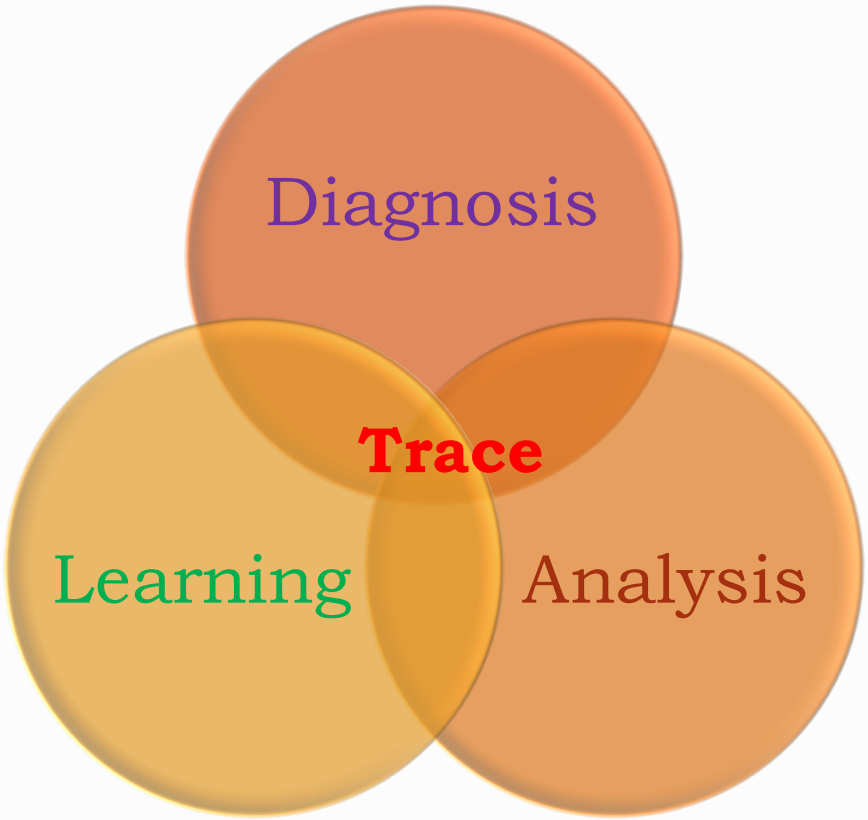
- Overview
- Trace Building Blocks
- Diagnosis, Analysis and Learning
- References

What Is Dynamic Trace?

- Trace probe could be pre-defined or defined on the fly
- All probes are not enabled by default, zero performance impacts
- Users could enable one or multiple probes and hooks dynamically
  - Hook functions could be predefined or defined dynamically
  - Could be defined by CLI or programming scripts
- While probes get hit, hook functions could be invoked
  - Hook function could be following functions
    - Print trace logs
      - Event logs, stack trace, function graph, timestamp, duration calculation, histogram
    - Drop into kernel debugger (Not support by Linux?)
    - Panic to save core files

Why Dynamic Trace?

- Functional issues diagnosis
- Performance analysis
- System behaviors learning



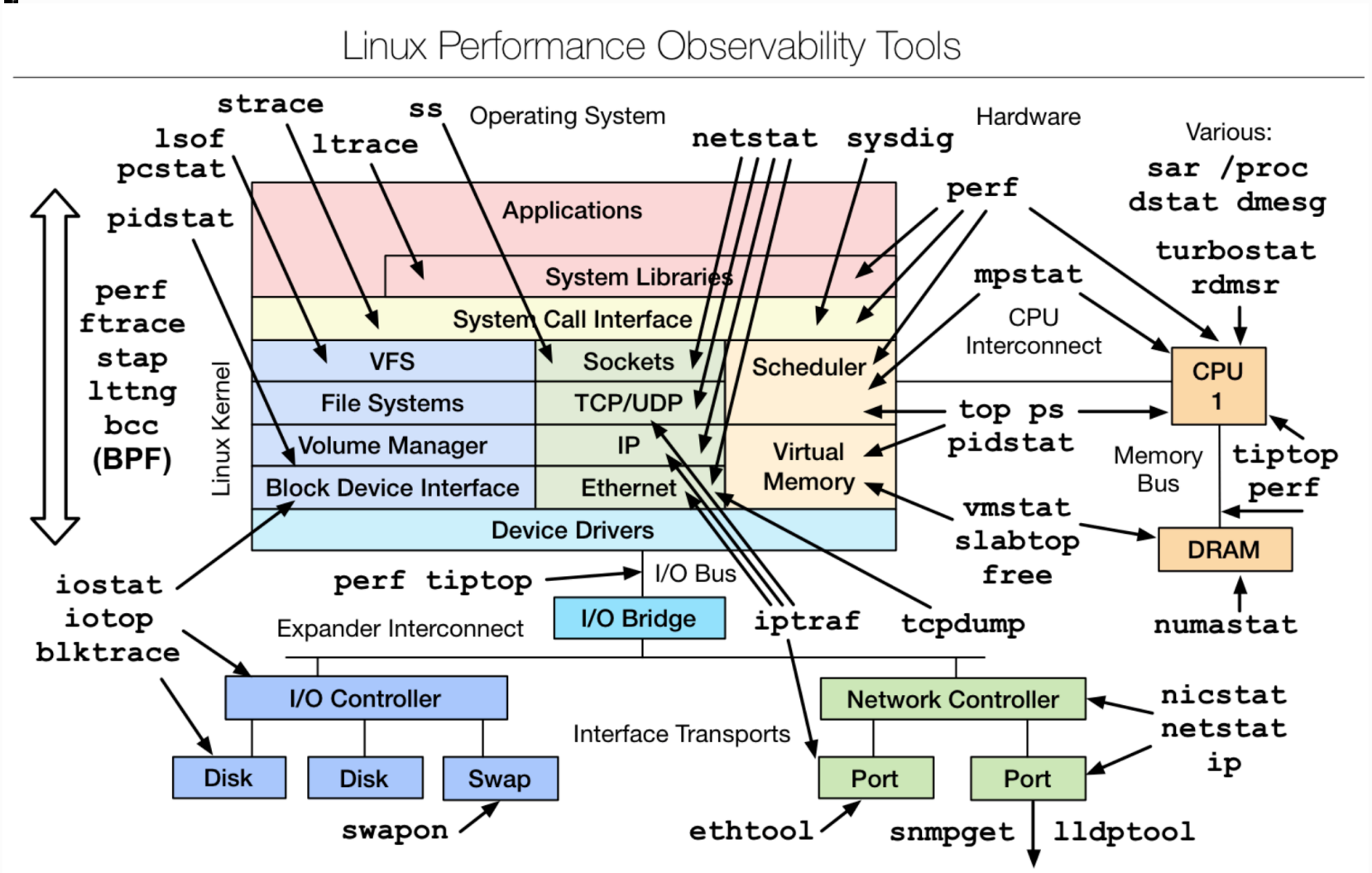
Dynamic Trace - Pros vs. Cons

- Pros
  - Good coverage by massive probes
  - Available in production mode
  - Fine granularity, could be API or source code lines level
  - Optimized for less overhead
  - Building blocks for new tools development
  - Have community and ecosystem support
    - Trace toolkits and application support
- Cons
  - Tools supporting programming need significant learning time
    - Master a new script language
    - Skills to process massive tracing data
  - Some dynamic trace scripts could crash kernel, like SystemTap
  - Performance could be impacted if the trace scripts are not well designed

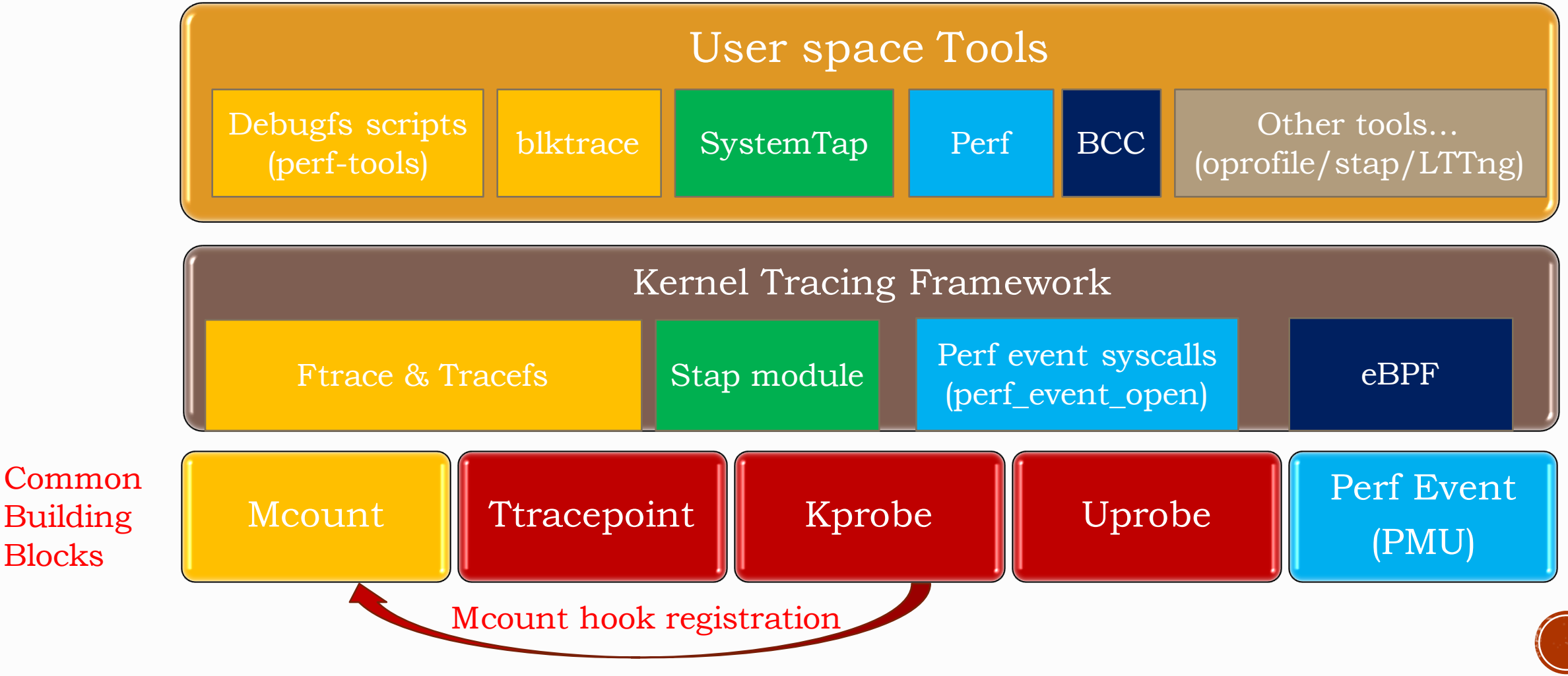
Dynamic Trace history

- 2004: Linux kprobes (2.6.9)
- 2005: Solaris Dtrace (10)
- 2008: Linux ftrace (2.6.27)
- 2009: Linux perf (2.6.31)
- 2009: Linux tracepoints (2.6.32)
- 2012: Dtrace: Oracle Unbreakable Enterprise Linux (2.6.39)
- 2012: Linux uprobes (3.5)
- 2010-2016: ftrace, kprobe, perf_events enhancements (3.7, 3.9 …4.6)
  - Ftrace: mcount hook supports saving arguments
  - Kprobe: optimization by using ftrace mcount hook
- 2014-2016: eBPF patches (3.15,3.19,4.0,4.1…4.6)

Big picture


Linux Performance Observability Tools
strace
ss
Operating System
Hardware
Various:
lsof
ltrace
netstat
sysdig
pcstat
perf
sar /proc
dstat dmesg
pidstat
Applications
turbostat
rdmsr
System Libraries
mpstat
perf
ftrace
stap
lttng
bcc
(BPF)
System Call Interface
CPU
Interconnect
VFS
Sockets
Scheduler
CPU
1
Linux Kernel
File Systems
TCP/UDP
top ps
pidstat
Volume Manager
IP
Virtual
Memory
Memory
Bus
tiptop
perf
Block Device Interface
Ethernet
vmstat
slabtop
free
Device Drivers
DRAM
iostat
iotop
blktrace
perf tiptop
I/O Bus
I/O Bridge
iptraf
tcpdump
numastat
Expander Interconnect
I/O Controller
Network Controller
nicstat
netstat
ip
Interface Transports
Disk
Disk
Swap
Port
Port
swapon
ethtool
snmpget
lldptool
http://www.brendangregg.com/linuxperf.html 2016

Conceptual View



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Predefined Trace Events

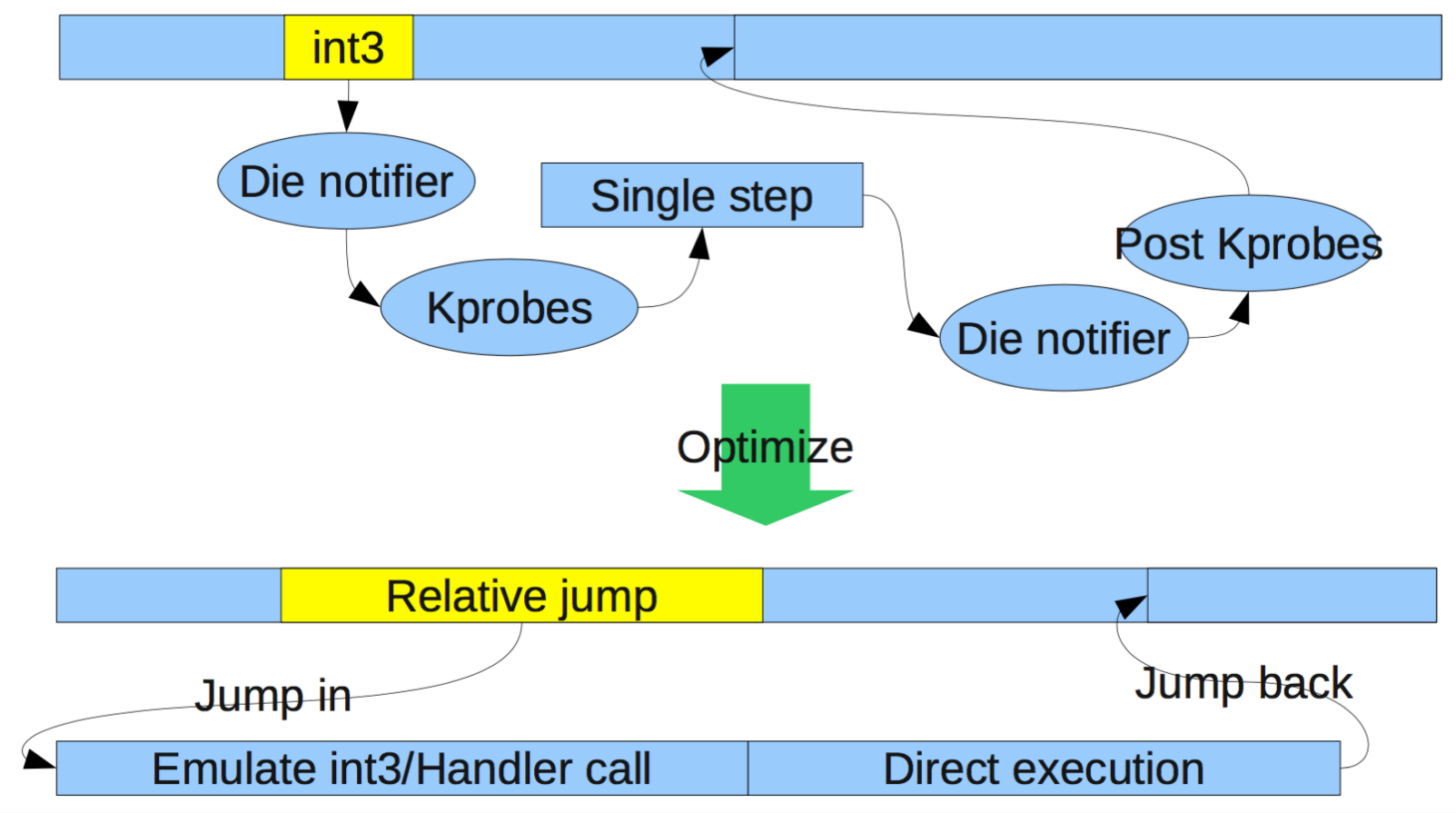
- Mcount
  - Kernel function entry trace
  - Implicit instrumentation at function entry point
    - Compiler insert instrumentations at kernel build time
      - By leveraging gcc –pg option
    - Replace instrumentation with noop instructions at kernel boot time
    - While tracer is enabled, noop got replaced by calling mcount hook function
  - Transparent to its users, not declarations in code
- Tracepoint
  - Kernel predefined trace probe
  - Explicit instrumentation in kernel code
    - Predefined by kernel & driver code, which need explicit declarations
    - By default off, but leaves the noop instructions for dynamic enabling
    - After enable, the noop instruction gets replaced by jump, which goes to real tracing code

Dynamic Software Trace Events

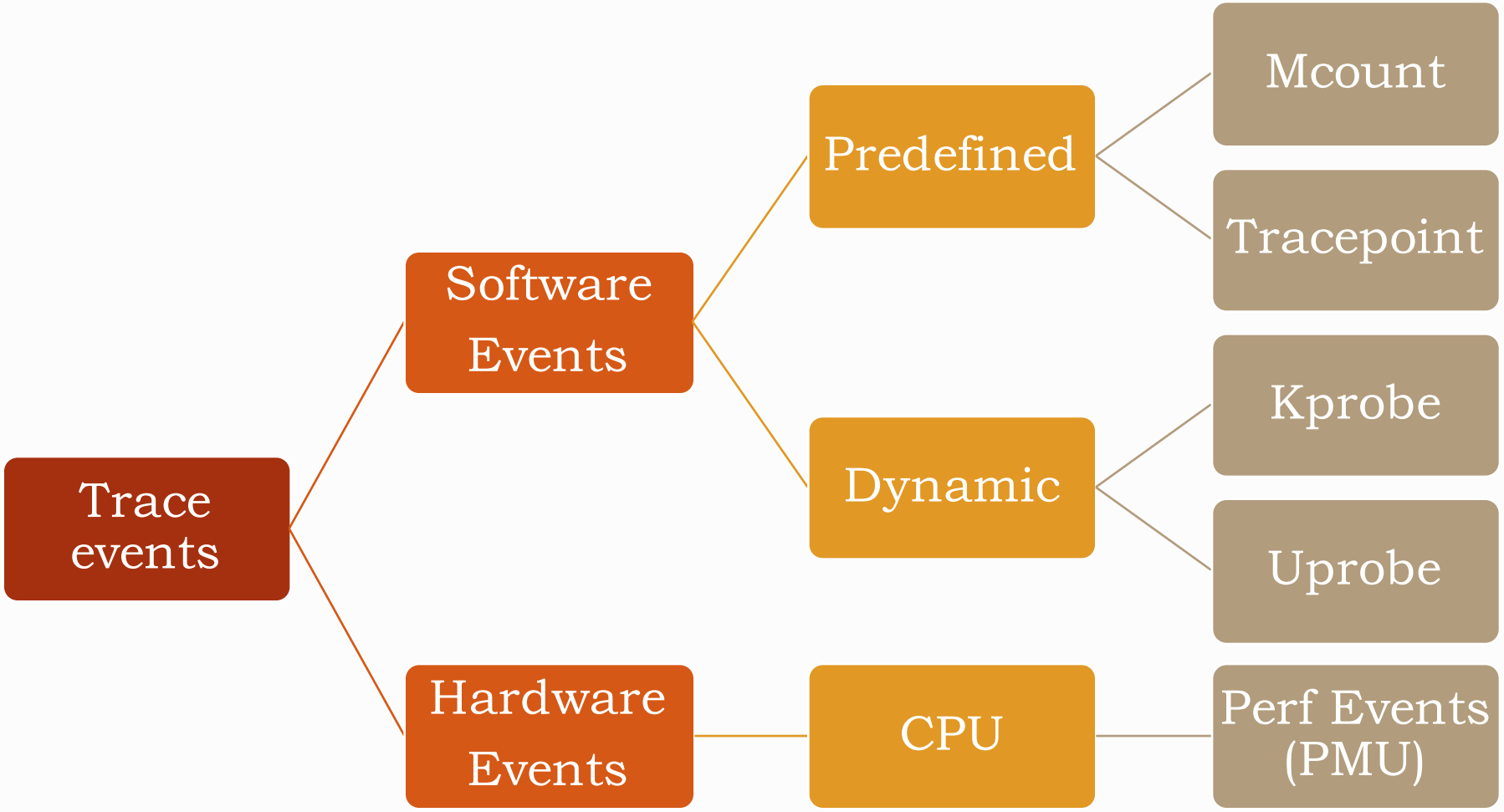
- Kprobe
  - Define a trace event in kernel dynamically
    - Replace the probed instruction with a breakpoint, mcount hook, or jump instruction
    - Hit the probe then jump to kprobe instruments
  - Three type of probes, for writing kernel modules based on C language
    - Kprobe: any instructions in a kernel function
    - Jprobe: entry point of a kernel function, for handling arg list (support mcount hook)
    - Return Probe: return point of a kernel function, for handling return address
- Uprobe
  - Define a trace event in user space dynamically
    - A user space counterpart to kprobe
    - A kernel hook can be invoked whenever a process executes a specific instruction location
  - Two type of probes
    - Uprobe: setting breakpoints for any instructions in user space functions
    - Uretprobe: hit the probe while return from user space function

Trace Internal - Kprobe Example

- 3 core technologies
  - Binary hot patch
  - Breakpoint
  - Language support



Summary - Trace Event Type



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Functional Issues Diagnosis

- Troubleshooting
- Error monitoring
- Bug report and fixes
- Trace data presentation
  - Stack backtrace
    - Inputs arg values
    - Return value
    - Error handling branch
    - Print any global or local variables
  - Trace events related to errors

Diagnosis Process

- A. Find a problem
- B. Make an assumption or ask a question
- C. Find the proper tracepoints or understand related source code
- D. Search a trace tool or write your own trace tool
  - May need consult from programming manuals
- E. Verify assumption by running tracing tools
- F. Trace results analysis
  - May need write a tool to process trace data
- G. Repeat step B until address the issues

Diagnosis Example - 1

- A. rmmod: ERROR: Module sampleblk is in use
- B. Why did rmmod return the error? What was the error?
- C. Run strace rmmod to study rmmod process
  - Results showed that it is module reference code issue
  - module:module_get trace point could help on this issue
- D. The tool tpoint could trace the trace points: module:module_get
- E. Run tpoint and reproduce the bug

  $ sudo ./tpoint module:module_get

  Tracing module:module_get. Ctrl-C to end.

  systemd-udevd-2986 [000] .... 196.382796: module_get: sampleblk call_site=get_disk refcnt=2

  systemd-udevd-2986 [000] .... 196.383071: module_get: sampleblk call_site=get_disk refcnt=3
- F. Got the tpoint logs, found that who is using the module
- Please find the detailed information from Linux Block Driver – 1 section 4.2.

Diagnosis Example - 2

- Problem: kprobe event format is difficult, any alternative solution?
- For example 2, using SystemTap could address the same issue,
- Query the do_unlinkat available input arguments and local varibales,

```
$ sudo stap -L 'kernel.function("do_unlinkat")'
kernel.function("do_unlinkat@fs/namei.c:3857") $dfd:int $pathname:char const* $path:struct path
$last:struct qstr $type:int $delegated_inode:struct inode*
```

- Run below SystemTap one liner command,

```
$ sudo stap -e 'probe kernel.function("do_unlinkat") { printf("%s \n", kernel_string($pathname))} '
```

- Notes:
  - Green is function name and source code information.
  - Red is input arguments
  - Blue is local variable
  - Please find SystemTap book from here.

Diagnosis Example - 3

- Problem: An unauthorized application is removing SQLite journal file
- Find what could you probe, and list source code line by line,

```
# perf probe -L do_unlinkat | head -n2
<do_unlinkat@/lib/modules/4.6.0-rc3+/build/fs/namei.c:0>
      0  static long do_unlinkat(int dfd, const char __user *pathname)
# perf probe -V do_unlinkat | grep pathname
                     char*        pathname
```

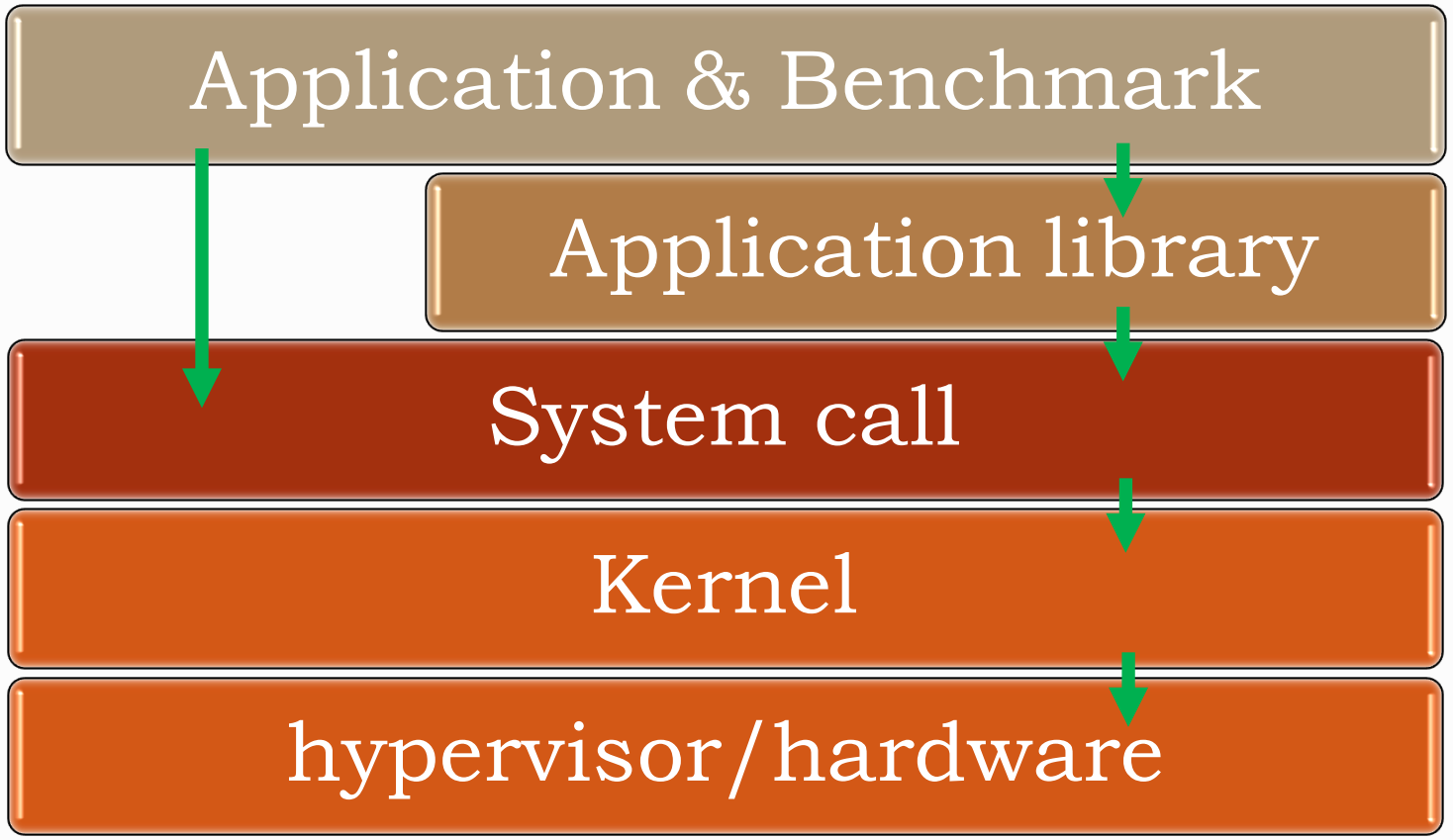
- Using perf probe to get the 2nd arg of do_unlinkat

```
# perf probe --add 'do_unlinkat pathname:string'
```

- Monitor all file removing operation within 3600 seconds

```
# perf record -e probe:do_unlinkat –aR sleep 3600
# perf script
        sysmon  1964 [056] 237504.227636: do_unlinkat: (ffffffff810ed1b0)
pathname="/ddr/registry/m0/alerts_floating.db3-journal"
        sysmon  1964 [056] 237509.233384: do_unlinkat: (ffffffff810ed1b0)
pathname="/ddr/registry/m0/alerts_floating.db3-journal"
```

Perf Analysis - Conceptual View



- App & Test Centric

- Resource & Machine Centric

Perf Analysis - Methodologies

App & Test Centric

- Problem statement method
- Functional diagram method
- Workload Characterization
- Workload Analysis
- RED Method

Resource & Machine Centric

- Resource Analysis
- USE Method
- Kernel Resource Analysis

Perf Analysis - Trace vs. Profiling

- Trace
  - Hit the probe, and record
  - Trace buffer could overflow, and trace events could be dropped
- Profiling
  - Sampling the probe events with certain frequency (typically 1HZ)
  - Driven by timer (1HZ = 1ms)
    - NMI interrupts – by CPU PMU NMI events, which is better
    - Timer interrupts
- Trace data presentation
  - Function graph
  - Timestamp or Latency calculations for each operations or functions
  - Stack back trace or function name statistic related to quick or fast path
  - Perf Histogram: latency, data size, trace events counters
  - Virtualized trace data
    - Excel (Line Chart, Histogram), Flamegraph, Heatmap

Analysis - Workload Characterization

- Who should be perf analysis target?
  - Identify application (pid, tid, users)
- Why should it be analysis target?
  - Bad perf number or metrics?
    - Computing - Busy CPU
    - Storage - Throughput, IOPS
    - Network – RX/TX throughput, IP forwarding
- How to trace or profiling the target?
  - Reproduce problem by running app, micro-benchmark
  - Select tools or writing scripts
- What should be investigated for the target?
  - Computing - on/off CPU analysis, code path and context
  - Storage and Network - IO pattern analysis, code path, context

Analysis - USE Method

- For every resource, check…
  - Utilization - busy time or sleep time
  - Saturation - queue length or time
  - Error - software or hardware errors
- Resource include…(refer to Brendan's USE check list)
  - Computing
    - App, sheduler, memory allocator, major/minor faults, swaping, locks…
    - CPU, Memory, Interconnection (QPI)
  - Storage
    - App, file system, block layer, multi-path, raid, protocol stacks(SCSI, NVMe), disk driver
    - PCIe bus, Storage bus (SAS, NVMe…), Disk or HBA counters
  - Network
    - App, TCP, UDP, NIC driver, bonding, virtual switch…
    - PCIe bus, NIC perf counters

Analysis - Trace Example 1

- Trace file IO size distribution to understand workload
- The ./fiohist.stp is written by SystemTap scripts

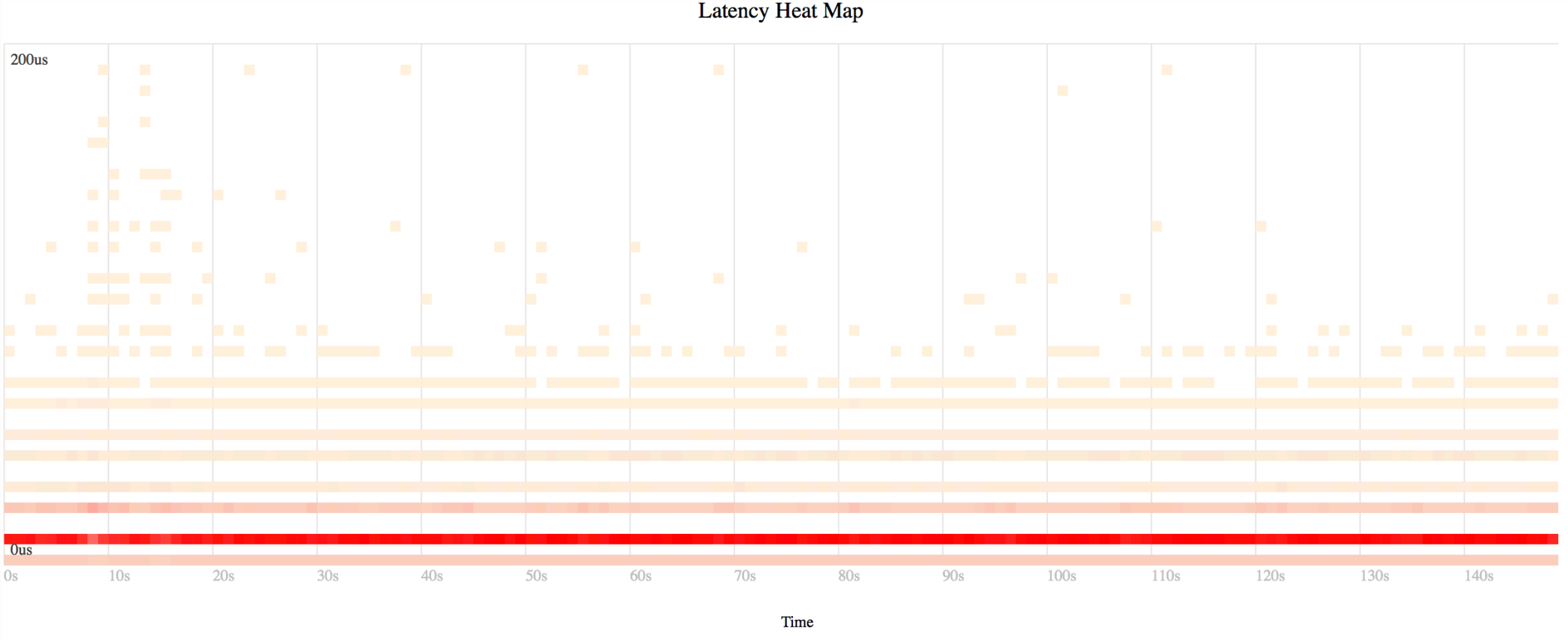
```
$ sudo fio fs_seq_write_sync_001
$ sudo ./fiohist.stp 94302
starting probe
^C
IO Summary:

                                 read     read                write          write
        name     open     read  KB tot    B avg    write      KB tot         B avg
         fio     7917        0       0        0  3698312 14793248          4096

Write I/O size (bytes):

process name: fio
value |-------------------------------------------------------------------------------------------------count
 1024 |                                                                                                    0
 2048 |                                                                                                    0
 4096 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@  3698312
 8192 |                                                                                                    0
16384 |                                                                                                    0
```

Analysis - Trace Example 2

- Block IO latency analysis to understand the workload
- The iosnoop is based on Ftrace and written by bash & awk (perf-tools project)

```
$ sudo /ws/perf-tools/iosnoop -d 253,1 -s –t
Tracing block I/O. Ctrl-C to end.
STARTs         ENDs         COMM         PID    TYPE DEV      BLOCK      BYTES     LATms
11165.022265   11165.022273   fio        11426  W    253,1    2486       57344     0.01
11165.022278   11165.022291   fio        11426  W    253,1    3142       130560    0.01
11165.022292   11165.022305   fio        11426  W    253,1    3397       130560    0.01
11165.022305   11165.022319   fio        11426  W    253,1    3652       130560    0.01
11165.022319   11165.022333   fio        11426  W    253,1    3907       130560    0.01
11165.022333   11165.022347   fio        11426  W    253,1    4162       130560    0.01
11165.022347   11165.022361   fio        11426  W    253,1    4417       130560    0.01
11165.022362   11165.022375   fio        11426  W    253,1    4672       130560    0.01
11165.022375   11165.022388   fio        11426  W    253,1    4927       130560    0.01
```

Analysis - Heatmap



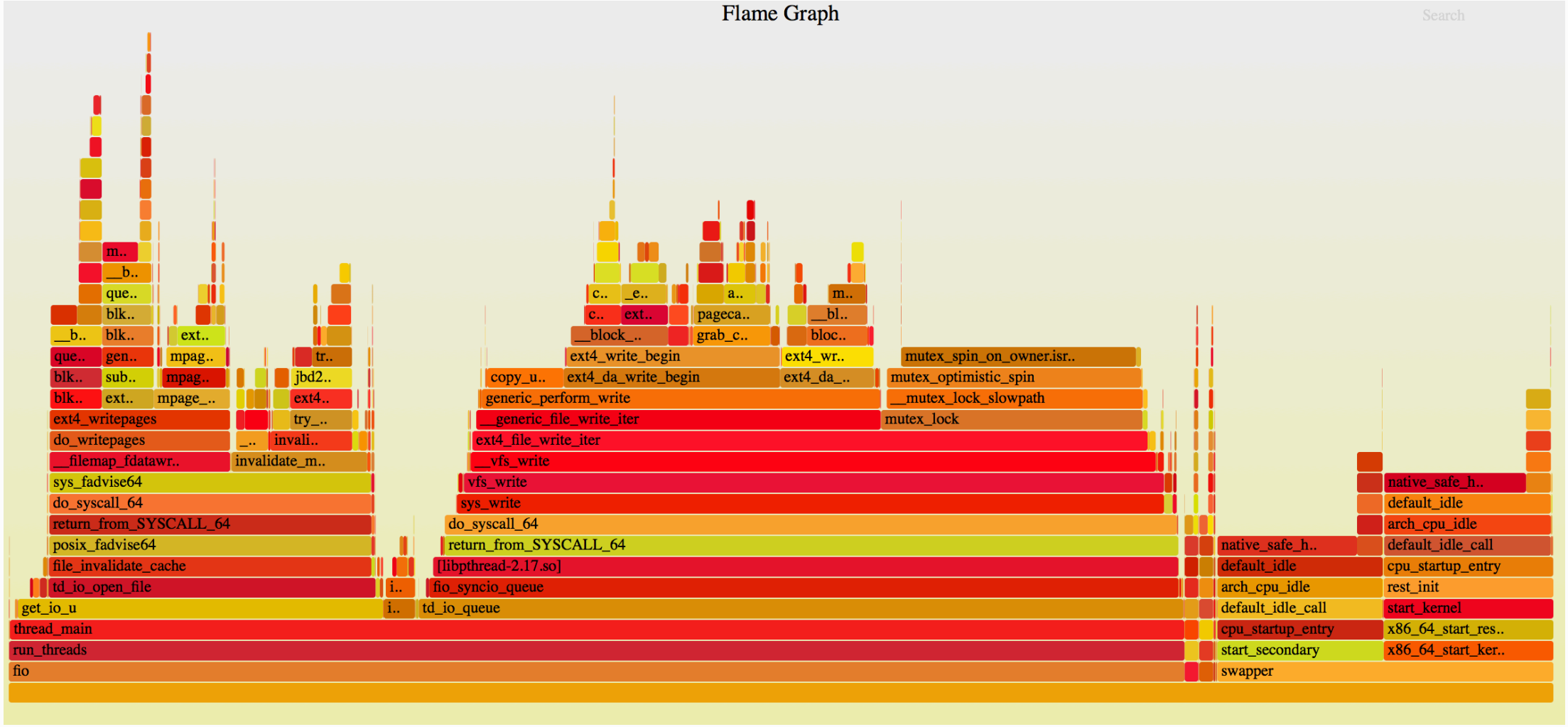
Analysis - Profiling Example

- Run FIO with write sequential IO test
- Sampling all applications and kernel activities on CPU

  $ sudo perf record -a -g --call-graph dwarf -F 997 sleep 60

  $ sudo perf report > perf_record_fs_seq_write_sync_001.log
- Virtualize profiling data by Flamegraph,
  - sudo perf script | stackcollapse-perf.pl > out.perf-folded
  - cat out.perf-folded | flamegraph.pl > perf-kernel.svg

Analysis - Flamegraph



System Behaviors Learning

- Learn runtime code path
  - Function pointers
  - Multiple code paths
  - Chain of stack backtraces
- Understand system behaviors under real workload
  - Fast vs. slow code path
  - Identify hot code path
- Present trace logs
  - Backtrace
  - Function graph
  - Statistic based on stack backtrace

Learning - Backtrace Example

- Understand block driver run time code path under real work load

```
# stap --all-modules -e 'probe module("sampleblk").function("sampleblk_request") {
print_backtrace() print("===\n") }'
        0xffffffffa04a1030 : sampleblk_request+0x0/0x0 [sampleblk]
        0xffffffff81313793 : __blk_run_queue+0x33/0x40 [kernel]
        0xffffffff8131380a : queue_unplugged+0x2a/0xb0 [kernel]
        0xffffffff81318e81 : blk_flush_plug_list+0x1d1/0x220 [kernel]
        0xffffffff8131928c : blk_finish_plug+0x2c/0x40 [kernel]
        0xffffffffa0729590 : ext4_writepages+0x4e0/0xcf0 [ext4]
        0xffffffff8119cd3e : do_writepages+0x1e/0x30 [kernel]
        0xffffffff81190b66 : __filemap_fdatawrite_range+0xc6/0x100 [kernel]
        0xffffffff811d5d96 : SyS_fadvise64+0x216/0x250 [kernel]
        0xffffffff81003c12 : do_syscall_64+0x62/0x110 [kernel]
        0xffffffff816bb721 : return_from_SYSCALL_64+0x0/0x6a [kernel]
       ===
```

Learning – Function Graph Example

- Backtrace vs. Function Graph
  - Bottom to top vs. top to bottom
  - Direct code path, vs. full code path coverage
  - Less tracing overhead vs. bigger overhead
- Understand fadvise64 syscall behaviors

  $ sudo ./funcgraph –d 1 -p 95069 SyS_fadvise64 > functiongraph.log

```
Tracing "SyS_fadvise64" for PID 95069 for 1 seconds...
   0)               |  SyS_fadvise64() {
   0)               |    __fdget() {
   0)   0.207 us    |      __fget_light();
   0)   0.369 us    |    }
   0)   0.026 us    |    _raw_spin_lock();
   0)   0.891 us    |  }
   0)               |  SyS_fadvise64() {
   0)               |    __fdget() {
   0)   0.039 us    |      __fget_light();
   0)   0.255 us    |    }
   0)   0.178 us    |    inode_congested();
   0)               |    __filemap_fdatawrite_range() {
   0)   0.026 us    |      _raw_spin_lock();
   0)   0.021 us    |      wbc_attach_and_unlock_inode();
   0)               |      do_writepages() {
```

Learning - Hot Path Example

```
    73.77%    73.77%  fio              [sampleblk]        [k] sampleblk_request
                      |
                      ---sampleblk_request
                         queue_unplugged
                         blk_flush_plug_list
                         |
                         |--74.45%-- blk_finish_plug
                         |          ext4_writepages
                         |          do_writepages
                         |          __filemap_fdatawrite_range
                         |          sys_fadvise64
                         |          do_syscall_64
                         |          return_from_SYSCALL_64
                         |          posix_fadvise64
                         |          0x100000004041a08
                         |
                          --25.55%-- blk_queue_bio
                                     generic_make_request
                                     submit_bio
                                     ext4_io_submit
                                     |
                                     |--99.95%-- ext4_writepages
                                     |          do_writepages
                                     |          __filemap_fdatawrite_range
                                     |          sys_fadvise64
                                     |          do_syscall_64
                                     |          return_from_SYSCALL_64
                                     |          posix_fadvise64
                                     |          0x100000004041a08
                                      --0.05%-- [...]
```

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Resources

- Links
  - Brendan Gregg website – many good articles
  - Brendan's Linux Perf collections
  - Perf examples by Brendan Gregg
  - Oliver Yang's Blog - blogs tagged with perf or trace
- Document
  - Ftrace Document
  - Kprobe Event Document
  - Tracepoint Document
  - Uprobe Event Document
  - SystemTap Document Collection
  - System Methodology Holistic Performance Analysis on Modern Systems
    - By Brendan Gregg, ACM Applicative System Methodology 2016.1
- Book
  - Systems Performance: Enterprise and the Cloud by Brendan Gregg

Q & A

Thank You