

Using Linux Trace Tools

For diagnosis, analysis, learning and fun...

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AGENDA

- Overview
- Trace Building Blocks
- Diagnosis, Analysis and Learning
- For Fun...



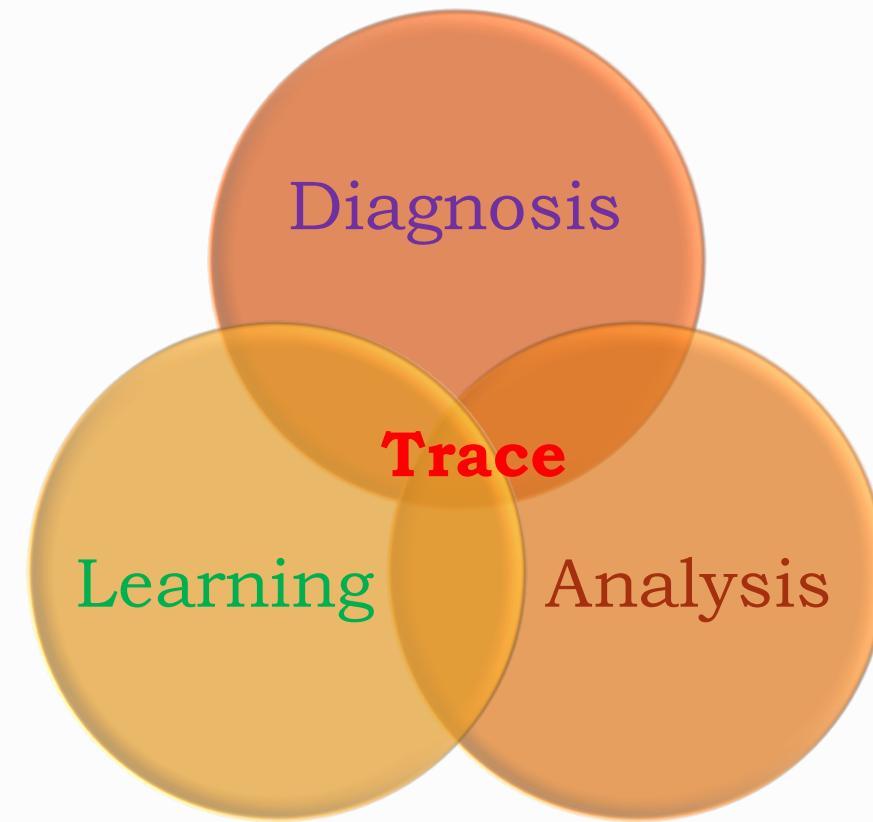
What Is Dynamic Trace?

- 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?

- Classic use cases...
 - Functional issues diagnosis
 - Performance analysis
 - System behaviors learning
- New use cases...
 - NFV ([IOVISOR](#))
 - Security...



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



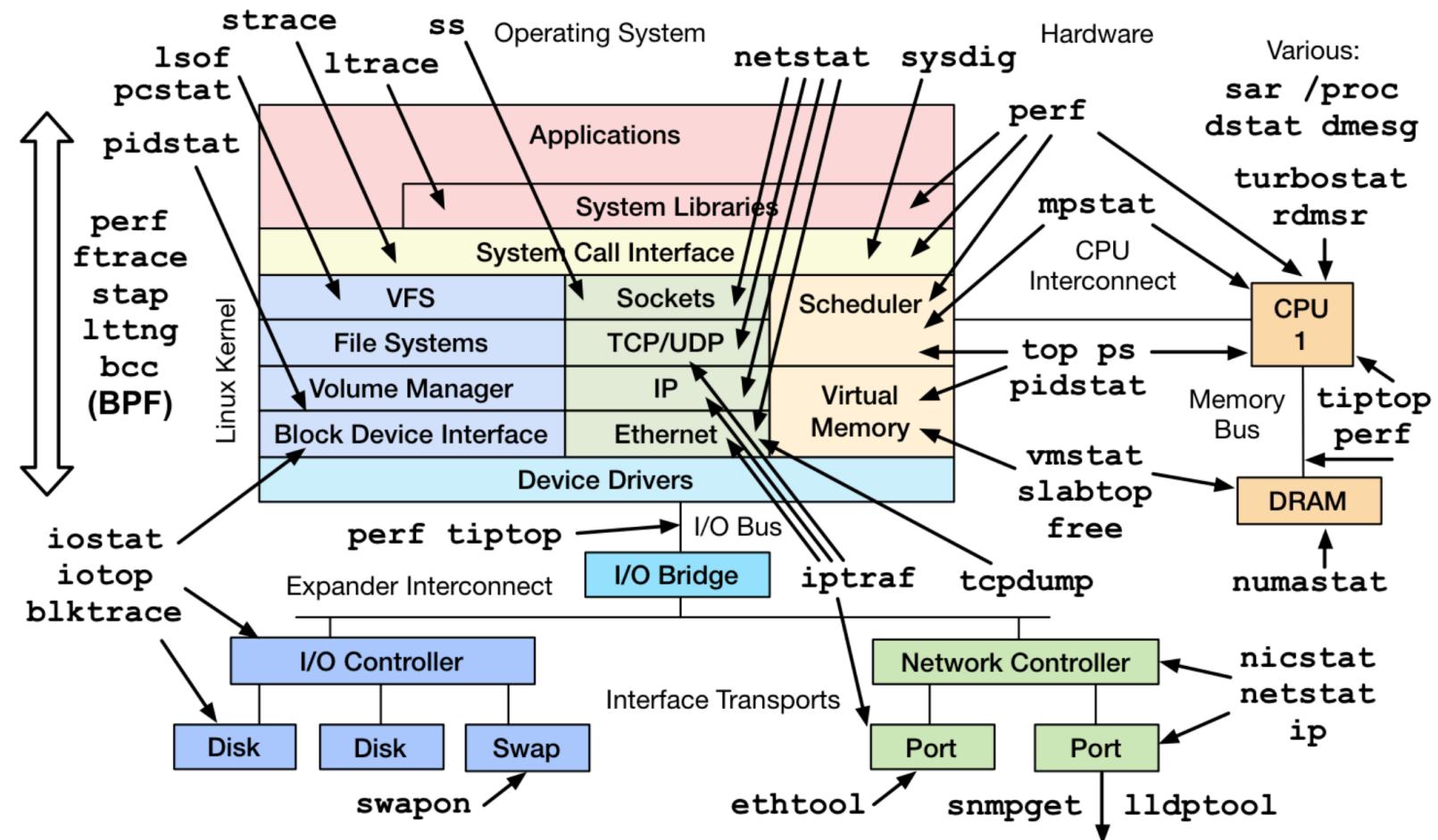
Dynamic Trace history

- 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

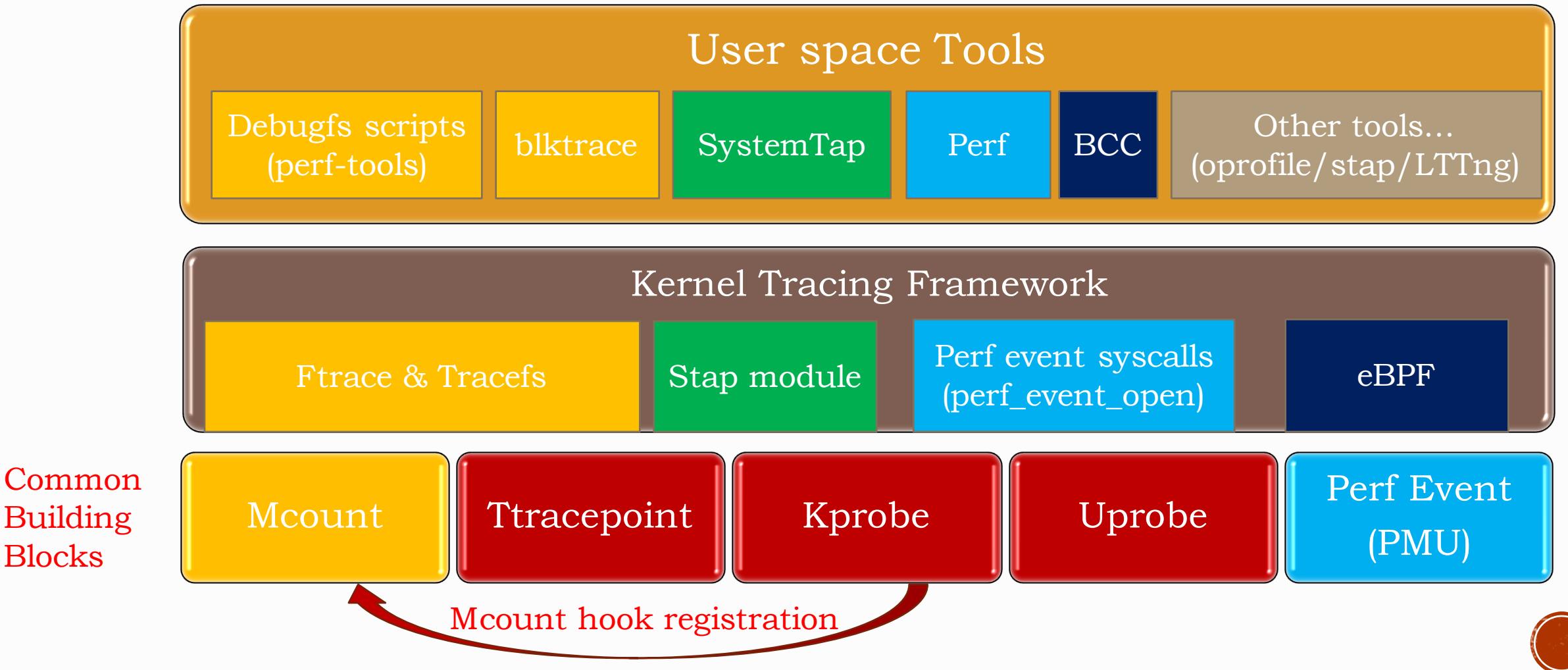


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Conceptual View



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



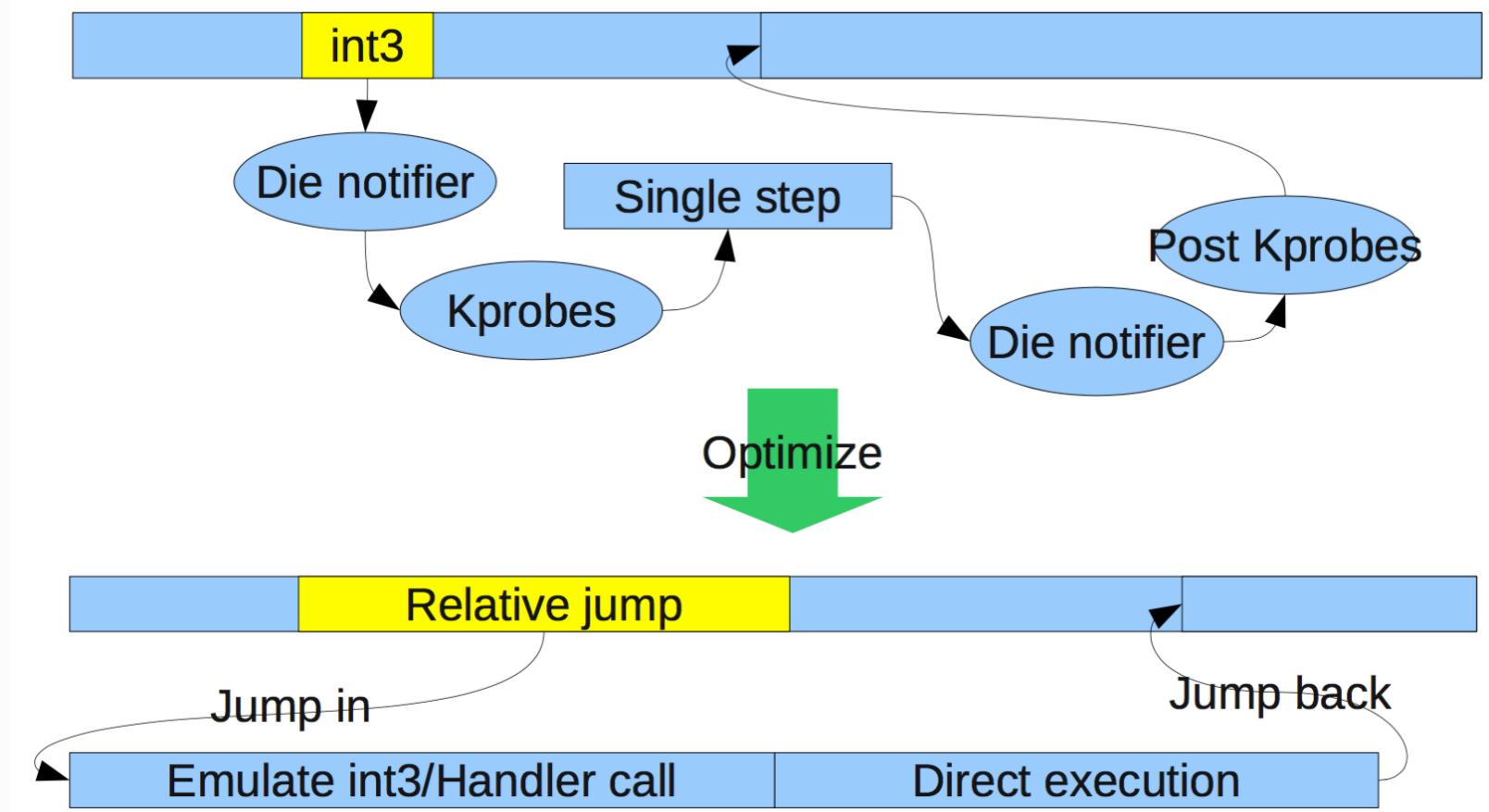
Dynamic Software Trace Events

- 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



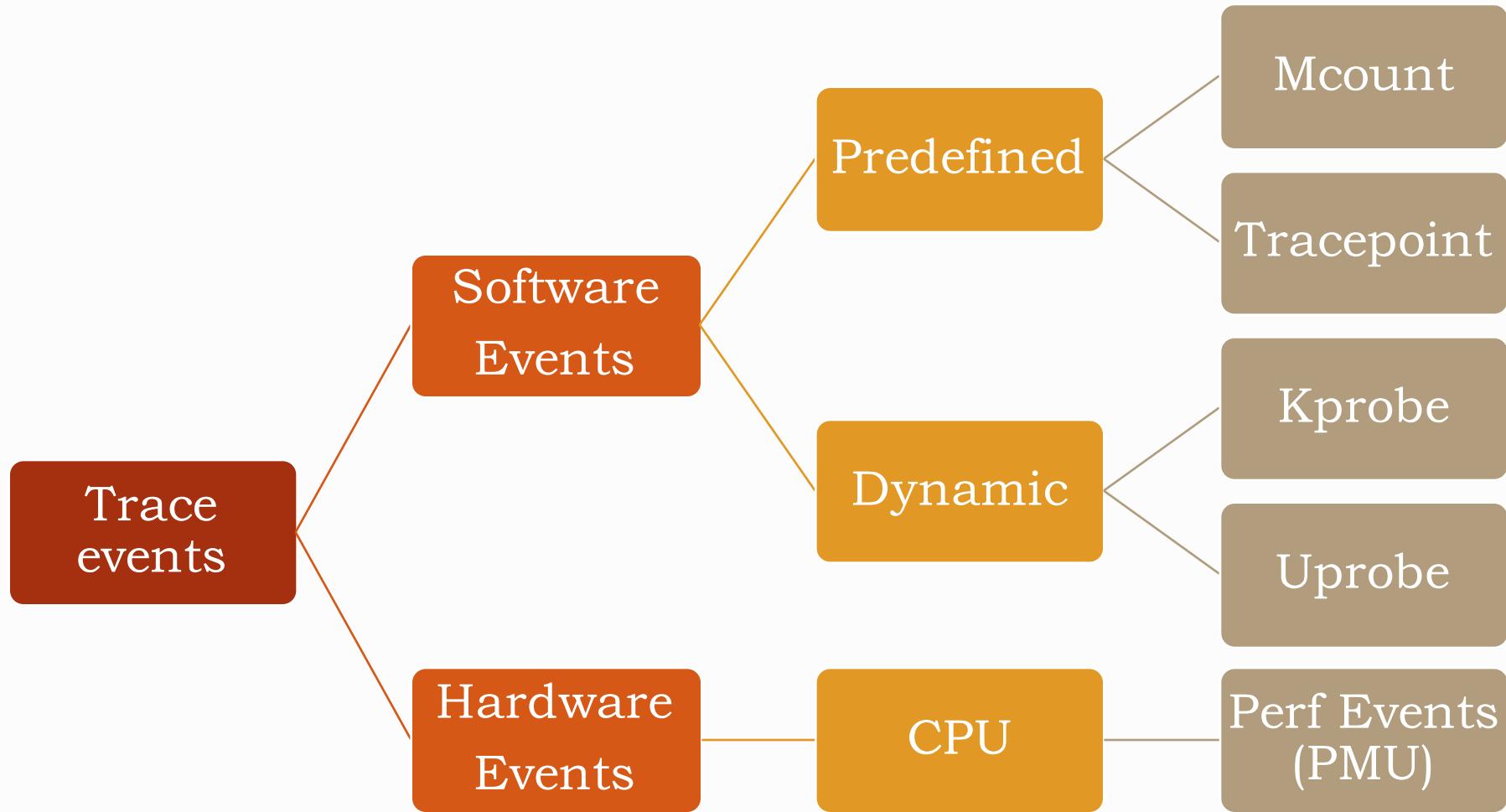
Hardware Events

- Based on hardware mechanisms
 - CPU PMU registers
 - Hardware breakpoints
- Still works for VM
 - Depends on PMU virtualization
- Perf events
 - Unified syntax to refer the events
 - sudo perf list | grep -i hardware

```
cpu-cycles OR cycles [Hardware event]
instructions [Hardware event]
cache-references [Hardware event]
cache-misses [Hardware event]
branch-instructions OR branches [Hardware event]
branch-misses [Hardware event]
bus-cycles [Hardware event]
stalled-cycles-frontend OR idle-cycles-frontend [Hardware event]
stalled-cycles-backend OR idle-cycles-backend [Hardware event]
ref-cycles [Hardware event]
L1-dcache-loads [Hardware cache event]
L1-dcache-load-misses [Hardware cache event]
L1-dcache-stores [Hardware cache event]
L1-dcache-store-misses [Hardware cache event]
L1-dcache-prefetches [Hardware cache event]
L1-dcache-prefetch-misses [Hardware cache event]
L1-icache-loads [Hardware cache event]
L1-icache-load-misses [Hardware cache event]
L1-icache-prefetches [Hardware cache event]
L1-icache-prefetch-misses [Hardware cache event]
LLC-loads [Hardware cache event]
LLC-load-misses [Hardware cache event]
LLC-stores [Hardware cache event]
LLC-store-misses [Hardware cache event]
LLC-prefetches [Hardware cache event]
LLC-prefetch-misses [Hardware cache event]
dTLB-loads [Hardware cache event]
dTLB-load-misses [Hardware cache event]
dTLB-stores [Hardware cache event]
dTLB-store-misses [Hardware cache event]
dTLB-prefetches [Hardware cache event]
dTLB-prefetch-misses [Hardware cache event]
iTLB-loads [Hardware cache event]
iTLB-load-misses [Hardware cache event]
branch-loads [Hardware cache event]
branch-load-misses [Hardware cache event]
node-loads [Hardware cache event]
node-load-misses [Hardware cache event]
node-stores [Hardware cache event]
node-store-misses [Hardware cache event]
node-prefetches [Hardware cache event]
node-prefetch-misses [Hardware cache event]
rNNN [Raw hardware event descriptor]
cpu/t1=v1[,t2=v2,t3 ...]/modifier [Raw hardware event descriptor]
mem:<addr>[:access] [Hardware breakpoint]
```



Summary - Trace Event Type



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- *Diagnosis, Analysis and Learning*
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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: 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"
```

Diagnosis Example - 3

- For example 2, using SystemTap could address the same issue,
- Query the do_unlinkat available input arguments and local variables,

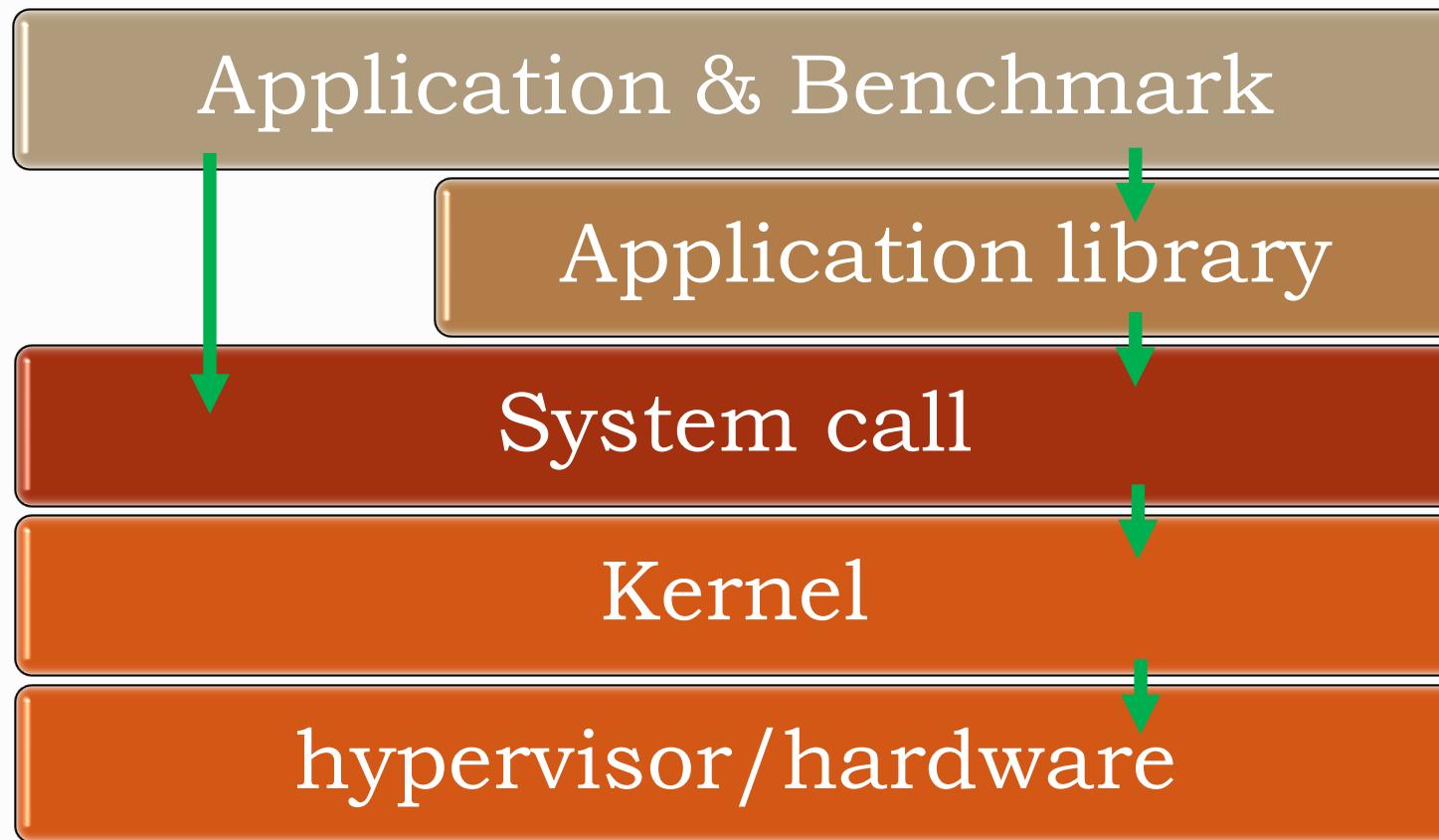
```
$ sudo stap -L 'kernel.function("do_unlinkat")'  
kernel.function("do_unlinkat@fs/namei.c:3857") $dfd:int $pathname:char const* $path:struct  
path $last:struct qstr $type:int $delegated_inode:struct inode*
```

- 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](#).



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, scheduler, memory allocator, major/minor faults, swapping, 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
```



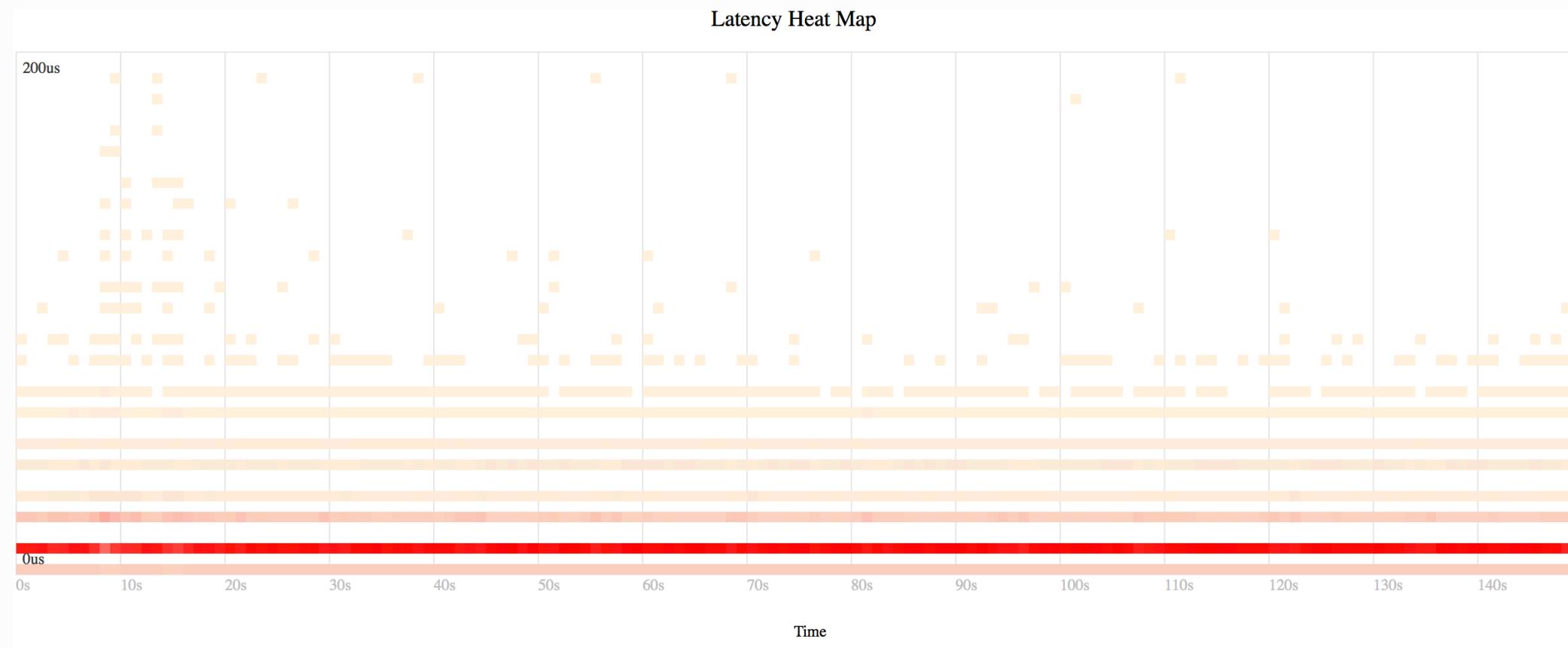
Analysis - Trace Example 2

- 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

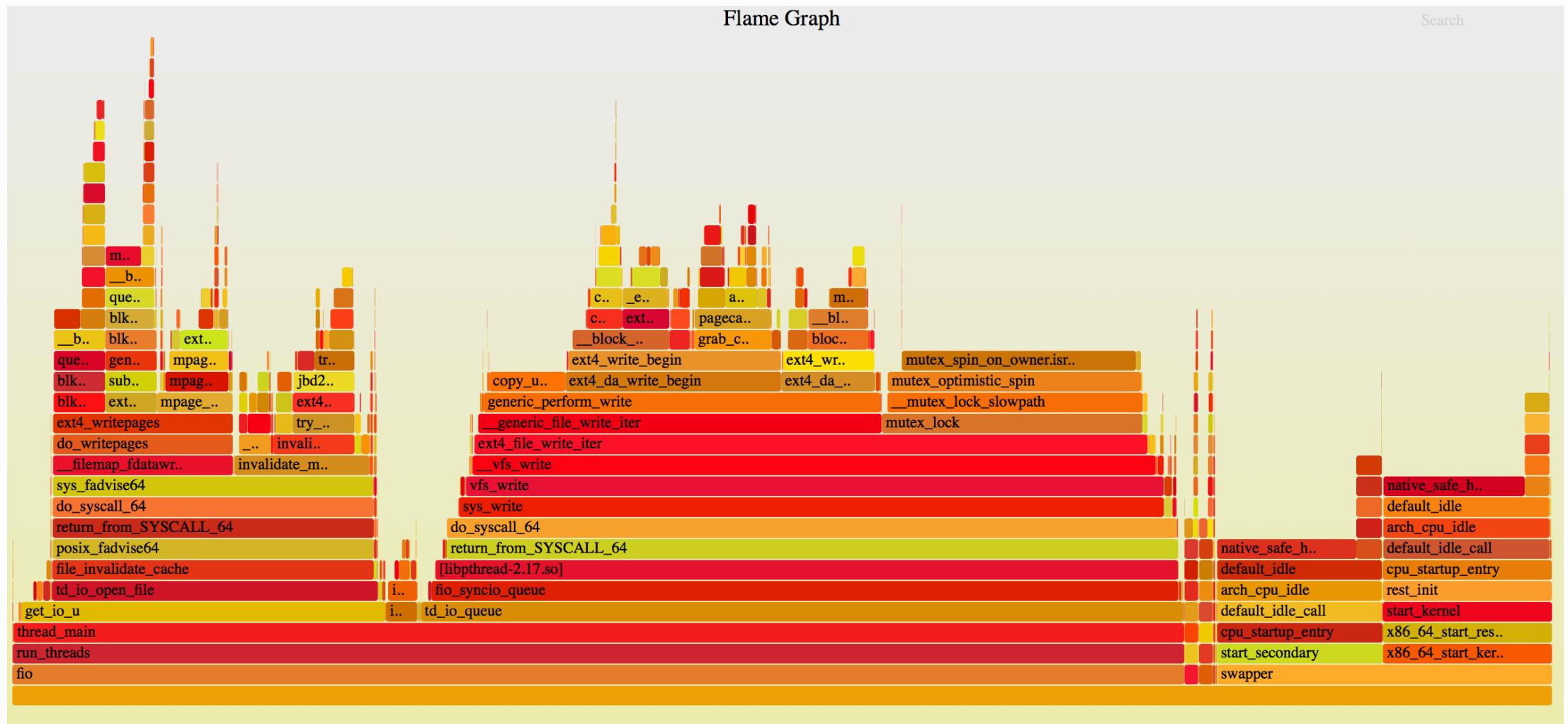


Analysis - Profiling Example

- 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") }'
```

```
0xfffffffffa04a1030 : 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]  
0xfffffffffa0729590 : ext4_writepages+0x4e0/0xcf0 [ext4]  
0xffffffff8119cd3e : do_writepages+0x1e/0x30 [kernel]  
0xffffffff81190b66 : __filemap_fdatasync_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)           |     __fget_light();
 0)           |   }
 0)           |   __raw_spin_lock();
 0)           | }
 0)           | SyS_fadvise64() {
 0)           |   __fdget() {
 0)           |     __fget_light();
 0)           |   }
 0)           |   inode_congested();
 0)           |   __filemap_fdatawrite_range() {
 0)           |     __raw_spin_lock();
 0)           |     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%-- [...]
```



Learning – Uprobe Example

- Under FIO benchmark behaviors
 - Question: How and why fadvise64 system call gets called?
 - Trace fio by using perf probe:
 - \$ sudo perf probe -x /lib64/libc.so.6 -F | grep fadvise64
 - \$ sudo perf probe -x /lib64/libc.so.6 -L posix_fadvise64
 - \$ sudo perf probe -x /lib64/libc.so.6 -V posix_fadvise64
 - \$ sudo perf probe -x /lib64/libc.so.6 -a 'posix_fadvise64 advise'
 - \$ sudo perf record -e probe_libc:posix_fadvise64 -aR -g --call-graph dwarf sleep 60
 - \$ sudo perf report
 - \$ sudo perf script
 - Please [access trace logs here.](#)



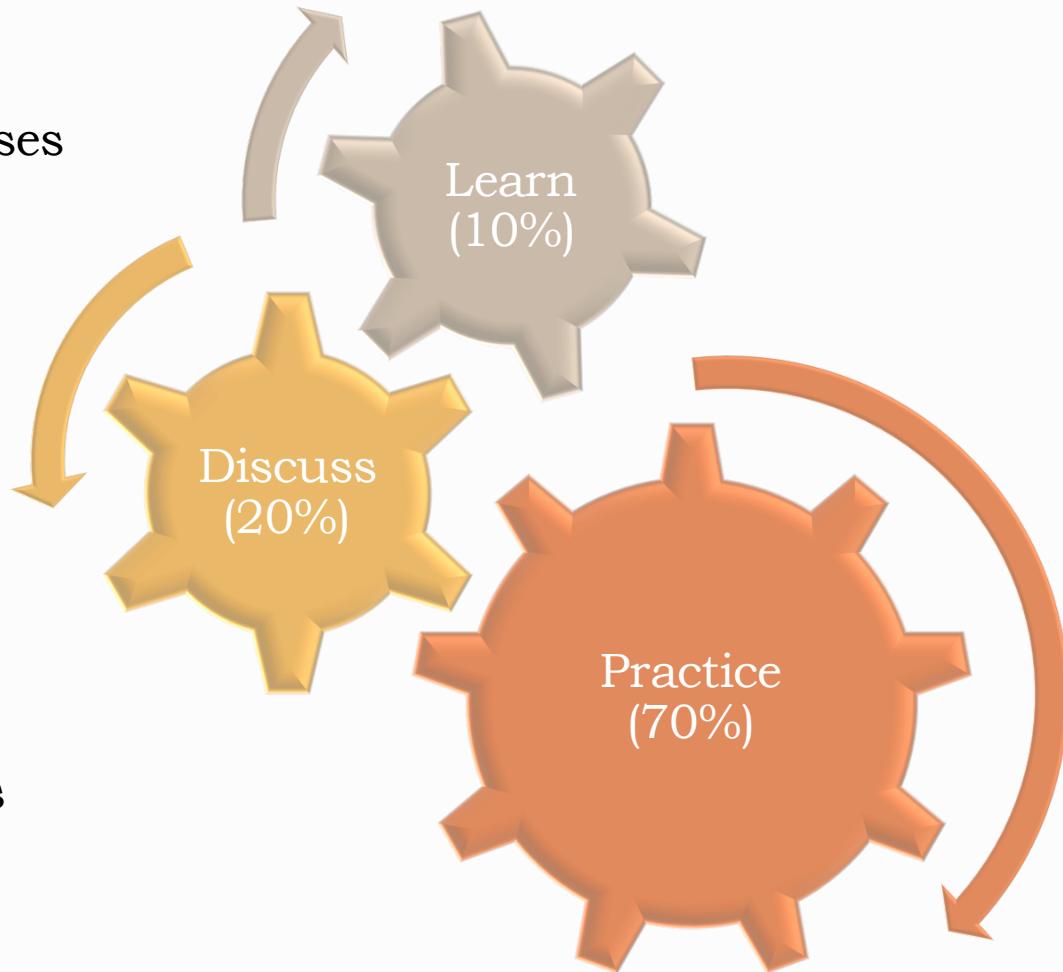
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Have Fun!

- Practice first
 - Have the basic concepts about use cases
 - Use it before understand
 - Leverage toolkits and examples
- Discuss efficiently
 - Define question clearly
 - Know the knowledge dependencies
- Learn objectively
 - Have a specific goal
 - Use case: Developer vs. Admin
 - What are learning outcomes
 - Find right reference: book, documents



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

