Observe your system

with perf, ftrace, eBPF and systemtap

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Before we begin

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Agenda

- Motivations
- Tracepoints
- Perf
- ftrace
- eBPF
- SystemTap

Motivations

- **system administrators vs application developers**

Motivations

- These tools requires root (often)
- Allows injection of code directly in kernel space
- Debugging the kernel
- Troubleshooting systems in production
- Performance analysis

Tracepoints

- **Tracepoints, or static event. “Almost” kernel ABI**
  - Stable.
- **Kprobes, aka attach handler to an arbitrary kernel function.**
  - Said function could be removed, or renamed… Scripts may not last long and need continuous fixing/porting.

Tracepoints

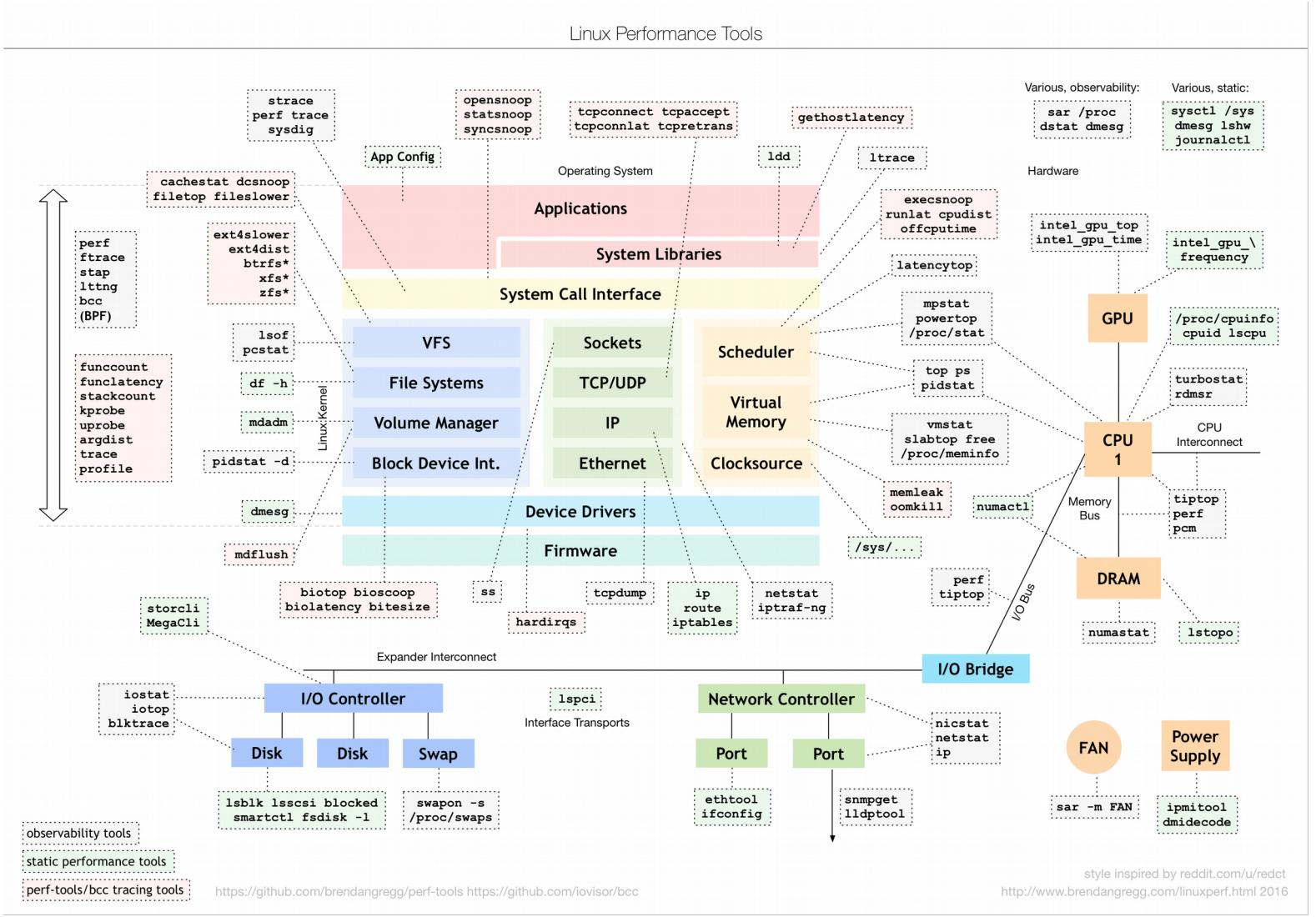
- **block:block_rq_insert:** who is creating I/O, what type, how much
- **block:block_rq_complete:** to correlate insert w/ completions
- **block:block_dirty_buffer:** in case of excessive amount of writeback
- **block:block_plug/block:block_unplug:** why requests merge or not
- **compaction:mm_compaction_try_to_compact_pages:** trying to allocate continuous ranges
- **compaction:mm_compaction_begin/compaction:mm_compaction_end:** for how long compaction lasted
- **filemap:mm_filemap_add_to_page_cache/filemap:mm_filemap_delete_from_page_cache:** track what pages are resident in memory and for how long
- **kmem:*alloc*/kmem:*free*:** slab allocations and frees

Tracepoints

- **migrate:mm_migrate_pages:** numa balancing
- **net:*** network latencies
- **sched:sched_process_exec:** a process starts execution
- **sched:sched_stat*:** a process stalled
- **sched:sched_migrate_task/sched:sched_move_numa:** process migration
- **syscalls:***
- **vmscan:mm_vmscan_kswapd_wake:** model page behaviour
- **vmscan:mm_vmscan_direct_reclaim_begin/vmscan:mm_vmscan_direct_reclaim_end:** heavy memory pressure

Tracepoints

- **writeback:balance_dirty_pages:** generate stalls
- **writeback:writeback_congestion_wait/writeback:writeback_wait_iff_congested:** excessive amount of writeback



http://www.brendangregg.com/linuxperf.html

perf & perf_events

- perf_events is the kernel infrastructure, perf is the userspace tool
- Lives in tree at tools/perf
- The primary developers are Ingo Molnar and Peter Zijlstra
- Supports CPU performance counters, software events, tracepoints, kprobes and uprobes
- Manpages are provided, see man -k perf
- Require kernel built with appropriate configuration options for some functionalities

perf & perf_events

```
bench           General framework for benchmark suites
evlist          List the event names in a perf.data file
inject          Filter to augment the events stream with additional information
kmem            Tool to trace/measure kernel memory properties
kvm             Tool to trace/measure kvm guest os
list            List all symbolic event types
lock            Analyze lock events
mem             Profile memory accesses
record          Run a command and record its profile into perf.data
report          Read perf.data (created by perf record) and display the profile
sched           Tool to trace/measure scheduler properties (latencies)
script          Read perf.data (created by perf record) and display trace output
stat            Run a command and gather performance counter statistics
top             System profiling tool.
trace           strace inspired tool
probe           Define new dynamic tracepoints
```

perf & perf_events

```
$ perf record -a sleep 5
$ perf report

# Samples: 2K of event 'cycles:ppp'
# Event count (approx.): 1043962924
# Overhead  Command          Shared Object                Symbol

    24.05%  swapper          [kernel.kallsyms]            [k] 0xffffffff813da762
     1.16%  mplayer          mplayer                      [.] 0x0000000000260028
     1.03%  soffice.bin      libc-2.22.so                 [.] __memmove_avx_unaligned
     0.55%  emacs-gtk        emacs-gtk                    [.] 0x000000000015c976
     0.55%  mplayer          mplayer                      [.] 0x0000000000260015
     0.55%  gnome-terminal-  libc-2.22.so                 [.] __memset_sse2
     0.50%  mplayer          libavcodec.so.57.48.101      [.] 0x00000000006a48d0
     0.46%  soffice.bin      libpixman-1.so.0.34.0        [.] 0x000000000008dc3a
     0.40%  mplayer          mplayer                      [.] 0x0000000000260012
```

perf & perf_events

```
$ perf script | head
```

```
            perf  9449 [000] 41595.445170:          1 cycles:ppp:  ffffffff8118165e event_function ([
            perf  9449 [000] 41595.445174:          1 cycles:ppp:  ffffffff8100c13a intel_pmu_handle_
            perf  9449 [000] 41595.445175:          9 cycles:ppp:  ffffffff81036980 native_sched_cloc
            perf  9449 [000] 41595.445177:        180 cycles:ppp:  ffffffff81036980 native_sched_cloc
            perf  9449 [000] 41595.445178:       3931 cycles:ppp:  ffffffff81036980 native_sched_cloc
            perf  9449 [000] 41595.445180:      84205 cycles:ppp:  ffffffff8123333b do_vfs_ioctl ([ke
         swapper     0 [001] 41595.445191:          1 cycles:ppp:  ffffffff8100b350 intel_pmu_enable_
         swapper     0 [001] 41595.445193:          1 cycles:ppp:  ffffffff81058eb0 native_apic_mem_w
         swapper     0 [001] 41595.445195:         13 cycles:ppp:  ffffffff8103694d native_sched_cloc
         swapper     0 [001] 41595.445197:        214 cycles:ppp:  ffffffff8103694d native_sched_cloc
```

perf & perf_events

```
$ perf list | grep sched:
  sched:sched_kthread_stop                           [Tracepoint event]
  sched:sched_kthread_stop_ret                       [Tracepoint event]
  sched:sched_migrate_task                           [Tracepoint event]
  sched:sched_move_numa                              [Tracepoint event]
  sched:sched_pi_setprio                             [Tracepoint event]
  sched:sched_process_exec                           [Tracepoint event]
  sched:sched_process_exit                           [Tracepoint event]
  sched:sched_process_fork                           [Tracepoint event]
  sched:sched_process_free                           [Tracepoint event]
  sched:sched_process_hang                           [Tracepoint event]
  [...]
```

perf & perf_events

```
$ perf record -e sched:sched_stat_sleep -e sched:sched_switch -g
$ perf report
# Samples: 2M of event 'sched:sched_switch'
# Event count (approx.): 4246430127764
#
# Children      Self       Samples  Command          Shared Object         Symbol
    70.67%     0.00%             0  httpd            [kernel.kallsyms]     [k] schedule
                      |
                      ---schedule
                         __schedule
    70.67%    70.67%       1629298  httpd            [kernel.kallsyms]     [k] __schedule
                      |
                      |--67.92%-- pthread_cond_wait@@GLIBC_2.3.2
                      |          entry_SYSCALL_64_fastpath
                      |          sys_futex
                      |          do_futex
                      |          futex_wait
```

perf & perf_events

```
$ perf top

PerfTop:     644 irqs/sec  kernel:45.2%  exact: 100.0% [4000Hz cycles:ppp],  (all, 4 CPUs)
------------------------------------------------------------------------------

     4.74%  libz.so.1.2.8       [.] 0x0000000000002f36
     3.88%  [kernel]            [k] module_get_kallsym
     2.43%  [kernel]            [k] format_decode
     2.17%  perf                [.] symbols__insert
     1.73%  perf                [.] rb_next
     1.65%  [kernel]            [k] number
     1.43%  [kernel]            [k] kallsyms_expand_symbol.constprop.1
     1.27%  perf                [.] hex2u64
     1.12%  [kernel]            [k] string
     1.10%  perf                [.] rb_insert_color
```

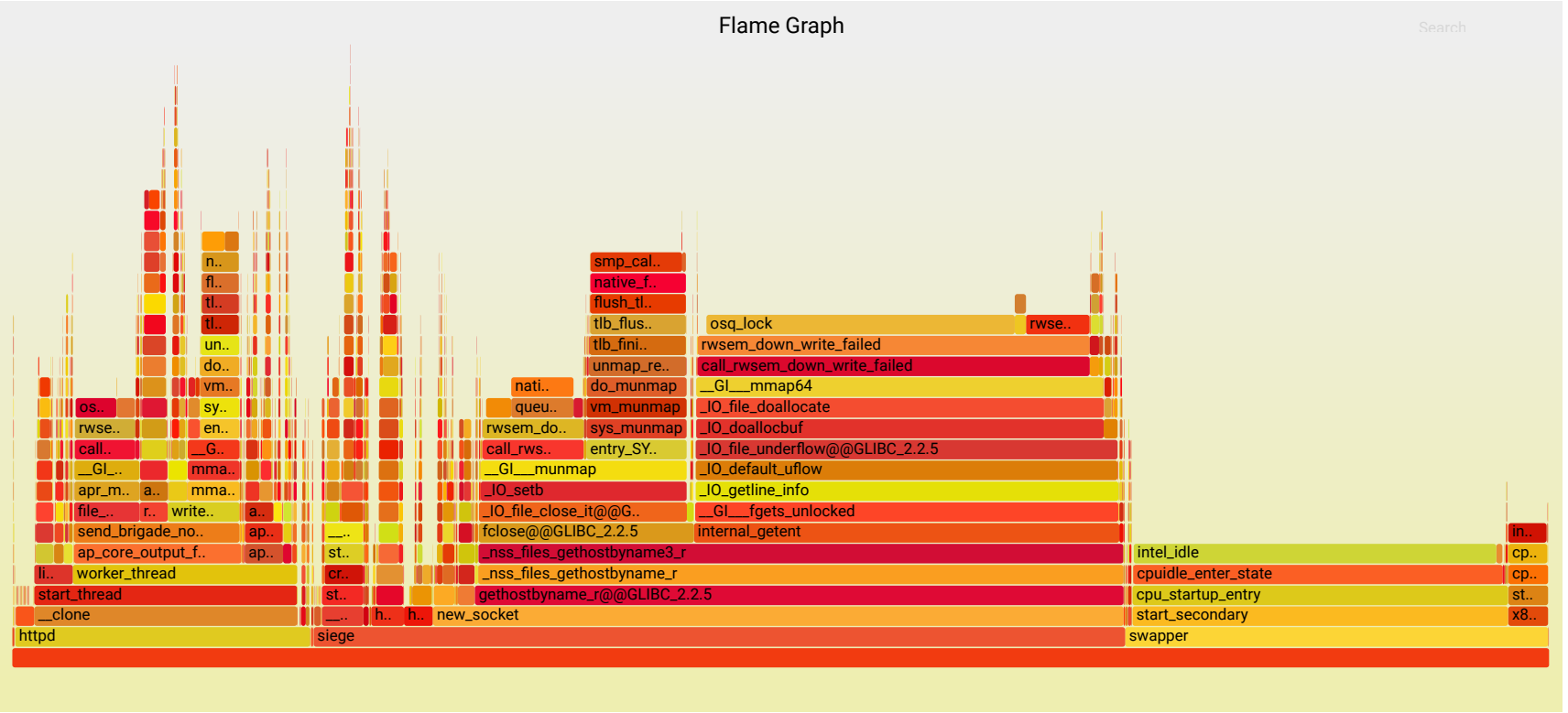
perf & perf_events

```
$ perf stat -a
^C
 Performance counter stats for 'system wide':

       7786.772339      task-clock (msec)         #    4.001 CPUs utilized
              742      context-switches          #    0.095 K/sec
               18      cpu-migrations            #    0.002 K/sec
                7      page-faults               #    0.001 K/sec
       81,834,321      cycles                    #    0.011 GHz
   <not supported>      stalled-cycles-frontend
   <not supported>      stalled-cycles-backend
       31,909,569      instructions              #    0.39  insns per cycle
        6,976,025      branches                  #    0.896 M/sec
          326,023      branch-misses             #    4.67% of all branches

       1.946330553 seconds time elapsed
```

perf & perf_events

```
$ perf sched record -a
$ perf sched map

          *.            41428.284823 secs .  => swapper:0
  *A0      .            41428.287425 secs A0 => rcu_sched:7
  *.       .            41428.287429 secs
   .       .  *B0       41428.289945 secs B0 => gnome-terminal-:2127
   .       .  *.        41428.289983 secs
  *A0      .   .        41428.291418 secs
  *.       .   .        41428.291420 secs
  *A0      .   .        41428.295423 secs
  *.       .   .        41428.295426 secs
   .  *C0  .   .        41428.296136 secs C0 => Timer:8743
   .  *.   .   .        41428.296149 secs
   .  *C0  .   .        41428.297198 secs
```

perf & perf_events



http://www.brendangregg.com/FlameGraphs/cpuflamegraphs.html#perf

perf & perf_events

Off-CPU analysis.

http://www.brendangregg.com/blog/2015-02-26/linux-perf-off-cpu-flame-graph.html

```
$ perf record -e sched:sched_stat_sleep -e sched:sched_switch \
    -e sched:sched_process_exit -a -g -o perf.data.raw sleep 1
$ perf inject -v -s -i perf.data.raw -o perf.data
```

perf & perf_events

Examples of analysis carried out with perf (by Ingo Molnar):

- **“The problem with prefetch” https://lwn.net/Articles/444336/**
- **“Software prefetches considered harmful” https://lwn.net/Articles/444346/**

ftrace

- Kernel tracer, available since ~2008
- Originated from the -rt kernel
- Maintained by Steven Rostedt
- Exposes tracepoints as files under /sys/kernel/debug/tracing
- Programmable via shell and unix tools
- Kernel needs to be compiled with specific options
- Documentation in tree at Documentation/trace/ftrace.txt
- Requires knowledge of kernel tracepoints
- Allows tracing of arbitrary kernel functions with kprobes
- Has CLI (trace-cmd) and GUI (kernelshark)

ftrace: kernel config

```
$ make allyesconfig
$ grep FTRACE .config
CONFIG_KPROBES_ON_FTRACE=y
CONFIG_HAVE_KPROBES_ON_FTRACE=y
CONFIG_PSTORE_FTRACE=y
CONFIG_HAVE_DYNAMIC_FTRACE=y
CONFIG_HAVE_DYNAMIC_FTRACE_WITH_REGS=y
CONFIG_HAVE_FTRACE_MCOUNT_RECORD=y
CONFIG_FTRACE=y
CONFIG_FTRACE_SYSCALLS=y
CONFIG_DYNAMIC_FTRACE=y
[...]
```

ftrace: tracepoints

```
$ mount -t debugfs nodev /sys/kernel/debug

/sys/kernel/debug/tracing # head available_events
kvmmmu:kvm_mmu_pagetable_walk
kvmmmu:kvm_mmu_paging_element
kvmmmu:kvm_mmu_set_accessed_bit
[...]

/sys/kernel/debug/tracing$ cat available_events | wc -l
1832
```

ftrace: tracepoints

Grouped by system:

```
608 syscalls
364 xfs
145 cfg80211
114 mac80211
 65 kvm
 48 btrfs
 39 i915
 35 xen
 28 writeback
 24 sched
 [...]
```

ftrace example: I/O

```
$ echo nop > current_tracer
$ echo 1 > events/block/block_rq_issue/enable
$ echo 1 > events/block/block_rq_complete/enable
$ cat trace_pipe

dd-6195  [000] d..2 24591.455048: block_rq_issue: 8,0 W 0 () 414091752 + 1344 [dd]
dd-6195  [000] d..2 24591.455078: block_rq_issue: 8,0 W 0 () 414093096 + 704 [dd]
dd-6195  [000] d..2 24591.455211: block_rq_issue: 8,0 W 0 () 414093800 + 1344 [dd]
dd-6195  [000] d..2 24591.455219: block_rq_issue: 8,0 W 0 () 414095144 + 704 [dd]
dd-6195  [000] d..2 24591.455345: block_rq_issue: 8,0 W 0 () 414095848 + 1368 [dd]
dd-6195  [000] d..2 24591.455353: block_rq_issue: 8,0 W 0 () 414097216 + 680 [dd]
dd-6195  [000] d..2 24591.455476: block_rq_issue: 8,0 W 0 () 414097896 + 1344 [dd]
dd-6195  [000] d..2 24591.455488: block_rq_issue: 8,0 W 0 () 414099240 + 704 [dd]
dd-6195  [000] d..2 24591.455594: block_rq_issue: 8,0 W 0 () 414099944 + 1352 [dd]
dd-6195  [000] d..2 24591.455601: block_rq_issue: 8,0 W 0 () 414101296 + 456 [dd]
```

ftrace canned scripts: perf-tool

https://github.com/brendangregg/perf-tools

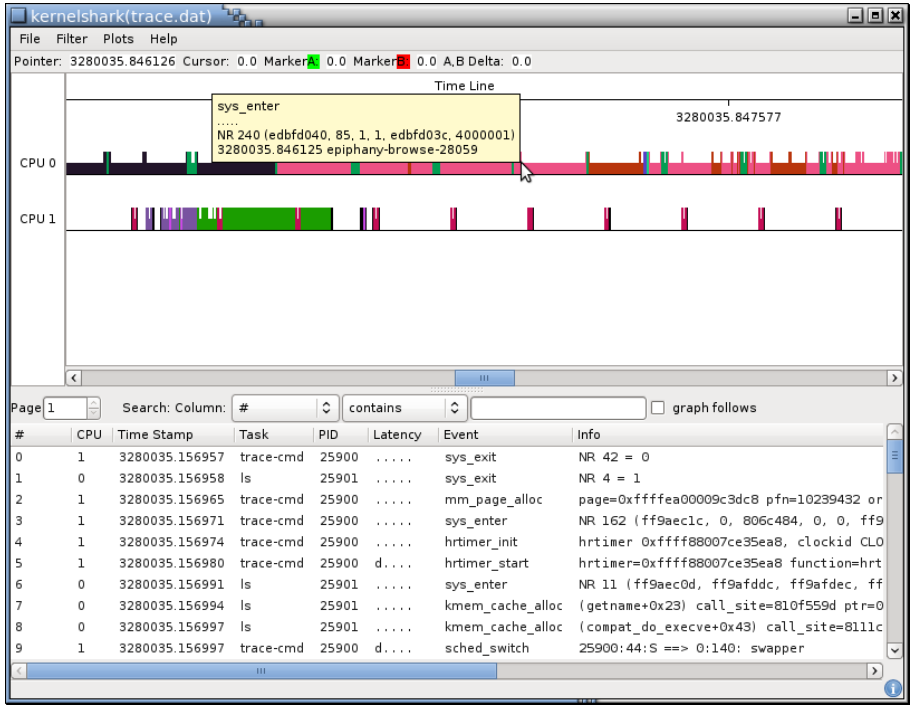
```
bitesize      - show disk I/O size as a histogram.
cachestat   - Measure page cache hits/misses.
execsnoop - trace process exec() with arguments.
funccount  - count kernel function calls matching specified wildcards.
iolatency    - summarize block device I/O latency as a histogram.
iosnoop     - trace block I/O events as they occur.
killsnoop   - trace kill() syscalls with process and signal details.
kprobe       - trace a given kprobe definition. Kernel dynamic tracing.
opensnoop - trace open() syscalls with file details.
tcpretrans  - show TCP retransmits, with address and other details.
```

ftrace CLI: trace-cmd

```
$ man -k trace-cmd
trace-cmd (1)         - interacts with Ftrace Linux kernel internal tracer
trace-cmd-check-events (1) - parse the event formats on local system
trace-cmd-extract (1) - extract out the data from the Ftrace Linux tracer.
trace-cmd-hist (1)    - show histogram of events in trace.dat file
trace-cmd-list (1)    - list available plugins, events or options for Ftrace.
trace-cmd-listen (1) - listen for incoming connection to record tracing.
trace-cmd-mem (1)     - show memory usage of certain kmem events
trace-cmd-options (1) - list available options from trace-cmd plugins
trace-cmd-profile (1) - profile tasks running live
trace-cmd-record (1) - record a trace from the Ftrace Linux internal tracer
trace-cmd-report (1) - show in ASCII a trace created by trace-cmd record
trace-cmd-reset (1)  - turn off all Ftrace tracing to bring back full performance
trace-cmd-restore (1) - restore a failed trace record
trace-cmd-show (1)    - show the contents of the Ftrace Linux kernel tracing buffer.
trace-cmd-snapshot (1) - take, reset, free, or show a Ftrace kernel snapshot
trace-cmd-split (1)   - split a trace.dat file into smaller files
trace-cmd-stack (1)   - read, enable or disable Ftrace Linux kernel stack tracing.
trace-cmd-start (1)   - start the Ftrace Linux kernel tracer without recording
trace-cmd-stat (1)    - show the status of the tracing (ftrace) system
trace-cmd-stop (1)    - stop the Ftrace Linux kernel tracer from writing to the ring buffer.
trace-cmd-stream (1) - stream a trace to stdout as it is happening
trace-cmd.dat (5)     - trace-cmd file format
```

ftrace GUI: kernelshark

http://people.redhat.com/srostedt/kernelshark/HTML/



ftrace: resources

- Documentation/trace/ftrace.txt
- http://lwn.net/Kernel/Index/ (search for “ftrace”, “tracing”)
- https://github.com/brendangregg/perf-tools
- linux-trace-users@vger.kernel.org mailing list

eBPF

- extended Berkeley Packet Filter
- BPF is kernel since a long time. Foundation for tcpdump
- eBPF merged in 4.1, ~2015
- Primary developer is Alexei Starovoitov
- In-kernel data aggregation
- Programs are statically verified, “safe” and low overhead
- Programs can be interpreted or Just-In-Time compiled (as opposed to a separate kernel module)
- C syntax, but reduced functionality (no loops, etc)
- Supported as backend by perf and soon SystemTap

eBPF

- **An eBPF program can only access data on its stack**
- **Cannot deref an arbitrary pointer**
- **…**
- **BCC (BPF Compiler Collection) makes this less painful**
  - https://github.com/iovisor/bcc
  - https://www.youtube.com/watch?v=eGlbouHkYPU In-Kernel Low Latency Tracing and Networking, Brenden Blanco
- **Examples in tree at samples/bpf**
- **Useful application: frequency-count of stack traces**
- **http://lwn.net/Kernel/Index/, search for “ebpf”**

SystemTap

- **Available since 2005**
- **The most powerful in terms of expressivity**
- **Out of tree**
- **Requires kernels debug symbols**
- **Maintained by Frank Ch. Eigler et al.**
- **Great care is needed**
- **Supports tracepoints, kprobes, uprobes**
- **Can even do live patching!**
  - See “Applying band-aids over security wounds with systemtap” https://archive.fosdem.org/2016/schedule/event/systemtap/

SystemTap

```
probe PROBEPOINT [, PROBEPOINT] { [STMT ...] }
```

- **Probepoint: a kernel event**
- **Stmt: a statement in the stap language**
  - **See https://sourceware.org/systemtap/langref/langref.html**
- **Examples at https://sourceware.org/systemtap/examples/**
- **See also `man -k stap`**

- **perf: robust and reliable. Limited flexibility.**
- **ftrace: available on all kernels, highly programmable. Requires knowledge of tracepoints.**
- **eBPF: safe, low overhead. Not easy to program. Needs recent kernel.**
- **SystemTap: best programmability. Overhead can be hard to predict.**

Questions!

http://www.suse.com/jobs