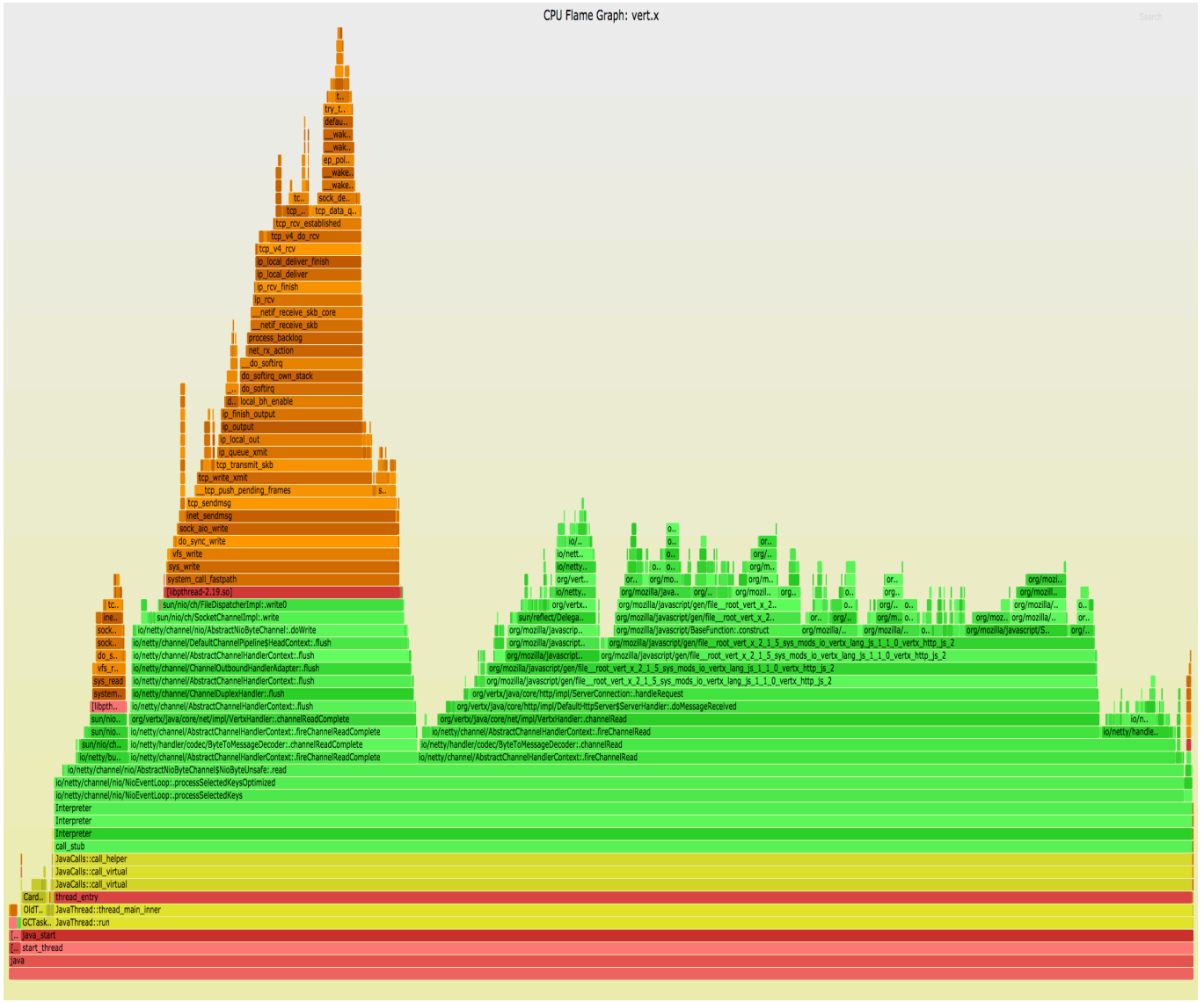


Using Linux `perf` at Netflix

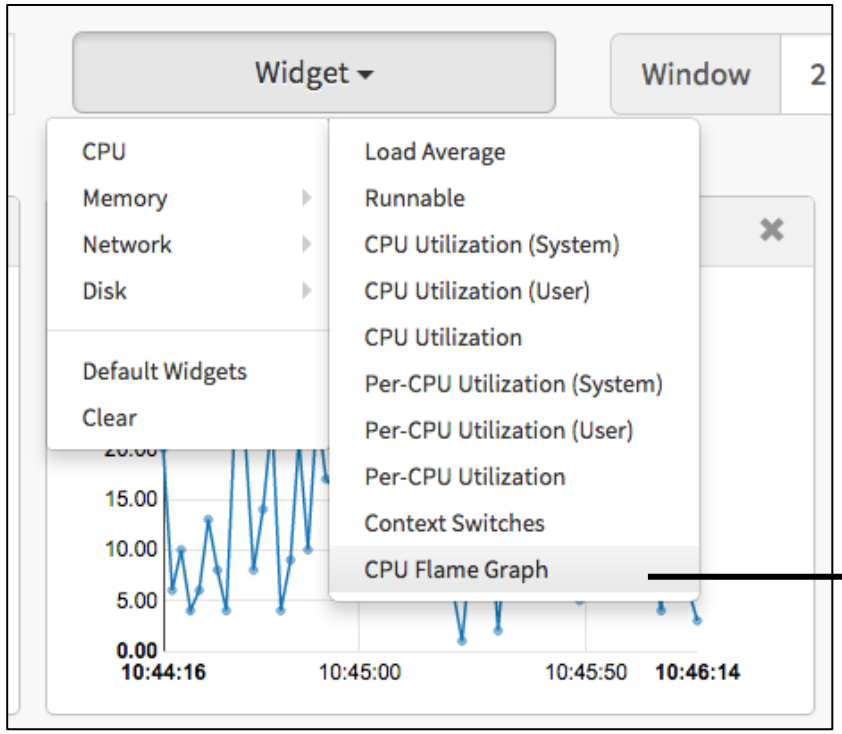
Brendan Gregg

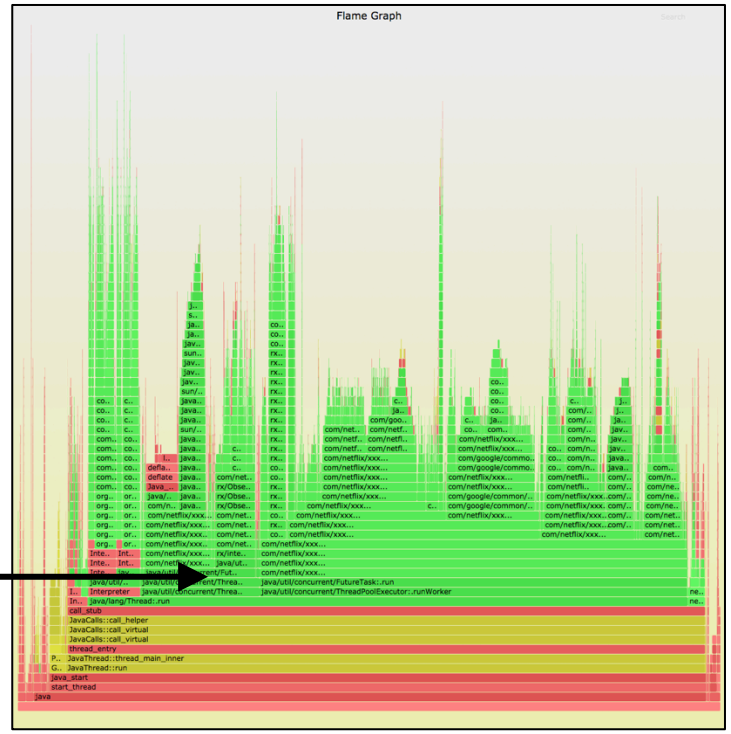
Senior Performance Architect

Sep 2017

Case Study: ZFS is eating my CPU

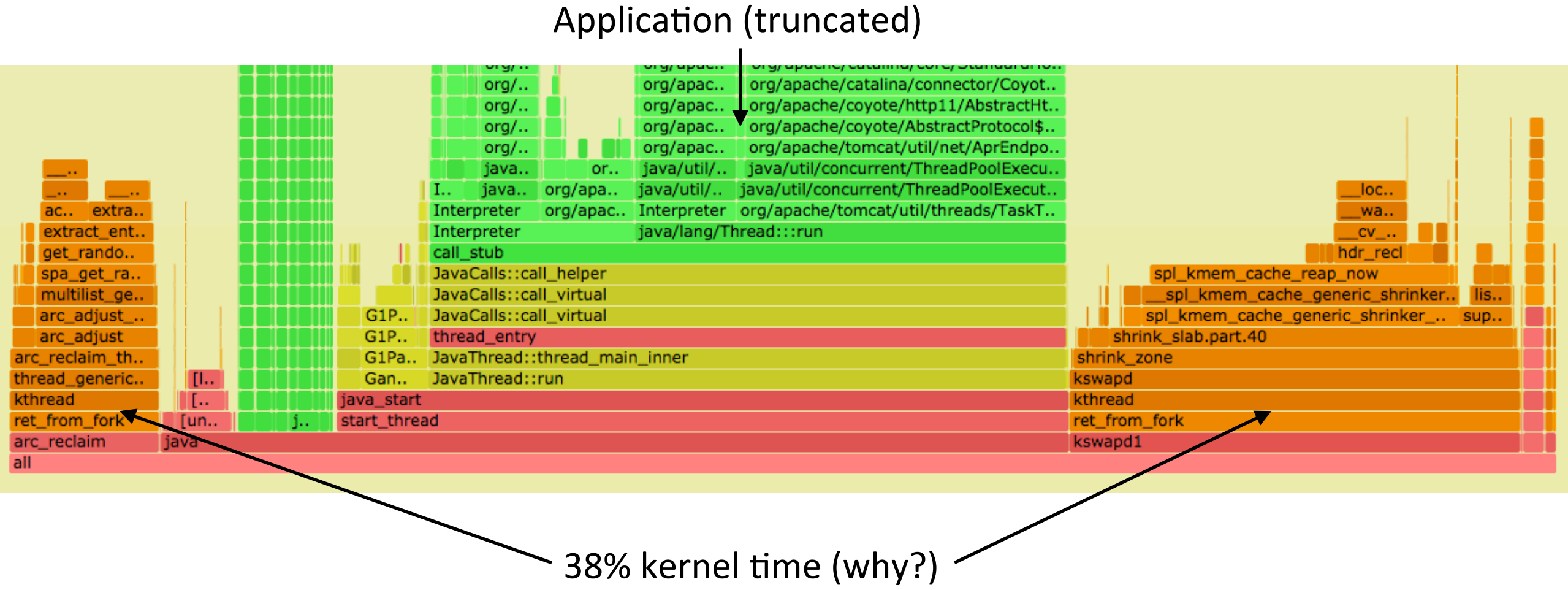
- Easy to debug using Netflix Vector & flame graphs
- How I expected it to look:





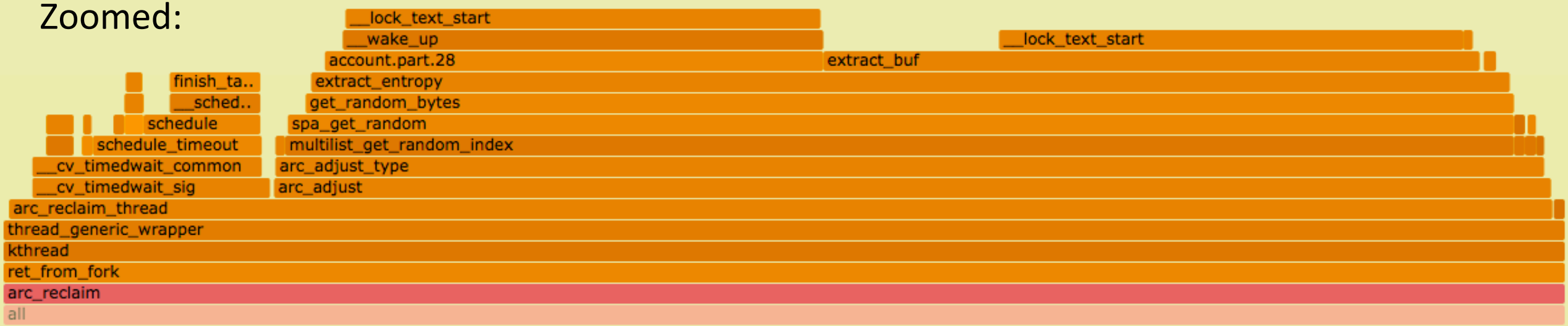
Case Study: ZFS is eating my CPU (cont.)

- How it really looked:



Case Study: ZFS is eating my CPU (cont.)

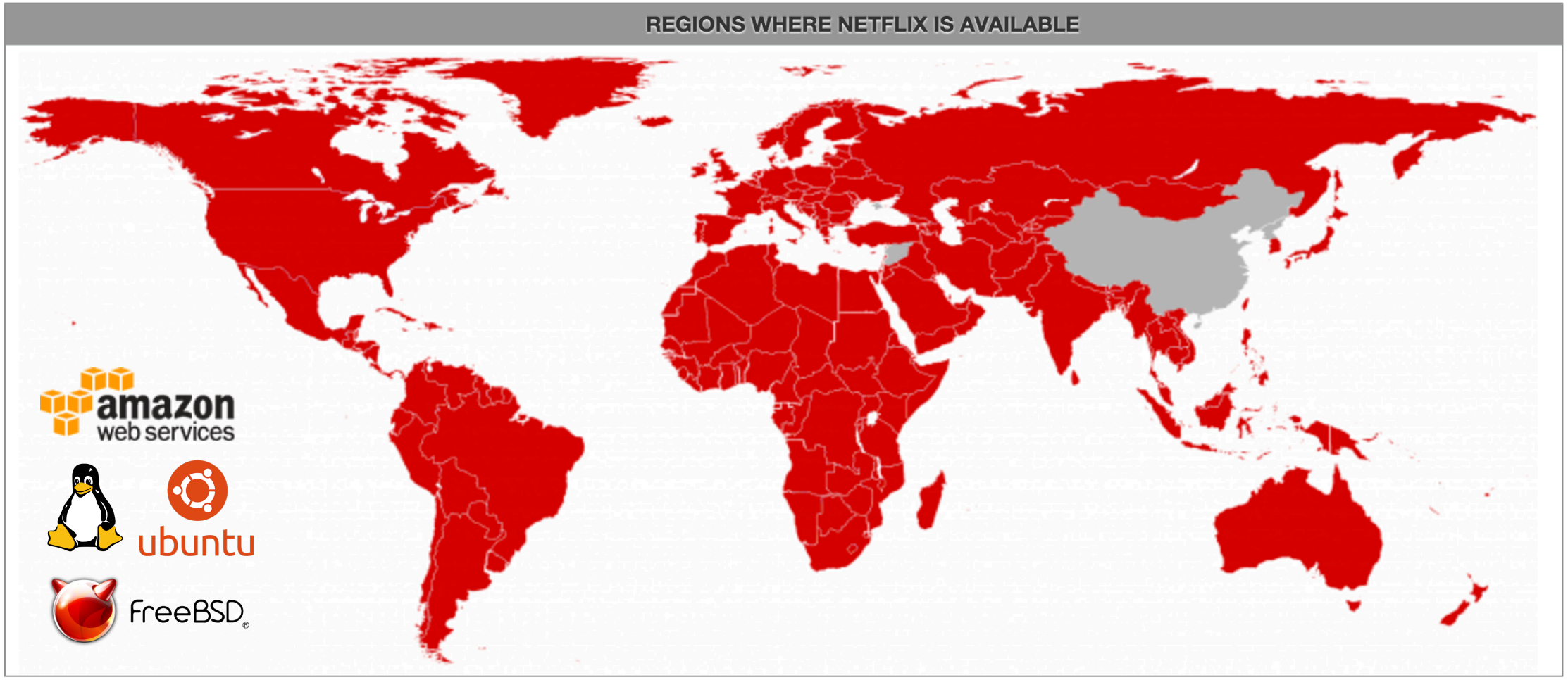
Zoomed:



- ZFS ARC (adaptive replacement cache) reclaim.
- But… ZFS is not in use. No pools, datasets, or ARC buffers.
- CPU time is in random entropy, picking which (empty) list to evict.

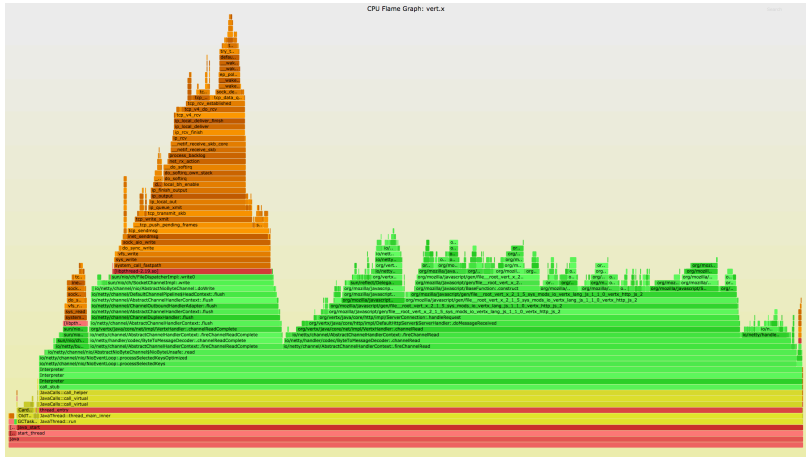
Bug: https://github.com/zfsonlinux/zfs/issues/6531

NETFLIX


REGIONS WHERE NETFLIX IS AVAILABLE
amazon
web services
ubuntu
FreeBSD

Agenda

1. Why Netflix Needs Linux Profiling
2. perf Basics
3. CPU Profiling & Gotchas
   - Stacks (gcc, Java)
   - Symbols (Node.js, Java)
   - Guest PMCs
   - PEBS
   - Overheads
4. perf Advanced




```
root@lgud-bgregg:~# perf stat -a -d sleep 10

 Performance counter stats for 'system wide':

      39996.388668 task-clock (msec)         #    3.999 CPUs u
         1,026,540 context-switches          #    0.026 M/sec
           193,563 cpu-migrations            #    0.005 M/sec
             4,835 page-faults               #    0.121 K/sec
    83,859,543,001 cycles                    #    2.097 GHz
    61,028,919,136 stalled-cycles-frontend   #   72.78% fronte
    50,812,852,642 stalled-cycles-backend    #   60.59% backen
    52,969,864,055 instructions              #    0.63  insns
                                             #    1.15  stalle
    10,223,584,755 branches                  #  255.613 M/sec
       376,529,869 branch-misses             #    3.68% of all
                 0 L1-dcache-loads           #    0.000 K/sec
     1,339,950,792 L1-dcache-load-misses     #    0.00% of all
       762,761,193 LLC-loads                 #   19.071 M/sec
   <not supported> LLC-load-misses:HG
```

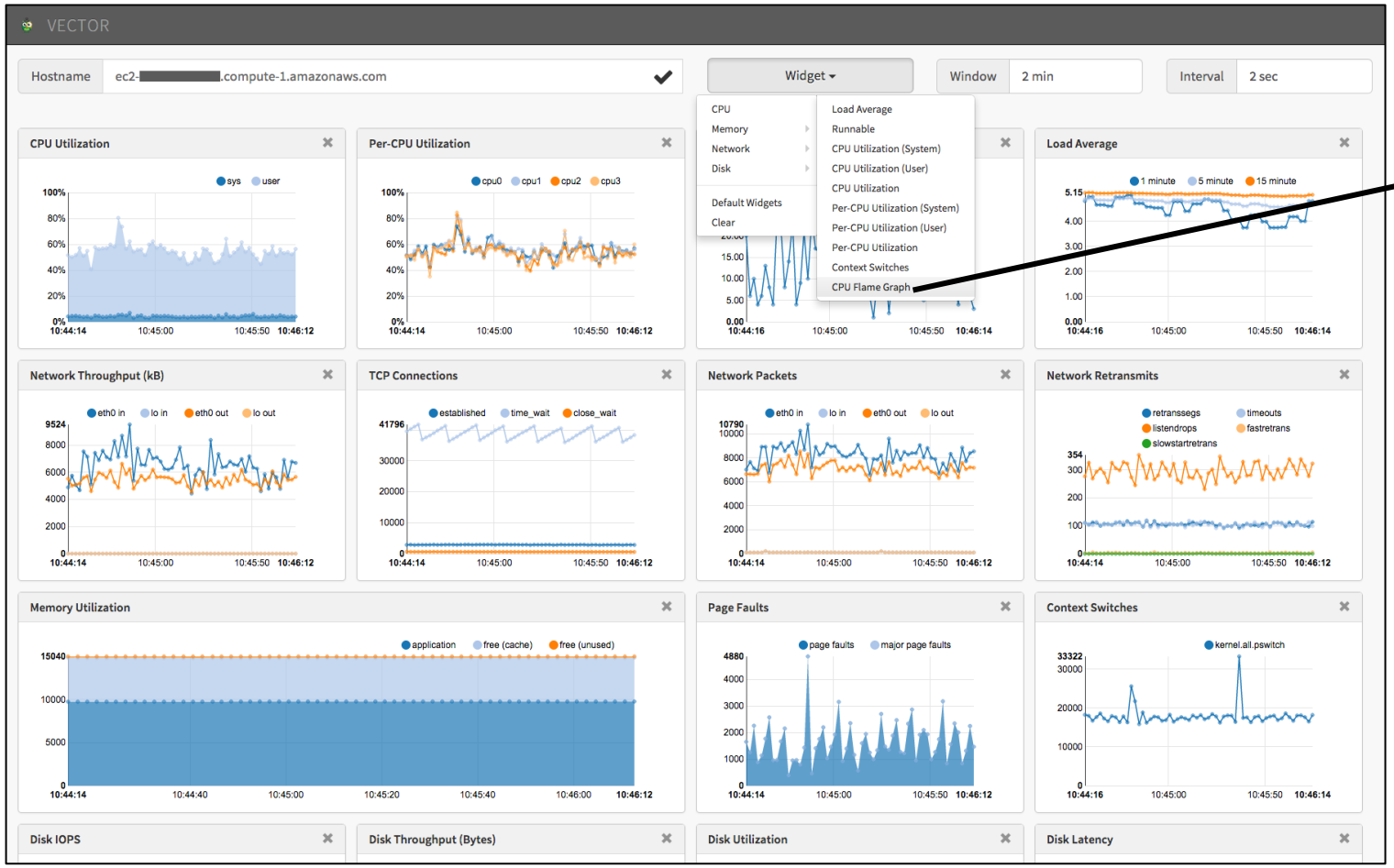
1. Why Netflix Needs Linux Profiling

Understand CPU usage quickly and completely

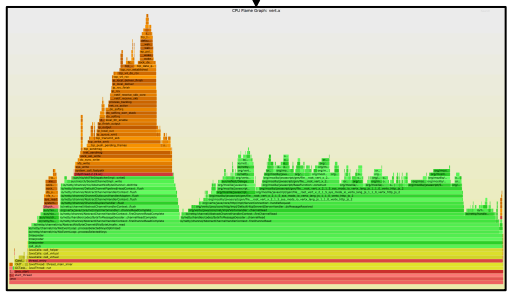
Quickly

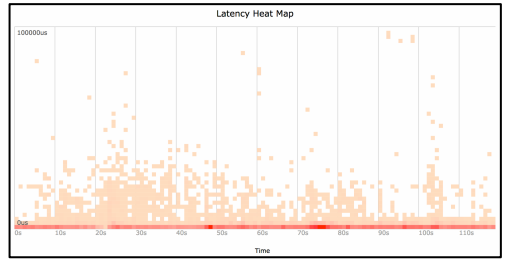
Vector

Eg, Netflix Vector (self-service UI):

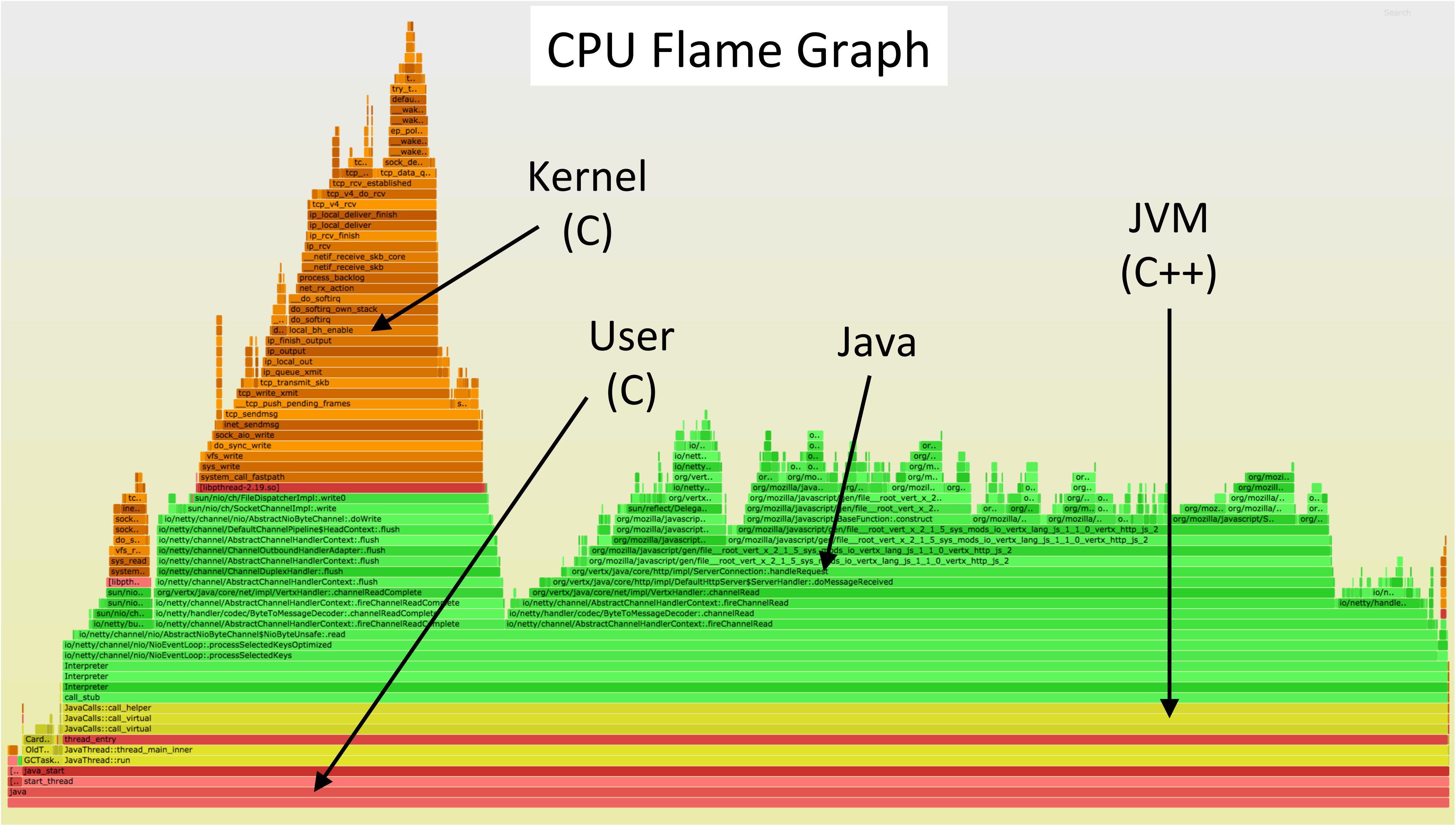


Flame Graphs
Heat Maps
…





Completely



Why Linux perf?

- Available
  - Linux, open source
- Low overhead
  - Tunable sampling, ring buffers
- Accurate
  - Application-basic samplers don't know what's really RUNNING; eg, Java and epoll
- No blind spots
  - See user, library, kernel with CPU sampling
  - With some work: hardirqs & SMI as well
- No sample skew
  - Unlike Java safety point skew

Why is this so important

- We typically scale microservices based on %CPU
  - Small %CPU improvements can mean big $avings
- CPU profiling is used by many activities
  - Explaining regressions in new software versions
  - Incident response
  - 3rd party software evaluations
  - Identify performance tuning targets
  - Part of CPU workload characterization
- perf does lots more, but we spend ~95% of our time looking at CPU profiles, and 5% on everything else
  - With new BPF capabilities (off-CPU analysis), that might go from 95 to 90%

CPU profiling should be easy, but…

JIT runtimes
no frame pointers
no debuginfo
stale symbol maps
container namespaces
…

2. perf Basics

perf (aka "perf_events")

- The official Linux profiler
  - In the linux-tools-common package
  - Source code & docs in Linux: **tools/perf**
- Supports many profiling/tracing features:
  - CPU Performance Monitoring Counters (PMCs)
  - Statically defined tracepoints
  - User and kernel dynamic tracing
  - Kernel line and local variable tracing
  - Efficient in-kernel counts and filters
  - Stack tracing, libunwind
  - Code annotation
- Some bugs in the past; has been stable for us

perf_events ponycorn

A Multitool of Subcommands

```
# perf

 usage: perf [--version] [--help] [OPTIONS] COMMAND [ARGS]

 The most commonly used perf commands are:
   annotate        Read perf.data (created by perf record) and display annotated code
   archive         Create archive with object files with build-ids found in perf.data file
   bench           General framework for benchmark suites
   buildid-cache   Manage build-id cache.
   buildid-list    List the buildids in a perf.data file
   c2c             Shared Data C2C/HITM Analyzer.
   config          Get and set variables in a configuration file.
   data            Data file related processing
   diff            Read perf.data files and display the differential profile
   evlist          List the event names in a perf.data file
   ftrace          simple wrapper for kernel's ftrace functionality
   inject          Filter to augment the events stream with additional information
   kallsyms        Searches running kernel for symbols
   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
   test            Runs sanity tests.
   timechart       Tool to visualize total system behavior during a workload
   top             System profiling tool.
   probe           Define new dynamic tracepoints
   trace           strace inspired tool

 See 'perf help COMMAND' for more information on a specific command.
```

from Linux 4.13

perf Basic Workflow

1. `list` -> find events
2. `stat` -> count them
3. `record`-> write event data to file
4. `report` -> browse summary
5. `script` -> event dump for post processing

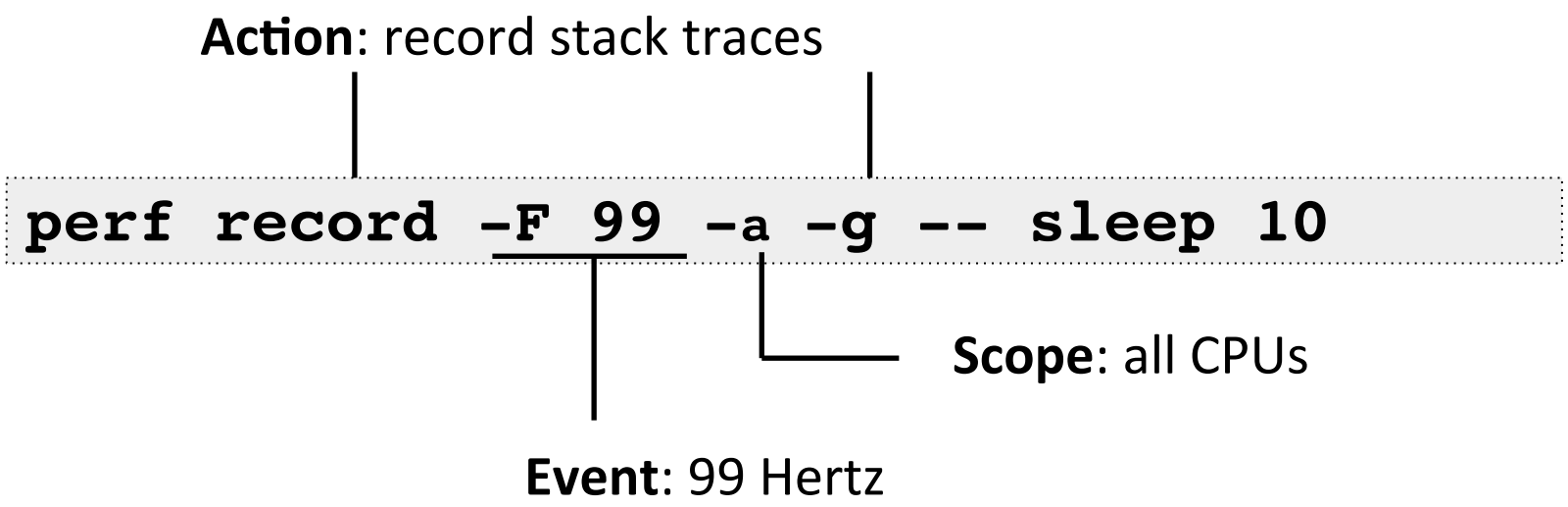
Basic Workflow Example

```
# perf list sched:*
[…]
  sched:sched_process_exec                   [Tracepoint event]
[…]
# perf stat -e sched:sched_process_exec -a -- sleep 10
 Performance counter stats for 'system wide':

                19      sched:sched_process_exec

      10.001327817 seconds time elapsed
# perf record -e sched:sched_process_exec -a -g -- sleep 10
[ perf record: Woken up 1 times to write data ]
[ perf record: Captured and wrote 0.212 MB perf.data (21 samples) ]
# perf report -n --stdio
# Children      Self       Samples  Trace output
# ........  ........  ............  ..................................................
     4.76%     4.76%             1  filename=/bin/bash pid=7732 old_pid=7732
               |
               ---_start
                  return_from_SYSCALL_64
                  do_syscall_64
                  sys_execve
                  do_execveat_common.isra.35
[…]
# perf script
sleep  7729 [003] 632804.699184: sched:sched_process_exec: filename=/bin/sleep pid=7729 old_pid=7729
                  44b97e do_execveat_common.isra.35 (/lib/modules/4.13.0-rc1-virtual/build/vmlinux)
                  44bc01 sys_execve (/lib/modules/4.13.0-rc1-virtual/build/vmlinux)
                  203acb do_syscall_64 (/lib/modules/4.13.0-rc1-virtual/build/vmlinux)
                  acd02b return_from_SYSCALL_64 (/lib/modules/4.13.0-rc1-virtual/build/vmlinux)
                     c30 _start (/lib/x86_64-linux-gnu/ld-2.23.so)
[…]
```

1. found an event of interest
2. 19 per 10 sec is a very low rate, so safe to record
3. 21 samples captured
4. summary style may be sufficient, or,
5. script output in time order

perf stat/record Format

- These have three main parts: action, event, scope.
- e.g., profiling on-CPU stack traces:



Note: sleep 10 is a dummy command to set the duration

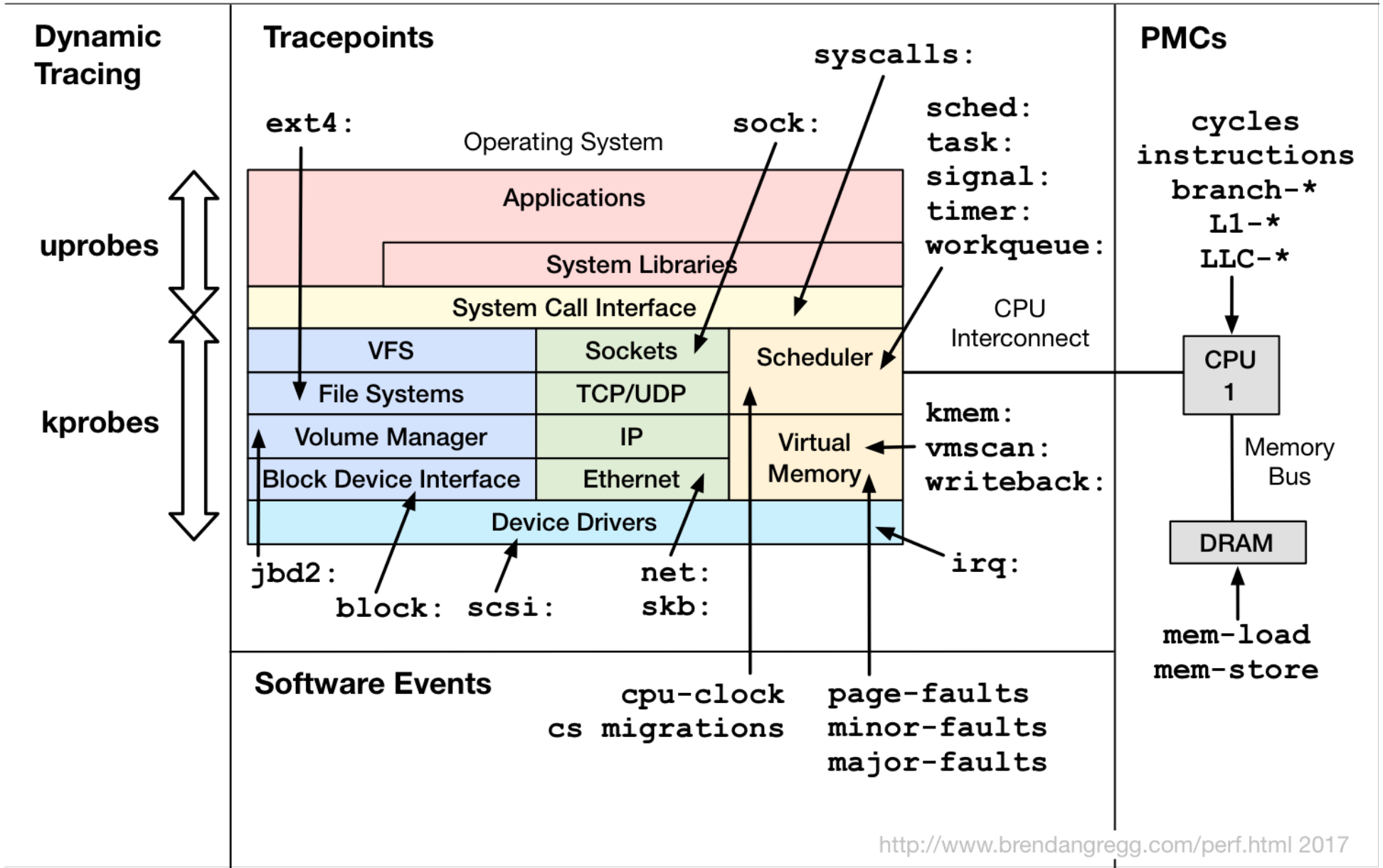
perf Actions

- Count events (perf stat …)
  - Uses an efficient in-kernel counter, and prints the results
- Sample events (perf record …)
  - Records details of every event to a dump file (perf.data)
    - Timestamp, CPU, PID, instruction pointer, …
  - This incurs higher overhead, relative to the rate of events
  - Include the call graph (stack trace) using -g
- Other actions include:
  - List events (perf list)
  - Report from a perf.data file (perf report)
  - Dump a perf.data file as text (perf script)
  - top style profiling (perf top)

perf Events

- Custom timers
  - e.g., 99 Hertz (samples per second)
- Hardware events
  - CPU Performance Monitoring Counters (PMCs)
- Tracepoints
  - Statically defined in software
- Dynamic tracing
  - Created using uprobes (user) or kprobes (kernel)
  - Can do kernel line tracing with local variables (needs kernel debuginfo)

perf Events: Map



perf Events: List

```
# perf list
List of pre-defined events (to be used in -e):
  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]
[…]
  cpu-clock                                           [Software event]
  task-clock                                          [Software event]
  page-faults OR faults                               [Software event]
  context-switches OR cs                              [Software event]
  cpu-migrations OR migrations                        [Software event]
[…]
  L1-dcache-loads                                     [Hardware cache event]
  L1-dcache-load-misses                               [Hardware cache event]
  L1-dcache-stores                                    [Hardware cache event]
[…]
  skb:kfree_skb                                       [Tracepoint event]
  skb:consume_skb                                     [Tracepoint event]
  skb:skb_copy_datagram_iovec                         [Tracepoint event]
  net:net_dev_xmit                                    [Tracepoint event]
  net:net_dev_queue                                   [Tracepoint event]
  net:netif_receive_skb                               [Tracepoint event]
  net:netif_rx                                        [Tracepoint event]
[…]
```

perf Scope

- System-wide: all CPUs (`-a`)
- Target PID (`-p PID`)
- Target command (…)
- Specific CPUs (`-c …`)
- User-level only (`<event>:u`)
- Kernel-level only (`<event>:k`)
- A custom filter to match variables (`--filter …`)
- This cgroup (container) only (`--cgroup …`)

One-Liners: Listing Events

```
# Listing all currently known events:
perf list

# Searching for "sched" tracepoints:
perf list | grep sched

# Listing sched tracepoints:
perf list 'sched:*'
```

Dozens of perf one-liners:
http://www.brendangregg.com/perf.html#OneLiners

One-Liners: Counting Events

```
# CPU counter statistics for the specified command:
perf stat command

# CPU counter statistics for the entire system, for 5 seconds:
perf stat -a sleep 5

# Detailed CPU counter statistics for the specified PID, until Ctrl-C:
perf stat -dp PID

# Various CPU last level cache statistics for the specified command:
perf stat -e LLC-loads,LLC-load-misses,LLC-stores,LLC-prefetches command

# Count system calls for the specified PID, until Ctrl-C:
perf stat -e 'syscalls:sys_enter_*' -p PID

# Count block device I/O events for the entire system, for 10 seconds:
perf stat -e 'block:*' -a sleep 10

# Show system calls by process, refreshing every 2 seconds:
perf top -e raw_syscalls:sys_enter -ns comm
```

One-Liners: Profiling Events

```
# Sample on-CPU functions for the specified command, at 99 Hertz:
perf record -F 99 command

# Sample CPU stack traces for the specified PID, at 99 Hertz, for 10 seconds:
perf record -F 99 -p PID -g -- sleep 10

# Sample CPU stack traces for the entire system, at 99 Hertz, for 10 seconds:
perf record -F 99 -ag -- sleep 10

# Sample CPU stacks, once every 10,000 Level 1 data cache misses, for 5 secs:
perf record -e L1-dcache-load-misses -c 10000 -ag -- sleep 5

# Sample CPU stack traces, once every 100 last level cache misses, for 5 secs:
perf record -e LLC-load-misses -c 100 -ag -- sleep 5

# Sample on-CPU kernel instructions, for 5 seconds:
perf record -e cycles:k -a -- sleep 5

# Sample on-CPU user instructions, for 5 seconds:
perf record -e cycles:u -a -- sleep 5
```

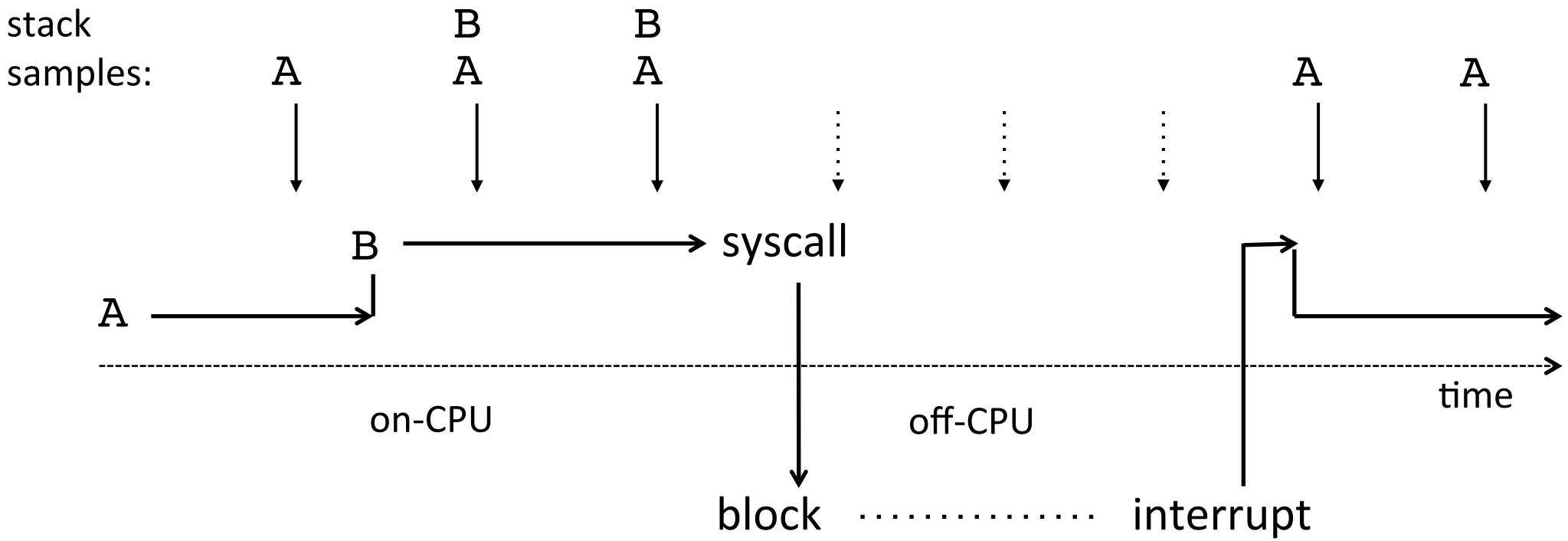
One-Liners: Reporting

```
# Show perf.data in an ncurses browser (TUI) if possible:
perf report

# Show perf.data with a column for sample count:
perf report -n

# Show perf.data as a text report, with data coalesced and percentages:
perf report --stdio

# List all raw events from perf.data:
perf script

# List all raw events from perf.data, with customized fields:
perf script -f comm,tid,pid,time,cpu,event,ip,sym,dso

# Dump raw contents from perf.data as hex (for debugging):
perf script -D

# Disassemble and annotate instructions with percentages (needs debuginfo):
perf annotate --stdio
```

3. CPU Profiling

CPU Profiling

- Record stacks at a timed interval: simple and effective
  - Pros: Low (deterministic) overhead
  - Cons: Coarse accuracy, but usually sufficient



perf Record

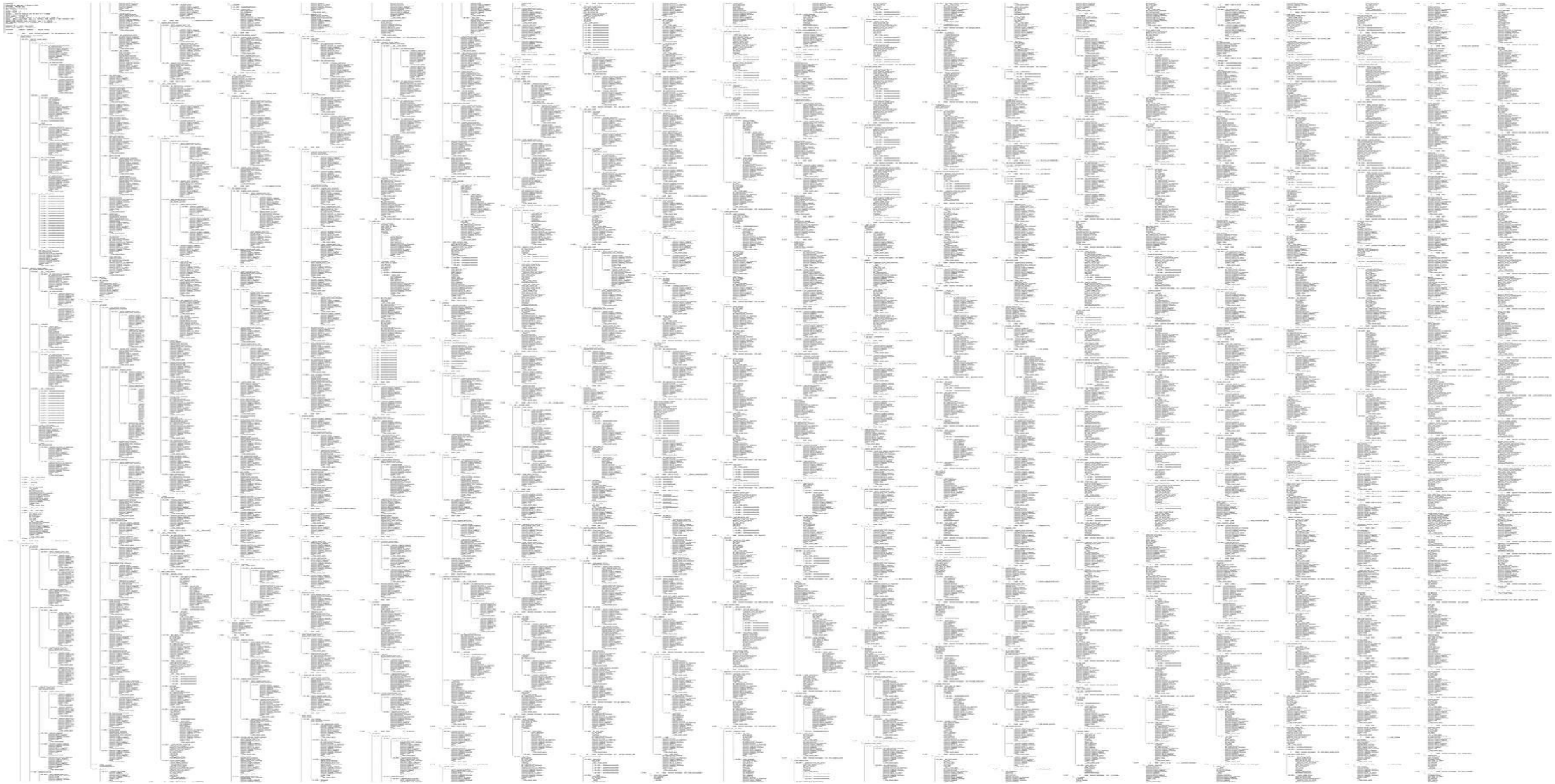
```
# perf record -F 99 -ag -- sleep 30
[ perf record: Woken up 9 times to write data ]
[ perf record: Captured and wrote 2.745 MB perf.data (~119930 samples) ]
# perf report -n --stdio
1.40%   162             java  [kernel.kallsyms]       [k] _raw_spin_lock
          |
          --- _raw_spin_lock
              |
              |--63.21%-- try_to_wake_up
              |           |
              |           |--63.91%-- default_wake_function
              |           |           |
              |           |           |--56.11%-- __wake_up_common
              |           |           |           __wake_up_locked
              |           |           |           ep_poll_callback
              |           |           |           __wake_up_common
              |           |           |           __wake_up_sync_key
              |           |           |           |
              |           |           |           |--59.19%-- sock_def_readable
[…78,000 lines truncated…]
```

Sampling full stack traces at 99 Hertz

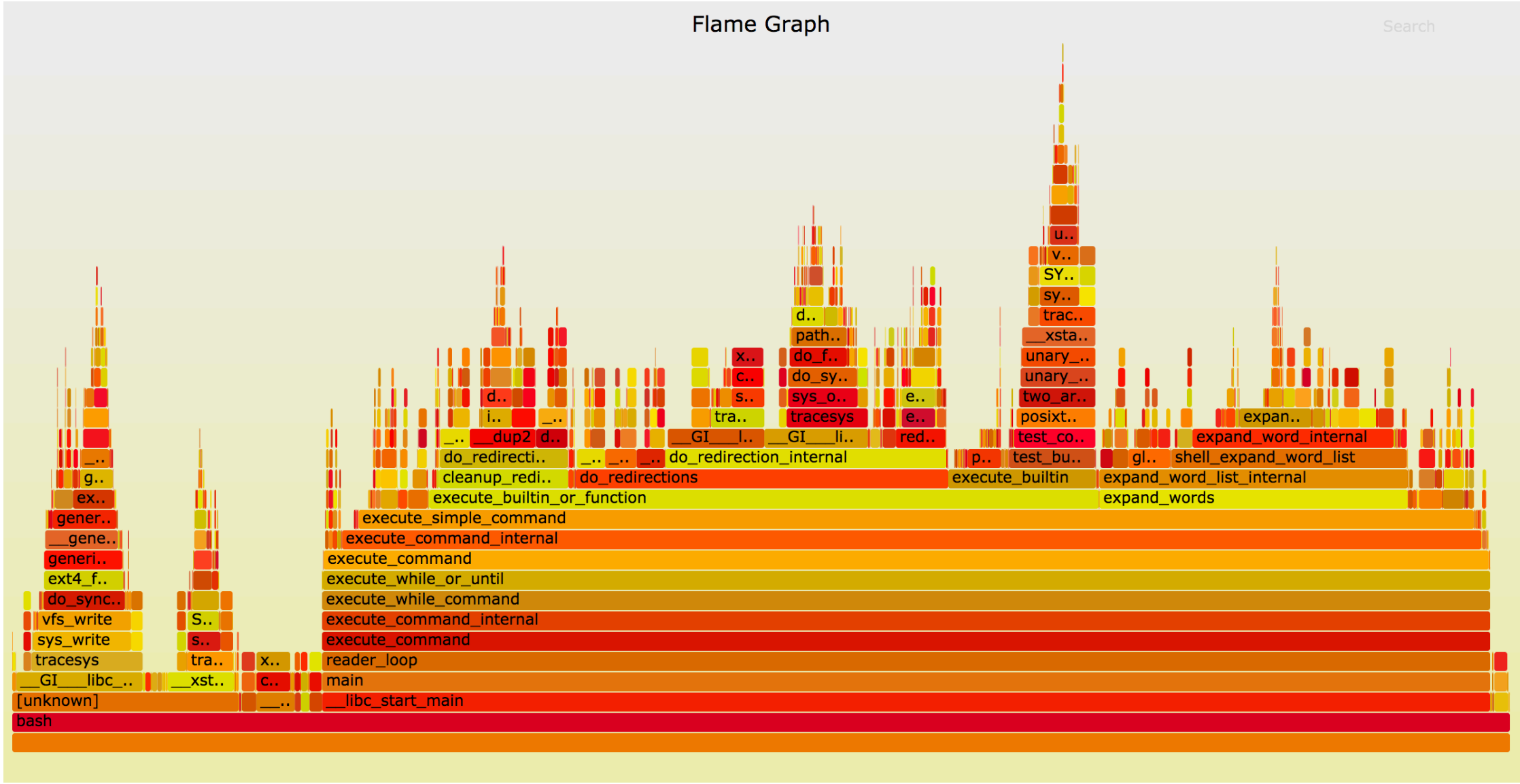
perf Reporting

- perf report summarizes by combining common paths
- Previous output truncated 78,000 lines of summary
- The following is what a mere 8,000 lines looks like…

perf report



… as a Flame Graph



Flame Graphs

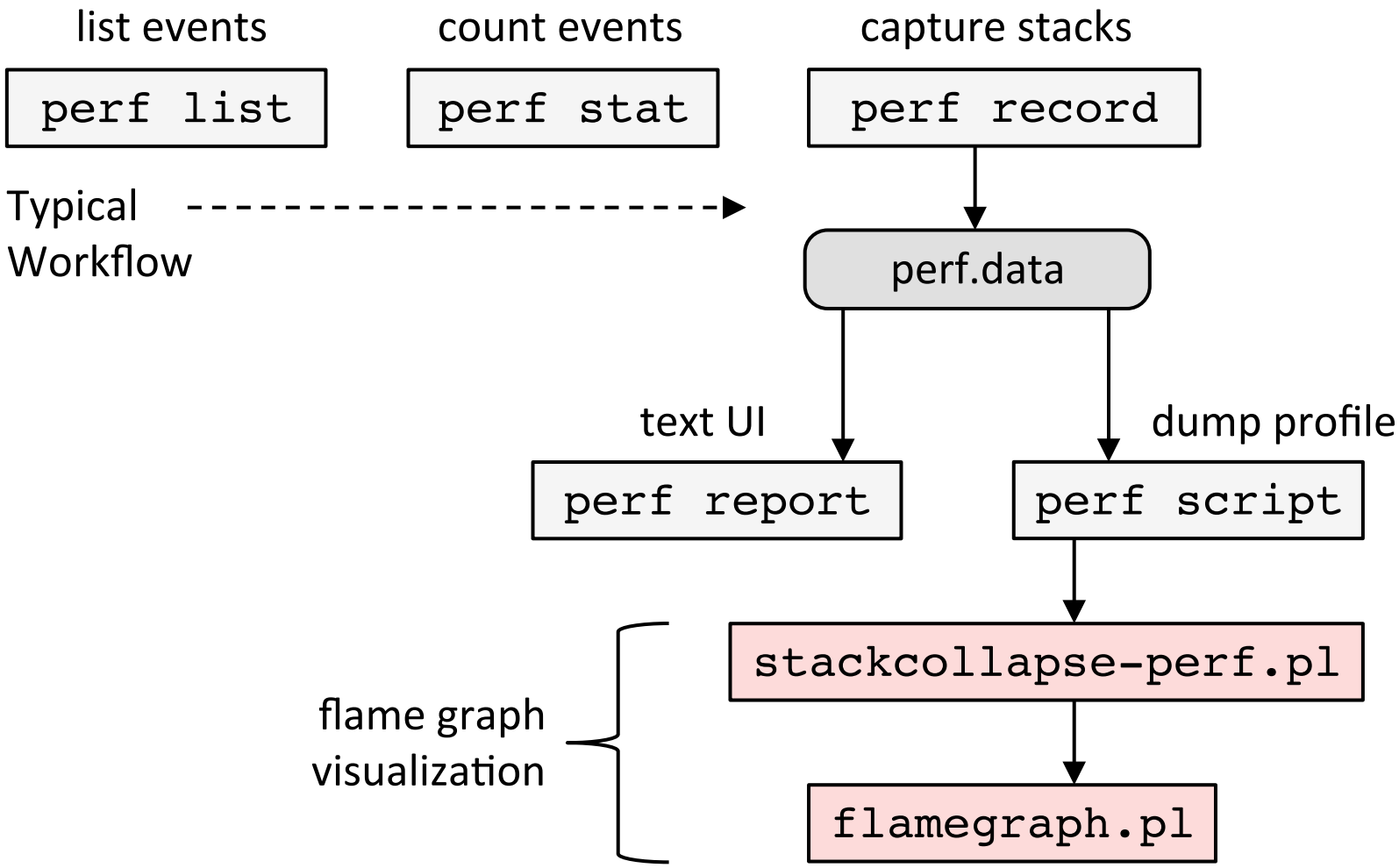
```
git clone --depth 1 https://github.com/brendangregg/FlameGraph
cd FlameGraph
perf record -F 99 -a –g -- sleep 30
perf script | ./stackcollapse-perf.pl | ./flamegraph.pl > perf.svg
```

- Flame Graphs:
  - **x-axis**: alphabetical stack sort, to maximize merging
  - **y-axis**: stack depth
  - **color**: random, or hue can be a dimension
    - e.g., software type, or difference between two profiles for non-regression testing ("differential flame graphs")
  - interpretation: top edge is on-CPU, beneath it is ancestry
- Just a Perl program to convert perf stacks into SVG
  - Includes JavaScript: open in a browser for interactivity
- Easy to get working http://www.brendangregg.com/FlameGraphs/cpuflamegraphs.html

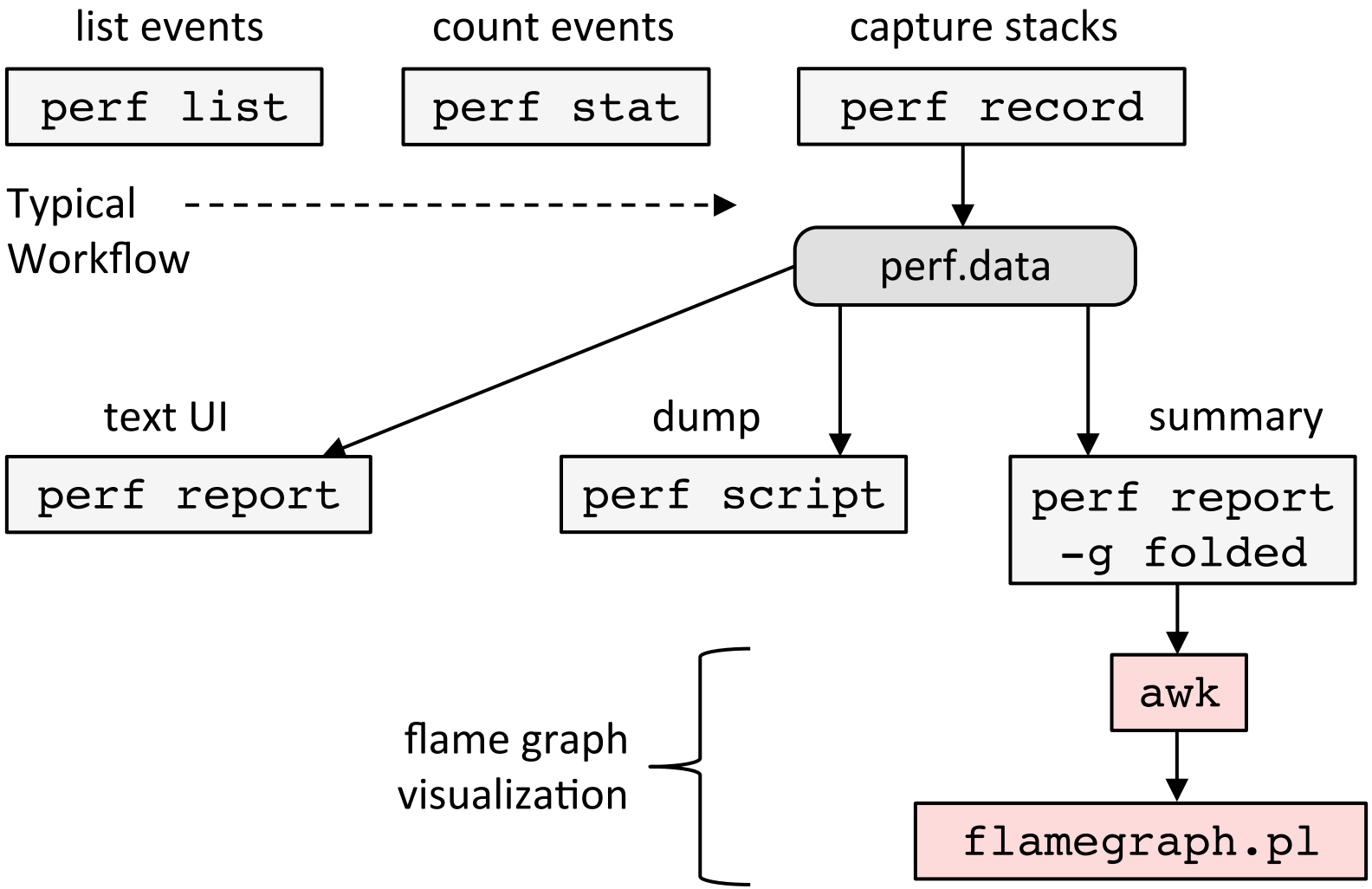
flamegraph.pl Options

```
$ flamegraph.pl --help
USAGE: flamegraph.pl [options] infile > outfile.svg

      --title TEXT     # change title text
      --subtitle TEXT  # second level title (optional)
      --width NUM      # width of image (default 1200)
      --height NUM     # height of each frame (default 16)
      --minwidth NUM   # omit smaller functions (default 0.1 pixels)
      --fonttype FONT  # font type (default "Verdana")
      --fontsize NUM   # font size (default 12)
      --countname TEXT # count type label (default "samples")
      --nametype TEXT  # name type label (default "Function:")
      --colors PALETTE # set color palette. choices are: hot (default), mem,
                       # io, wakeup, chain, java, js, perl, red, green, blue,
                       # aqua, yellow, purple, orange
      --hash           # colors are keyed by function name hash
      --cp             # use consistent palette (palette.map)
      --reverse        # generate stack-reversed flame graph
      --inverted       # icicle graph
      --negate         # switch differential hues (blue<->red)
      --notes TEXT     # add notes comment in SVG (for debugging)
      --help           # this message

      eg,
      flamegraph.pl --title="Flame Graph: malloc()" trace.txt > graph.svg
```

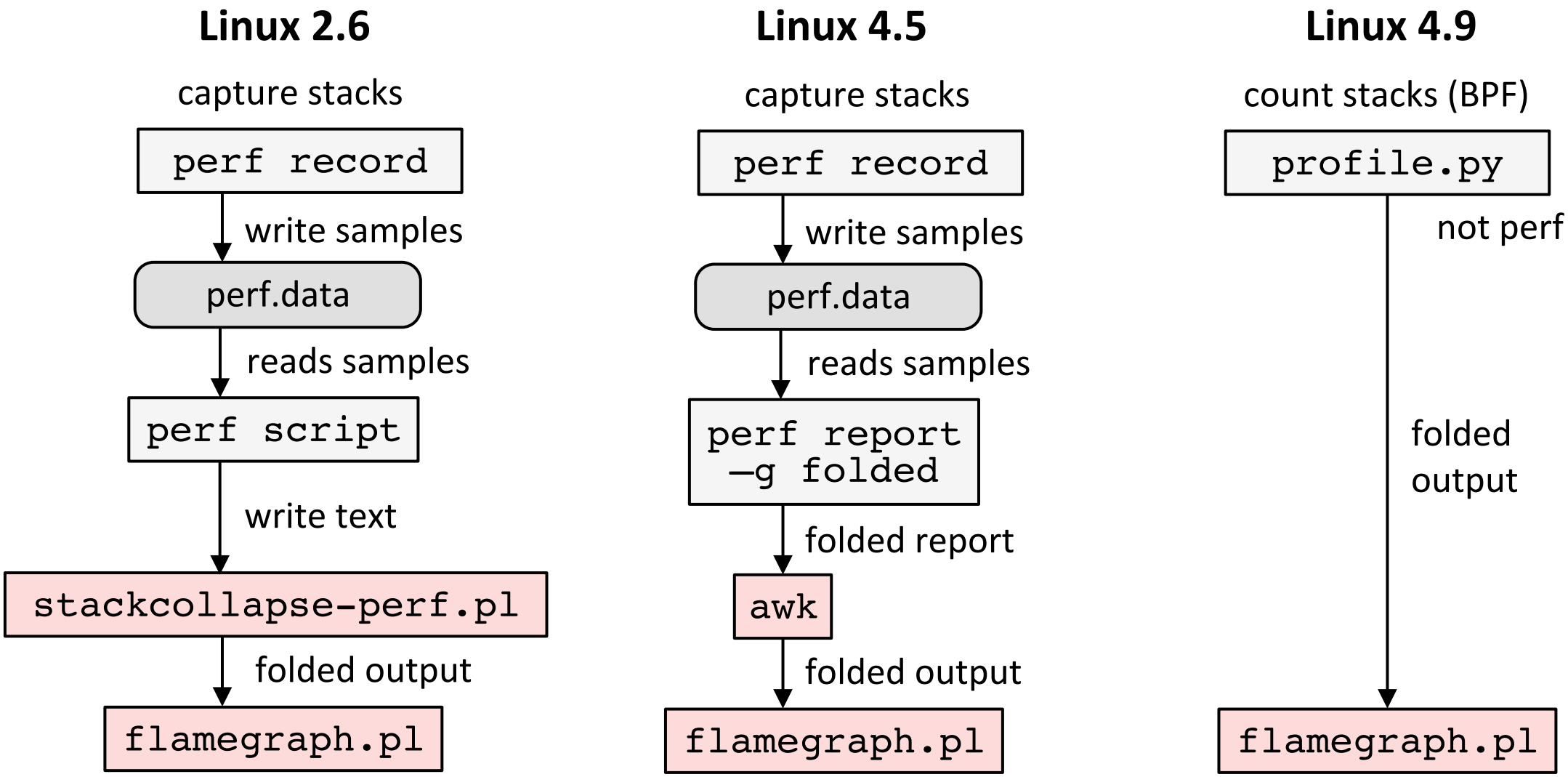
perf Flame Graph Workflow (Linux 2.6+)



perf Flame Graph Workflow (Linux 4.5+)



Flame Graph Optimizations



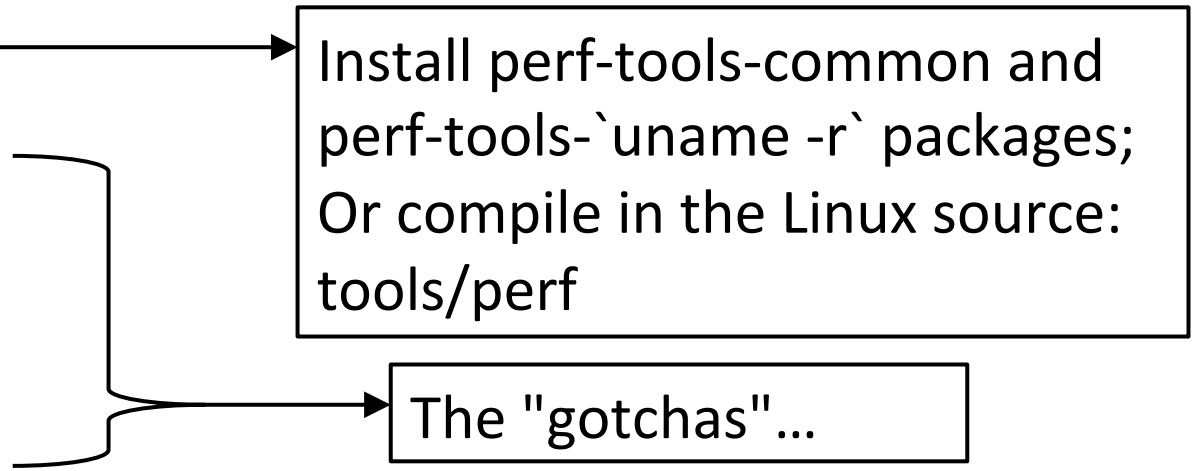
Gotchas

When we've tried to use perf

- Stacks don't work (missing)
- Symbols don't work (hex numbers)
- Instruction profiling looks bogus
- PMCs don't work in VM guests
- Container break things
- Overhead is too high

How to *really* get started

1. Get "perf" to work
2. Get stack walking to work
3. Fix symbol translation
4. Get IPC to work
5. Test perf under load



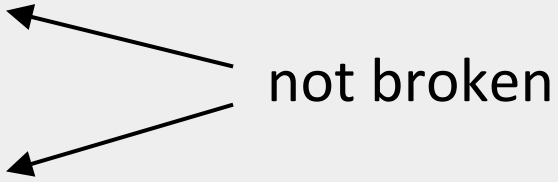
Gotcha #1 Broken Stacks

```
perf record -F 99 -a –g -- sleep 30
perf report -n --stdio
```

1. Take a CPU profile
2. Run perf report
3. If stacks are often < 3 frames, or don't reach "thread start" or "main", they are probably broken. Fix them.

Identifying Broken Stacks

```
28.10%            146      sed  libc-2.19.so       [.] re_search_internal
                  |
                  --- re_search_internal
                      |
                      |--12.25%-- 0x3
                      |           0x100007
                      |
                      |--96.78%-- re_search_stub
                      |           rpl_re_search
                      |           match_regex
                      |           do_subst
                      |           execute_program
                      |           process_files
                      |           main
                      |           __libc_start_main
                      |
                       --3.22%-- rpl_re_search
                                 match_regex
                                 do_subst
                                 execute_program
                                 process_files
                                 main
                                 __libc_start_main
```



Identifying Broken Stacks

```
78.50%            409      sed  libc-2.19.so       [.] 0x00000000000dd7d4
                  |
                  |--3.65%-- 0x7f2516d5d10d
                  |
                  |--2.19%-- 0x7f2516d0332f
                  |
                  |--1.22%-- 0x7f2516cffbd2
                  |
                  |--1.22%-- 0x7f2516d5d5ad
```

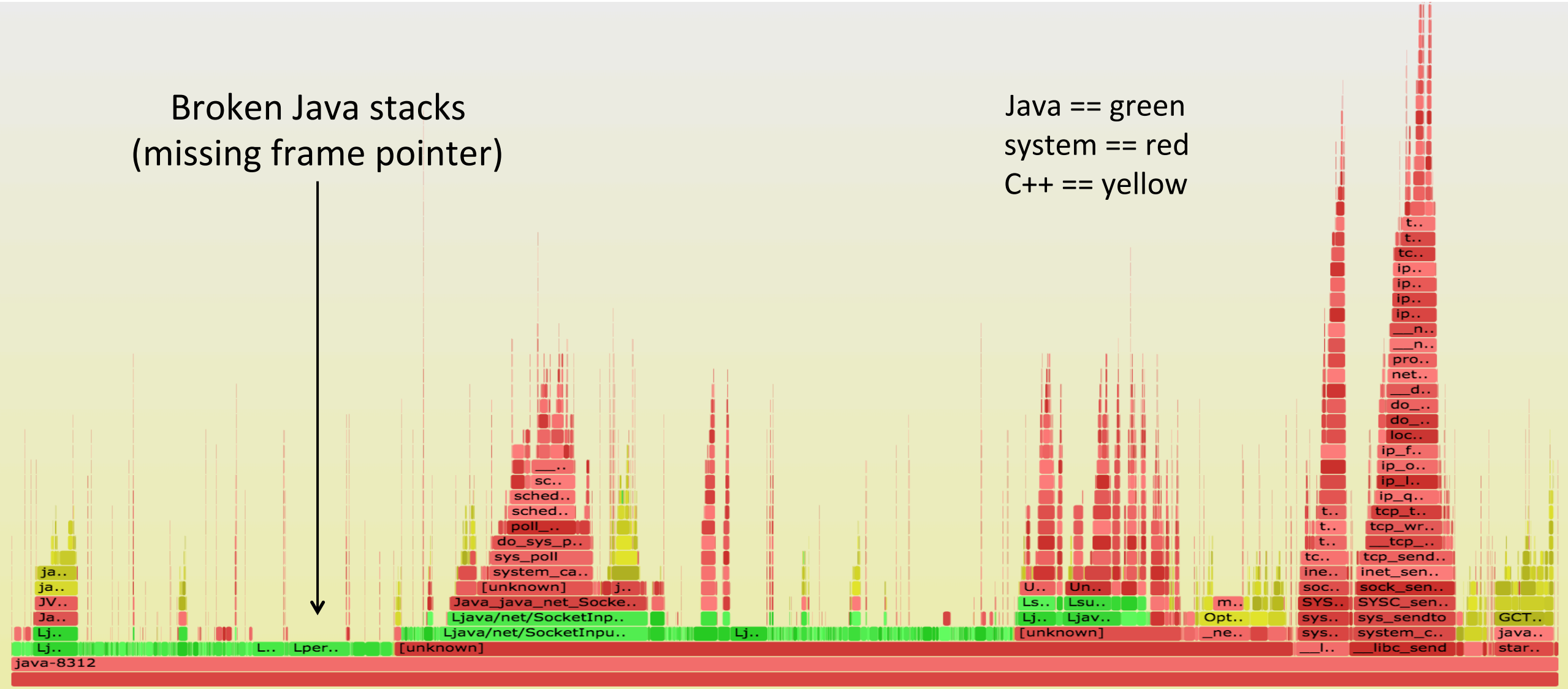
broken

```
                  |--11.65%-- 0x40a447
                  |           0x40659a
                  |           0x408dd8
                  |           0x408ed1
                  |           0x402689
                  |           0x7fa1cd08aec5
                  |
                  |--1.33%-- 0x40a4a1
                  |           |
                  |           |--60.01%-- 0x40659a
                  |           |           0x408dd8
                  |           |           0x408ed1
                  |           |           0x402689
                  |           |           0x7fa1cd08aec5
```

probably not broken

missing symbols, but
that's another problem

Broken Stacks Flame Graph



Fixing Broken Stacks

- Either:
- Fix frame pointer-based stack walking (the default)
  - Pros: simple, supports any system stack walker
  - Cons: might cost a little extra CPU to make available
- Use libunwind and DWARF: perf record -g dwarf
  - Pros: more debug info
  - Cons: not on older kernels, and inflates instance size
  - … there's also ORC on the latest kernel
- Application support
  - https://github.com/jvm-profiling-tools/async-profiler
- Our current preference is (A), but (C) is also promising
  - So how do we fix the frame pointer…

gcc -fno-omit-frame-pointer

- *Once upon a time*, x86 had fewer registers, and the frame pointer register was reused for general purpose to improve performance. This breaks system stack walking.
- gcc provides `-fno-omit-frame-pointer` to fix this
  - Please make this the default in gcc!

Java -XX:+PreserveFramePointer

- I hacked frame pointers in the JVM (JDK-8068945) and Oracle rewrote it as -XX:+PreserveFramePointer. Lets perf do FP stack walks of Java.

```
--- openjdk8clean/hotspot/src/cpu/x86/vm/macroAssembler_x86.cpp 2014-03-04…
+++ openjdk8/hotspot/src/cpu/x86/vm/macroAssembler_x86.cpp 2014-11-07 …
@@ -5236,6 +5236,7 @@
     // We always push rbp, so that on return to interpreter rbp, will be
     // restored correctly and we can correct the stack.
     push(rbp);
+    mov(rbp, rsp);
     // Remove word for ebp
     framesize -= wordSize;

--- openjdk8clean/hotspot/src/cpu/x86/vm/c1_MacroAssembler_x86.cpp …
+++ openjdk8/hotspot/src/cpu/x86/vm/c1_MacroAssembler_x86.cpp …
[...]
```

Involved changes like this: fixing x86-64 function prologues

- Costs some overhead to use. Usually <1%. Rare cases 10%.

Broken Java Stacks

```
# perf script
[…]
java  4579 cpu-clock:
  ffffffff8172adff tracesys ([kernel.kallsyms])
      7f4183bad7ce pthread_cond_timedwait@@GLIBC_2…

java  4579 cpu-clock:
      7f417908c10b [unknown] (/tmp/perf-4458.map)

java  4579 cpu-clock:
      7f4179101c97 [unknown] (/tmp/perf-4458.map)

java  4579 cpu-clock:
      7f41792fc65f [unknown] (/tmp/perf-4458.map)
  a2d53351ff7da603 [unknown] ([unknown])

java  4579 cpu-clock:
      7f4179349aec [unknown] (/tmp/perf-4458.map)

java  4579 cpu-clock:
      7f4179101d0f [unknown] (/tmp/perf-4458.map)
[…]
```

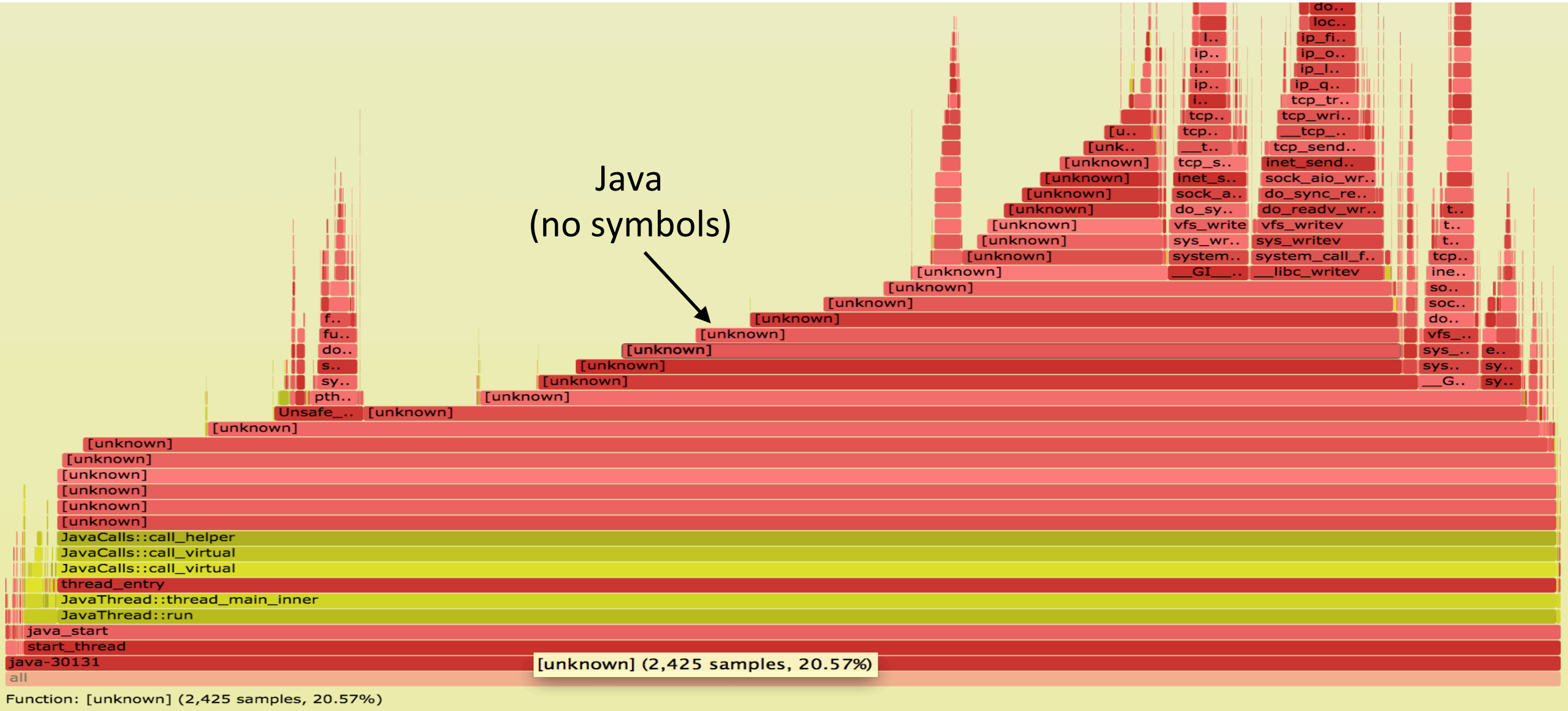
- Check with "perf script" to see stack samples
- These are 1 or 2 levels deep (junk values)

Fixed Java Stacks

```
# perf script
[…]
java 8131 cpu-clock:
    7fff76f2dce1 [unknown] ([vdso])
    7fd3173f7a93 os::javaTimeMillis() (/usr/lib/jvm…
    7fd301861e46 [unknown] (/tmp/perf-8131.map)
    7fd30184def8 [unknown] (/tmp/perf-8131.map)
    7fd30174f544 [unknown] (/tmp/perf-8131.map)
    7fd30175d3a8 [unknown] (/tmp/perf-8131.map)
    7fd30166d51c [unknown] (/tmp/perf-8131.map)
    7fd301750f34 [unknown] (/tmp/perf-8131.map)
    7fd3016c2280 [unknown] (/tmp/perf-8131.map)
    7fd301b02ec0 [unknown] (/tmp/perf-8131.map)
    7fd3016f9888 [unknown] (/tmp/perf-8131.map)
    7fd3016ece04 [unknown] (/tmp/perf-8131.map)
    7fd30177783c [unknown] (/tmp/perf-8131.map)
    7fd301600aa8 [unknown] (/tmp/perf-8131.map)
    7fd301a4484c [unknown] (/tmp/perf-8131.map)
    7fd3010072e0 [unknown] (/tmp/perf-8131.map)
    7fd301007325 [unknown] (/tmp/perf-8131.map)
    7fd301007325 [unknown] (/tmp/perf-8131.map)
    7fd3010004e7 [unknown] (/tmp/perf-8131.map)
    7fd3171df76a JavaCalls::call_helper(JavaValue*,…
    7fd3171dce44 JavaCalls::call_virtual(JavaValue*…
    7fd3171dd43a JavaCalls::call_virtual(JavaValue*…
    7fd31721b6ce thread_entry(JavaThread*, Thread*)…
    7fd3175389e0 JavaThread::thread_main_inner() (/…
    7fd317538cb2 JavaThread::run() (/usr/lib/jvm/nf…
    7fd3173f6f52 java_start(Thread*) (/usr/lib/jvm/…
    7fd317a7e182 start_thread (/lib/x86_64-linux-gn…
```

- With -XX:+PreserveFramePointer stacks are full, and go all the way to start_thread()
- This is what the CPUs are really running: inlined frames are not present

Fixed Stacks Flame Graph



Gotcha #2 Missing Symbols

- Missing symbols should be obvious in perf report/script:

```
71.79%            334      sed   sed                [.] 0x000000000001afc1
                  |
                  |--11.65%-- 0x40a447
                  |           0x40659a
                  |           0x408dd8
                  |           0x408ed1
                  |           0x402689
                  |           0x7fa1cd08aec5
```

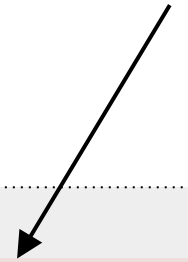
broken

```
12.06%             62       sed  sed                [.] re_search_internal
                   |
                   --- re_search_internal
                       |
                       |--96.78%-- re_search_stub
                       |           rpl_re_search
                       |           match_regex
                       |           do_subst
                       |           execute_program
                       |           process_files
                       |           main
                       |           __libc_start_main
```

not broken

Fixing Symbols

- For installed packages:
  A. Add a -dbgsym package, if available
  B. Recompile from source
- For JIT (Java, Node.js, …):
  A. Create a /tmp/perf-PID.map file. perf already looks for this
     - Map format is "START SIZE symbolname"
  B. Or use a symbol loggers. Eg tools/perf/jvmti.



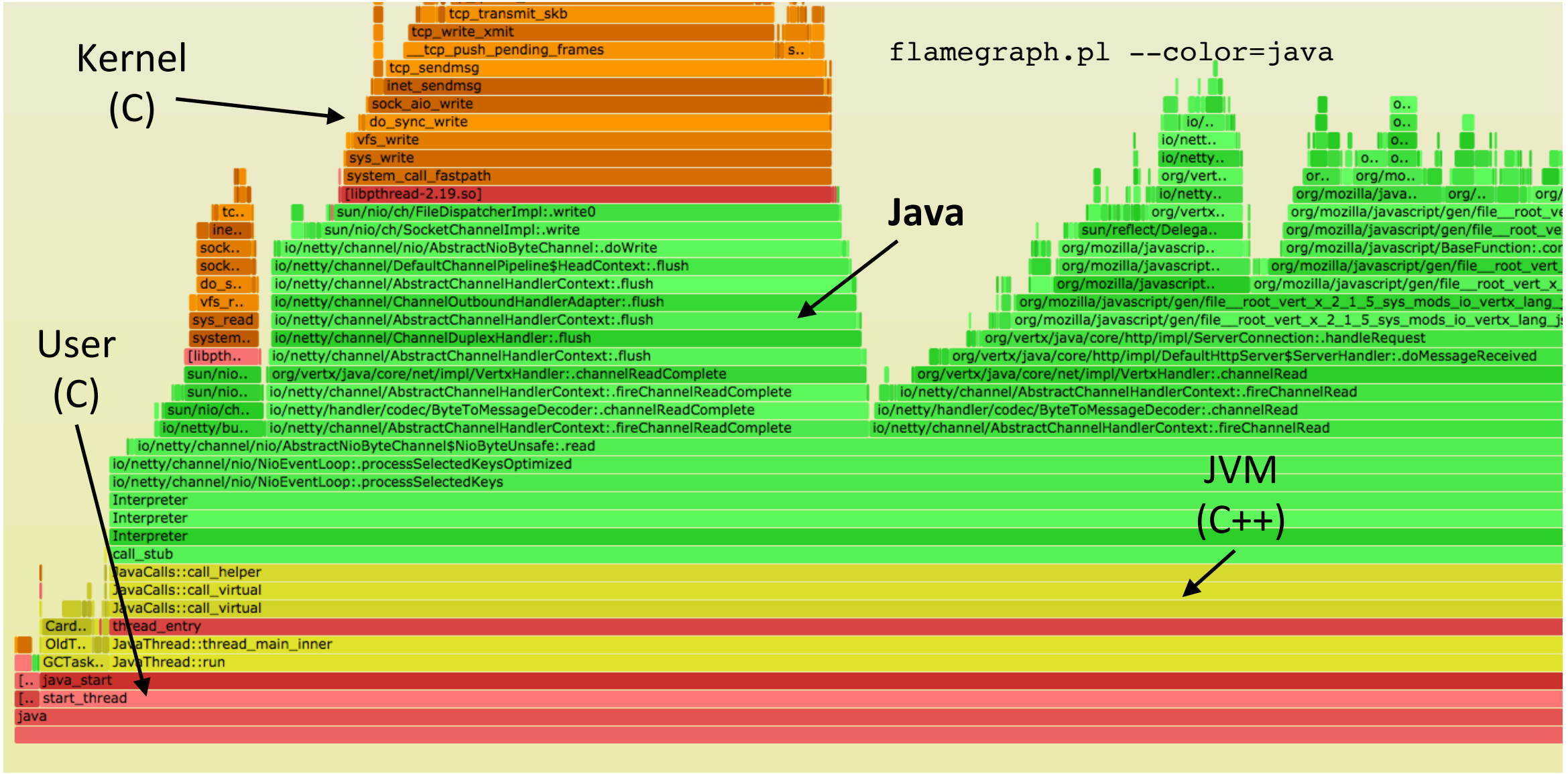
```
# perf script
Failed to open /tmp/perf-8131.map, continuing without symbols
[…]
java 8131 cpu-clock:
    7fff76f2dce1 [unknown] ([vdso])
    7fd3173f7a93 os::javaTimeMillis() (/usr/lib/jvm…
    7fd301861e46 [unknown] (/tmp/perf-8131.map)
[…]
```

Java Symbols

- perf-map-agent
  - Agent attaches and writes the map file on demand (previous versions attached on Java start, and wrote continually)
  - https://github.com/jvm-profiling-tools/perf-map-agent
    (was https://github.com/jrudolph/perf-map-agent)
- Automation: jmaps
  - We use scripts to find Java processes and dump their map files, paying attention to file ownership etc
  - https://github.com/brendangregg/FlameGraph/blob/master/jmaps
  - Needs to run as close as possible to the profile, to minimize symbol churn

```
# perf record -F 99 -a -g -- sleep 30; jmaps
```

Java Flame Graph: Stacks & Symbols



Java: Inlining

A. Disabling inlining:
   - -XX:-Inline
   - Many more Java frames
   - 80% slower (in this case)
   - May not be necessary: inlined flame graphs often make enough sense
   - Or tune -XX:MaxInlineSize and -XX:InlineSmallCode to reveal more frames, without costing much perf: can even go faster!

B. Symbol agents can uninline
   - perf-map-agent unfoldall
   - We sometimes need and use this

Node.js: Stacks & Symbols

- Frame pointer stacks work
- Symbols currently via a logger
  - `--perf-basic-prof`: everything. We found it can log over 1 Gbyte/day.
  - `--perf-basic-prof-only-functions`: tries to only log symbols we care about.
- perf may not use the most recent symbol in the log
  - We tidy logs before using them: https://raw.githubusercontent.com/brendangregg/Misc/master/perf_events/perfmaptidy.pl
- Future v8's may support on-demand symbol dumps

Gotcha #3 Instruction Profiling

```
# perf annotate -i perf.data.noplooper --stdio
 Percent |      Source code & Disassembly of noplooper
------------------------------------------------------
         :      Disassembly of section .text:
         :
         :      00000000004004ed <main>:
         :        4004ed:       push   %rbp
         :        4004ee:       mov    %rsp,%rbp
         :        4004f1:       nop
         :        4004f2:       nop
         :        4004f3:       nop
         :        4004f4:       nop
         :        4004f5:       nop
         :        4004f6:       nop
         :        4004f7:       nop
         :        4004f8:       nop
         :        4004f9:       nop
         :        4004fa:       nop
         :        4004fb:       nop
         :        4004fc:       nop
         :        4004fd:       nop
         :        4004fe:       nop
         :        4004ff:       nop
         :        400500:       nop
         :        400501:       jmp    4004f1 <main+0x4>
```

16 NOPs in a loop

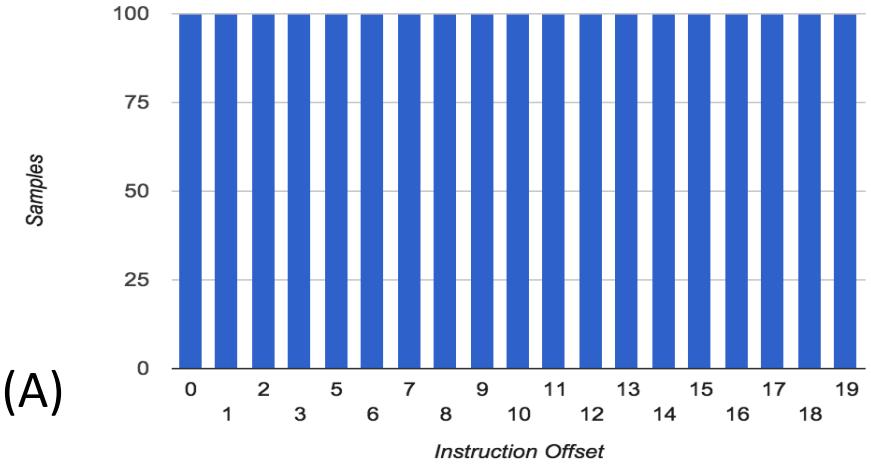
Let's profile instructions to see which are hot!

(have I lost my mind?)

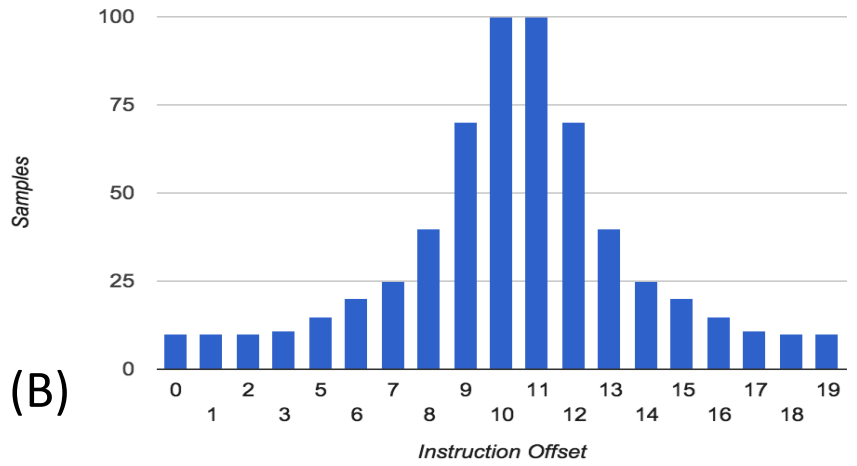
Instruction Profiling

- Even distribution (A)? Or something else?

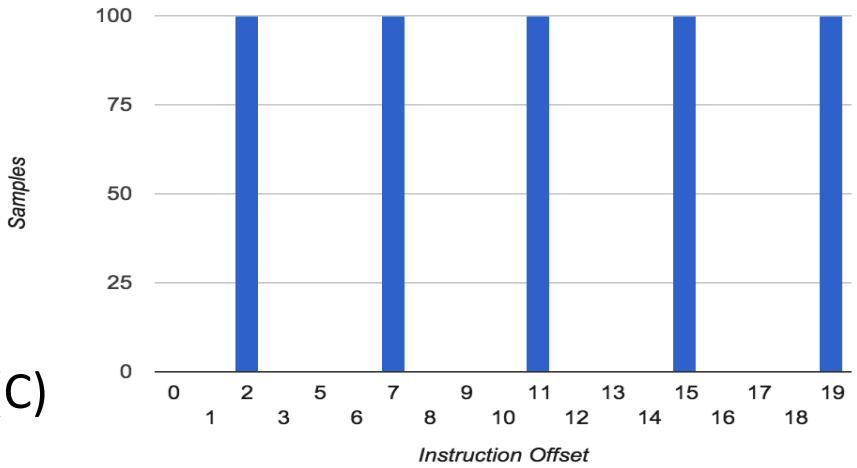
(A)



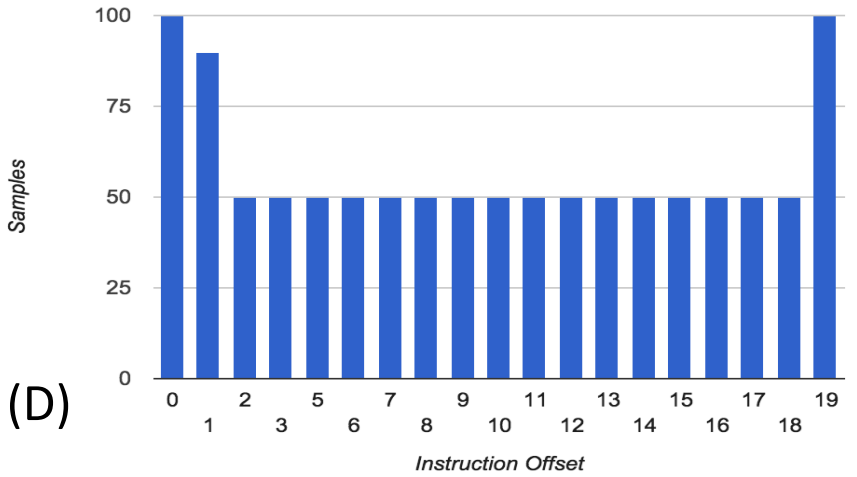
(B)



(C)

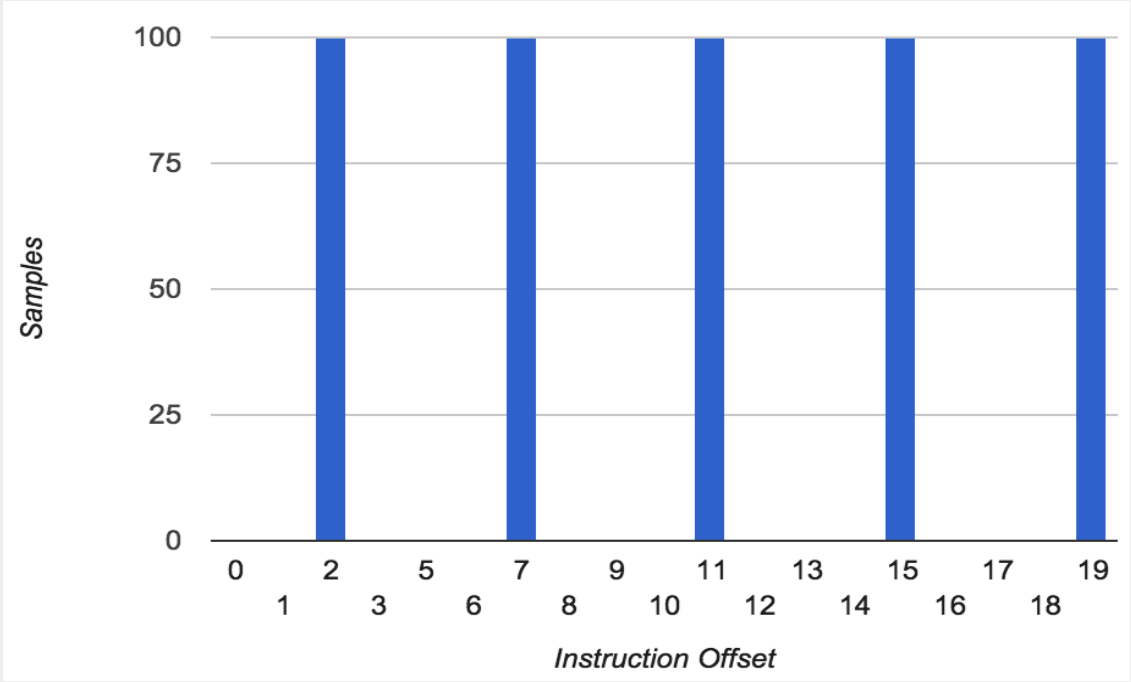


(D)



Instruction Profiling

```
# perf annotate -i perf.data.noplooper --stdio
 Percent |      Source code & Disassembly of noplooper
------------------------------------------------------
         :      Disassembly of section .text:
         :
         :      00000000004004ed <main>:
    0.00 :        4004ed:       push   %rbp
    0.00 :        4004ee:       mov    %rsp,%rbp
   20.86 :        4004f1:       nop
    0.00 :        4004f2:       nop
    0.00 :        4004f3:       nop
    0.00 :        4004f4:       nop
   19.84 :        4004f5:       nop
    0.00 :        4004f6:       nop
    0.00 :        4004f7:       nop
    0.00 :        4004f8:       nop
   18.73 :        4004f9:       nop
    0.00 :        4004fa:       nop
    0.00 :        4004fb:       nop
    0.00 :        4004fc:       nop
   19.08 :        4004fd:       nop
    0.00 :        4004fe:       nop
    0.00 :        4004ff:       nop
    0.00 :        400500:       nop
   21.49 :        400501:       jmp    4004f1 <main+0x4>
```



Go home instruction pointer, you're drunk

PEBS

- I believe this is due to parallel and out-of-order execution of micro-ops: the sampled IP is the resumption instruction, not what is currently executing. And skid.
- PEBS may help: Intel's Precise Event Based Sampling
- perf_events has support:
  - perf record -e cycles:pp
  - The 'p' can be specified multiple times:
    - 0 - SAMPLE_IP can have arbitrary skid
    - 1 - SAMPLE_IP must have constant skid
    - 2 - SAMPLE_IP requested to have 0 skid
    - 3 - SAMPLE_IP must have 0 skid
  - … from tools/perf/Documentation/perf-list.txt

Gotcha #4 VM Guests

- Using PMCs from most VM guests:

```
# perf stat -a -d sleep 5

 Performance counter stats for 'system wide':

      10003.718595 task-clock (msec)      #    2.000 CPUs utilized      [100.00%]
               323 context-switches       #    0.032 K/sec              [100.00%]
                17 cpu-migrations         #    0.002 K/sec              [100.00%]
               233 page-faults            #    0.023 K/sec
   <not supported> cycles
   <not supported> stalled-cycles-frontend
   <not supported> stalled-cycles-backend
   <not supported> instructions
   <not supported> branches
   <not supported> branch-misses
   <not supported> L1-dcache-loads
   <not supported> L1-dcache-load-misses
   <not supported> LLC-loads
   <not supported> LLC-load-misses

        5.001607197 seconds time elapsed
```

VM Guest PMCs

- Without PMCs, %CPU is ambiguous. We need IPC.
  - Can't measure instructions per cycle (IPC), cache hits/misses, MMU/TLB events, etc.
- Is fixable: eg, Xen can enable PMCs (`vpmu` boot option)
  - I added vpmu support for subsets, eg, vpmu=arch for Intel architectural set (7 PMCs only)
  - http://www.brendangregg.com/blog/2017-05-04/the-pmcs-of-ec2.html

Event Name	UMask	Event Select	Example Event Mask Mnemonic
UnHalted Core Cycles	00H	3CH	CPU_CLK_UNHALTED.THREAD_P
Instruction Retired	00H	C0H	INST_RETIRED.ANY_P
UnHalted Reference Cycles	01H	3CH	CPU_CLK_THREAD_UNHALTED.REF_XCLK
LLC Reference	4FH	2EH	LONGEST_LAT_CACHE.REFERENCE
LLC Misses	41H	2EH	LONGEST_LAT_CACHE.MISS
Branch Instruction Retired	00H	C4H	BR_INST_RETIRED.ALL_BRANCHES
Branch Misses Retired	00H	C5H	BR_MISP_RETIRED.ALL_BRANCHES

architectural set

  - Now available on the largest AWS EC2 instance types

VM Guest MSRs

- Model Specific Registers (MSRs) may be exposed when PMCs are not
- Better than nothing. Can solve some issues.

```
# ./showboost
CPU MHz      : 2500
Turbo MHz    : 2900 (10 active)
Turbo Ratio : 116% (10 active)
CPU 0 summary every 5 seconds...

TIME         C0_MCYC       C0_ACYC         UTIL   RATIO    MHz
17:28:03    4226511637    4902783333       33%    116%    2900
17:28:08    4397892841    5101713941       35%    116%    2900
17:28:13    4550831380    5279462058       36%    116%    2900
17:28:18    4680962051    5429605341       37%    115%    2899
17:28:23    4782942155    5547813280       38%    115%    2899
[...]
```

  - showboost is from my msr-cloud-tools collection (on github)

VM Guest PEBS

- Not possible yet in Xen
  - please fix
- Ditto for LBR, BTS, processor trace

Gotcha #5 Containers

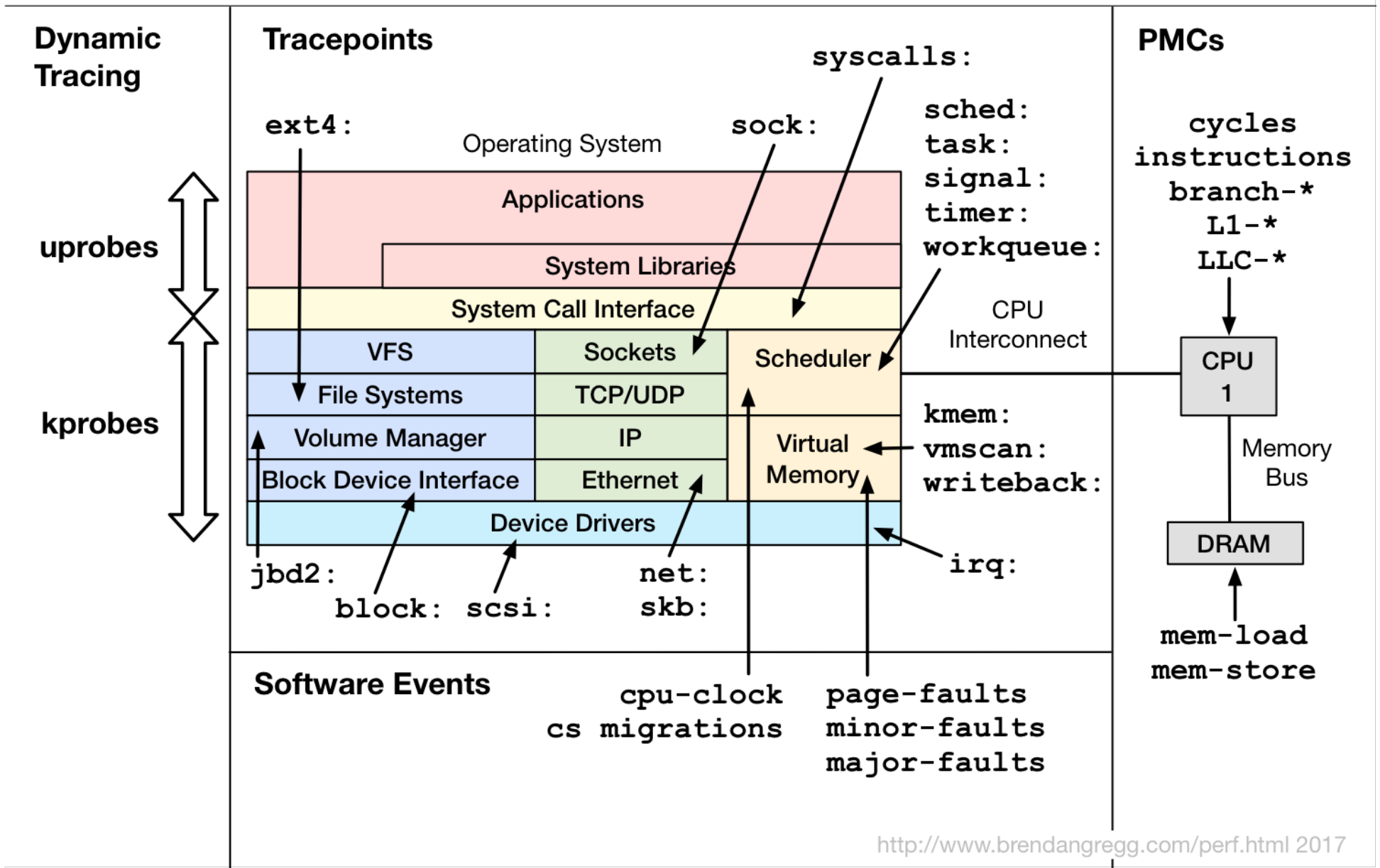
- perf from the host can't find symbol files in different mount namespaces
- We currently workaround it
  - http://blog.alicegoldfuss.com/making-flamegraphs-with-containerized-java/
- Should be fixed in 4.14
  - Krister Johansen's patches

Gotcha #6 Overhead

- Overhead is relative to the rate of events instrumented
- `perf stat` does in-kernel counts: relatively low overhead
- `perf record` writes perf.data, which has slightly higher CPU overhead, plus file system and disk I/O
- Test before use
  - In the lab
  - Run perf stat to understand rate, before perf record
- Also consider `--filter`, to filter events in-kernel

4. perf Advanced

perf for Tracing Events



http://www.brendangregg.com/perf.html 2017

Tracepoints

```
# perf record -e block:block_rq_insert -a
^C[ perf record: Woken up 1 times to write data ]
[ perf record: Captured and wrote 0.172 MB perf.data (~7527 samples) ]

# perf script
[…]
  java 9940 [015] 1199510.044783: block_rq_insert: 202,1 R 0 () 4783360 + 88 [java]
  java 9940 [015] 1199510.044786: block_rq_insert: 202,1 R 0 () 4783448 + 88 [java]
  java 9940 [015] 1199510.044786: block_rq_insert: 202,1 R 0 () 4783536 + 24 [java]
  java 9940 [000] 1199510.065195: block_rq_insert: 202,1 R 0 () 4864088 + 88 [java]
[…]
```

process PID [CPU] timestamp: eventname:

format string

```
include/trace/events/block.h: java 9940 [015] 1199510.044783: block_rq_insert: 202,1 R 0 () 4783360 + 88 [java]
DECLARE_EVENT_CLASS(block_rq,
[...]
 TP_printk("%d,%d %s %u (%s) %llu + %u [%s]",
                MAJOR(__entry->dev), MINOR(__entry->dev),
                __entry->rwbs, __entry->bytes, __get_str(cmd),
                (unsigned long long)__entry->sector,
                __entry->nr_sector, __entry->comm)
```

kernel source may be the only docs

Also see: cat /sys/kernel/debug/tracing/events/block/block_rq_insert/format

One-Liners: Static Tracing

```
# Trace new processes, until Ctrl-C:
perf record -e sched:sched_process_exec -a

# Trace all context-switches with stack traces, for 1 second:
perf record -e context-switches –ag -- sleep 1

# Trace CPU migrations, for 10 seconds:
perf record -e migrations -a -- sleep 10

# Trace all connect()s with stack traces (outbound connections), until Ctrl-C:
perf record -e syscalls:sys_enter_connect –ag

# Trace all block device (disk I/O) requests with stack traces, until Ctrl-C:
perf record -e block:block_rq_insert -ag

# Trace all block device issues and completions (has timestamps), until Ctrl-C:
perf record -e block:block_rq_issue -e block:block_rq_complete -a

# Trace all block completions, of size at least 100 Kbytes, until Ctrl-C:
perf record -e block:block_rq_complete --filter 'nr_sector > 200'

# Trace all block completions, synchronous writes only, until Ctrl-C:
perf record -e block:block_rq_complete --filter 'rwbs == "WS"'

# Trace all block completions, all types of writes, until Ctrl-C:
perf record -e block:block_rq_complete --filter 'rwbs ~ "*W*"'

# Trace all ext4 calls, and write to a non-ext4 location, until Ctrl-C:
perf record -e 'ext4:*' -o /tmp/perf.data -a
```

One-Liners: Dynamic Tracing

```
# Add a tracepoint for the kernel tcp_sendmsg() function entry (--add optional):
perf probe --add tcp_sendmsg

# Remove the tcp_sendmsg() tracepoint (or use --del):
perf probe -d tcp_sendmsg

# Add a tracepoint for the kernel tcp_sendmsg() function return:
perf probe 'tcp_sendmsg%return'

# Show avail vars for the tcp_sendmsg(), plus external vars (needs debuginfo):
perf probe -V tcp_sendmsg --externs

# Show available line probes for tcp_sendmsg() (needs debuginfo):
perf probe -L tcp_sendmsg

# Add a tracepoint for tcp_sendmsg() line 81 with local var seglen (debuginfo):
perf probe 'tcp_sendmsg:81 seglen'

# Add a tracepoint for do_sys_open() with the filename as a string (debuginfo):
perf probe 'do_sys_open filename:string'

# Add a tracepoint for myfunc() return, and include the retval as a string:
perf probe 'myfunc%return +0($retval):string'

# Add a tracepoint for the user-level malloc() function from libc:
perf probe -x /lib64/libc.so.6 malloc

# List currently available dynamic probes:
perf probe -l
```

One-Liners: Advanced Dynamic Tracing

```
# Add a tracepoint for tcp_sendmsg(), with three entry regs (platform specific):
perf probe 'tcp_sendmsg %ax %dx %cx'

# Add a tracepoint for tcp_sendmsg(), with an alias ("bytes") for %cx register:
perf probe 'tcp_sendmsg bytes=%cx'

# Trace previously created probe when the bytes (alias) var is greater than 100:
perf record -e probe:tcp_sendmsg --filter 'bytes > 100'

# Add a tracepoint for tcp_sendmsg() return, and capture the return value:
perf probe 'tcp_sendmsg%return $retval'

# Add a tracepoint for tcp_sendmsg(), and "size" entry argument (debuginfo):
perf probe 'tcp_sendmsg size'

# Add a tracepoint for tcp_sendmsg(), with size and socket state (debuginfo):
perf probe 'tcp_sendmsg size sk->__sk_common.skc_state'

# Trace previous probe when size > 0, and state != TCP_ESTABLISHED(1) (debuginfo):
perf record -e probe:tcp_sendmsg --filter 'size > 0 && skc_state != 1' -a
```

- Kernel debuginfo is an onerous requirement for the Netflix cloud
- We can use registers instead (as above). But which registers?

The Rosetta Stone of Registers

One server instance with kernel debuginfo, and -nv (dry run, verbose):

```
# perf probe -nv 'tcp_sendmsg size sk->__sk_common.skc_state'
[…]
Added new event:
Writing event: p:probe/tcp_sendmsg tcp_sendmsg+0 size=%cx:u64 skc_state=+18(%si):u8
  probe:tcp_sendmsg (on tcp_sendmsg with size skc_state=sk->__sk_common.skc_state)

You can now use it in all perf tools, such as:

      perf record -e probe:tcp_sendmsg -aR sleep 1
```

Copy-n-paste!

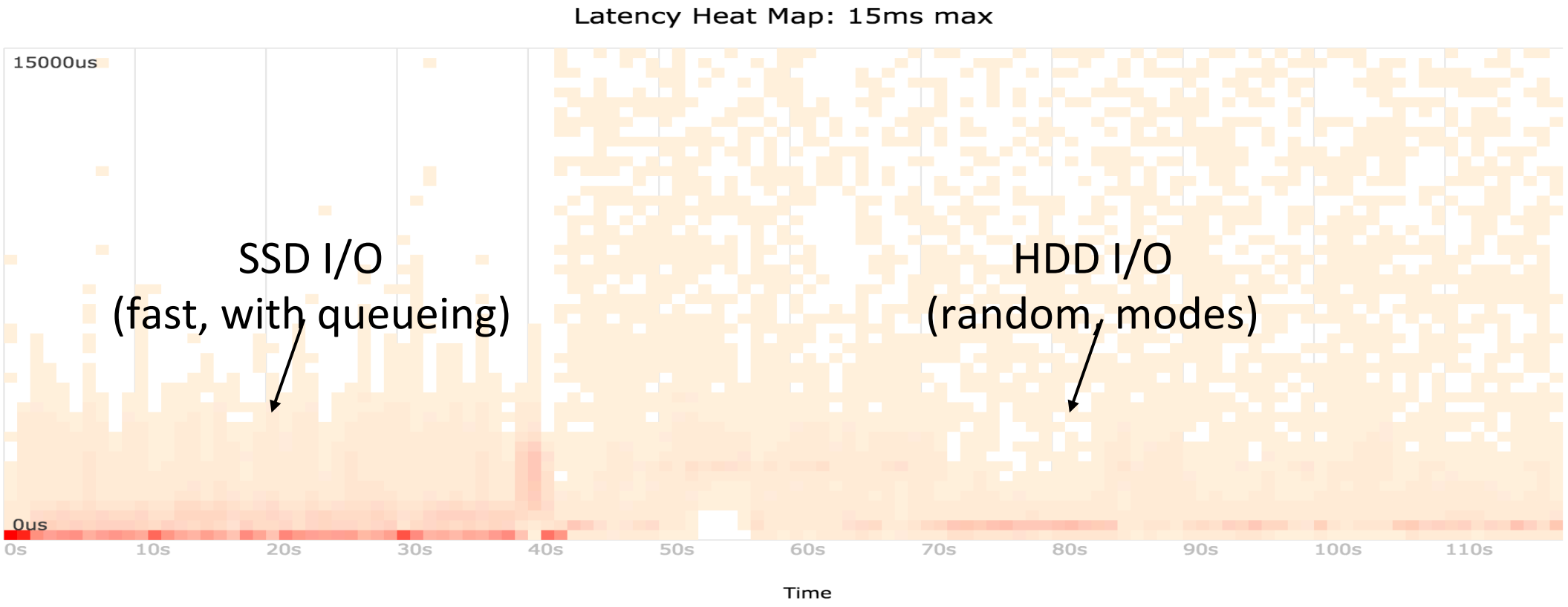
All other instances (of the same kernel version):

```
# perf probe 'tcp_sendmsg+0 size=%cx:u64 skc_state=+18(%si):u8'
Failed to find path of kernel module.
Added new event:
  probe:tcp_sendmsg    (on tcp_sendmsg with size=%cx:u64 skc_state=+18(%si):u8)

You can now use it in all perf tools, such as:

      perf record -e probe:tcp_sendmsg -aR sleep 1
```

Masami Hiramatsu was investigating a way to better automate this

perf Visualizations: Block I/O Latency Heat Map

- We automated this for analyzing disk I/O latency issues



http://www.brendangregg.com/blog/2014-07-01/perf-heat-maps.html

There's still a lot more to perf…

- Using PMCs
- perf scripting interface
- perf + eBPF
- perf sched
- perf timechart
- perf trace
- perf c2c (new!)
- perf ftrace (new!)
- …

Links & References

- perf_events
  - Kernel source: **tools/perf/Documentation**
  - https://perf.wiki.kernel.org/index.php/Main_Page
  - http://www.brendangregg.com/perf.html
  - http://web.eece.maine.edu/~vweaver/projects/perf_events/
  - **Mailing list** http://vger.kernel.org/vger-lists.html#linux-perf-users
- perf-tools: https://github.com/brendangregg/perf-tools
- PMU tools: https://github.com/andikleen/pmu-tools
- perf, ftrace, and more: http://www.brendangregg.com/linuxperf.html
- Java frame pointer patch
  - http://mail.openjdk.java.net/pipermail/hotspot-compiler-dev/2014-December/016477.html
  - https://bugs.openjdk.java.net/browse/JDK-8068945
- Node.js: http://techblog.netflix.com/2014/11/nodejs-in-flames.html
- Methodology: http://www.brendangregg.com/methodology.html
- Flame graphs: http://www.brendangregg.com/flamegraphs.html
- Heat maps: http://www.brendangregg.com/heatmaps.html
- eBPF: http://lwn.net/Articles/603983/

Thank You

- Questions?
- http://www.brendangregg.com
- http://slideshare.net/brendangregg
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