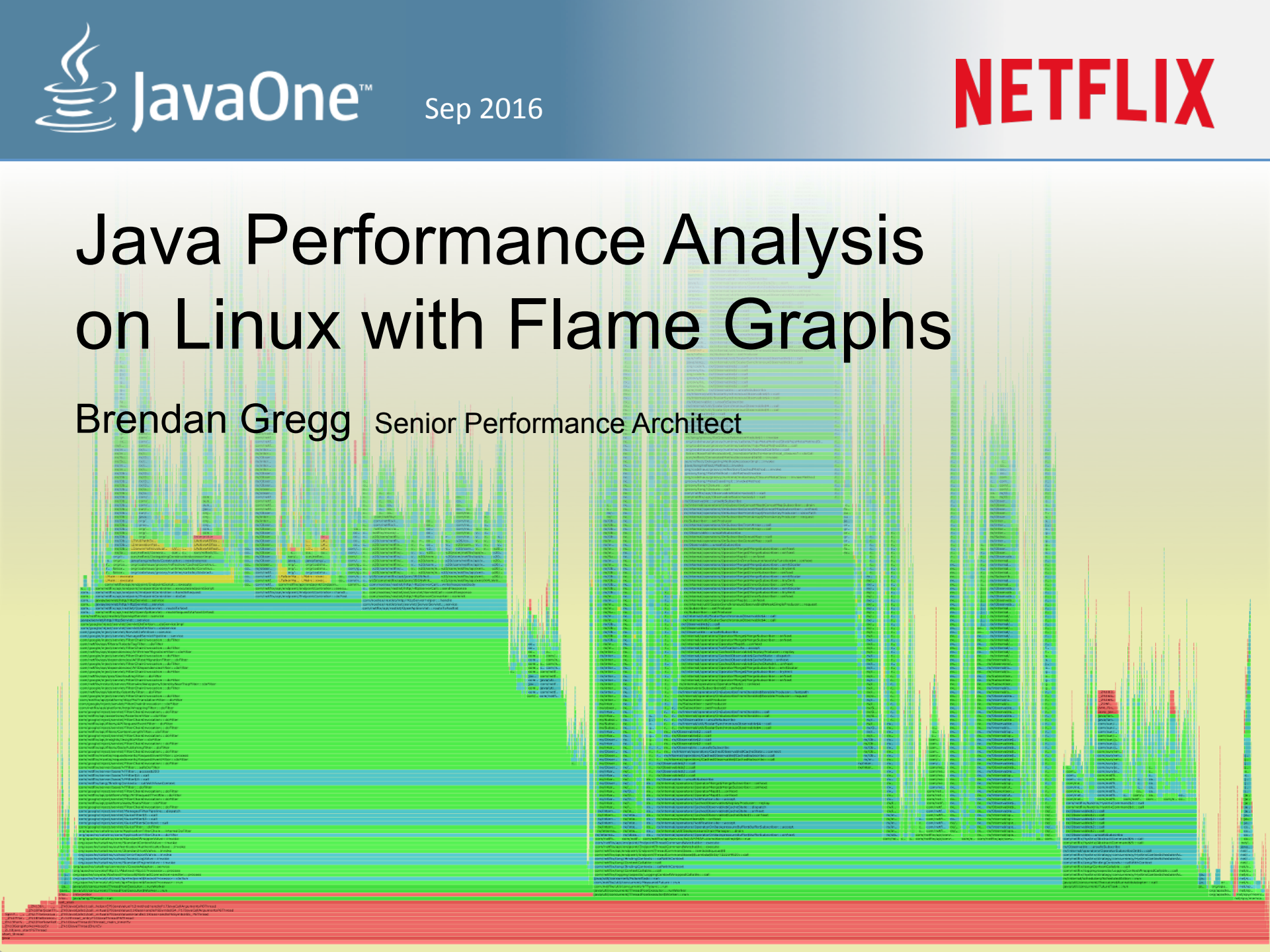
JavaOne™ Sep 2016

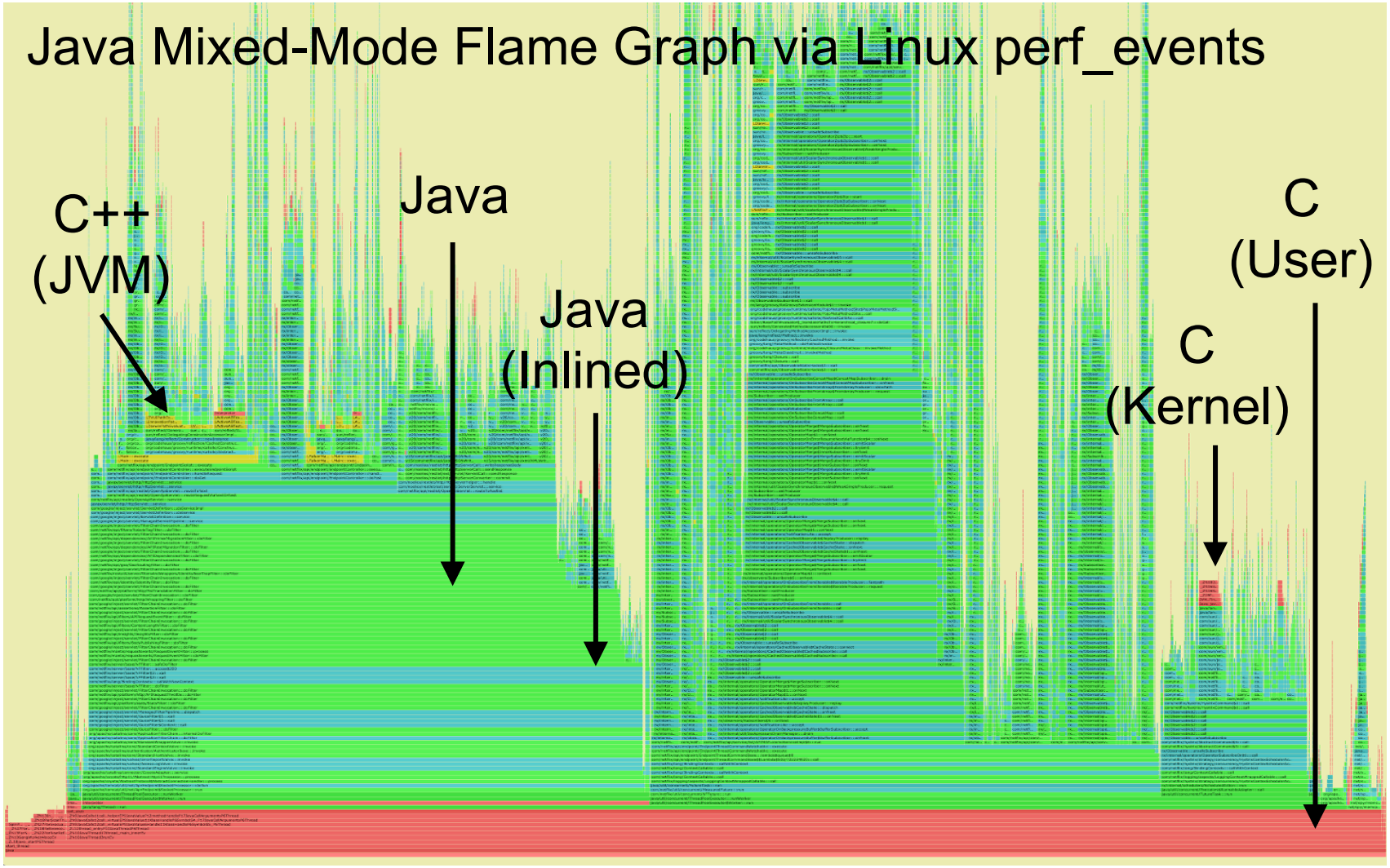
NETFLIX

Java Performance Analysis on Linux with Flame Graphs

Brendan Gregg Senior Performance Architect

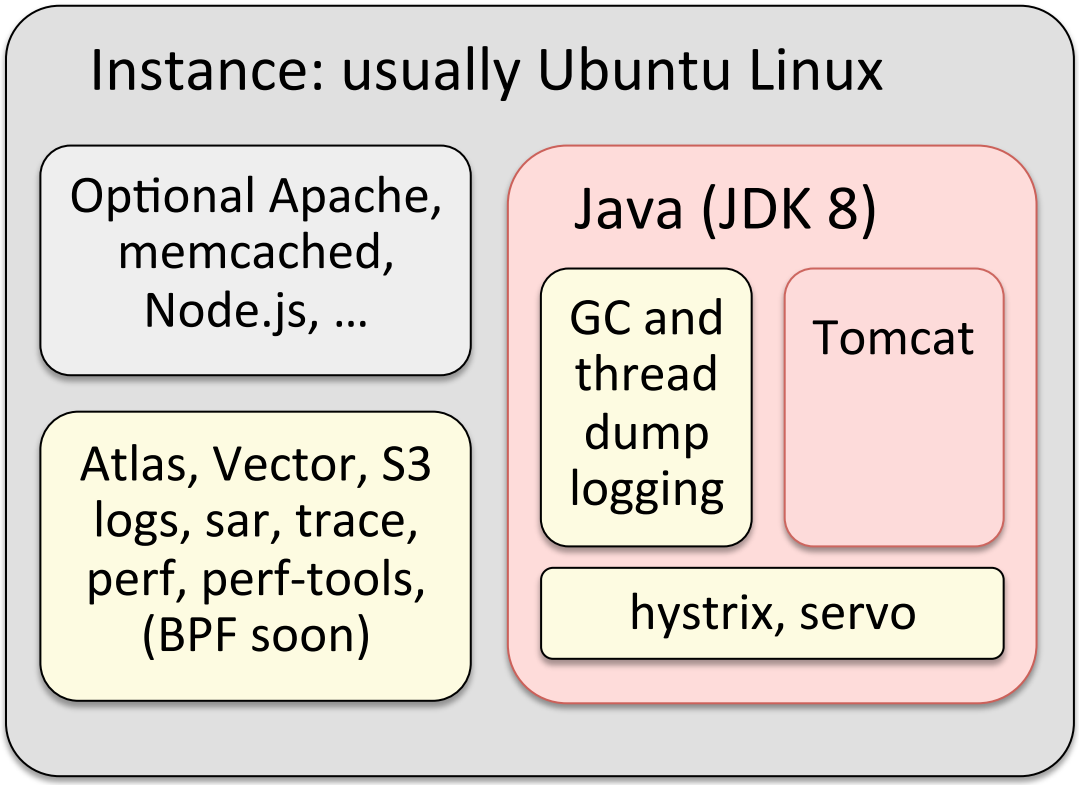


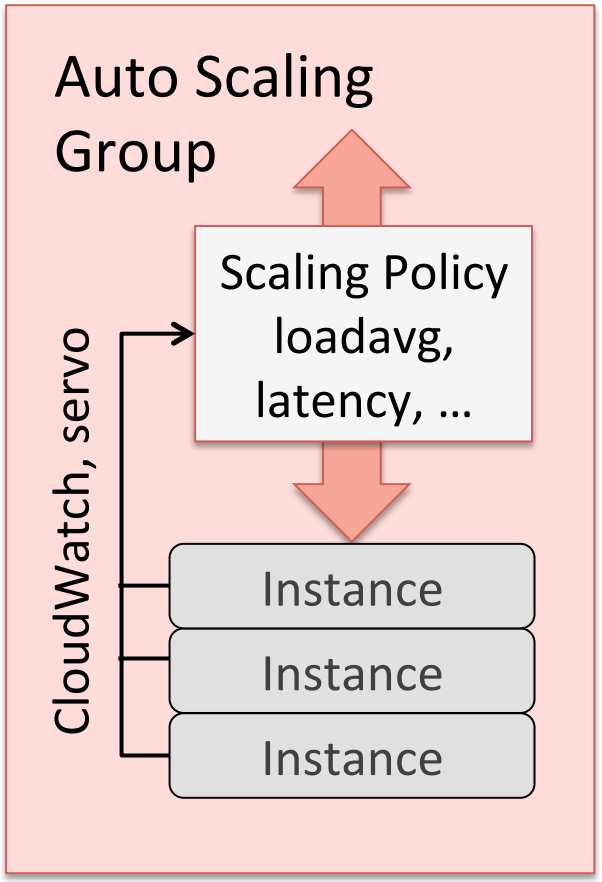
Complete Visibility



NETFLIX Cloud

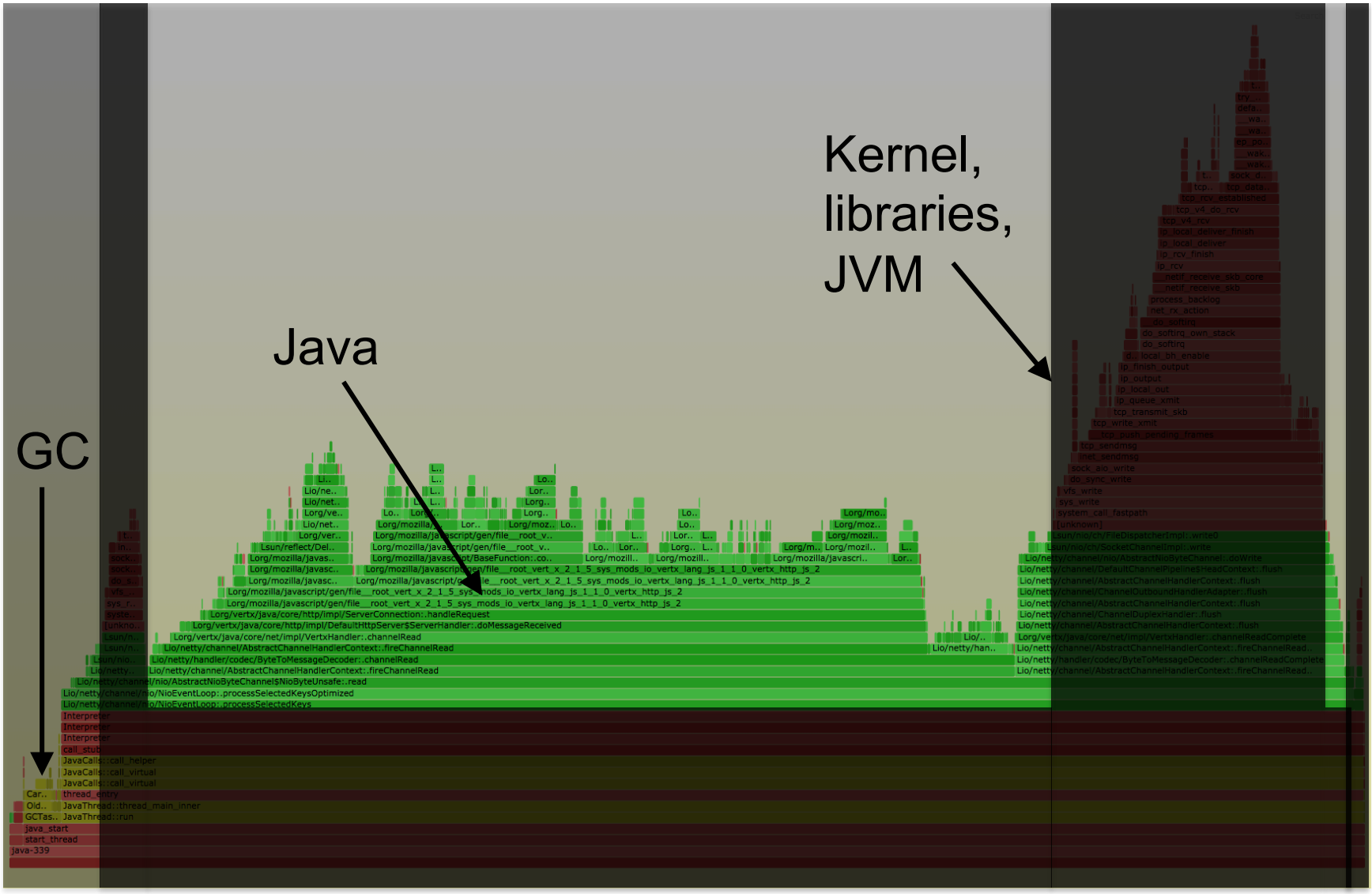
- Tens of thousands of AWS EC2 instances
- Mostly Java (Oracle JVM)





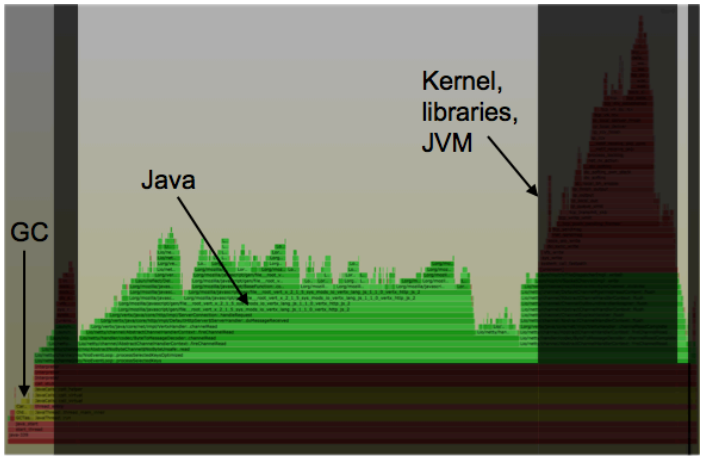
The Problem with Profilers

Java Profilers

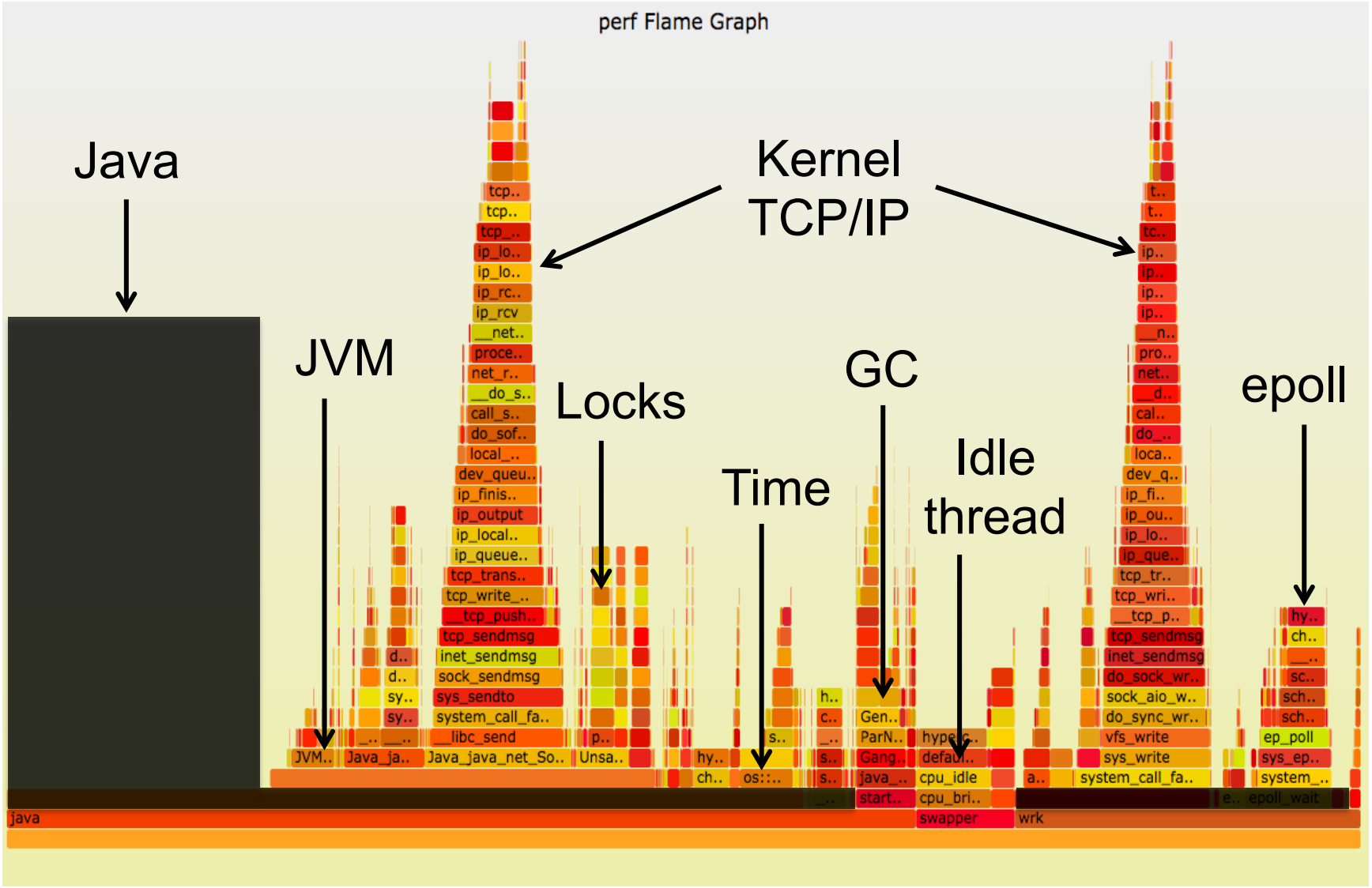


Java Profilers

- Visibility
  - Java method execution
  - Object usage
  - GC logs
  - Custom Java context
- Typical problems:
  - Sampling often happens at safety/yield points (skew)
  - Method tracing has massive observer effect
  - Misidentifies RUNNING as on-CPU (e.g., epoll)
  - Doesn't include or profile GC or JVM CPU time
  - Tree views not quick (proportional) to comprehend
- Inaccurate (skewed) and incomplete profiles

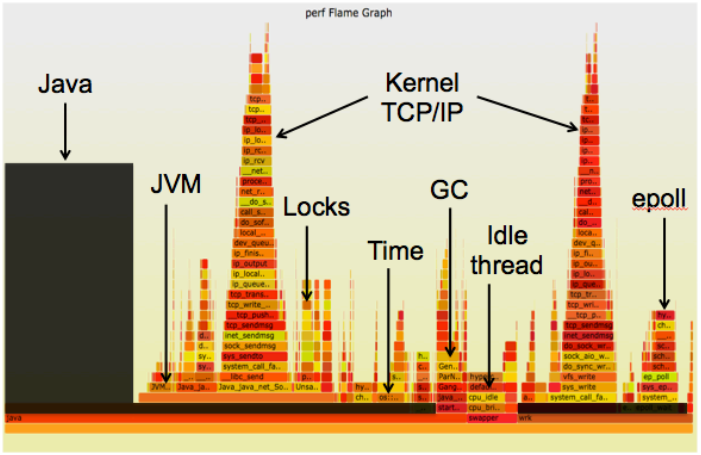


System Profilers



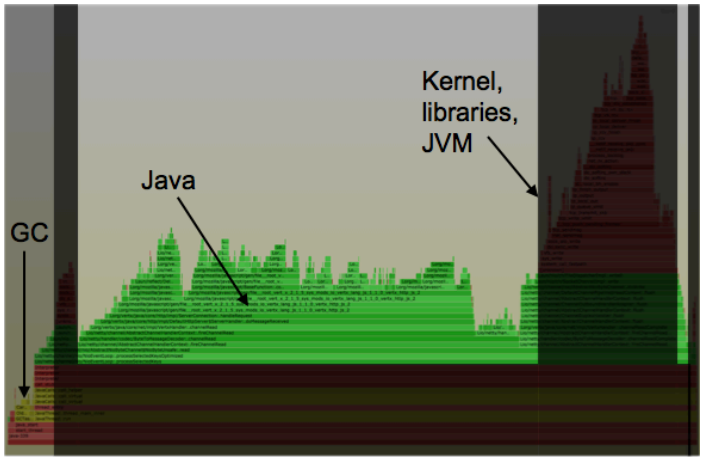
System Profilers

- Visibility
  - JVM (C++)
  - GC (C++)
  - libraries (C)
  - kernel (C)
- Typical problems (x86):
  - Stacks missing for Java
  - Symbols missing for Java methods
- Other architectures (e.g., SPARC) have fared better
- Profile everything except Java

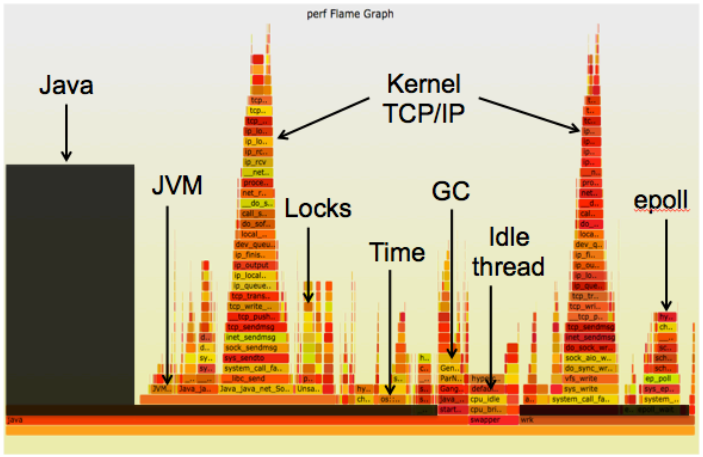


Workaround

- Capture both:



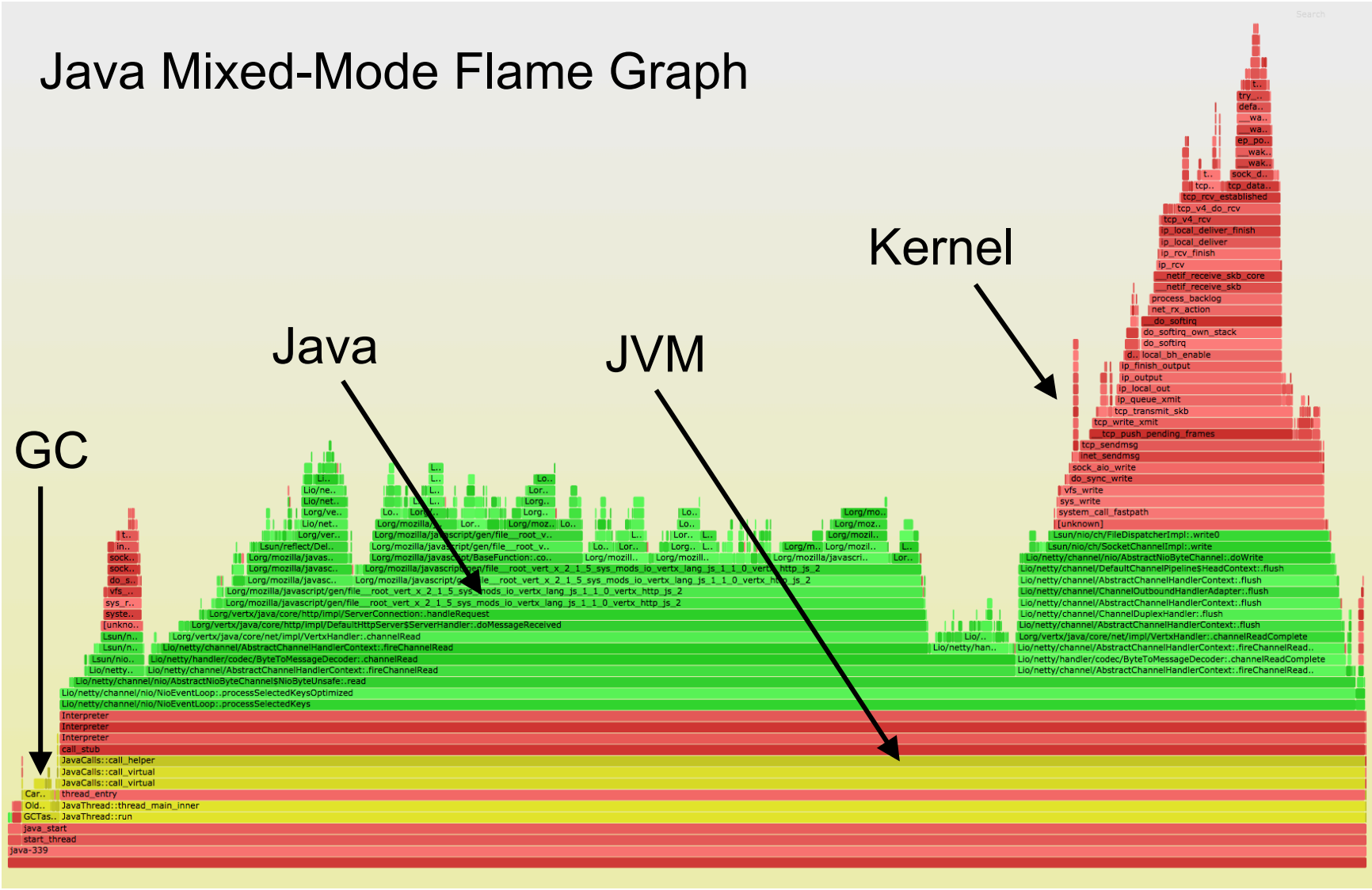
Java



System

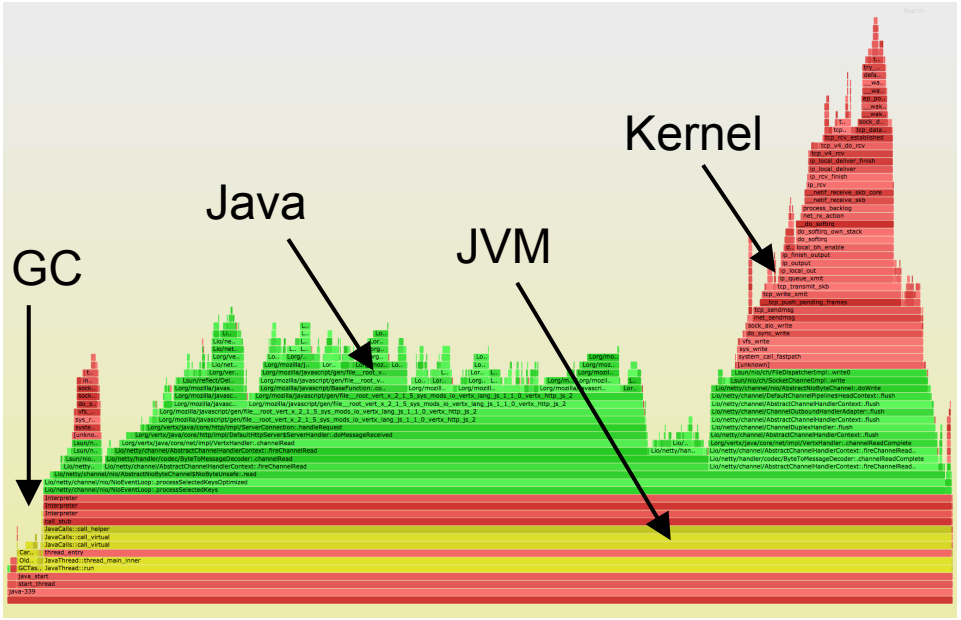
- An improvement, but system stacks are missing Java context, and therefore hard to interpret

Solution


Java Mixed-Mode Flame Graph
Kernel
Java
JVM
GC
Interpreter
call_stub
JavaCalls::call_helper
JavaCalls::call_virtual
thread_entry
JavaThread::thread_main_inner
JavaThread::run
java_start
start_thread
java-339

Solution

- Fix system profiling, see everything:
  - Java methods
  - JVM (C++)
  - GC (C++)
  - libraries (C)
  - kernel (C)
  - Other apps

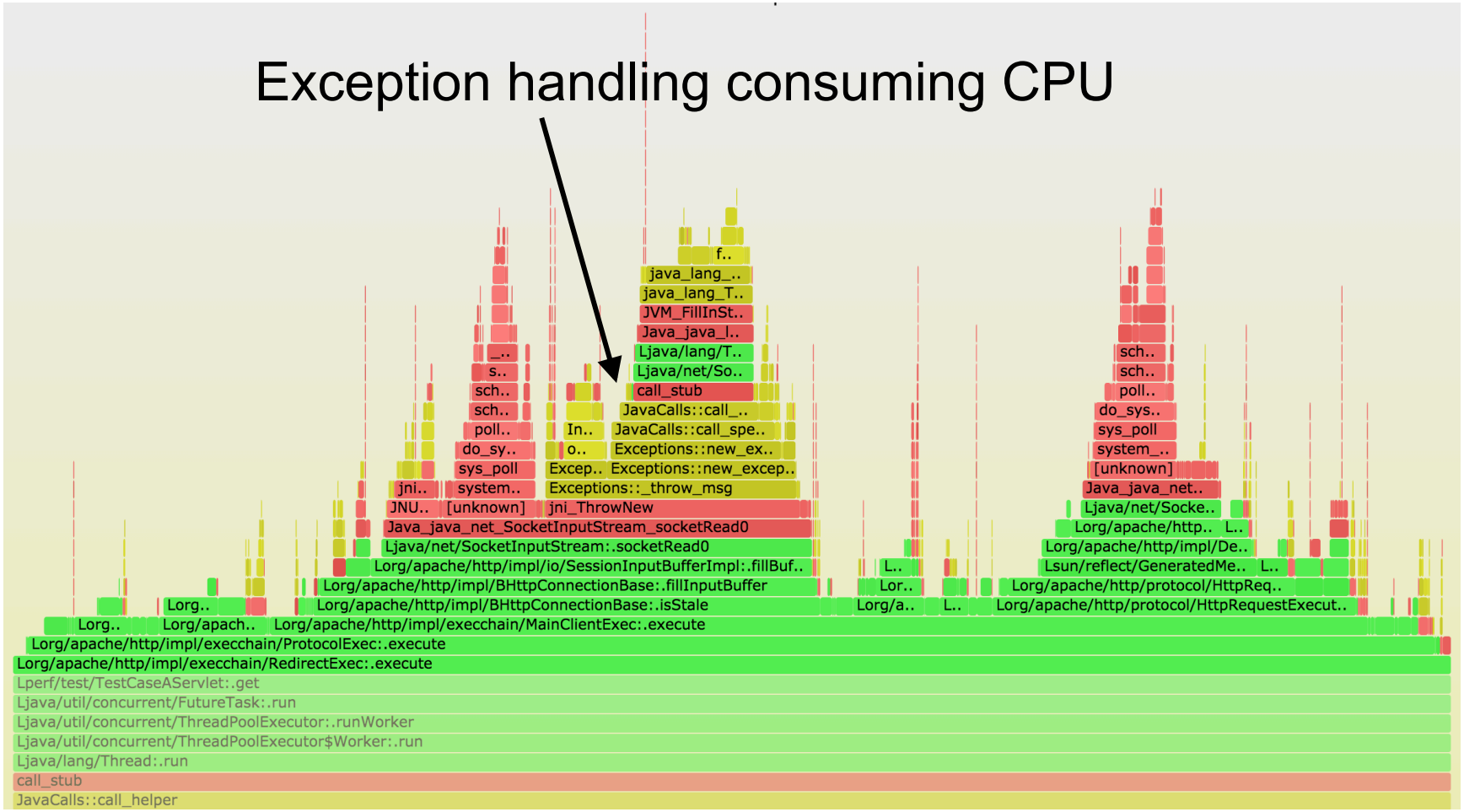


- Minor Problems:
  - 0-3% CPU overhead to enable frame pointers (usually <1%).
  - Symbol dumps can consume a burst of CPU
- **Complete** and **accurate** (asynchronous) profiling

Saving 13M CPU Minutes Per Day

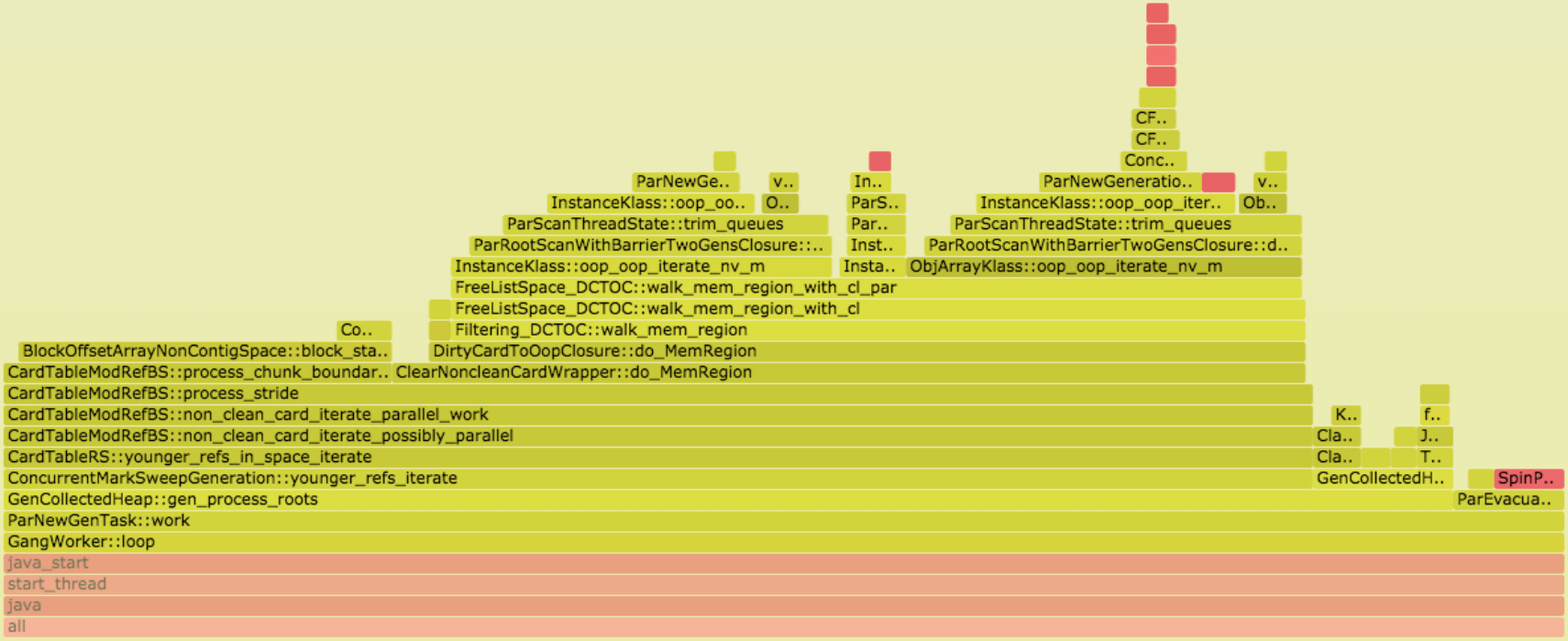
http://techblog.netflix.com/2016/04/saving-13-million-computational-minutes.html

System Example



Profiling GC

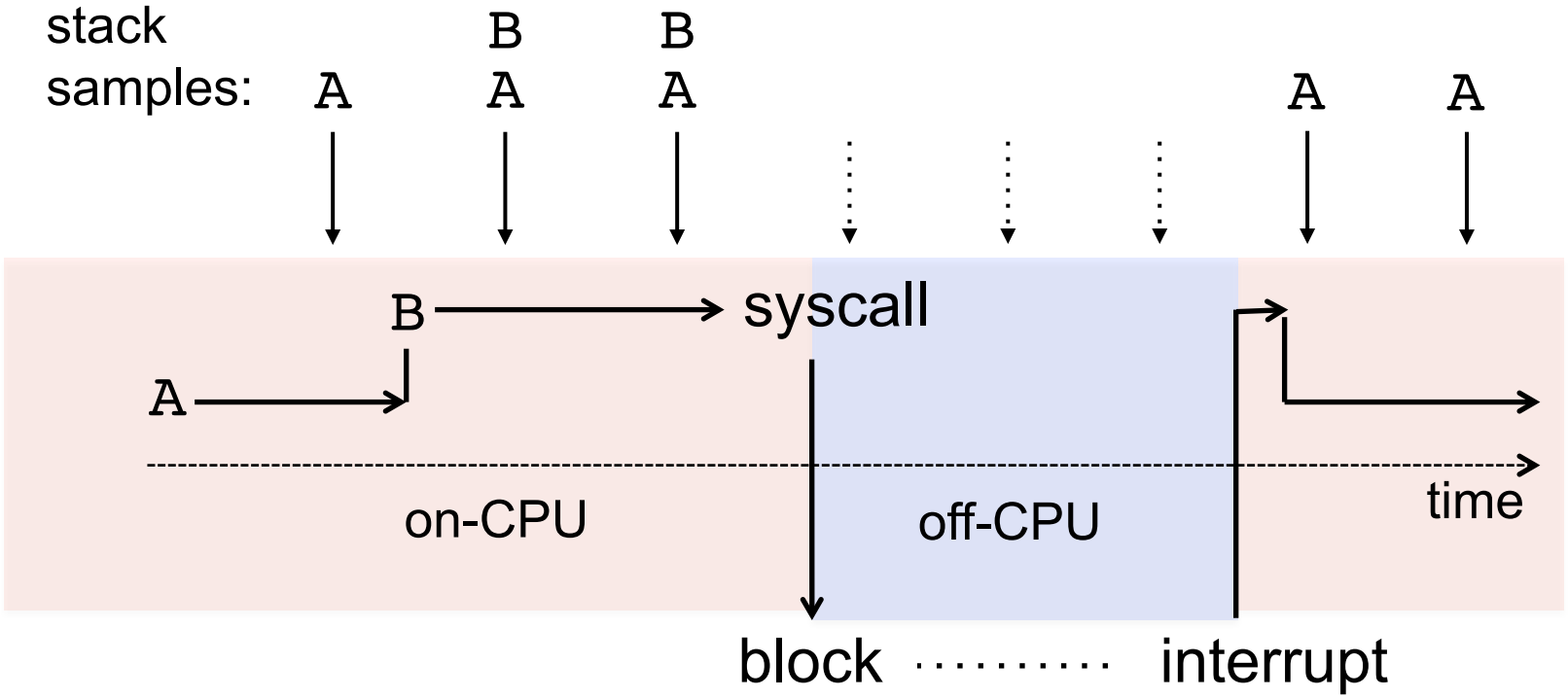
GC internals, visualized:



CPU Profiling

CPU Profiling

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



Stack Traces

- A code path snapshot. e.g., from jstack(1):

```
$ jstack 1819
[…]
"main" prio=10 tid=0x00007ff304009000
nid=0x7361 runnable [0x00007ff30d4f9000]
   java.lang.Thread.State: RUNNABLE
    at Func_abc.func_c(Func_abc.java:6)
    at Func_abc.func_b(Func_abc.java:16)
    at Func_abc.func_a(Func_abc.java:23)
    at Func_abc.main(Func_abc.java:27)
```

running
parent
g.parent
g.g.parent

System Profilers

- Linux
  - perf_events (aka "perf")
- Oracle Solaris
  - DTrace
- OS X
  - Instruments
- Windows
  - XPerf, WPA (which now has flame graphs!)
- And many others…

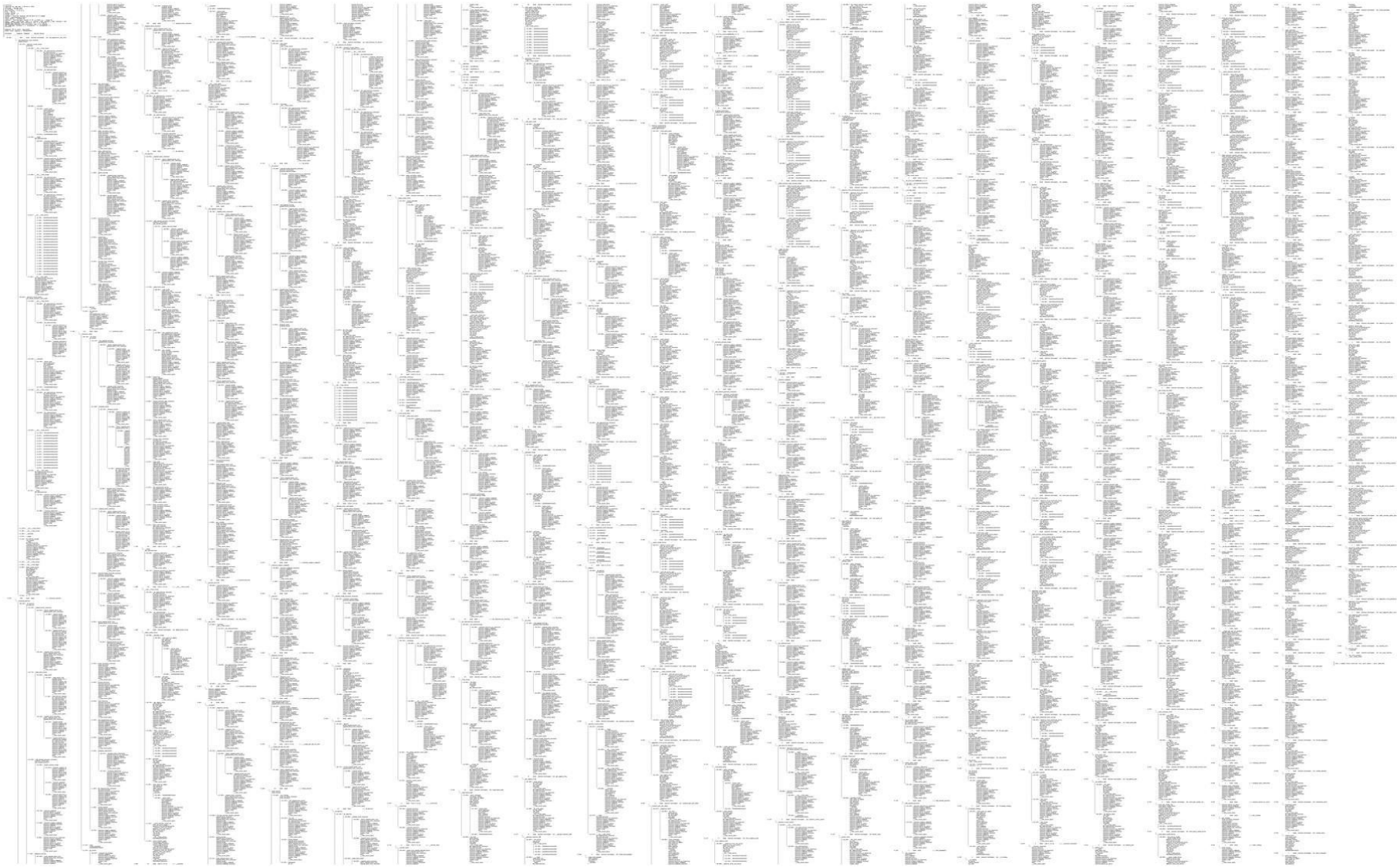
Linux perf_events

- Standard Linux profiler
  - Provides the `perf` command (multi-tool)
  - Usually pkg added by linux-tools-common, etc.
- Many event sources:
  - Timer-based sampling
  - Hardware events
  - Tracepoints
  - Dynamic tracing
- Can sample stacks of (almost) everything on CPU
  - Can miss hard interrupt ISRs, but these should be near-zero. They can be measured if needed (I wrote my own tools)

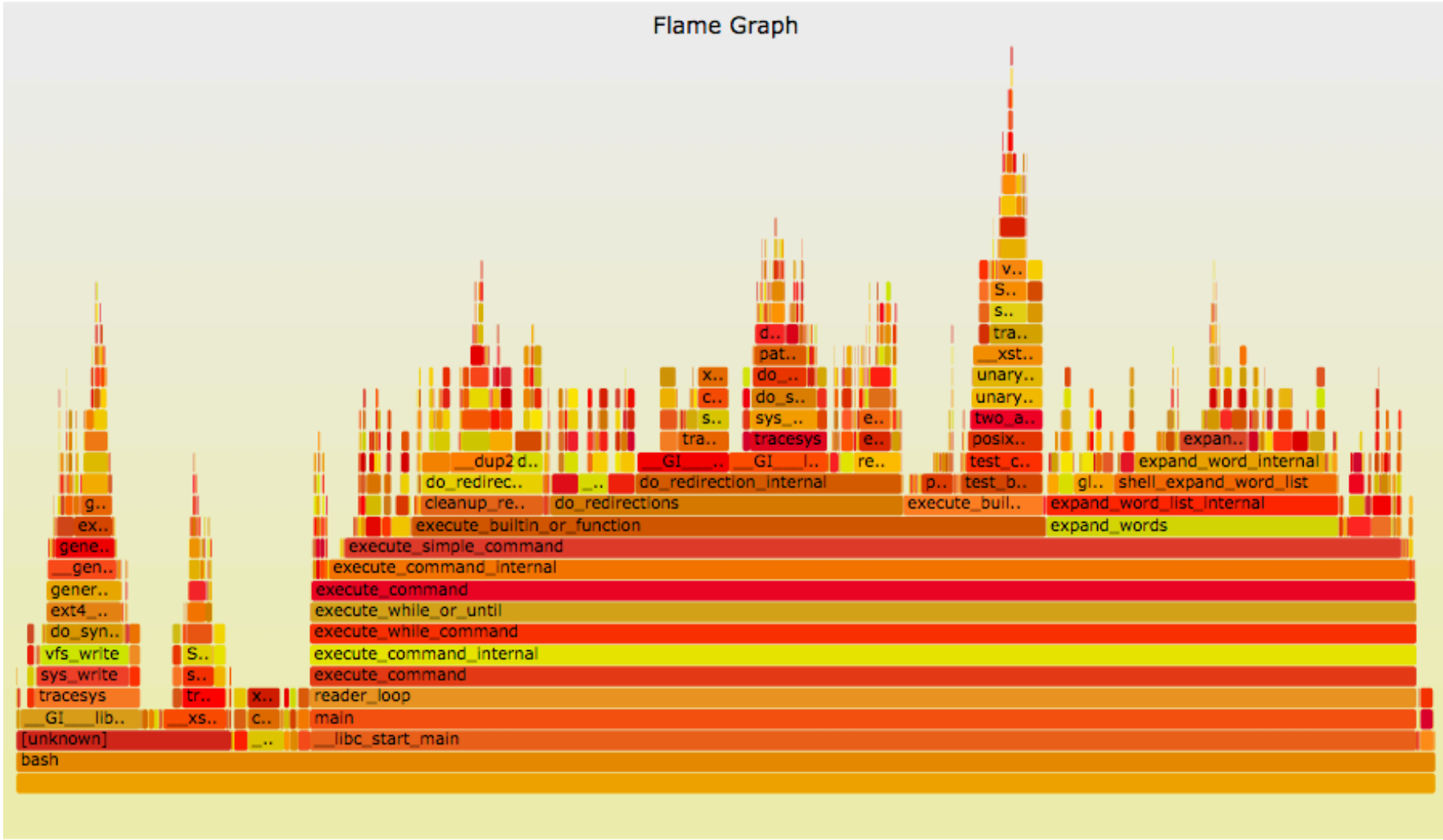
`perf` Profiling

```
# 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
[…]
# Overhead       Samples  Command      Shared Object                          Symbol
# ........  ............  .......  .................  ..............................
#
    20.42%           605     bash  [kernel.kallsyms]  [k] xen_hypercall_xen_version
                |
                --- xen_hypercall_xen_version
                    check_events
                   |
                   |--44.13%-- syscall_trace_enter
                   |           tracesys
                   |           |
                   |           |--35.58%-- __GI___libc_fcntl
                   |           |           |
                   |           |           |--65.26%-- do_redirection_internal
                   |           |           |           do_redirections
                   |           |           |           execute_builtin_or_function
                   |           |           |           execute_simple_command
[… ~13,000 lines truncated …]
```

Full perf report Output

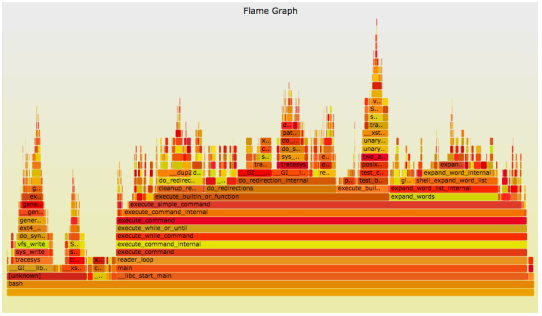


… as a Flame Graph

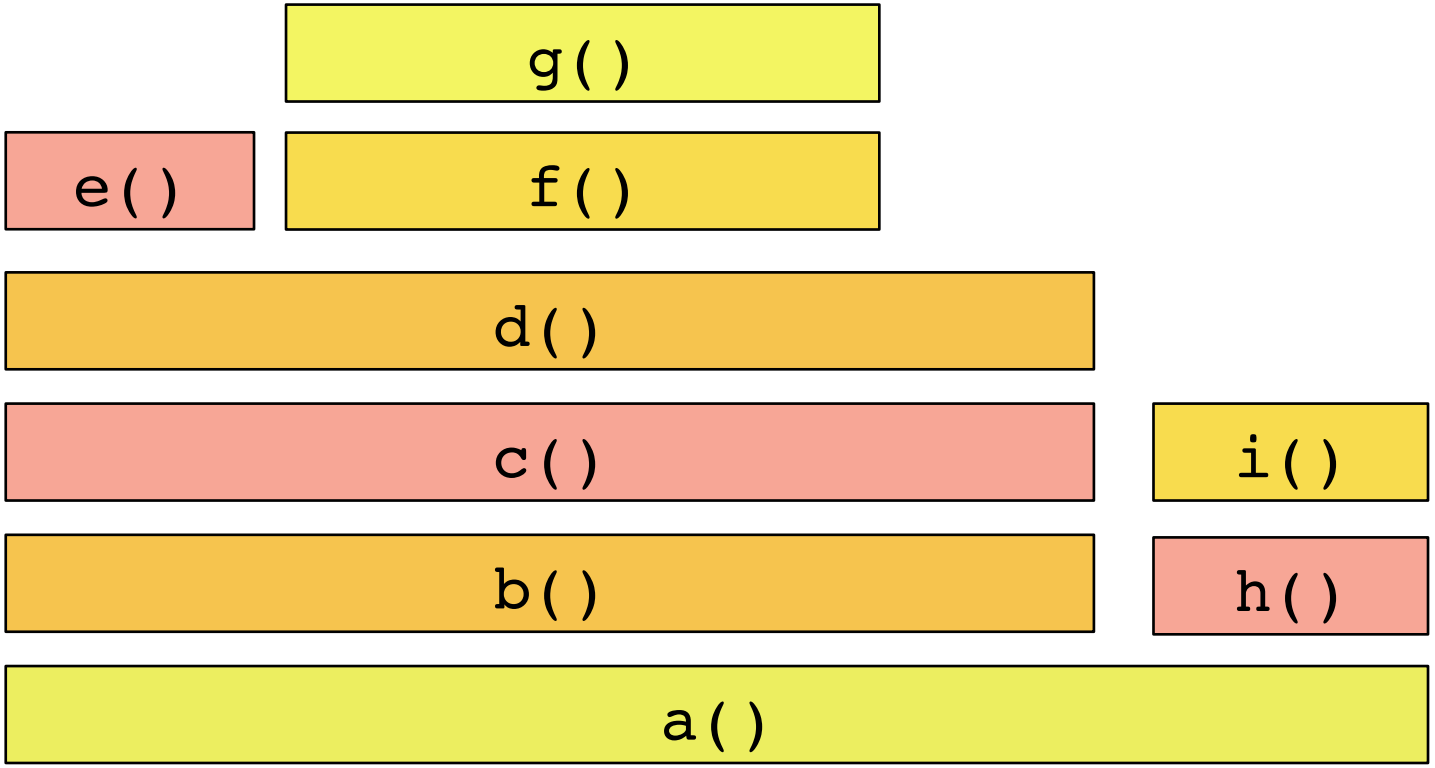


Flame Graphs

- Flame Graphs:
  - **x-axis**: alphabetical stack sort, to maximize merging
  - **y-axis**: stack depth
  - **color**: random (default), or a dimension
- Currently made from Perl + SVG + JavaScript
  - Multiple d3 versions are being developed
- References:
  - http://www.brendangregg.com/FlameGraphs/cpuflamegraphs.html
  - http://queue.acm.org/detail.cfm?id=2927301
  - "The Flame Graph" CACM, June 2016
- Easy to make
  - Converters for many profilers

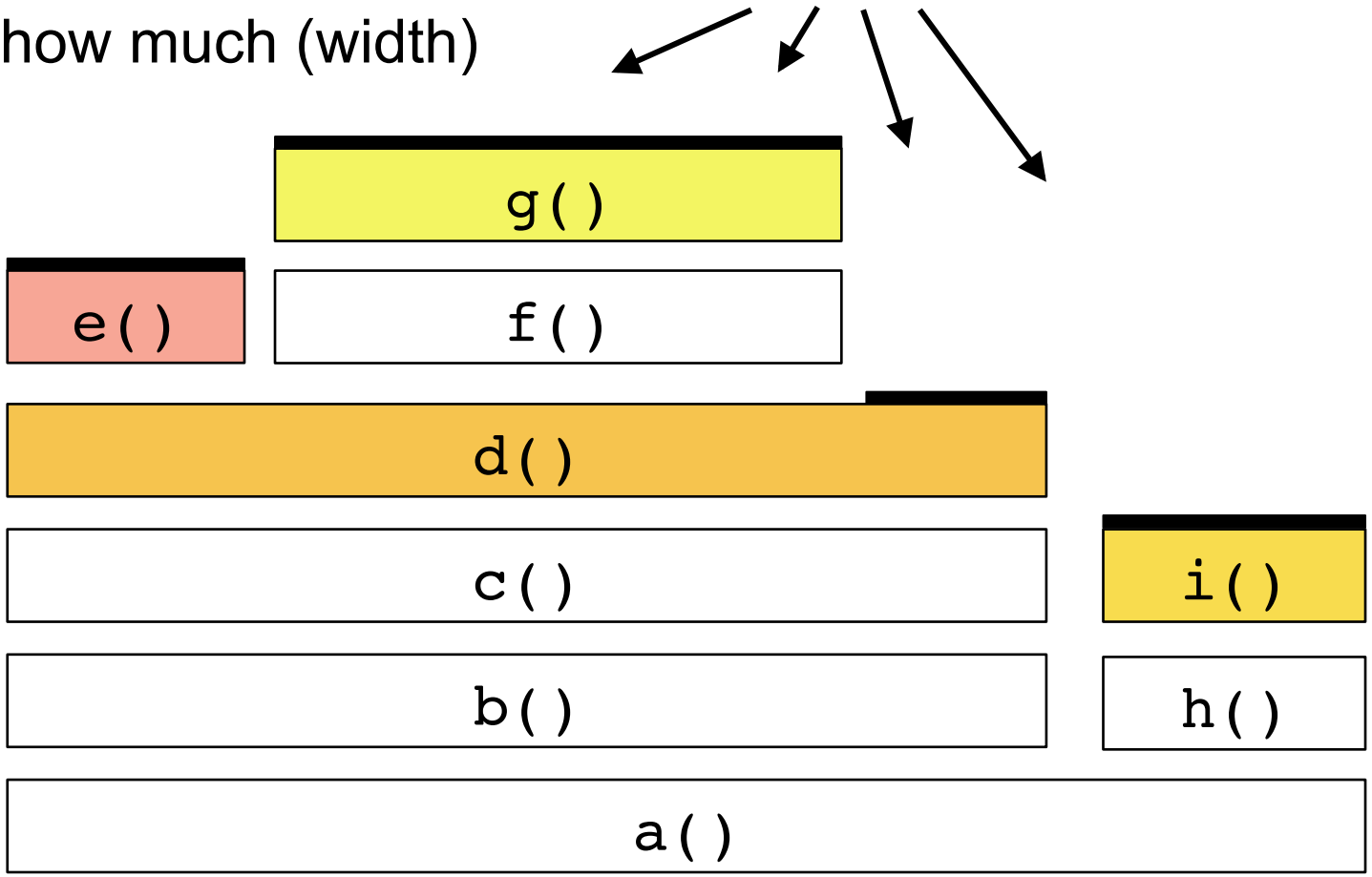


Flame Graph Interpretation



Flame Graph Interpretation (1/3)

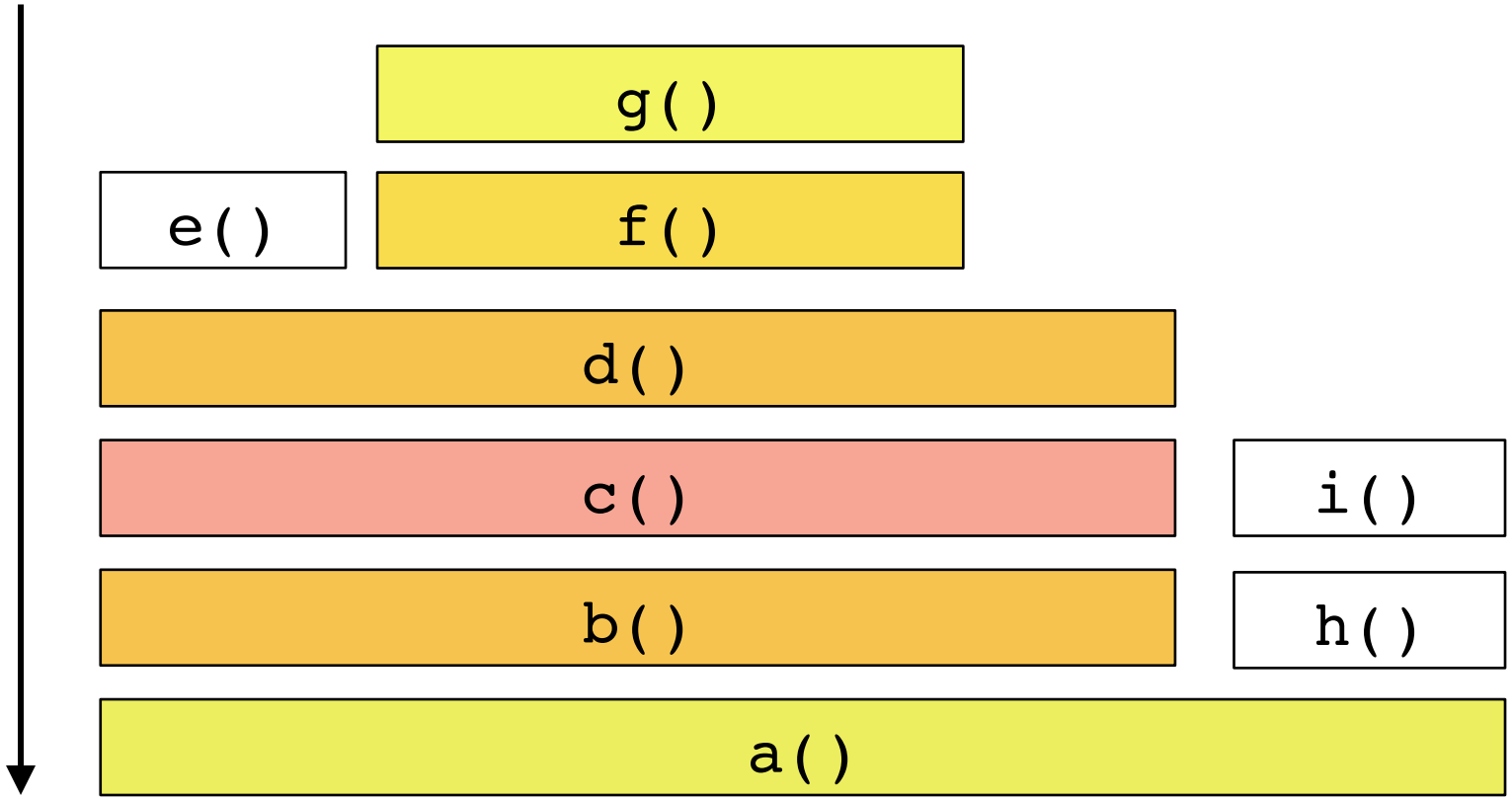
Top edge shows who is running on-CPU,
and how much (width)



Flame Graph Interpretation (2/3)

Top-down shows ancestry

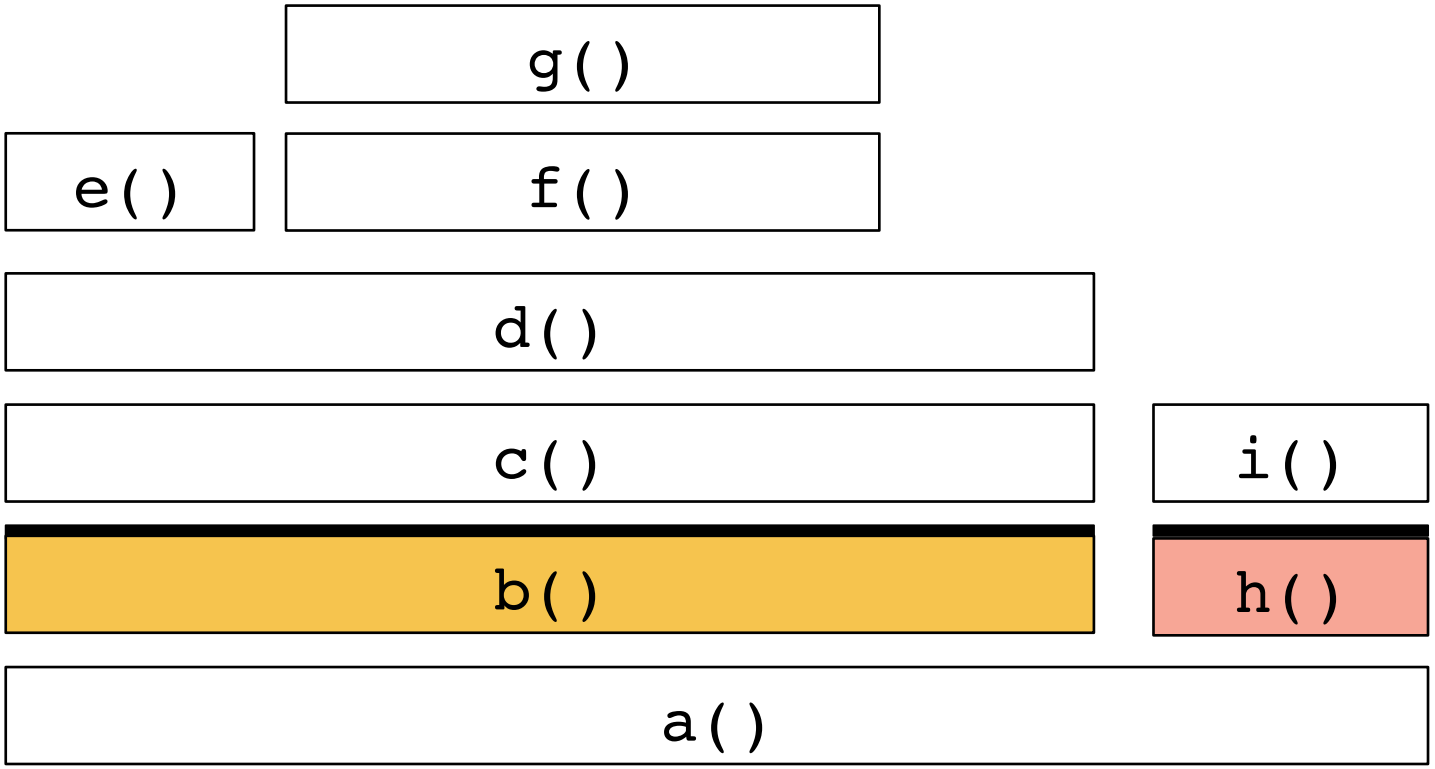
e.g., from g():



Flame Graph Interpretation (3/3)

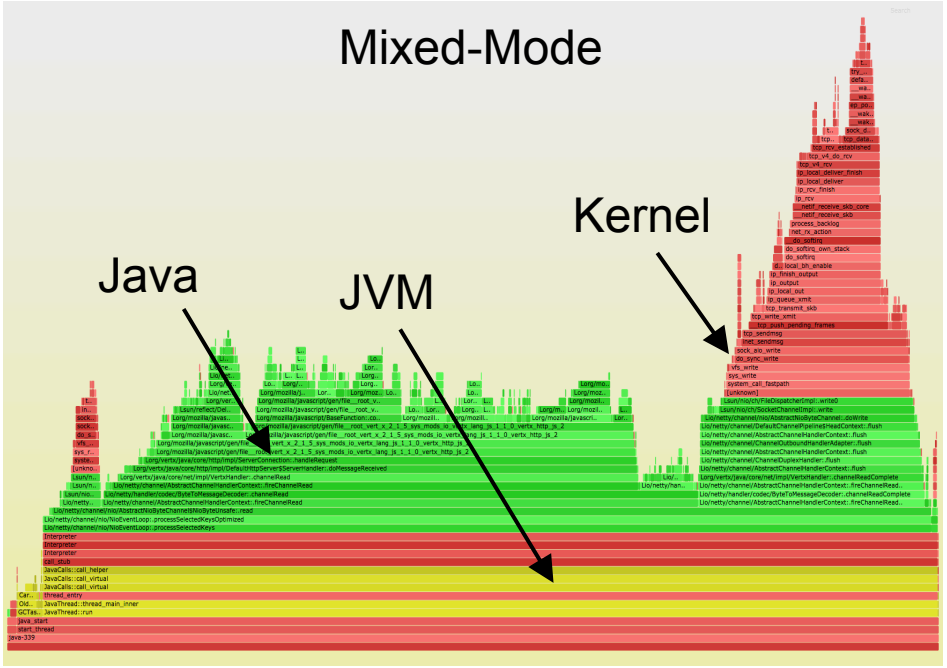
Widths are proportional to presence in samples

e.g., comparing b() to h() (incl. children)



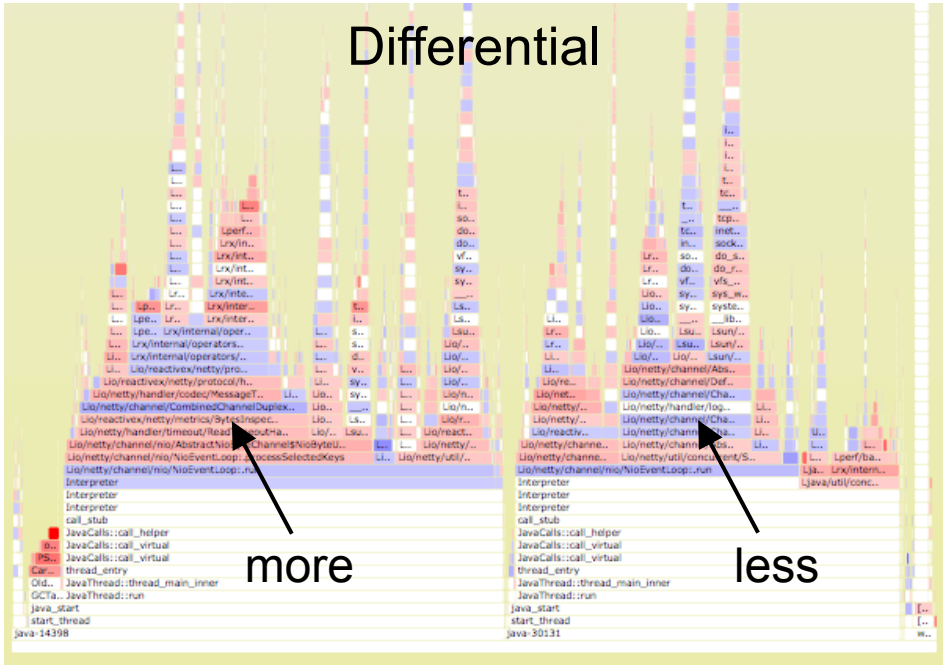
Mixed-Mode Flame Graphs

- Hues:
  - green == Java
  - aqua == Java (inlined)
    - if included
  - red == system
  - yellow == C++
- Intensity:
  - Randomized to differentiate frames
  - Or hashed on function name



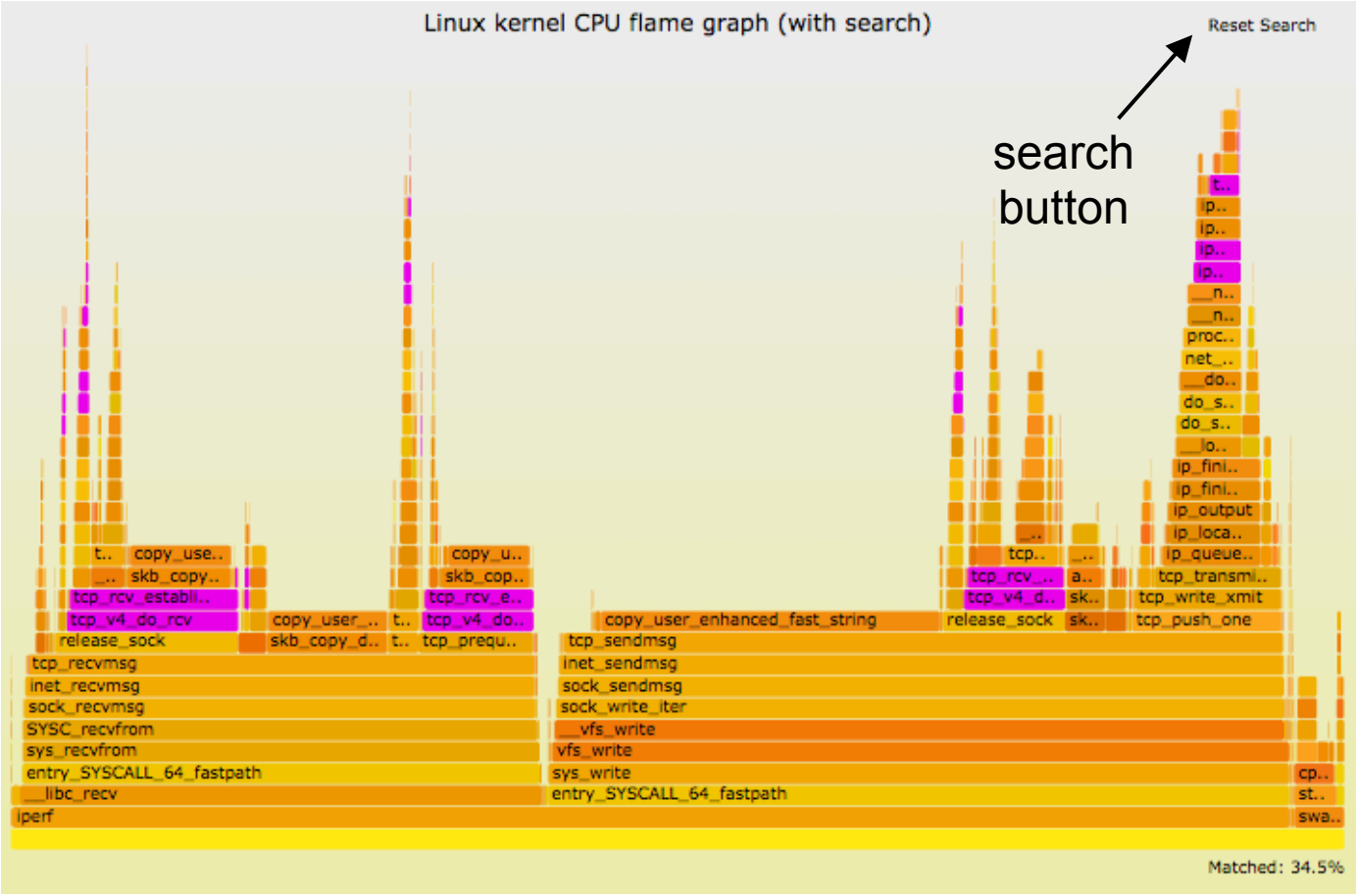
Differential Flame Graphs

- Hues:
  - red == more samples
  - blue == less samples
- Intensity:
  - Degree of difference
- Compares two profiles
- Can show other metrics: e.g., CPI
- Other types exist
  - flamegraphdiff



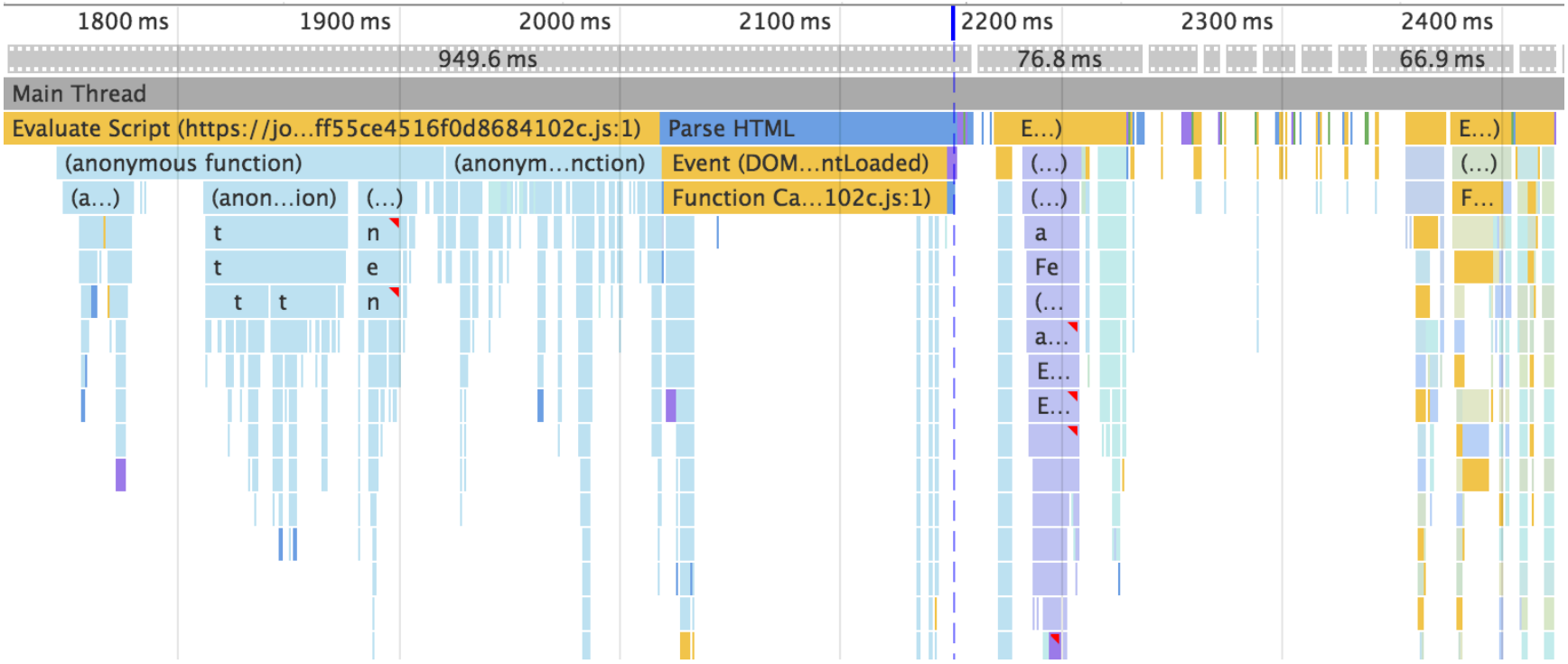
Flame Graph Search

- Color: magenta to show matched frames



Flame Charts

- Final note: these are useful, but are not flame *graphs*



- Flame **charts**: x-axis is time
- Flame **graphs**: x-axis is population (maximize merging)

Stack Tracing

Broken Java Stacks on x86

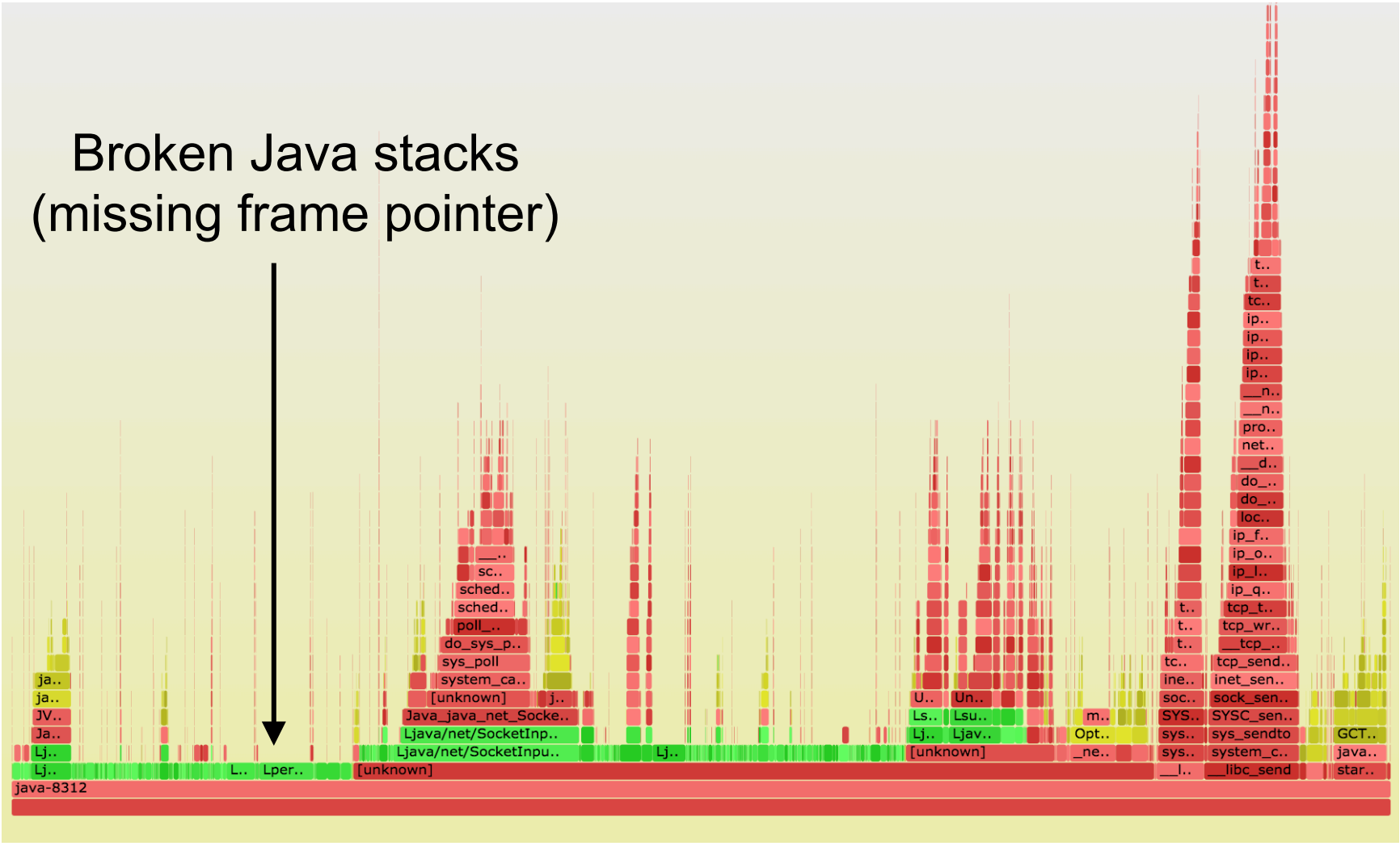
- These stacks are 1 or 2 levels deep, with junk values
- On x86 (x86_64), hotspot uses the frame pointer register (RBP) as general purpose

```
# perf record –F 99 –a –g – sleep 30
# perf script
[…]
java  4579 cpu-clock:
     7f417908c10b [unknown] (/tmp/perf-4458.map)

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

- This "compiler optimization" breaks (RBP-based) stack walking
- *Once upon a time*, x86 had fewer registers, and this made more sense
- gcc provides **`-fno-omit-frame-pointer`** to avoid doing this, but the JVM had no such option…

… as a Flame Graph



Fixing Stack Walking

Possibilities:

A. Fix frame pointer-based stack walking (the default)
   - Pros: simple, supported by many tools
   - Cons: might cost a little extra CPU

B. Use a custom walker (likely needing kernel support)
   - Pros: full stack walking (incl. inlining) & arguments
   - Cons: custom kernel code, can cost more CPU when in use

C. Try libunwind and DWARF
   - Even feasible with JIT?

Our current preference is (A)

-XX:+PreserveFramePointer

- I hacked OpenJDK x86_64 to support frame pointers
  - Taking RBP out of register pools, and adding function prologues. It worked, I shared the patch.
  - It became **JDK-8068945** for JDK 9 and **JDK-8072465** for JDK 8
- Zoltán Majó (Oracle) rewrote it, and it is now:
  - -XX:+PreserveFramePointer in **JDK 9** and **JDK 8** u60b19
  - Thanks to Zoltán, Oracle, and the other hotspot engineers for helping get this done!
- It might cost 0 – 3% CPU, depending on workload

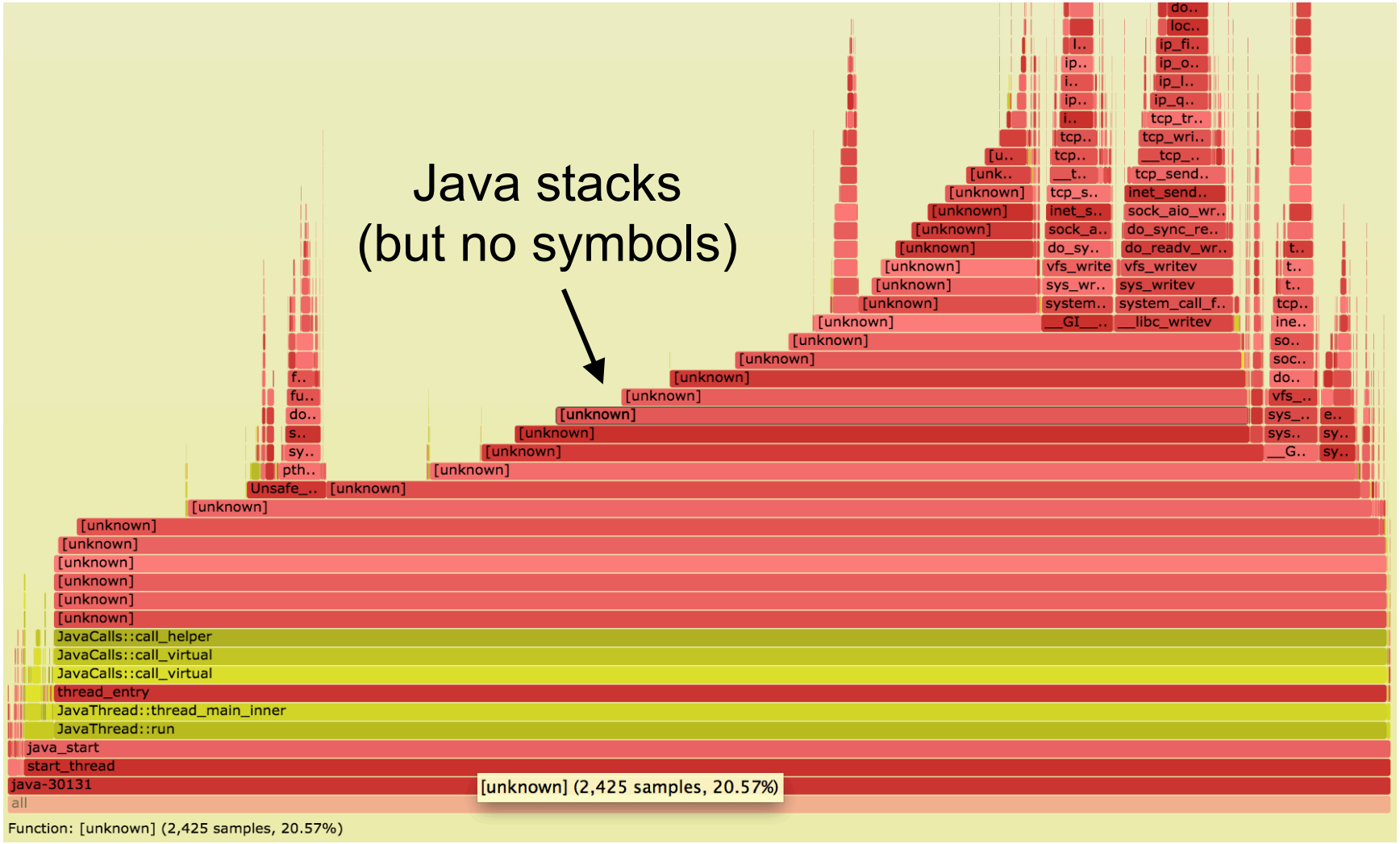
Fixed Java Stacks

```
# perf script
[…]
java  4579 cpu-clock:
        7f417908c10b [unknown] (/tmp/…

java  4579 cpu-clock:
        7f41792fc65f [unknown] (/tmp/…
    a2d53351ff7da603 [unknown] ([unkn…
[…]
```

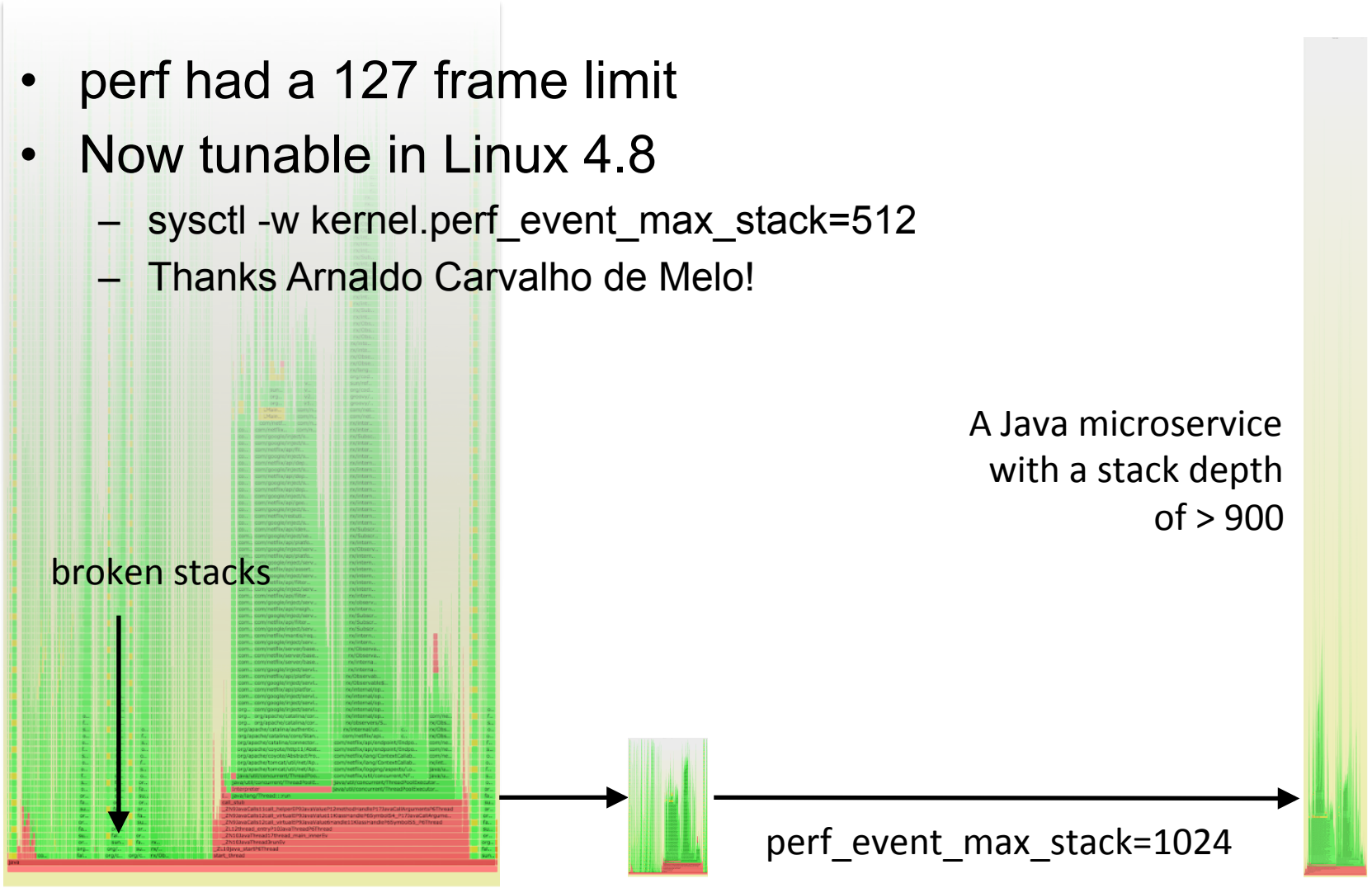
```
# perf script
[…]
java 8131 cpu-clock:
        7fff76f2dce1 [unknown] ([vdso])
        7fd3173f7a93 os::javaTimeMillis() (/usr/lib/jvm…
        7fd301861e46 [unknown] (/tmp/perf-8131.map)
        7fd30184def8 [unknown] (/tmp/perf-8131.map)
        7fd30174f544 [unknown] (/tmp/perf-8131.map)
        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…
```

Fixed Stacks Flame Graph



Stack Depth

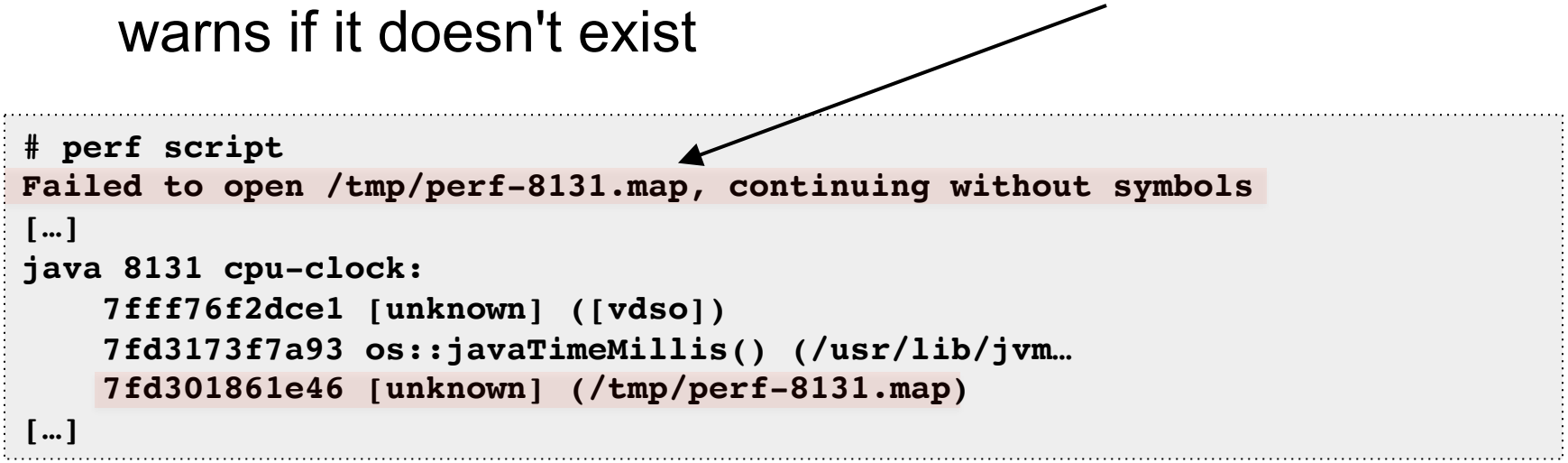
- perf had a 127 frame limit
- Now tunable in Linux 4.8
  - sysctl -w kernel.perf_event_max_stack=512
  - Thanks Arnaldo Carvalho de Melo!



Symbols

Fixing Symbols

- For JIT'd code, Linux perf already looks for an externally provided symbol file: /tmp/perf-PID.map, and warns if it doesn't exist

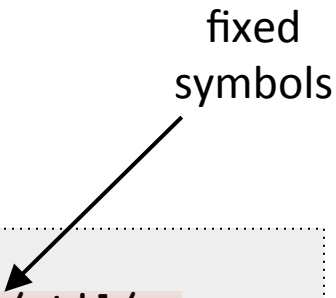


```
# perf script
Failed to open /tmp/perf-8131.map, continuing without symbols
[…]
java 8131 cpu-clock:
    7fff76f2dce1 [unknown] ([vdso])
    7fd3173f7a93 os::javaTimeMillis() (/usr/lib/jvm…
    7fd301861e46 [unknown] (/tmp/perf-8131.map)
[…]
```

- This file can be created by a Java agent

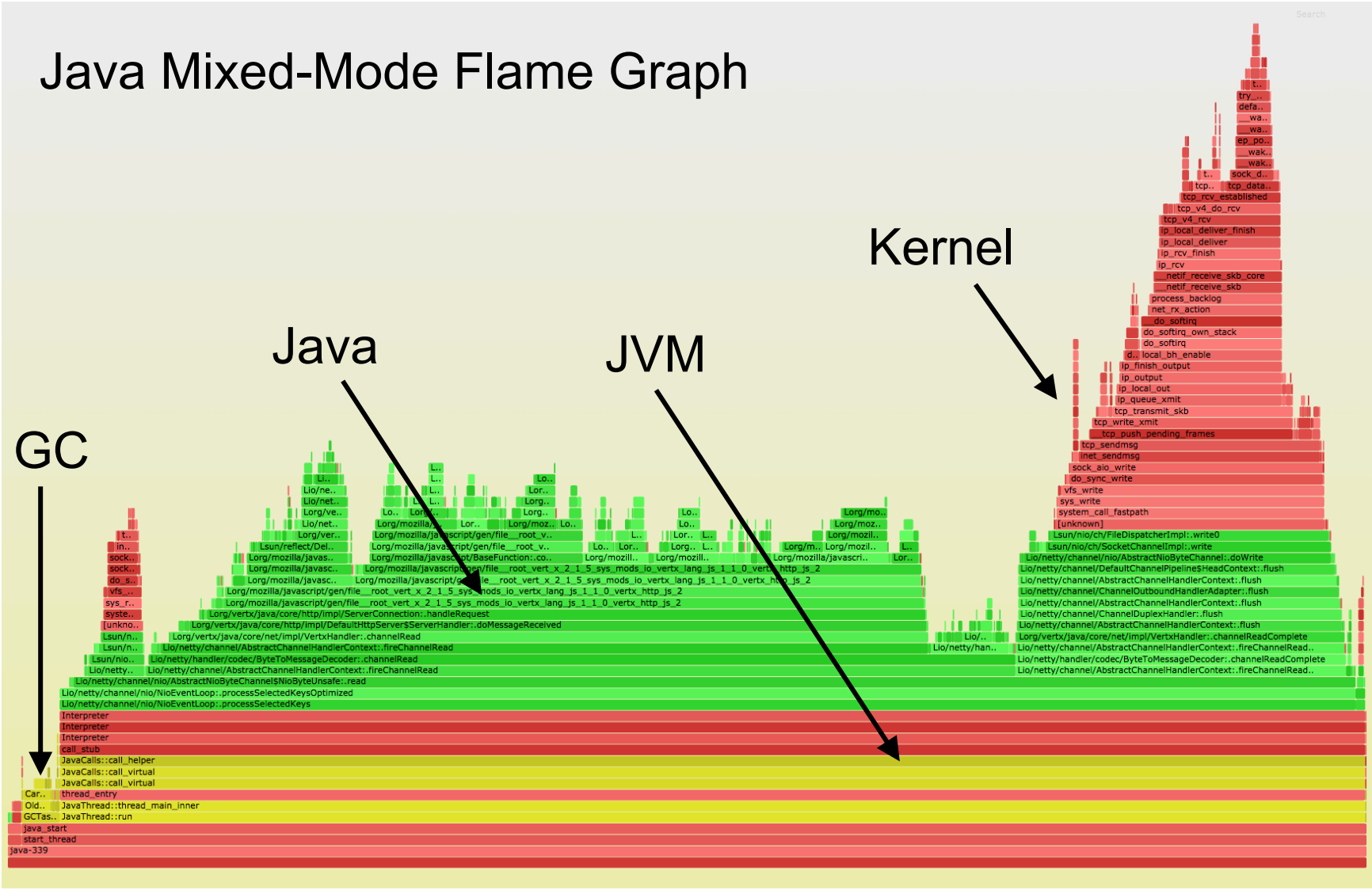
Java Symbols for perf

- perf-map-agent
  - https://github.com/jrudolph/perf-map-agent
  - Agent attaches and writes the /tmp file on demand (previous versions attached on Java start, wrote continually)
  - Thanks Johannes Rudolph!
- Use of a /tmp symbol file
  - Pros: simple, can be low overhead (snapshot on demand)
  - Cons: stale symbols
- Using a symbol logger with perf instead
  - Stephane Eranian contributed this to perf
  - See lkml for "perf: add support for profiling jitted code"

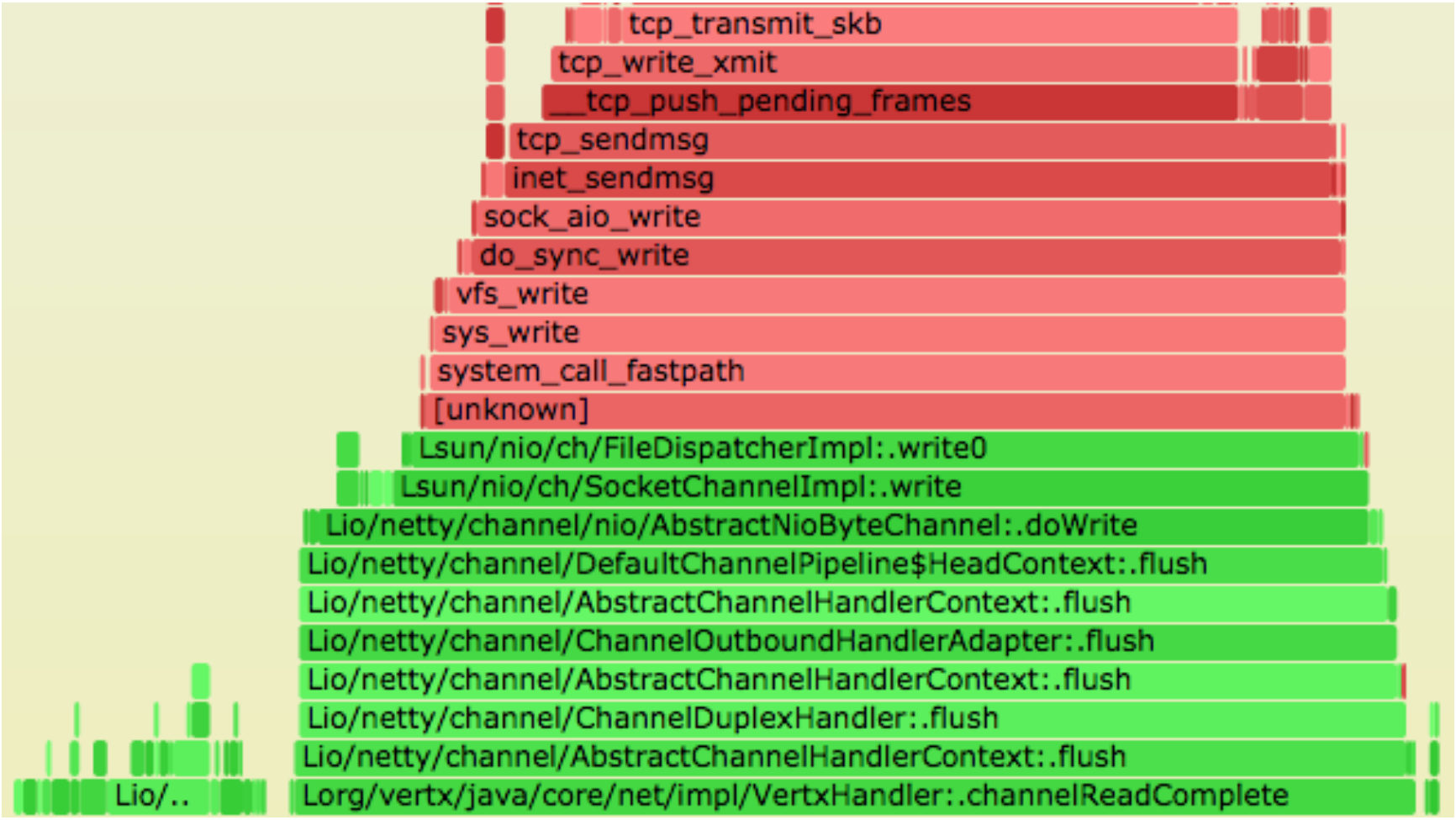



```
# perf script
 java 14025 [017]  8048.157085: cpu-clock:  7fd781253265 Ljava/util/
HashMap;::get (/tmp/perf-12149.map)
[…]
```

Stacks & Symbols

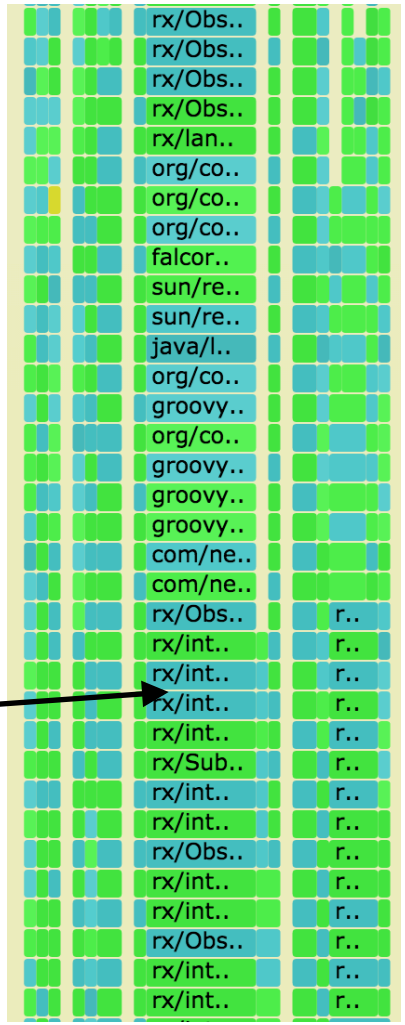


Stacks & Symbols (zoom)



Inlining

- Many frames may be missing (inlined)
  - Flame graph may still make enough sense
- Inlining can be tuned
  - -XX:-Inline to disable, but can be 80% slower!
  - -XX:MaxInlineSize and -XX:InlineSmallCode can be tuned a little to reveal more frames
    - Can even improve performance!
- perf-map-agent can un-inline (unfoldall)
  - Adds inlined frames to symbol dump
  - flamegraph.pl --color=java will color these aqua
  - Thanks Johannes Rudolph, T Jake Luciani, and Nitsan Wakart



Instructions

Instructions

1. Check Java version
2. Install perf-map-agent
3. Set -XX:+PreserveFramePointer
4. Profile Java
5. Dump symbols
6. Generate Mixed-Mode Flame Graph

Note these are unsupported: use at your own risk

Reference: http://techblog.netflix.com/2015/07/java-in-flames.html

1. Check Java Version

- Need JDK8u60 or better
  - for -XX:+PreserveFramePointer

```
$ java -version
java version "1.8.0_60"
Java(TM) SE Runtime Environment (build 1.8.0_60-b27)
Java HotSpot(TM) 64-Bit Server VM (build 25.60-b23, mixed mode)
```

- Upgrade Java if necessary

2. Install perf-map-agent

- Check https://github.com/jrudolph/perf-map-agent for the latest instructions. e.g.:

```
$ sudo bash
# apt-get install -y cmake
# export JAVA_HOME=/usr/lib/jvm/java-8-oracle
# cd /usr/lib/jvm
# git clone --depth=1 https://github.com/jrudolph/perf-map-agent
# cd perf-map-agent
# cmake .
# make
```

3. Set -XX:+PreserveFramePointer

- Needs to be set on Java startup
- Check it is enabled (on Linux):

```
$ ps wwp `pgrep –n java` | grep PreserveFramePointer
```

or

```
$ jcmd `pgrep –n java` VM.flags | grep PreserveFramePointer
```

- Measure overhead (should be small)

4. Profile Java

- Using Linux perf_events to profile all processes, at 99 Hertz, for 30 seconds (as root):

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

- Just profile one PID (broken on some older kernels):

```
# perf record -F 99 -p PID -g -- sleep 30
```

- These create a perf.data file

5. Dump Symbols

- See perf-map-agent docs for updated usage
- e.g., as the same user as java:

```
$ cd /usr/lib/jvm/perf-map-agent/out
$ java -cp attach-main.jar:$JAVA_HOME/lib/tools.jar \
    net.virtualvoid.perf.AttachOnce PID
```

- perf-map-agent contains helper scripts. I wrote my own:
  - https://github.com/brendangregg/Misc/blob/master/java/jmaps
- Dump symbols quickly after perf record to minimize stale symbols. How I do it:

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

6. Generate a Mixed-Mode Flame Graph

- Using my FlameGraph software:

```
# perf script > out.stacks01
# git clone --depth=1 https://github.com/brendangregg/FlameGraph
# cat out.stacks01 | ./FlameGraph/stackcollapse-perf.pl | \
    ./FlameGraph/flamegraph.pl --color=java --hash > flame01.svg
```

  - perf script reads perf.data with /tmp/*.map
  - out.stacks01 is an intermediate file; can be handy to keep
- Finally open flame01.svg in a browser
- Check for newer flame graph implementations (e.g., d3)

Optimizations

- Linux 2.6+, via perf.data and perf script:

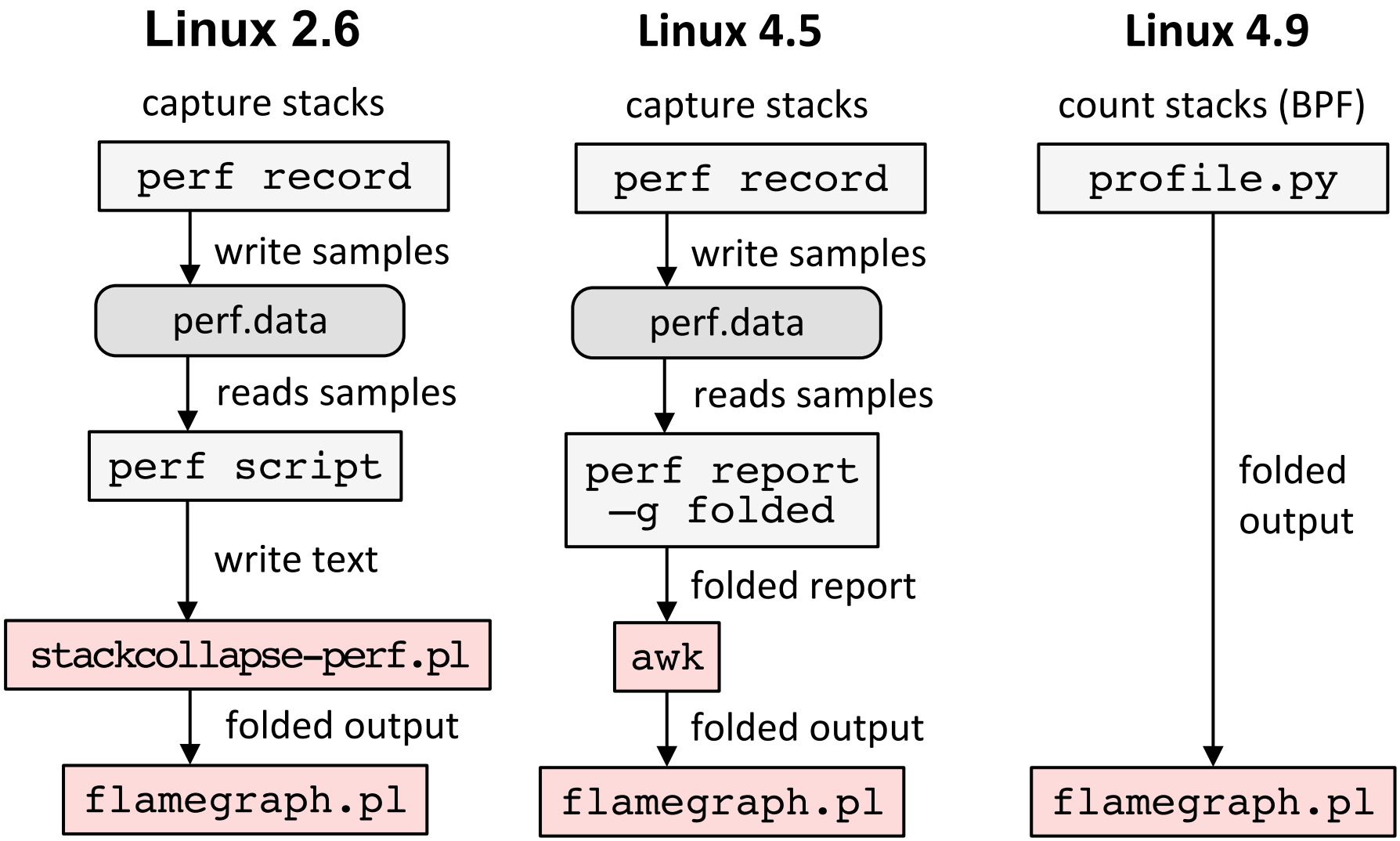
```
git clone --depth 1 https://github.com/brendangregg/FlameGraph
cd FlameGraph
perf record -F 99 -a –g -- sleep 30
perf script | ./stackcollapse-perf.pl |./flamegraph.pl > perf.svg
```

- Linux 4.5+ can use folded output
  - Skips the CPU-costly stackcollapse-perf.pl step; see: http://www.brendangregg.com/blog/2016-04-30/linux-perf-folded.html
- Linux 4.9+, via BPF:

```
git clone --depth 1 https://github.com/brendangregg/FlameGraph
git clone --depth 1 https://github.com/iovisor/bcc
./bcc/tools/profile.py -dF 99 30 | ./FlameGraph/flamegraph.pl > perf.svg
```

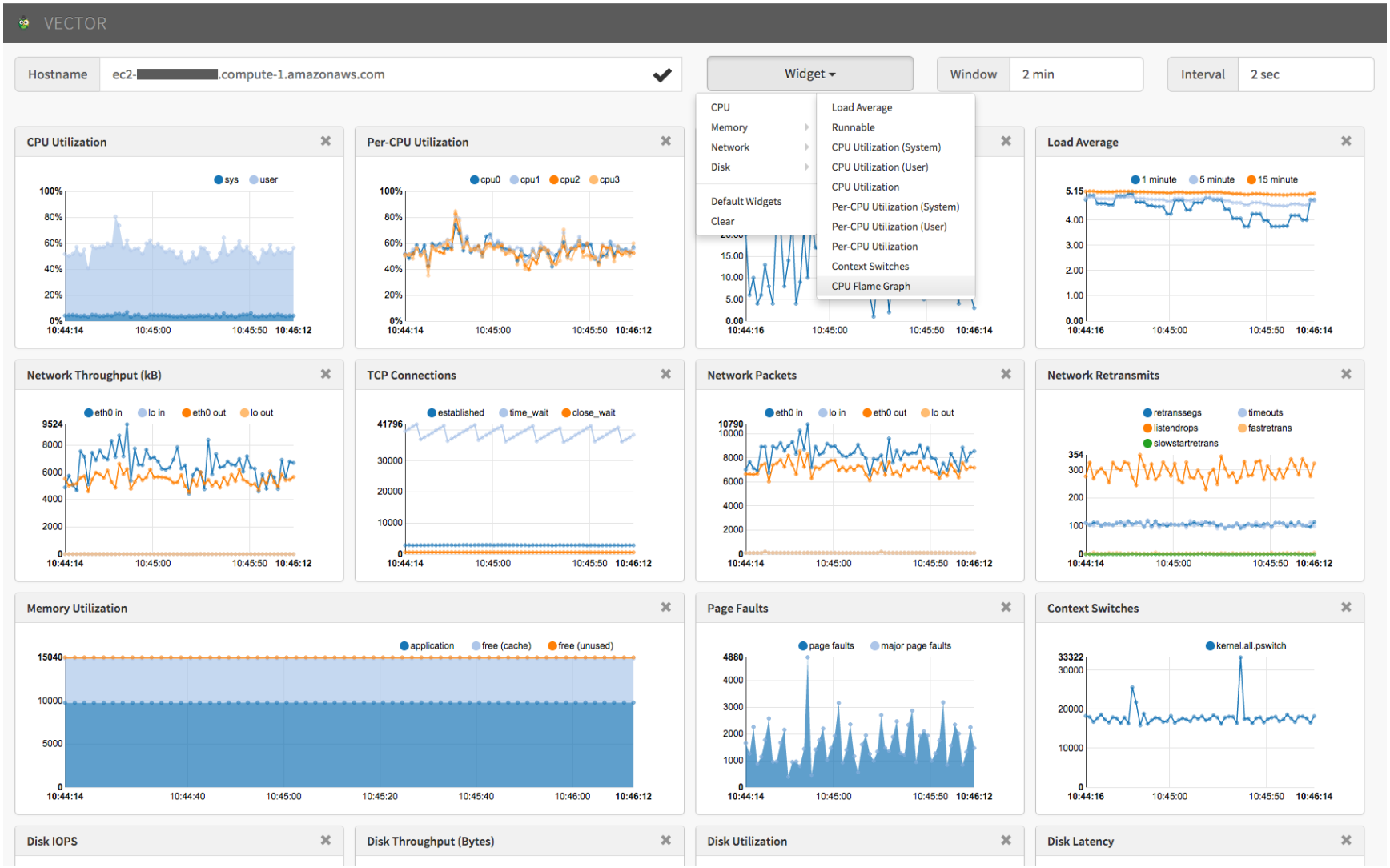
  - Most efficient: no perf.data file, summarizes in-kernel

Linux Profiling Optimizations

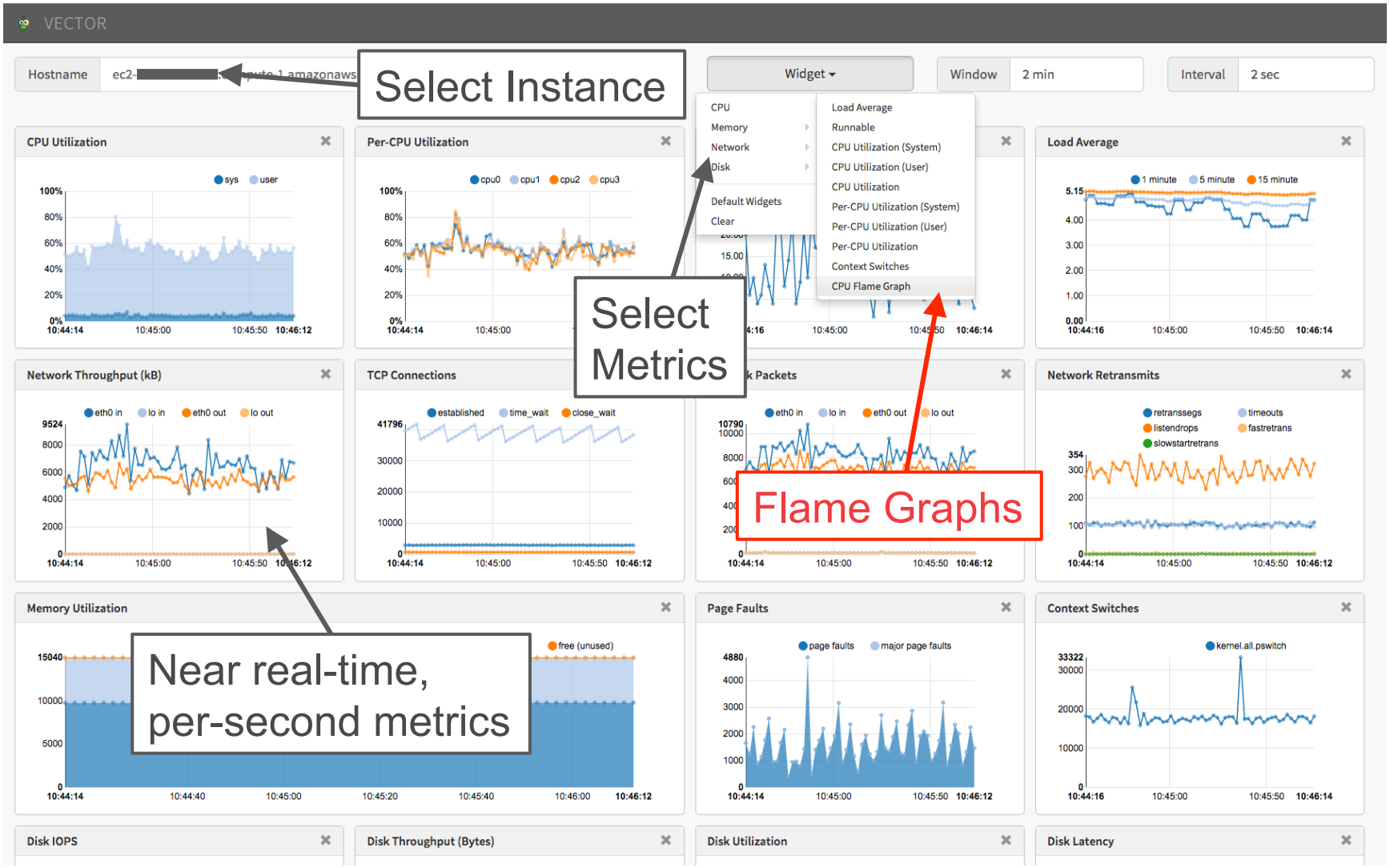


Automation

Netflix Vector



Netflix Vector



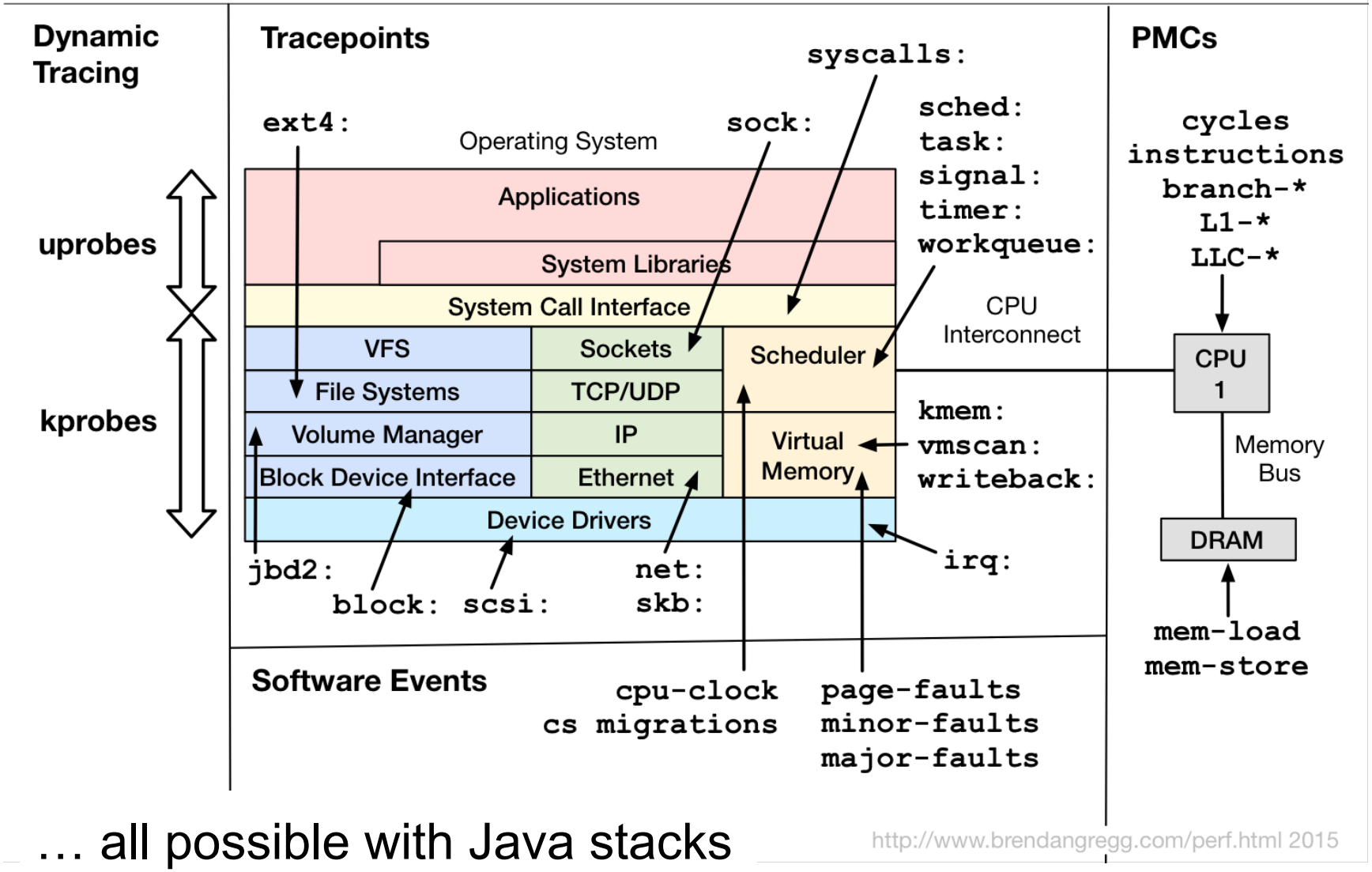
Netflix Vector

- Open source, on-demand, instance analysis tool
  - https://github.com/netflix/vector
- Shows various real-time metrics
- Flame graph support currently in development
  - Automating previous steps
  - Using it internally already
  - Also developing a new d3 front end

NETFLIX | OSS Netflix Open Source Software

Advanced Analysis

Linux perf_events Coverage



… all possible with Java stacks

http://www.brendangregg.com/perf.html 2015

Advanced Flame Graphs

- Any event can be flame graphed, provided it is issued in *synchronous* Java context
  - Java thread still on-CPU, and event is directly triggered
  - On-CPU Java context is valid
- Synchronous examples:
  - Disk I/O requests issued directly by Java → yes
    - direct reads, sync writes, page faults
  - Disk I/O completion interrupts → no*
  - Disk I/O requests triggered async, e.g., readahead → no*

    * can be made yes by tracing and associating context

Page Faults

- Show what triggered main memory (resident) to grow:

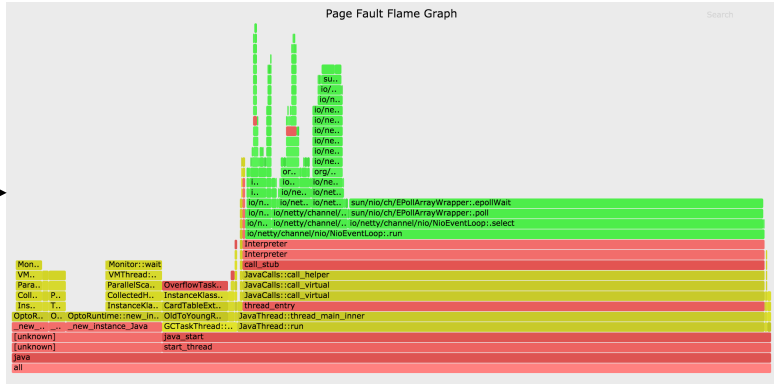
```
# perf record -e page-faults -p PID -g -- sleep 120
```

- "fault" as (physical) main memory is allocated on-demand, when a virtual page is first populated
- Low overhead tool to solve some types of memory leak

RES column in top(1)

```
  VIRT    RES  COMMAND
3972756 376876 java
 344752 231344 ab
      0      0 kworker/1:1
1069716  44032 evolution-calen
      0      0 ksoftirqd/2
```

grows because

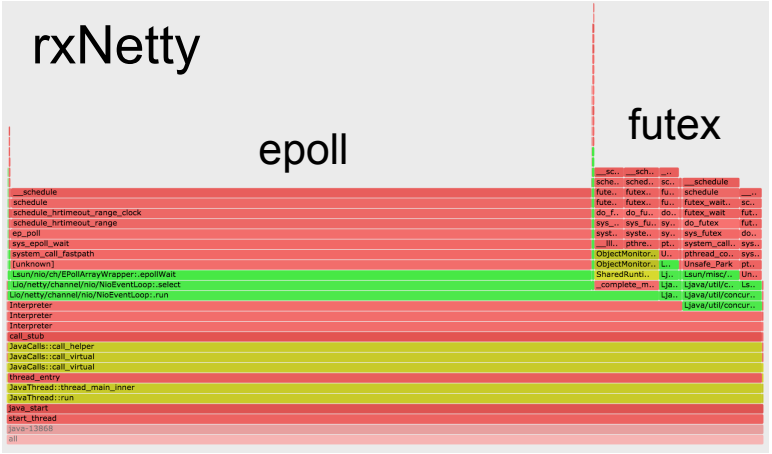


Context Switches

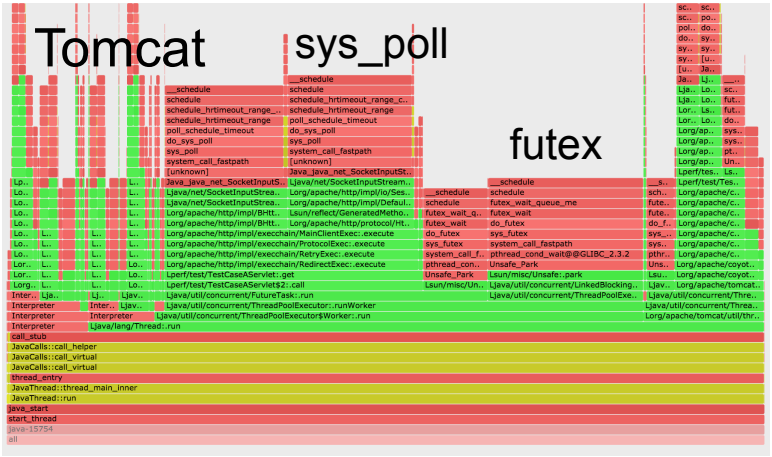
- Show why Java blocked and stopped running on-CPU:

```
# perf record -e context-switches -p PID -g -- sleep 5
```

- Identifies locks, I/O, sleeps
  - If code path shouldn't block and looks random, it's an involuntary context switch. I could filter these, but you should have solved them beforehand (CPU load).
- e.g., was used to understand framework differences:



vs

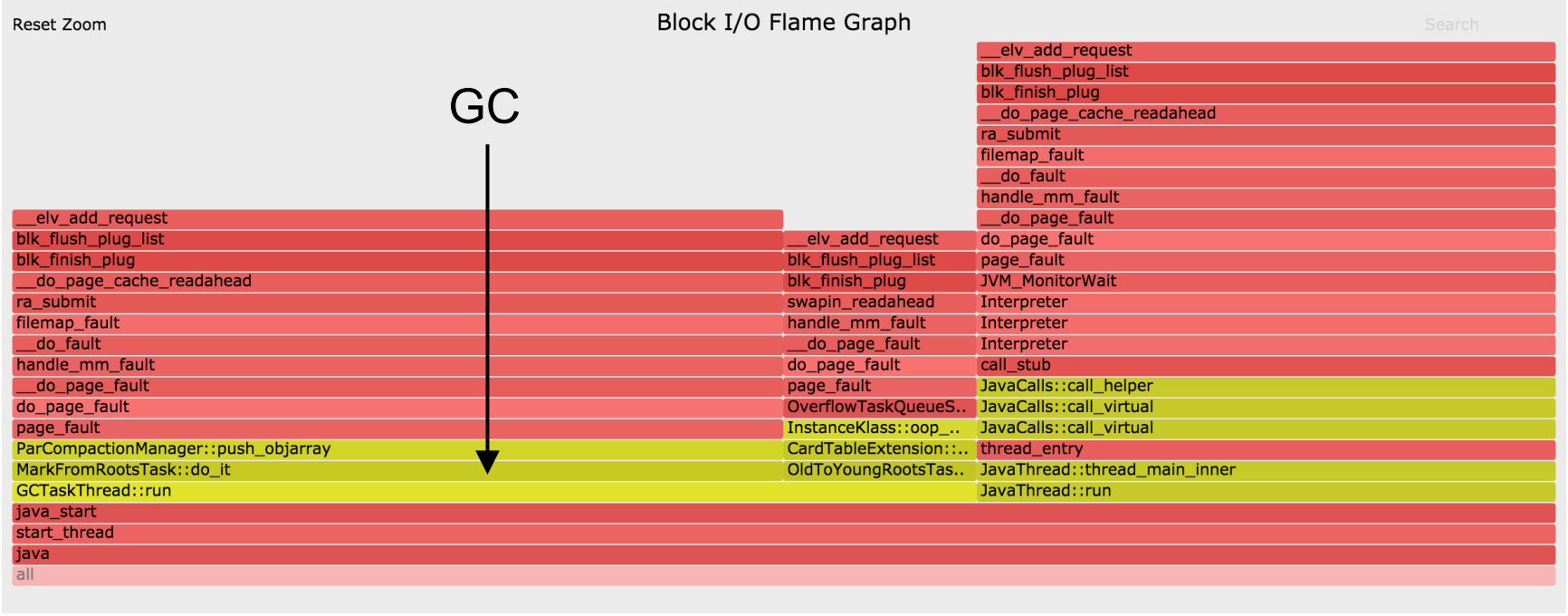


Disk I/O Requests

- Shows who issued disk I/O (sync reads & writes):

```
# perf record -e block:block_rq_insert -a -g -- sleep 60
```

- e.g.: page faults in GC? This JVM has swapped out!:

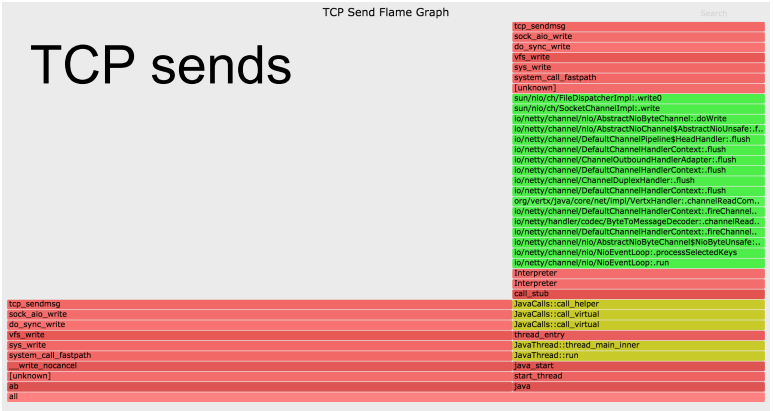


TCP Events

- TCP transmit, using dynamic tracing:

```
# perf probe tcp_sendmsg
# perf record -e probe:tcp_sendmsg -a -g -- sleep 1; jmaps
# perf script -f comm,pid,tid,cpu,time,event,ip,sym,dso,trace > out.stacks
# perf probe --del tcp_sendmsg
```

- Note: can be high overhead for high packet rates
  - For the current perf trace, dump, post-process cycle
- Can also trace TCP connect & accept (lower overhead)
- TCP receive is async
  - Could trace via socket read

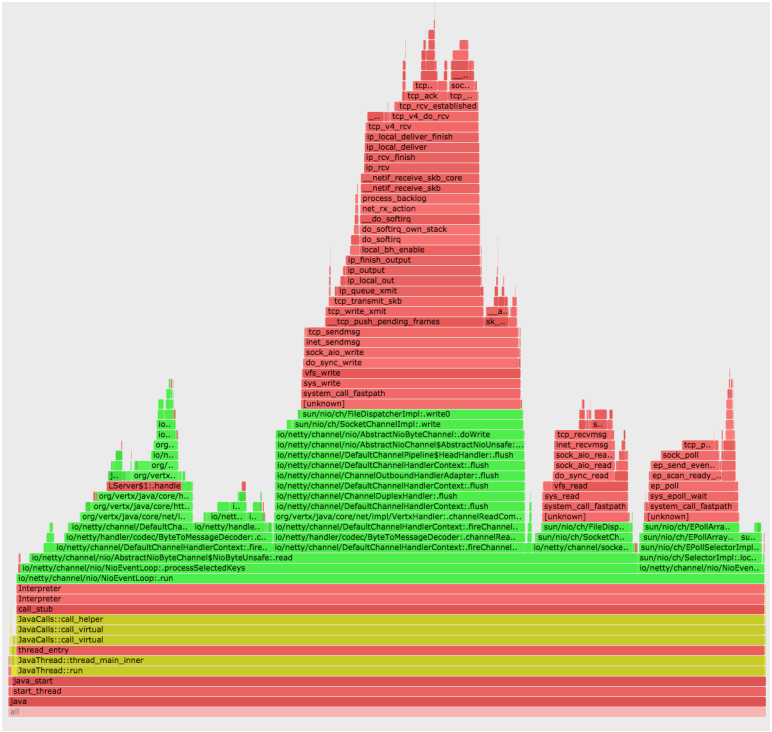


CPU Cache Misses

- In this example, sampling via Last Level Cache loads:

```
# perf record -e LLC-loads -c 10000 -a -g -- sleep 5; jmaps
# perf script -f comm,pid,tid,cpu,time,event,ip,sym,dso > out.stacks
```

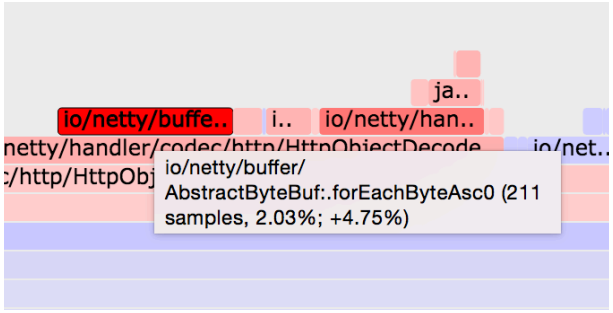
- -c is the count (samples once per count)
- Use other CPU counters to sample hits, misses, stalls

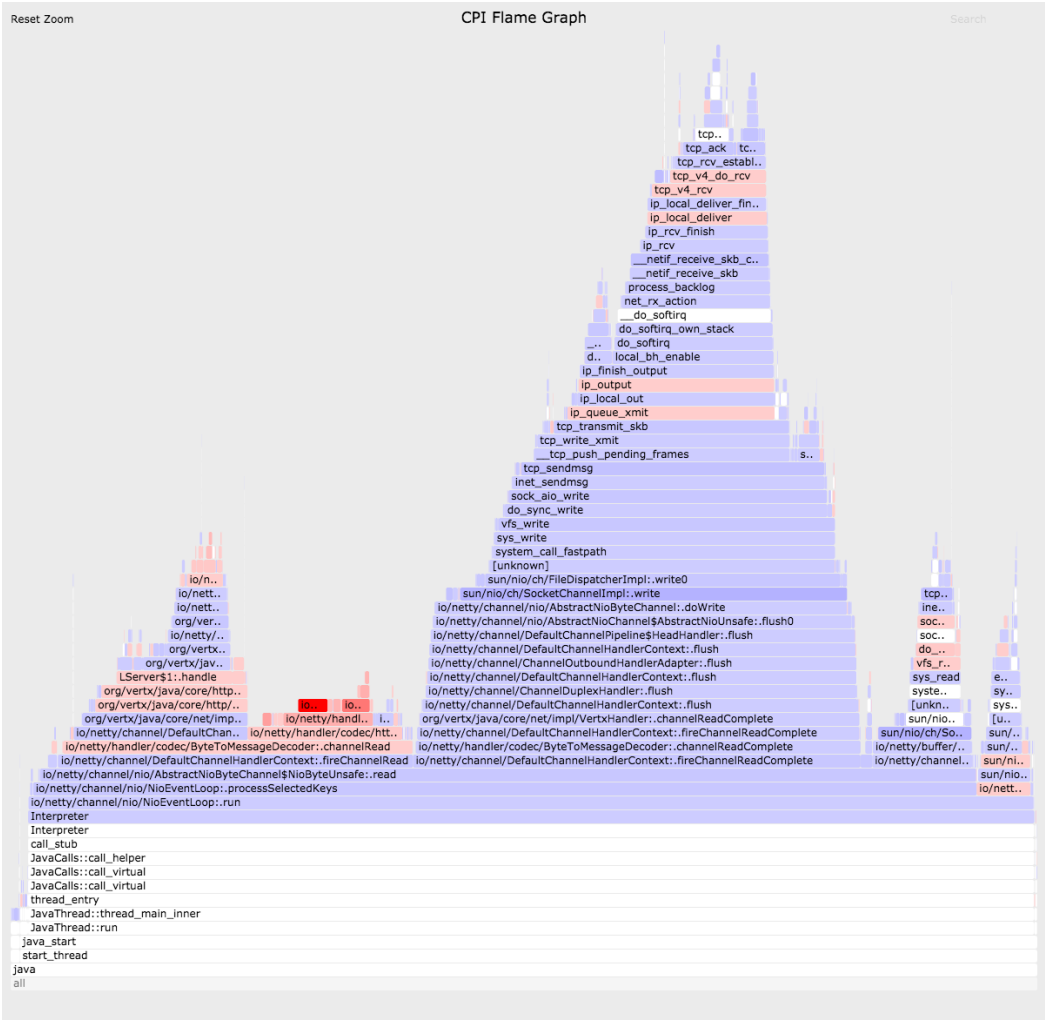


CPI Flame Graph

- Cycles Per Instruction!
  - red == instruction heavy
  - blue == cycle heavy (likely mem stall cycles)

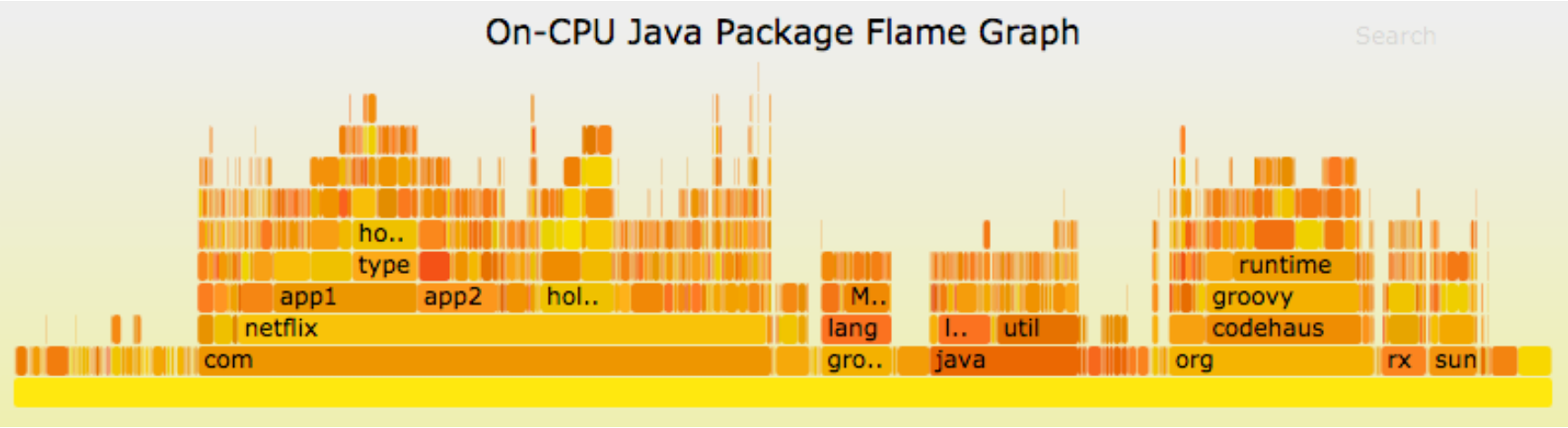
zoomed:





Java Package Flame Graph

- Sample on-CPU instruction pointer only (no stack)
  - Don't need -XX:+PreserveFramePointer
- y-axis: package name hierarchy
  - java / util / ArrayList / ::size



Linux 2.6+ (pre-BPF):

no -g (stacks)

```
# perf record -F 199 -a -- sleep 30; ./jmaps
# perf script | ./pkgsplit-perf.sh | ./flamegraph.pl > out.svg
```

Links & References

- Flame Graphs
  - http://www.brendangregg.com/flamegraphs.html
  - http://www.brendangregg.com/FlameGraphs/cpuflamegraphs.html
  - http://queue.acm.org/detail.cfm?id=2927301
  - "The Flame Graph" CACM, Vol. 56, No. 6 (June 2016)
  - http://techblog.netflix.com/2015/07/java-in-flames.html
  - http://techblog.netflix.com/2016/04/saving-13-million-computational-minutes.html
  - http://techblog.netflix.com/2014/11/nodejs-in-flames.html
  - http://www.brendangregg.com/blog/2014-11-09/differential-flame-graphs.html
- Linux perf_events
  - https://perf.wiki.kernel.org/index.php/Main_Page
  - http://www.brendangregg.com/perf.html
  - http://www.brendangregg.com/blog/2015-02-27/linux-profiling-at-netflix.html
  - Linux 4.5: http://www.brendangregg.com/blog/2016-04-30/linux-perf-folded.html
- Netflix Vector
  - https://github.com/netflix/vector
  - http://techblog.netflix.com/2015/04/introducing-vector-netflixs-on-host.html
- hprof: http://www.brendangregg.com/blog/2014-06-09/java-cpu-sampling-using-hprof.html

Thanks

- Questions?
- http://techblog.netflix.com
- http://slideshare.net/brendangregg
- http://www.brendangregg.com
- bgregg@netflix.com
- @brendangregg