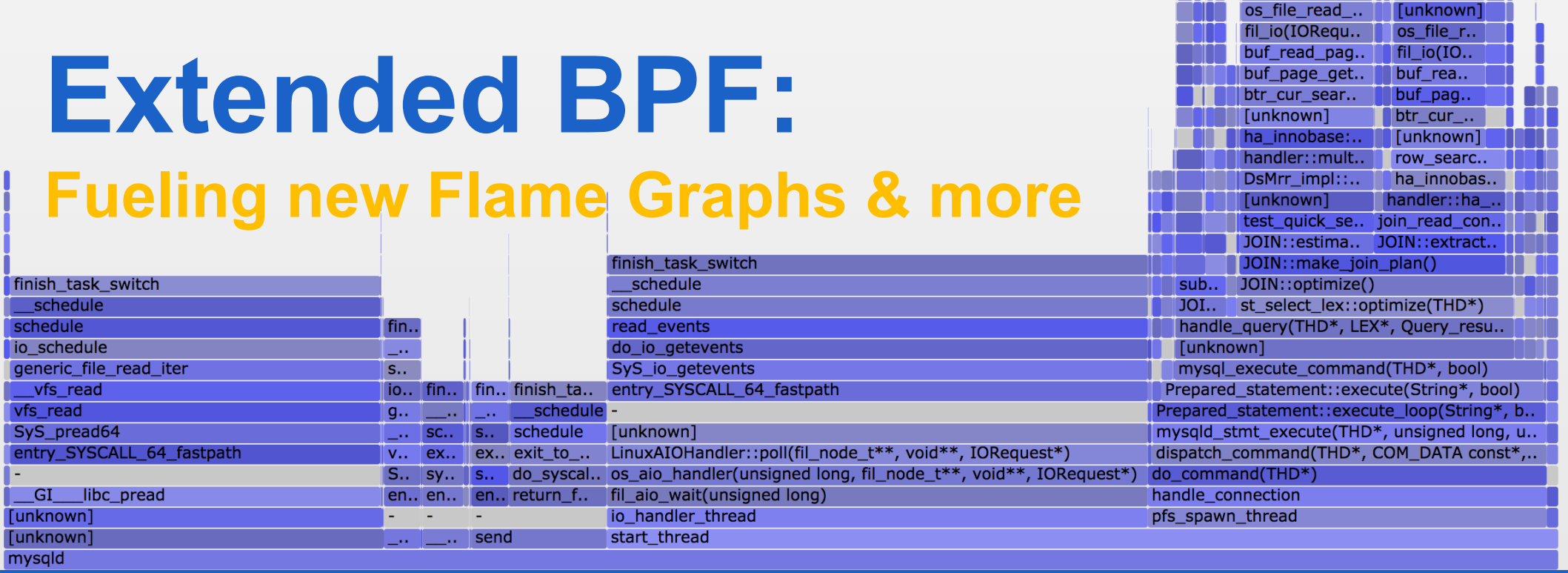
Extended BPF:

Fueling new Flame Graphs & more



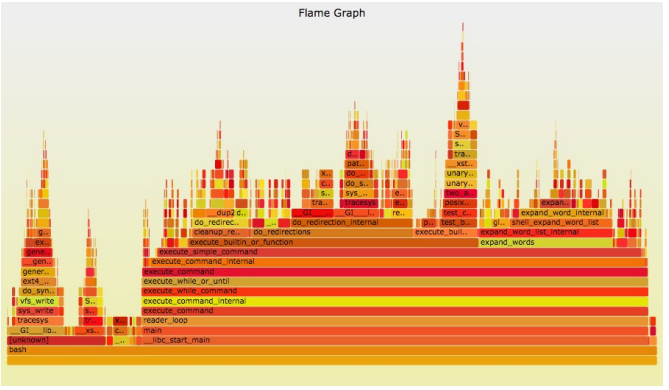
YOW! Perth

IN-PERSON CONFERENCE

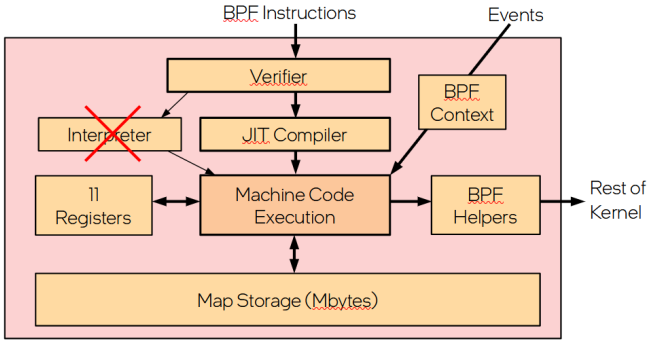
19 — 20 SEP 2022

Brendan Gregg

Agenda



1. CPU flame graphs



2. eBPF

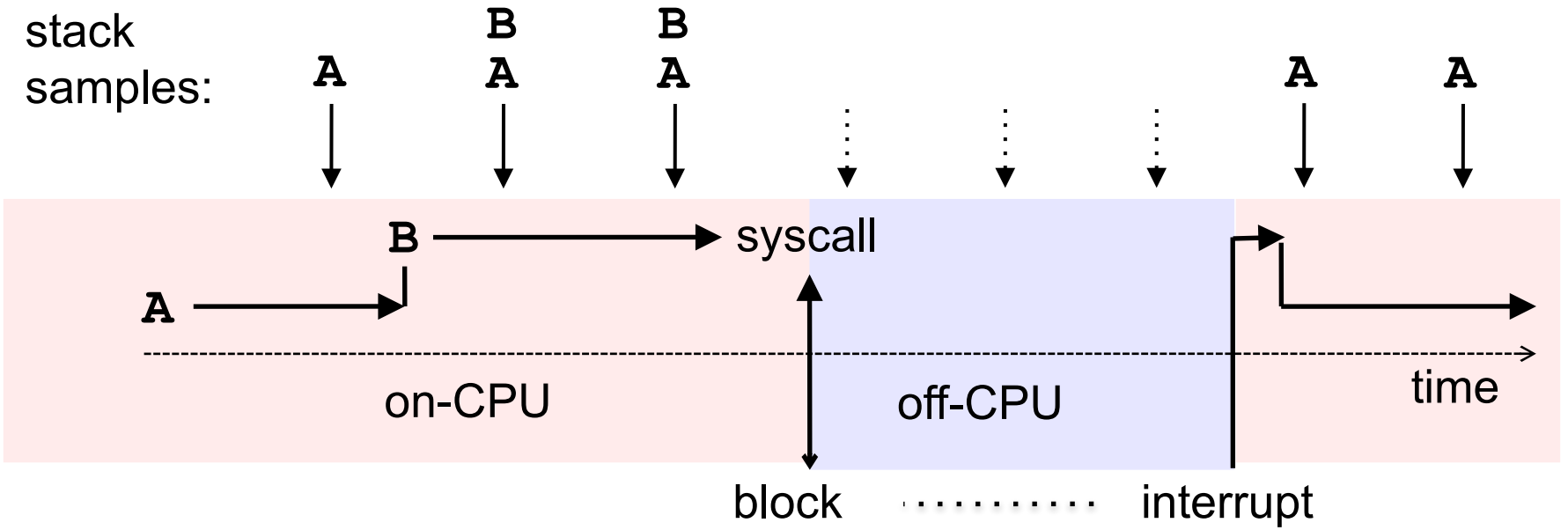
3. eBPF flame graphs

1. CPU Flame Graphs

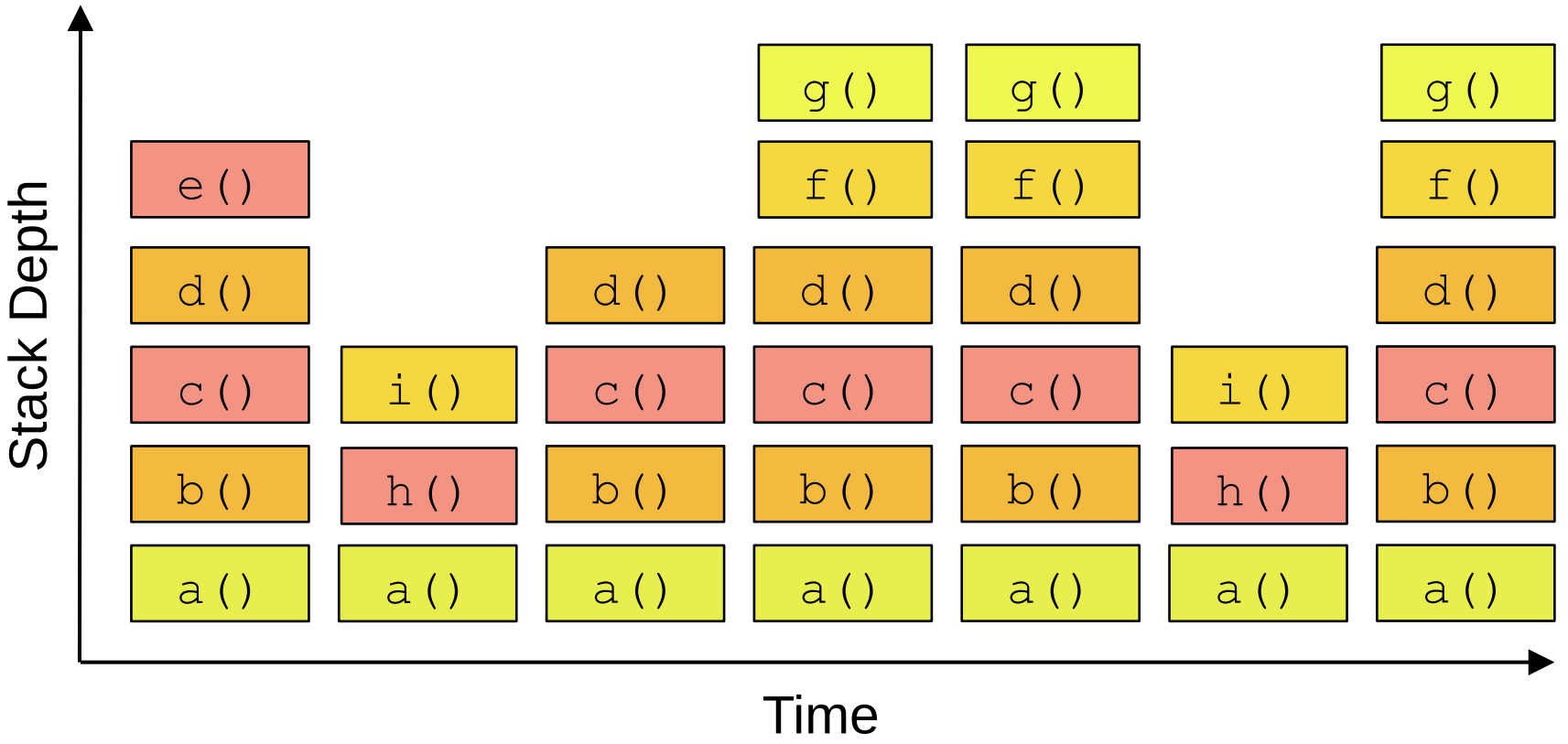
Stack Traces

```
$ 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)
```

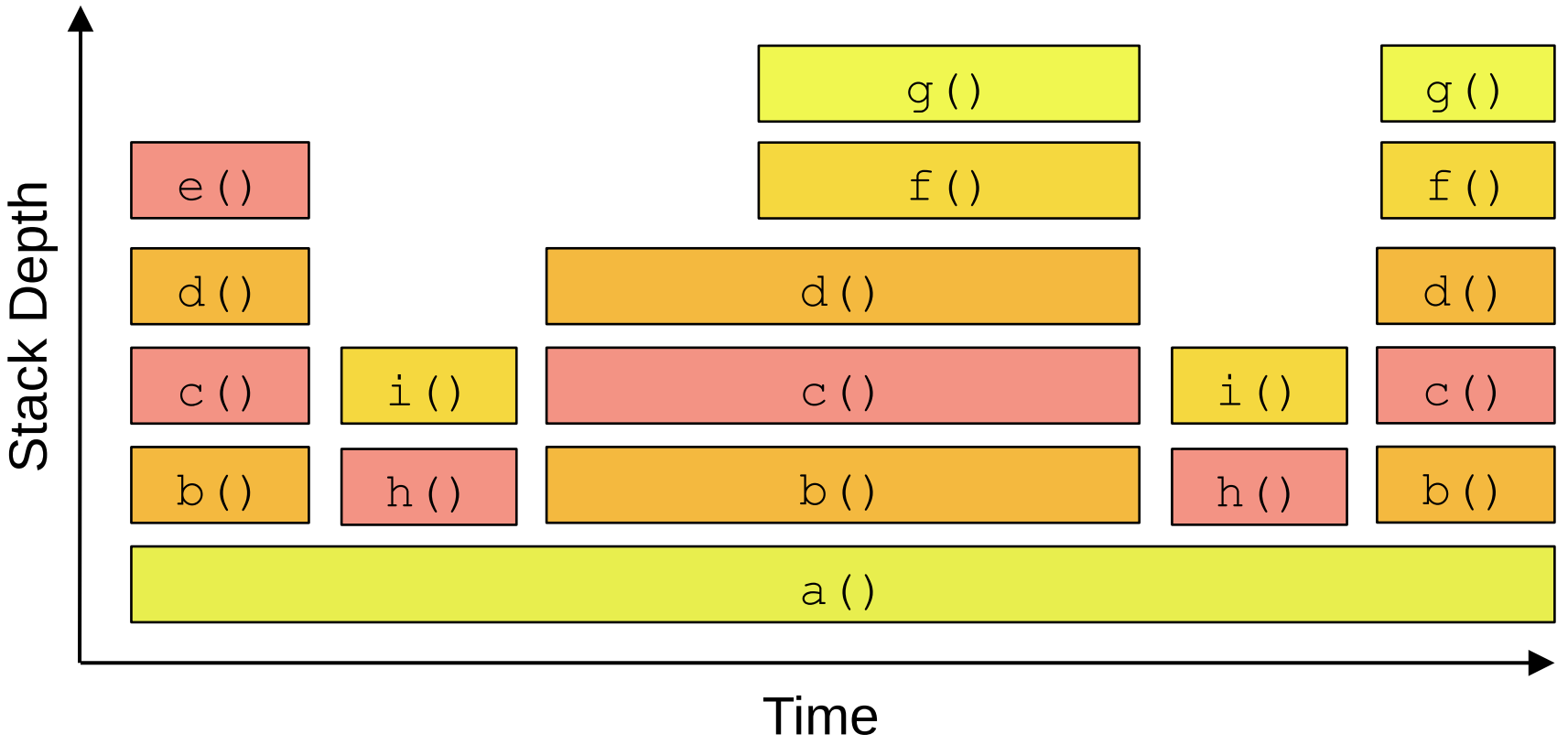
CPU Profiling



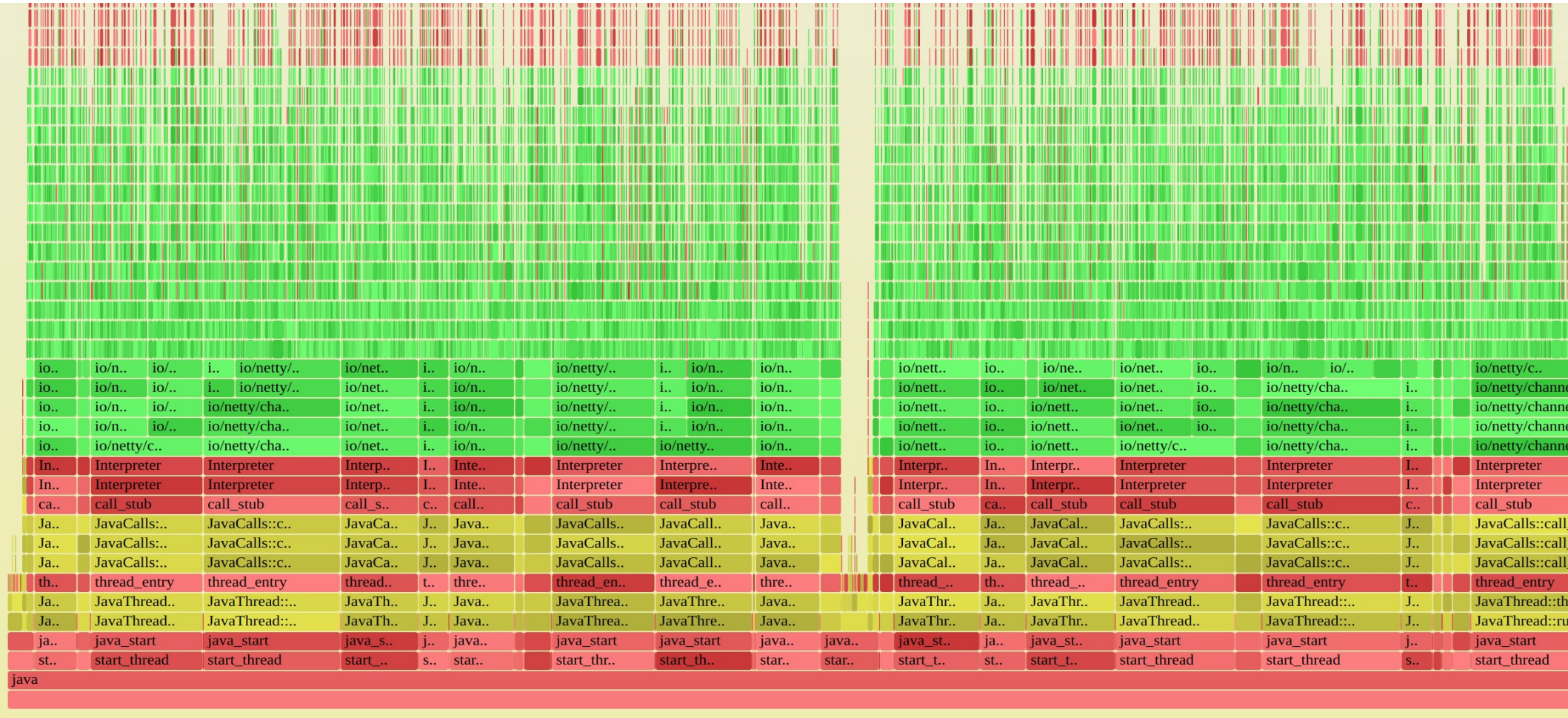
Stack Samples



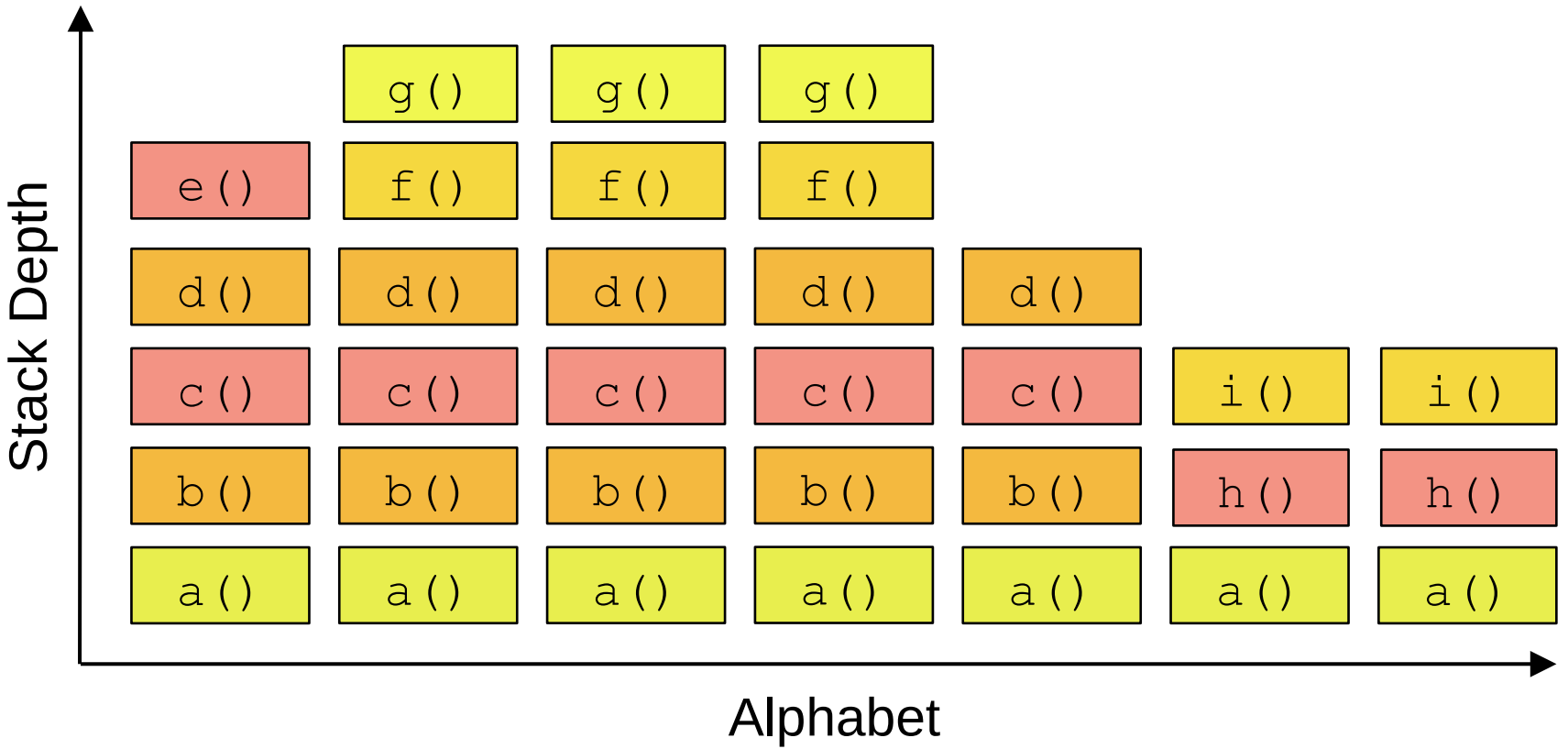
Stack Samples: Merged



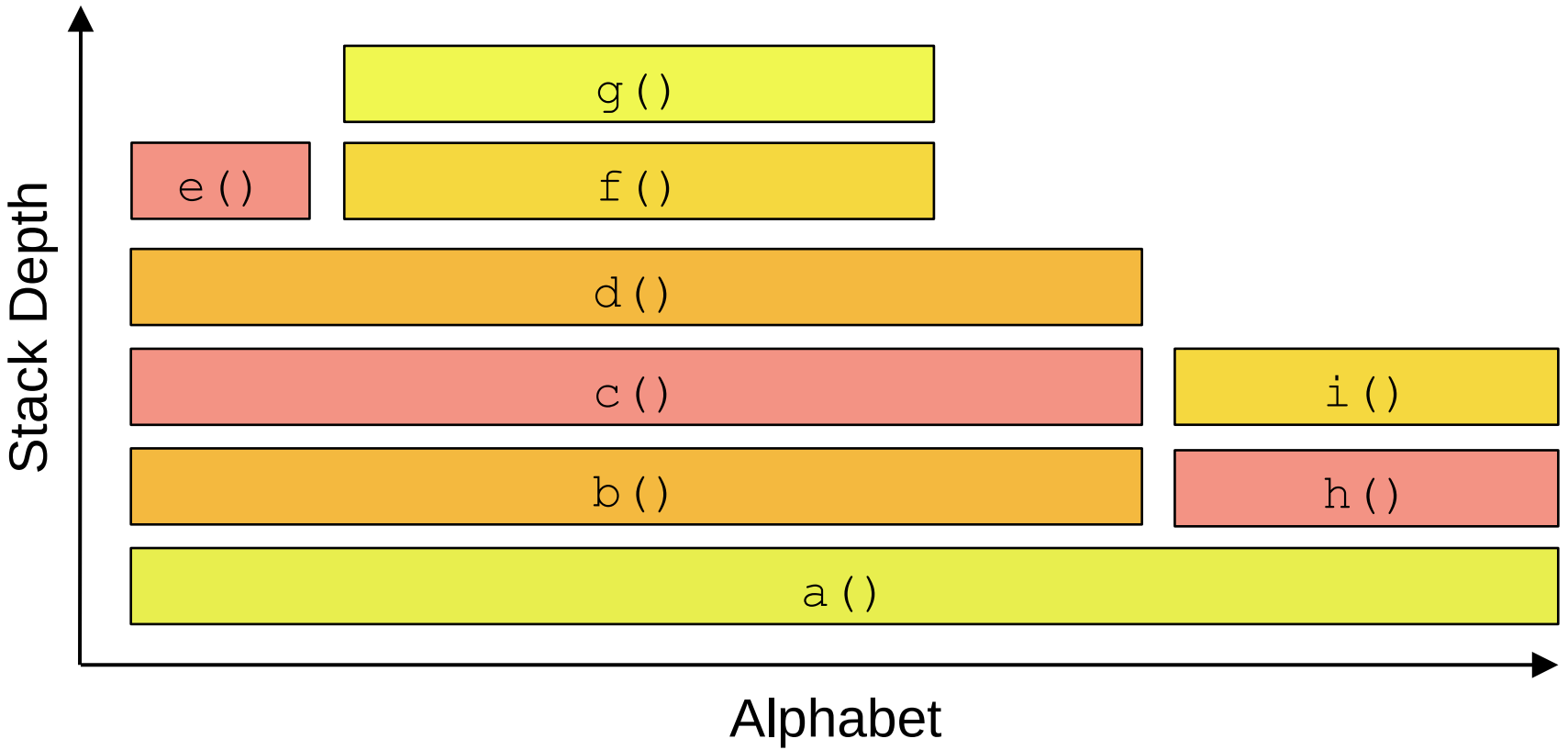
Example Profile (“hair graph”)



Alphabet Sort



Alphabet Merged (“Flame Graph”)



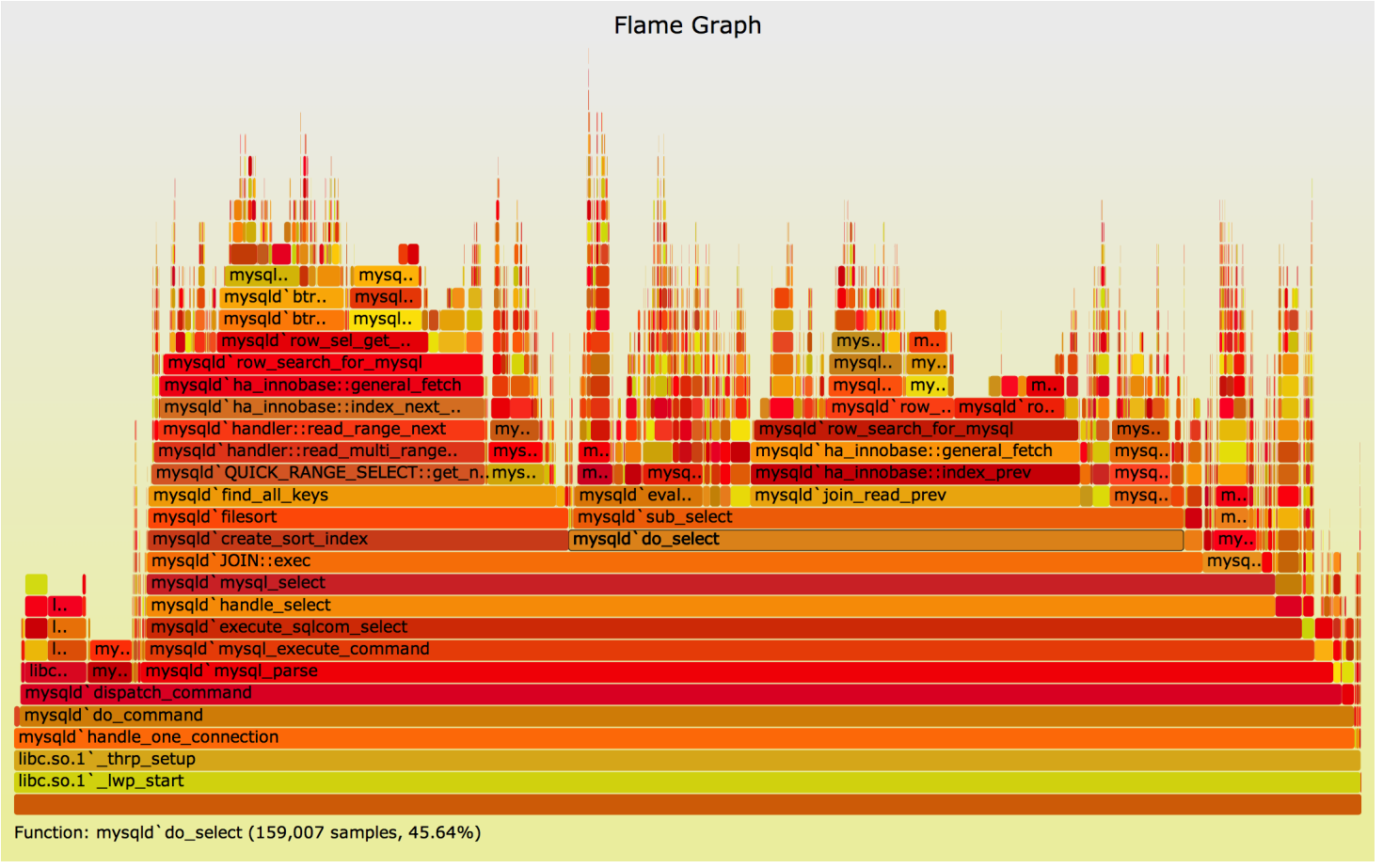
Example Profile: Flame Graph

Origin (2011): CPU Profiling

```
# dtrace -x ustackframes=100 -n 'profile-997 /execname == "mysqld"/ {
    @[ustack()] = count(); } tick-60s { exit(0); }'
[… over 500,000 lines truncated …]

              libc.so.1`__priocntlset+0xa
              libc.so.1`getparam+0x83
              libc.so.1`pthread_getschedparam+0x3c
              libc.so.1`pthread_setschedprio+0x1f
              mysqld`_Z16dispatch_command19enum_server_commandP3THDPcj+0x9ab
              mysqld`_Z10do_commandP3THD+0x198
              mysqld`handle_one_connection+0x1a6
              libc.so.1`_thrp_setup+0x8d
              libc.so.1`_lwp_start
             4884

              mysqld`_Z13add_to_statusP17system_status_varS0_+0x47
              mysqld`_Z22calc_sum_of_all_statusP17system_status_var+0x67
              mysqld`_Z16dispatch_command19enum_server_commandP3THDPcj+0x1222
              mysqld`_Z10do_commandP3THD+0x198
              mysqld`handle_one_connection+0x1a6
              libc.so.1`_thrp_setup+0x8d
              libc.so.1`_lwp_start
             5530
```

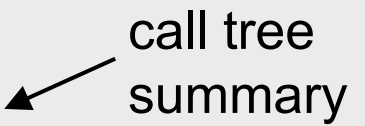
Full output

… as a Flame Graph

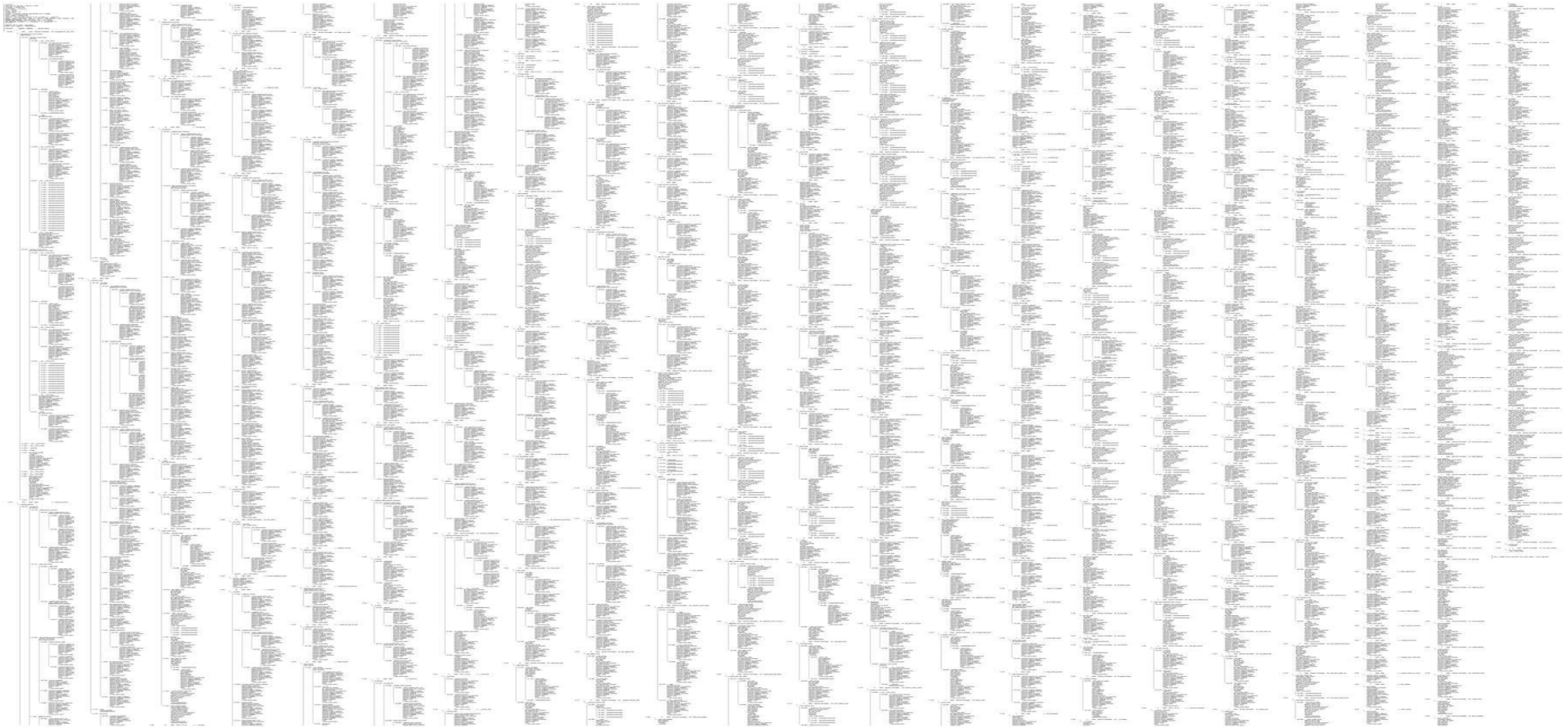


Linux example: perf Profiling

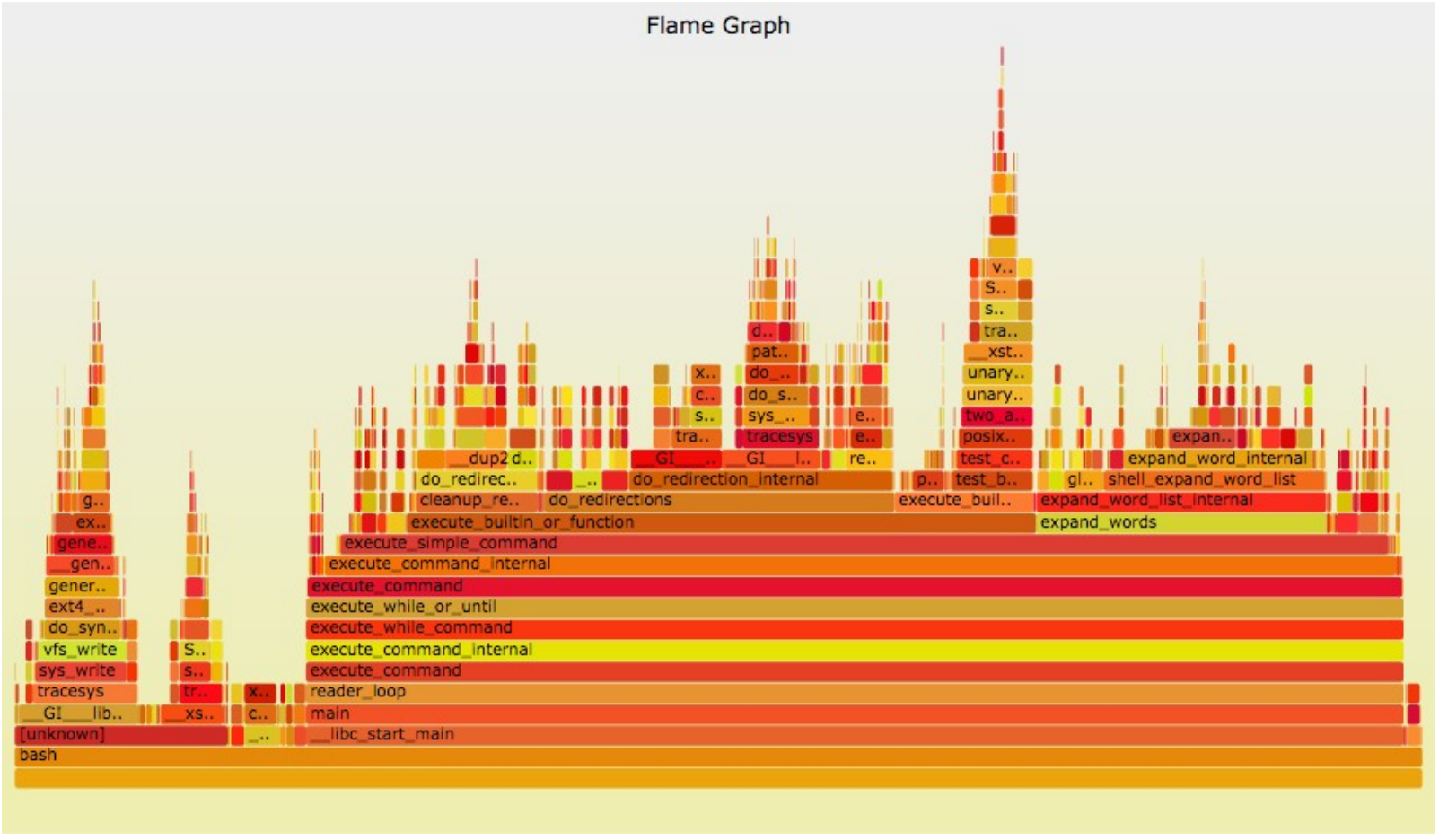
```
# perf record -F 99 -ag -- sleep 30
[ perf record: Woken up 9 times to write data ]
[ perf record: Captured and wrote 2.745 MB perf.data (~119930 samples) ]
# perf report -n -stdio
[…]
# Overhead       Samples  Command      Shared Object                          Symbol
# ........  ............  .......  .................  ..............................
#
    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 Output



… as a Flame Graph



Flame Charts (2013)

https://bugs.webkit.org/show_bug.cgi?id=111162

Ilya Tikhonovsky 2013-03-01 04:33:26 PST Description

Flame Chart may give to the developer a better clue what is going on with the performance without expanding the entire tree.

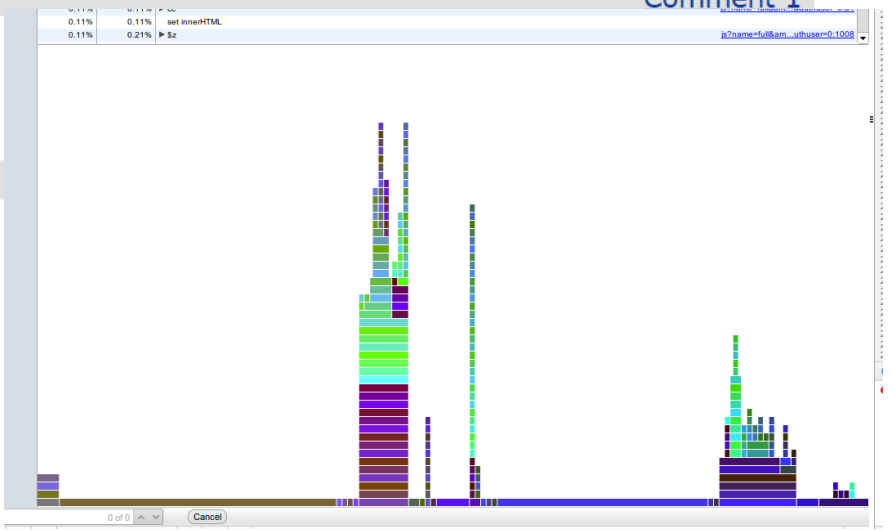
http://dtrace.org/blogs/brendan/2011/12/16/flame-graphs/

Ilya Tikhonovsky 2013-03-01 04:35:00 PST Comment 1

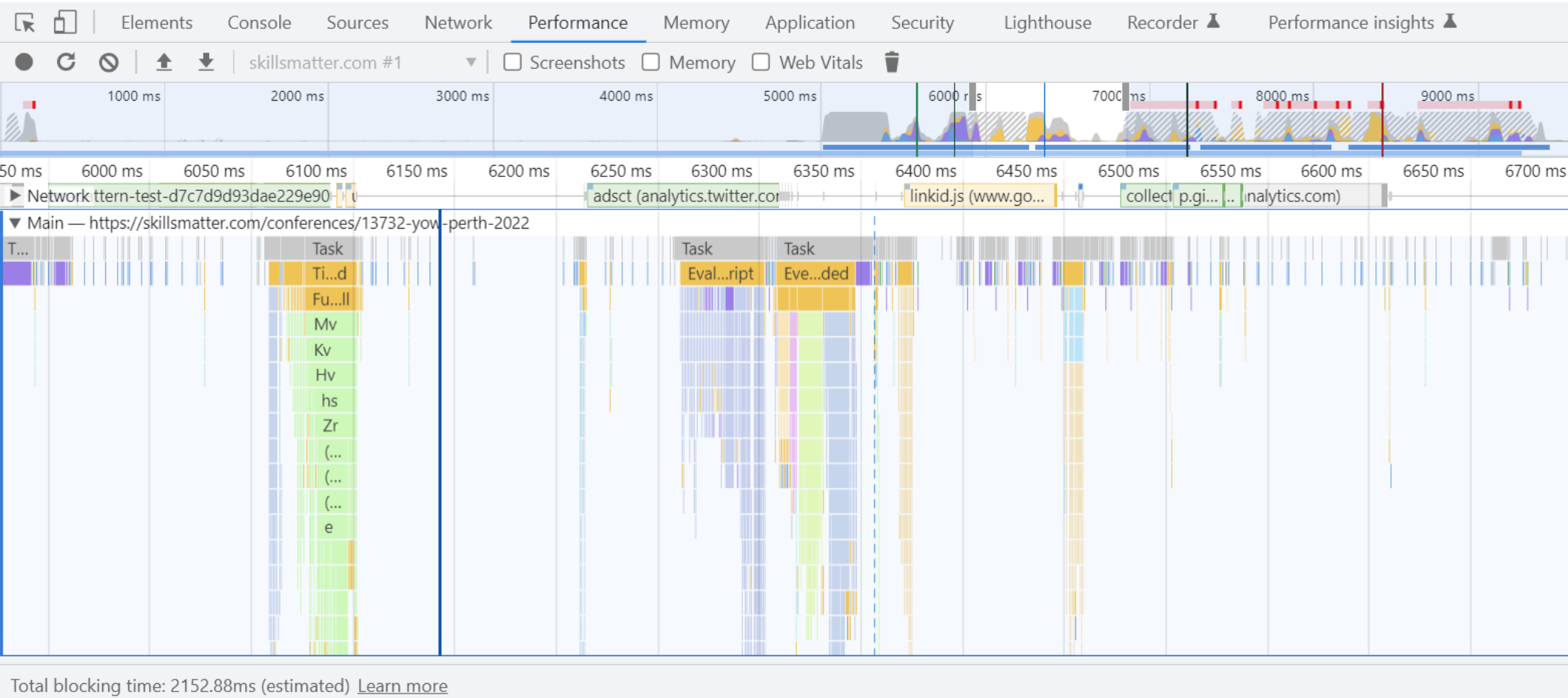
Created attachment 190933 [details]
screenshot

Ilya Tikhonovsky 2013-03-01 04:37:34 PST

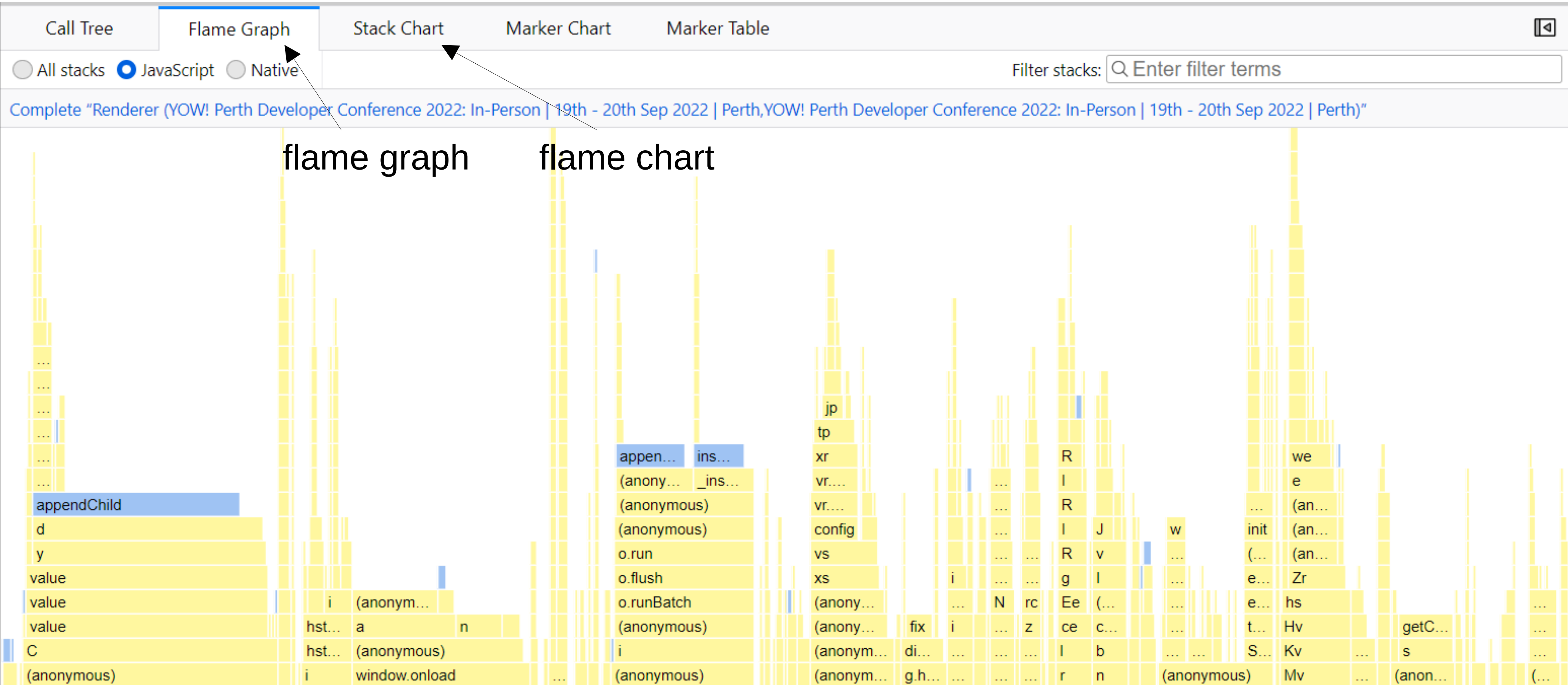
Created attachment 190934 [details]
Patch



Chrome DevTools Flame Charts (2022)



Firefox Profiler Flame Graph (2022)



Flame Graphs

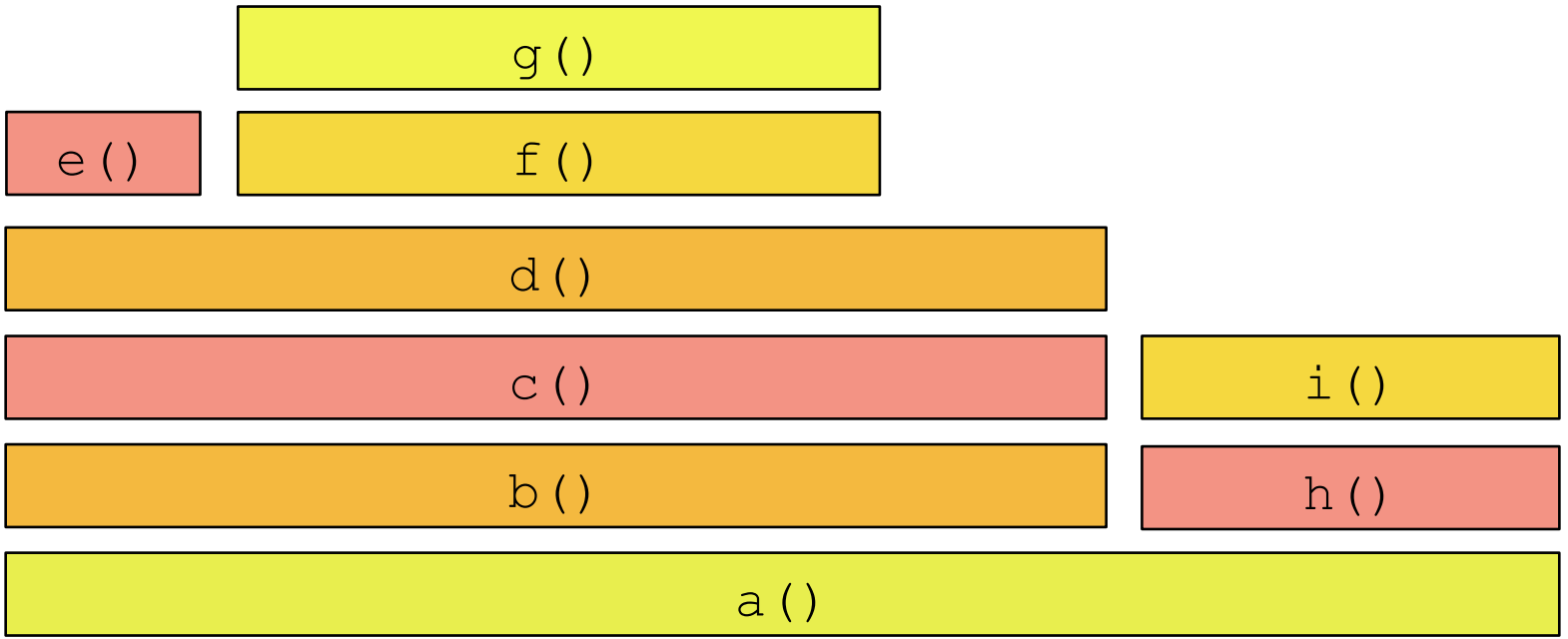
x-axis: population

alphabet sort or another frame merging algorithm

Flame Charts

x-axis: time

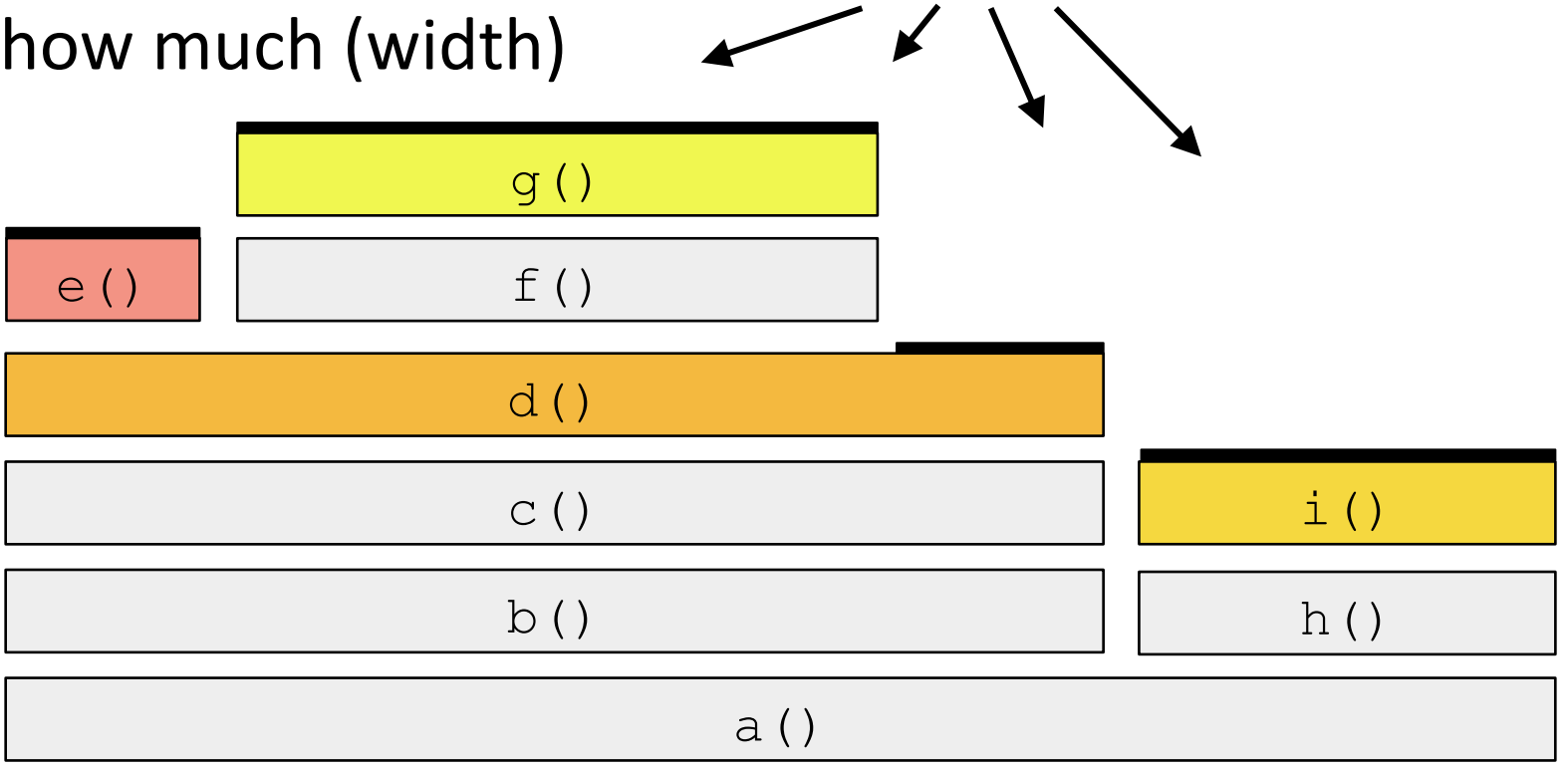
Flame Graph Interpretation



Flame Graph Interpretation (1/4)

Top edge shows who is running on-CPU,

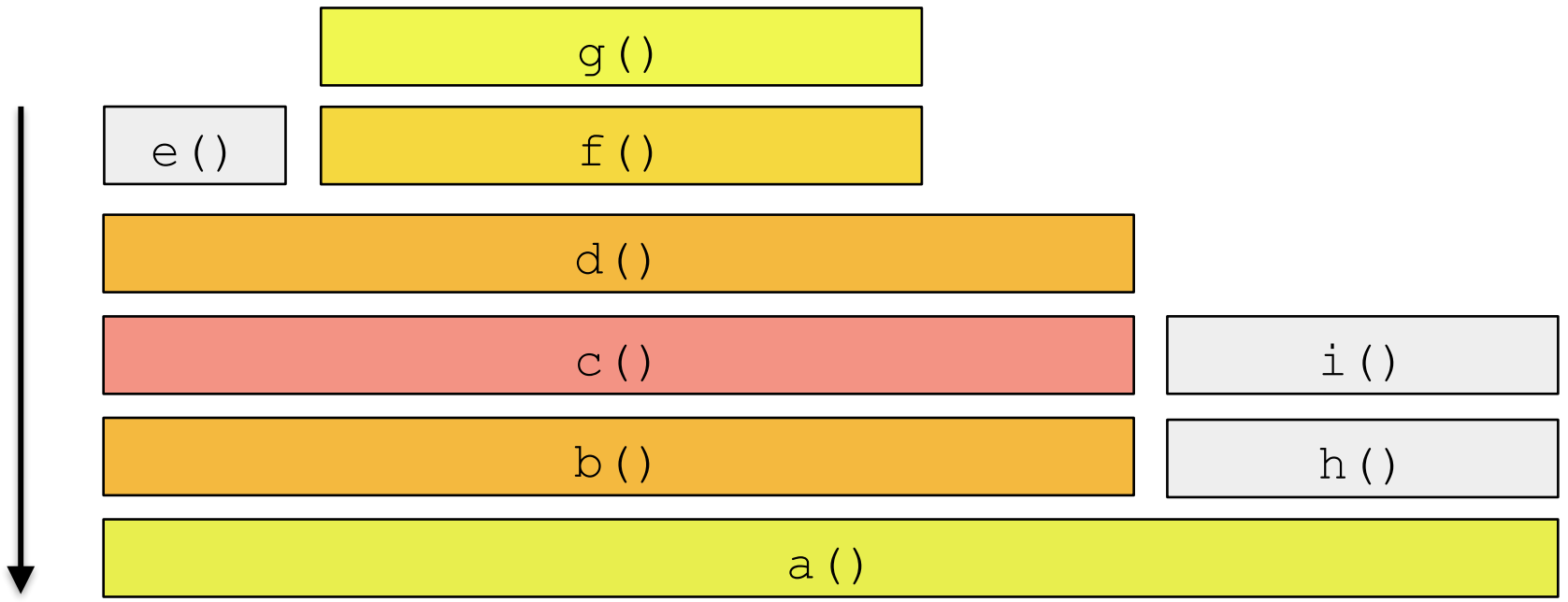
and how much (width)



Flame Graph Interpretation (2/4)

Top-down shows ancestry

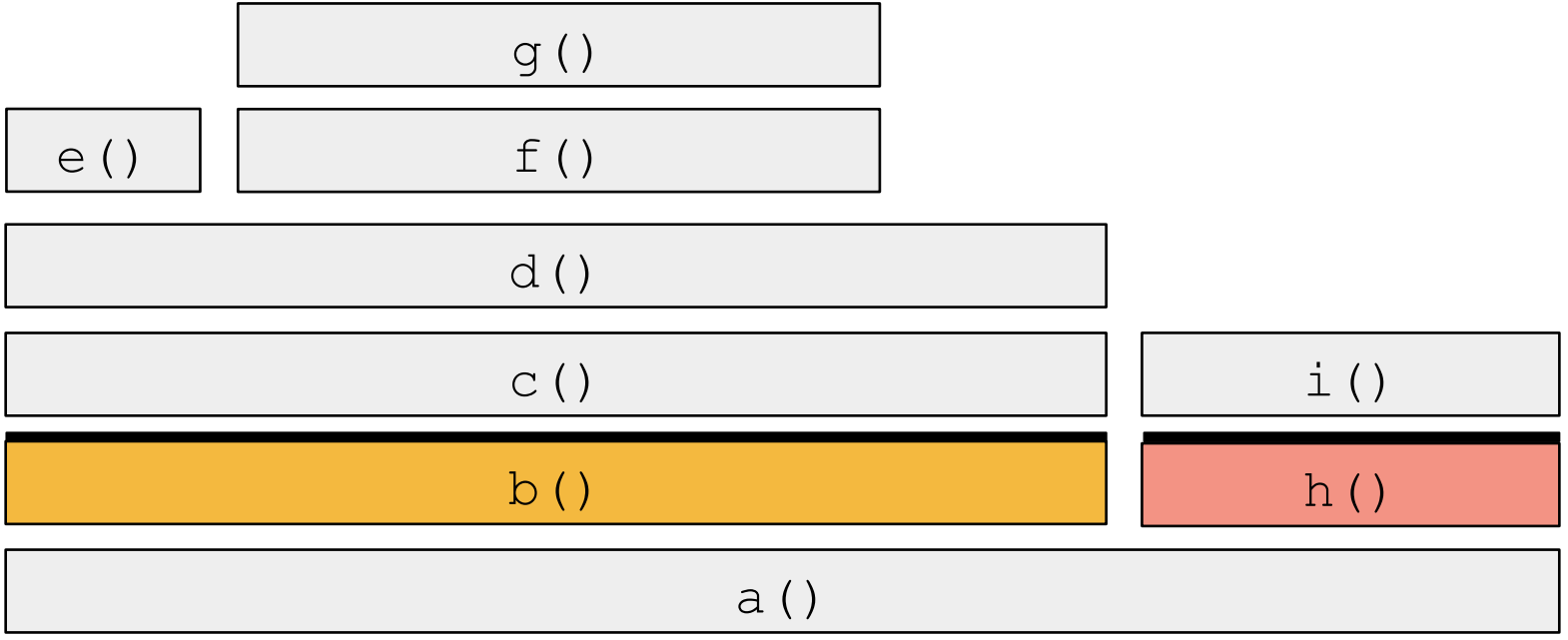
e.g., from g():



Flame Graph Interpretation (3/4)

Widths are proportional to presence in samples

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

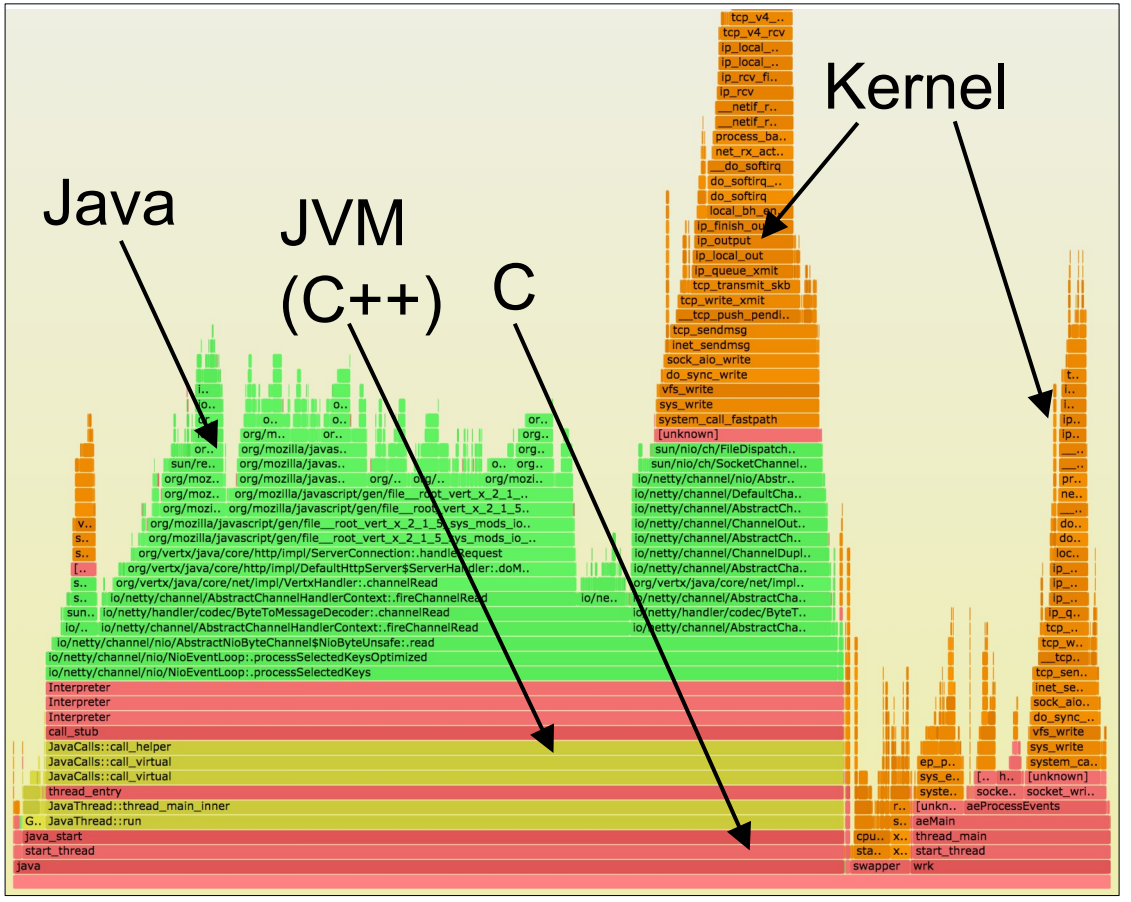


Flame Graph Interpretation (4/4)

Colors randomized to differentiate frames

Or used for code type; e.g.:

- green == JIT (e.g., Java)
- aqua == inlined
- red == user-level
- orange == kernel
- yellow == C++
- magenta == search term



Flame Graph Summary

Visualizes a collection of stack traces

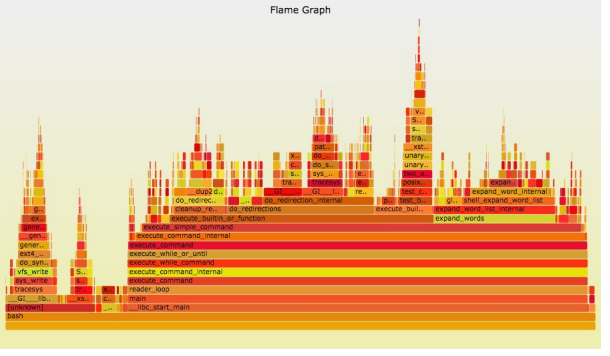
- **x-axis**: population: e.g., alphabetical sort to maximize merging
- **y-axis**: stack depth
- **color**: random (default) or a dimension

Original implementation: Perl + SVG + JavaScript

- **https://github.com/brendangregg/FlameGraph**
- Takes input from many different profilers

References:

- http://www.brendangregg.com/flamegraphs.html
- http://queue.acm.org/detail.cfm?id=2927301
- "The Flame Graph" CACM, June 2016

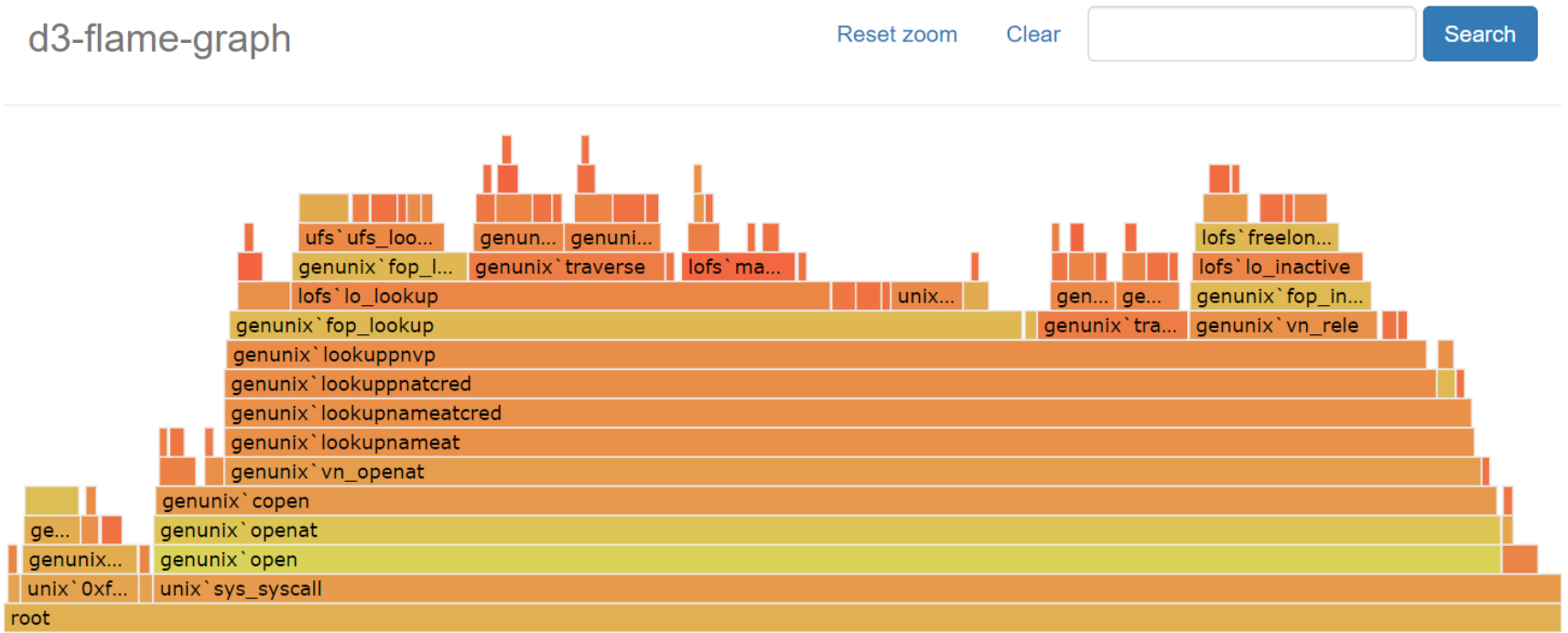


d3 Flame Graphs

Created by Martin Spier (my colleague at Netflix)

Used by Netflix's internal continuous profiler ("FlameCommander")

https://github.com/spiermar/d3-flame-graph



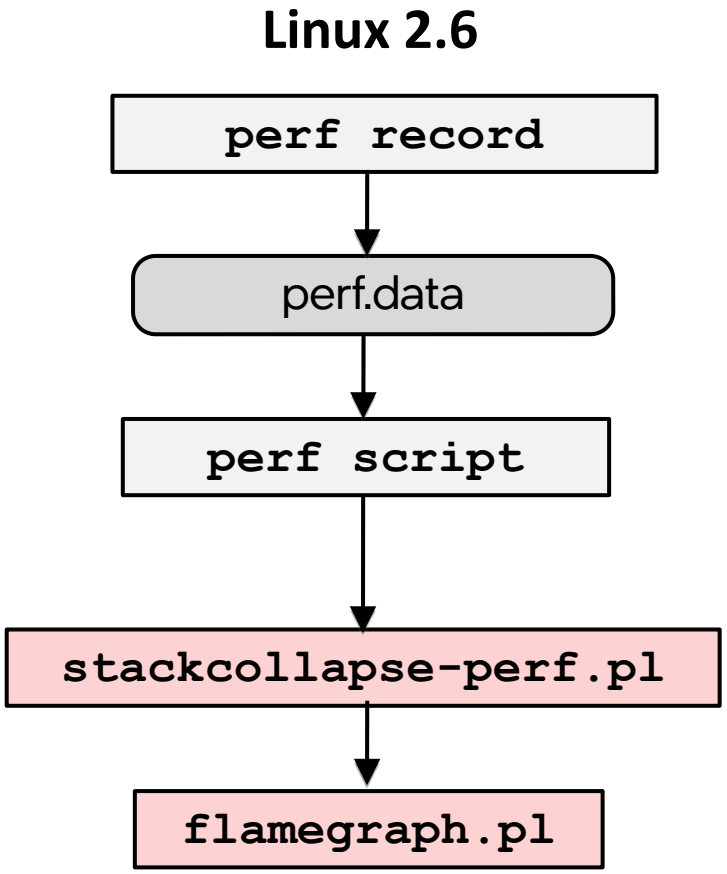
Linux CPU Flame Graphs in 3 Easy Steps

```
# git clone https://github.com/brendangregg/FlameGraph; cd FlameGraph
# perf record -F 49 -ag -- sleep 30
# perf script | ./stackcollapse-perf.pl | ./flamegraph.pl > out.svg
```

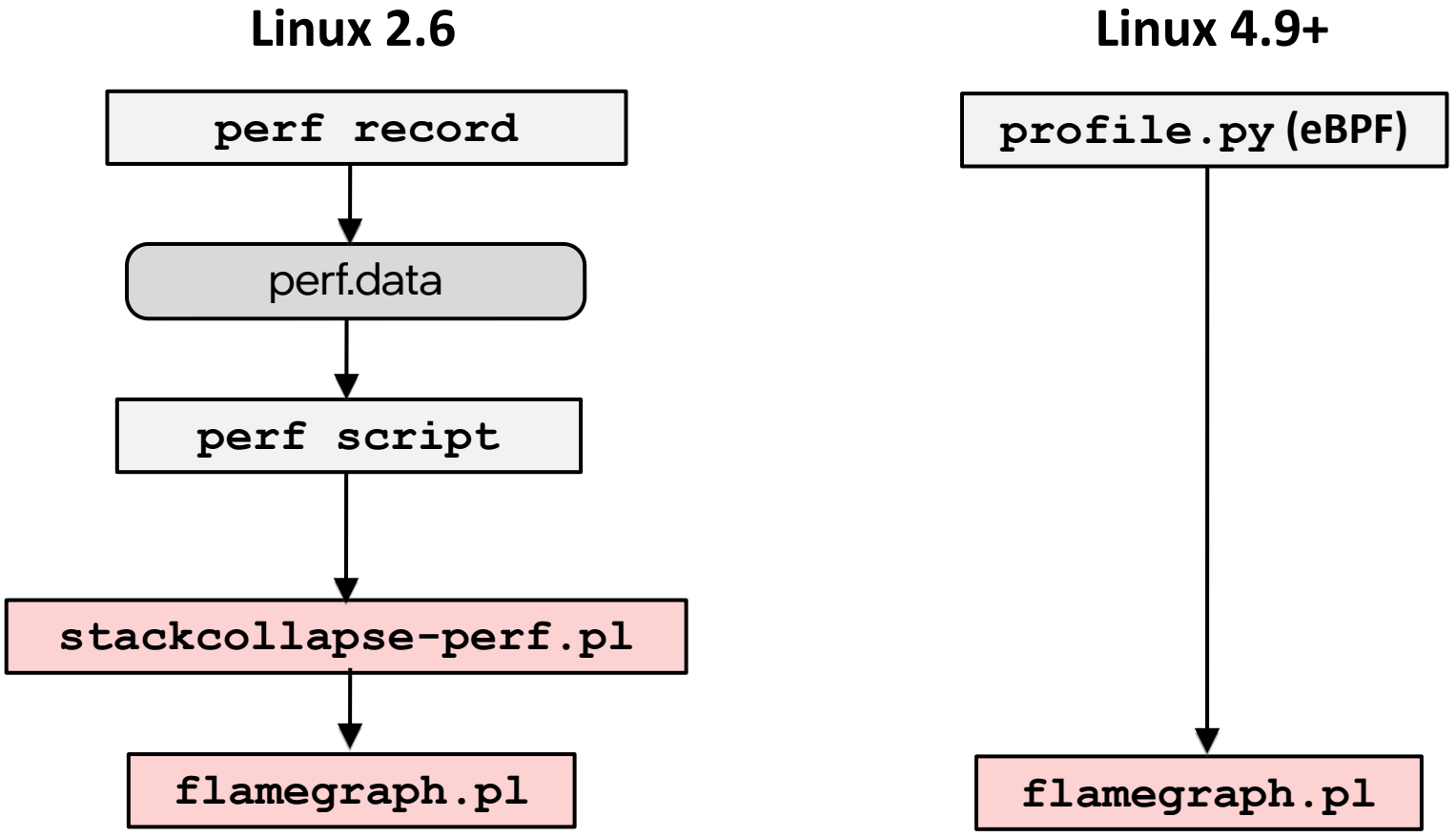
Some runtimes (e.g., JVM) require extra steps for stacks & symbols

see https://www.brendangregg.com/FlameGraphs/cpuflamegraphs.html

CPU Flame Graphs



eBPF-based CPU Flame Graphs



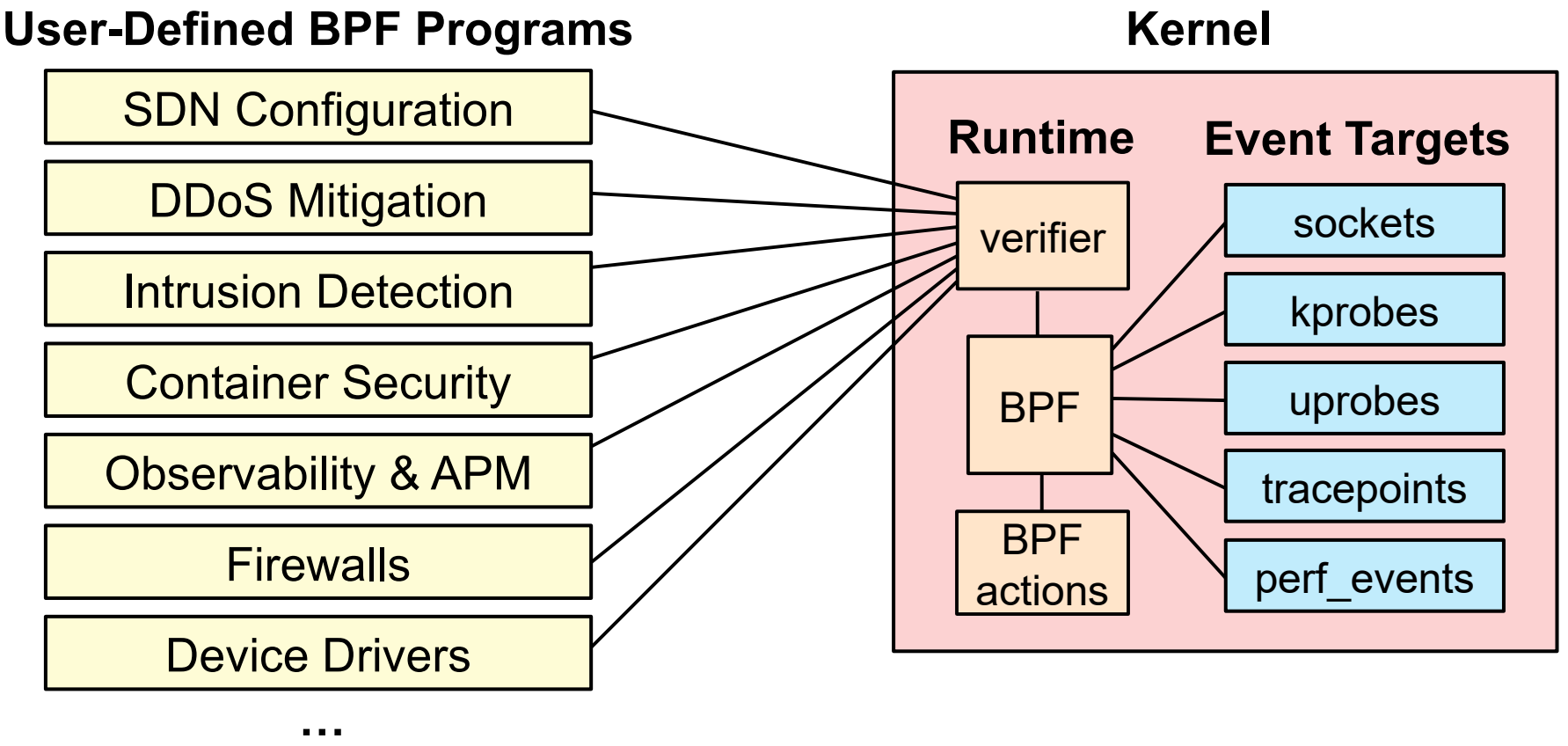
2. eBPF

BPF 1992: Berkeley Packet Filter

```
# tcpdump -d host 127.0.0.1 and port 80
(000) ldh      [12]
(001) jeq      #0x800           jt 2   jf 18
(002) ld       [26]
(003) jeq      #0x7f000001      jt 6   jf 4
(004) ld       [30]
(005) jeq      #0x7f000001      jt 6   jf 18
(006) ldb      [23]
(007) jeq      #0x84            jt 10  jf 8
(008) jeq      #0x6             jt 10  jf 9
(009) jeq      #0x11            jt 10  jf 18
(010) ldh      [20]
(011) jset     #0x1fff          jt 18  jf 12
(012) ldxb     4*([14]&0xf)
(013) ldh      [x + 14]
(014) jeq      #0x50            jt 17  jf 15
(015) ldh      [x + 16]
(016) jeq      #0x50            jt 17  jf 18
(017) ret      #262144
(018) ret      #0
```

A limited
virtual machine for
efficient packet filters

eBPF 2022


User-Defined BPF Programs
SDN Configuration
DDoS Mitigation
Intrusion Detection
Container Security
Observability & APM
Firewalls
Device Drivers
...
Kernel
Runtime
Event Targets
verifier
BPF
BPF actions
sockets
kprobes
uprobes
tracepoints
perf_events

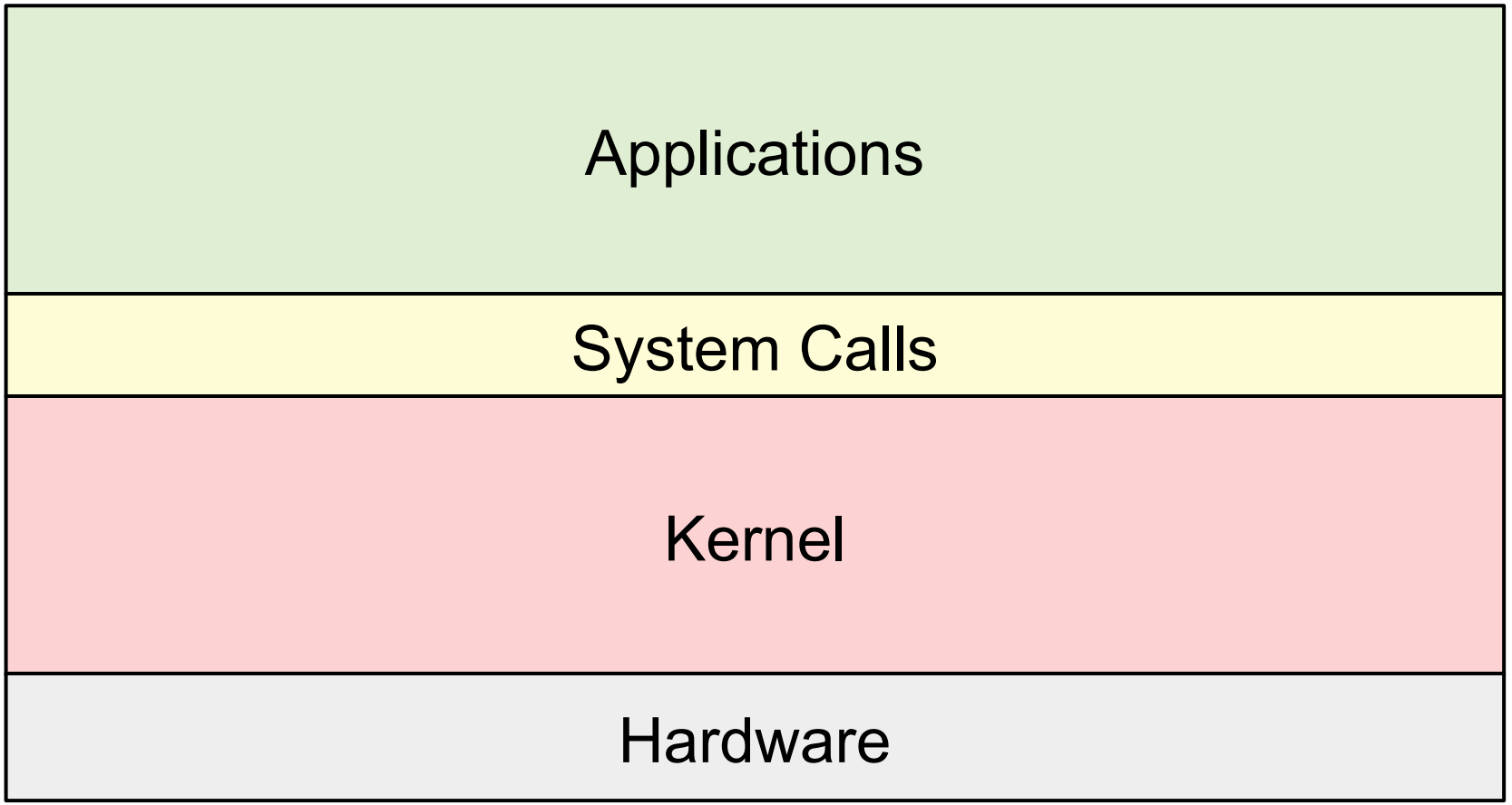
BPF (kernel engineers)

eBPF (marketing)

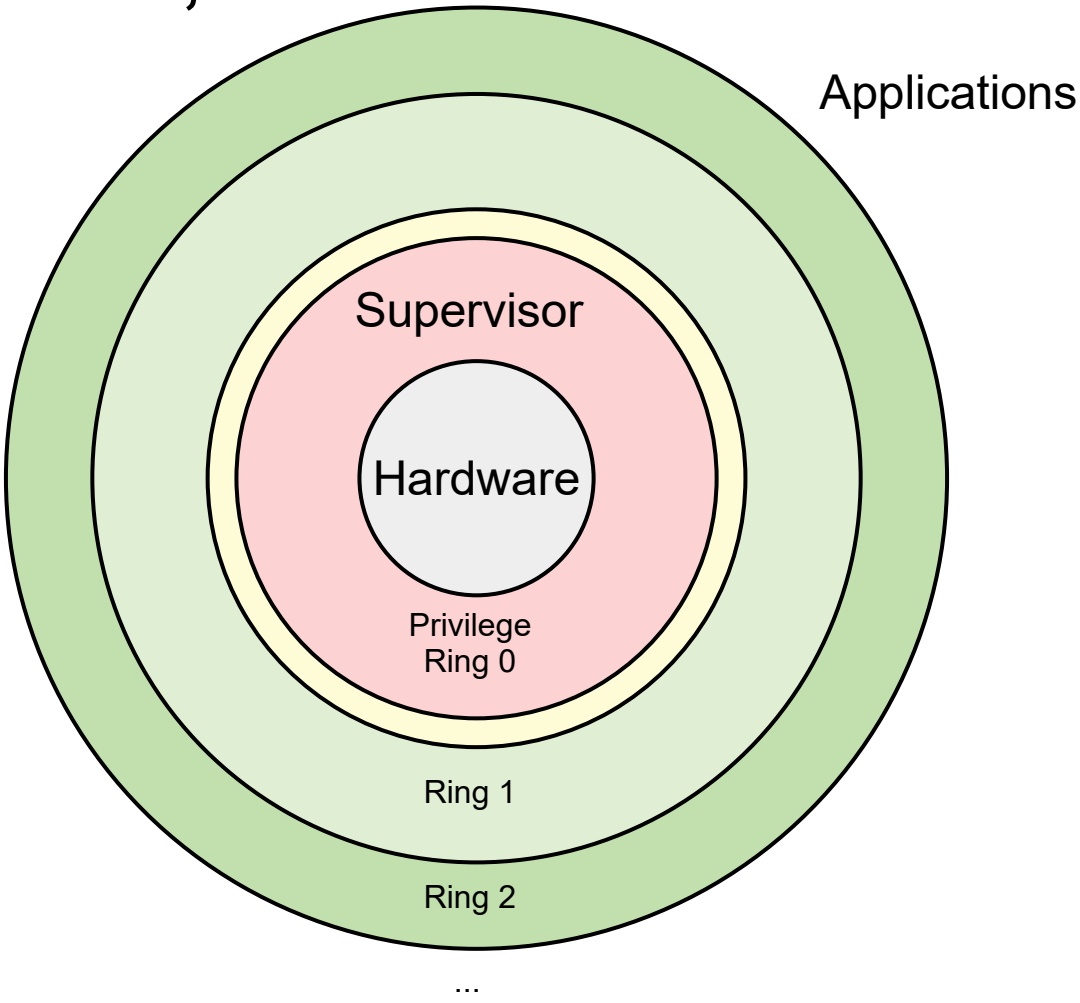
BPF is no longer an acronym

eBPF tracing pony

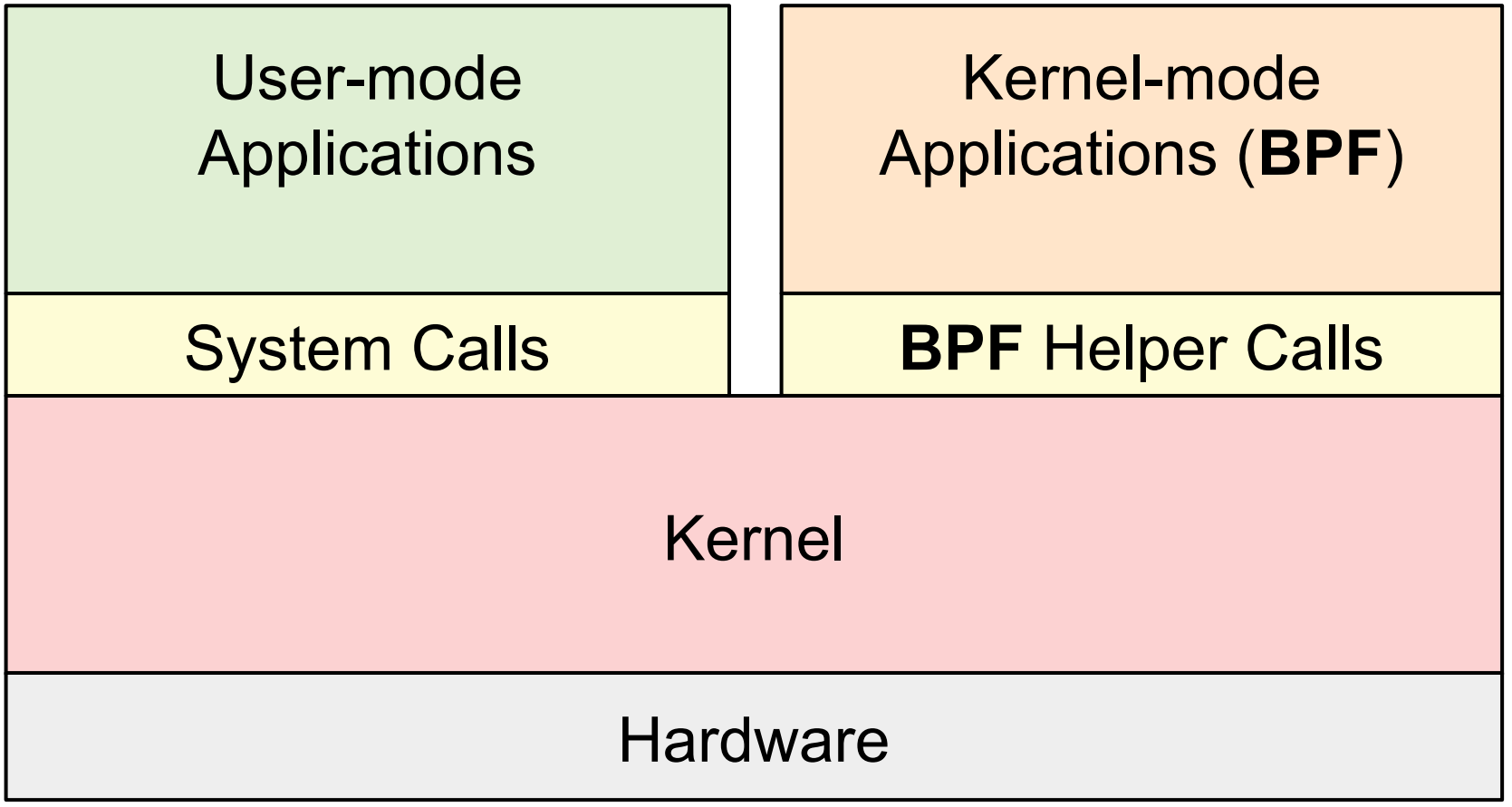
50 Years, one (dominant) OS model



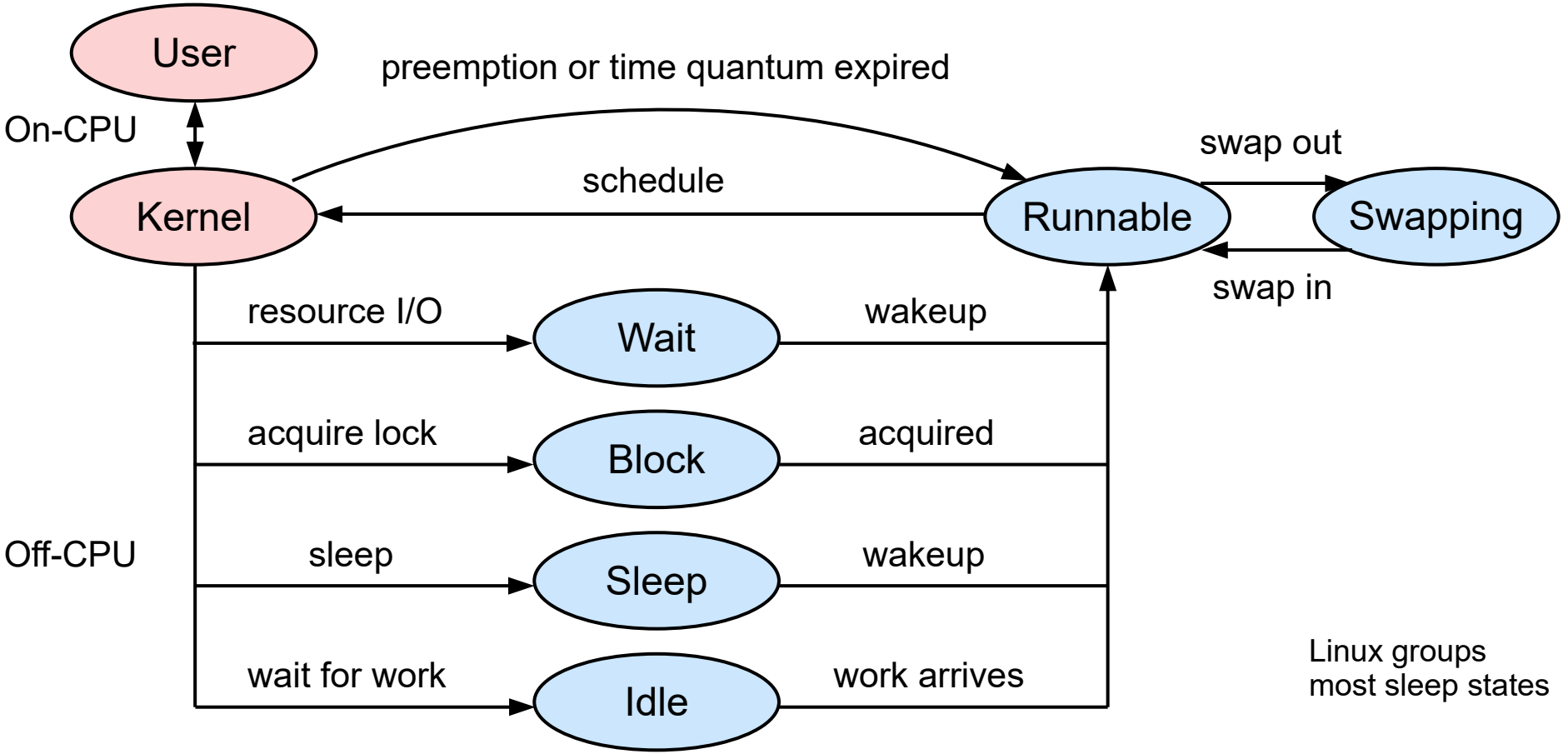
Origins: Multics, 1960s



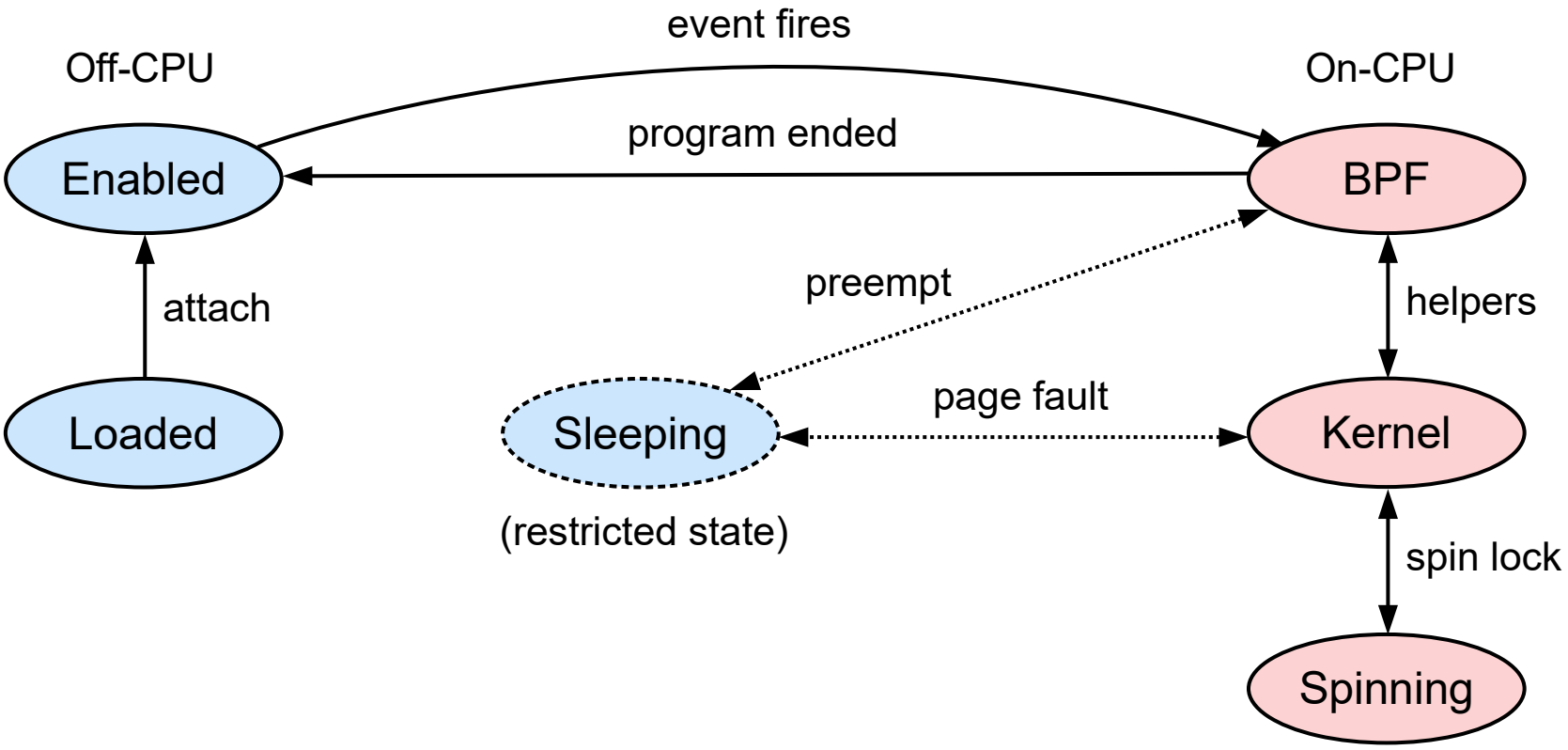
Modern Linux: A new OS model



50 Years, one process state model



BPF program state model



Netconf 2018
Alexei Starvoitov

BPF verifier in the future

- move away from existing brute force "walk all instructions" ap
  technology and static analysis
- remove #define BPF_COMPLEXITY_LIMIT 128k crutch
- remove #define BPF_MAXINSNS 4k
- support arbitrary large programs and libraries
  - 1 Million BPF instructions
- an algorithm to solve Rubik's cube will be expressible in BPF

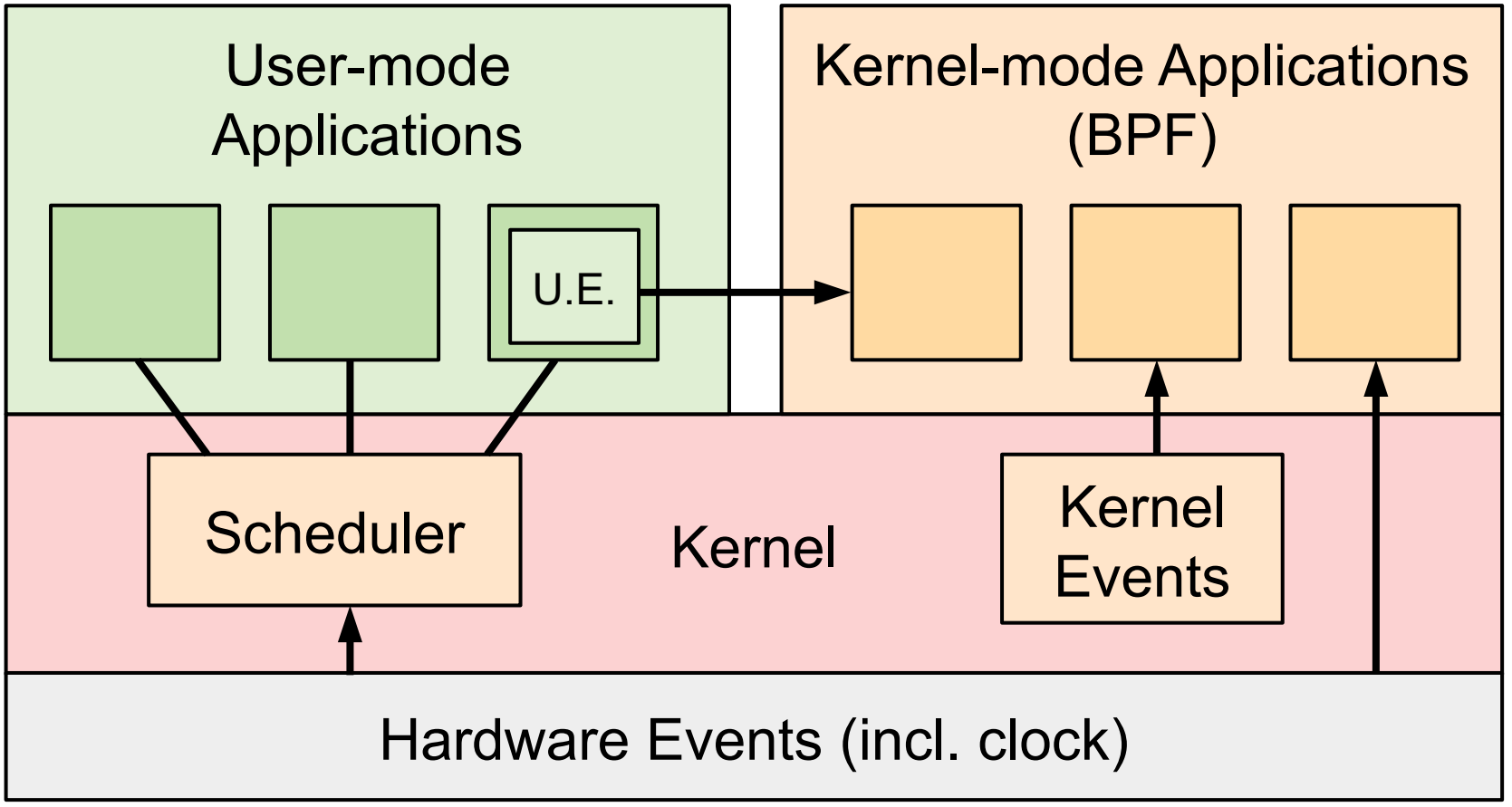
Kernel Recipes 2019, Alexei Starovoitov

~40 active BPF programs on every Facebook server

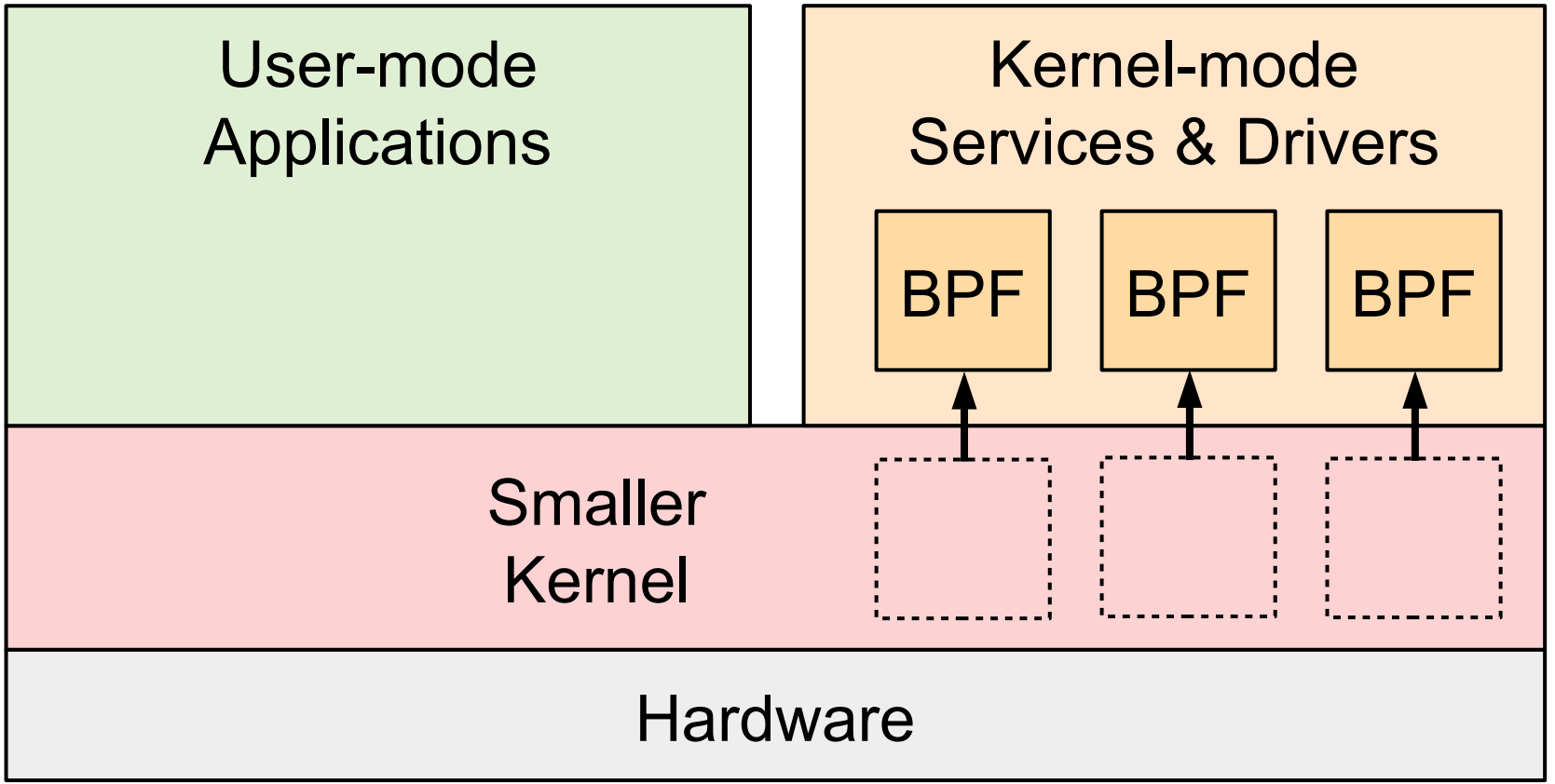
UbuntuMasters 2019, Brendan Gregg

~14 active BPF programs on every Netflix cloud instance

Modern Linux: Event-based Applications



Modern Linux is becoming Microkernel-ish



The word “microkernel” has already been invoked by Jonathan Corbet, Thomas Graf, Greg Kroah-Hartman, ...

Steven Rostedt
@srostedt

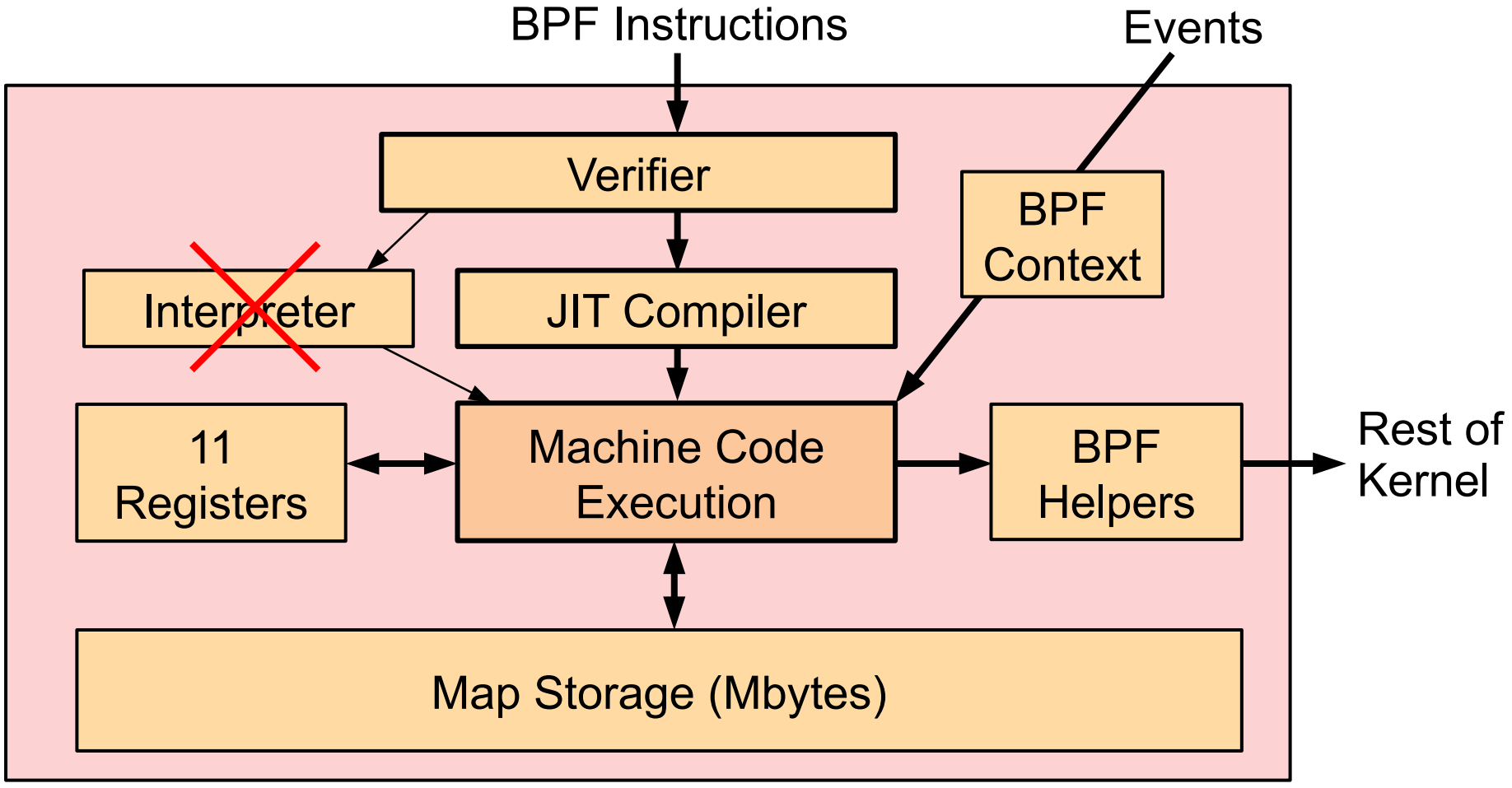
BPF will replace Linux #kr2019

2:06 AM · Sep 26, 2019 · Twitter for Android

18 Retweets **79** Likes

Microsoft are adding eBPF to Windows

BPF Internals




Is BPF Turing complete?

A New Type of Software

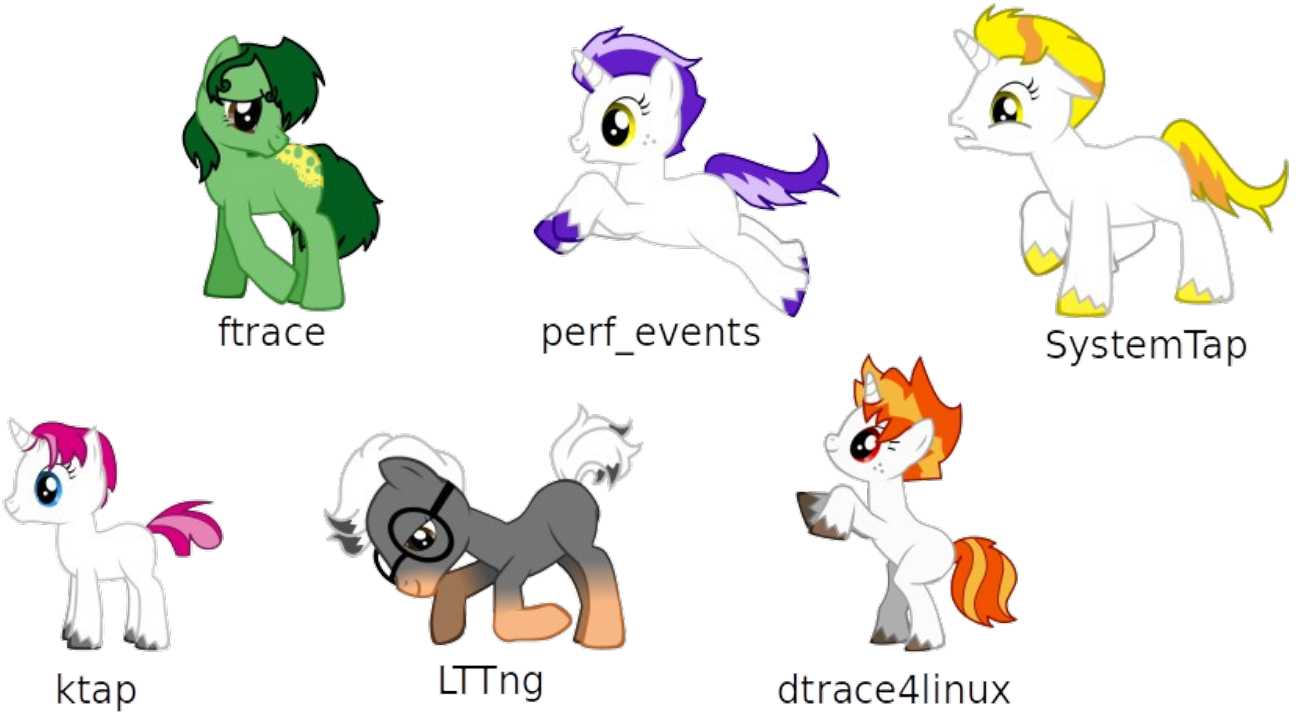
	Execution model	User defined	Compil-ation	Security	Failure mode	Resource access
User	task	yes	any	user based	abort	syscall, fault
Kernel	task	no	static	none	panic	direct
BPF	event	yes	JIT, CO-RE	verified, JIT	error message	restricted helpers

Example Use Case: BPF Observability (aka “Tracing”)

Example Use Case: BPF Observability (aka “Tracing”)

BPF enables a new class of
custom, **efficient**, and **production safe**
performance analysis tools

Linux tracing was a mess (with cute ponies)



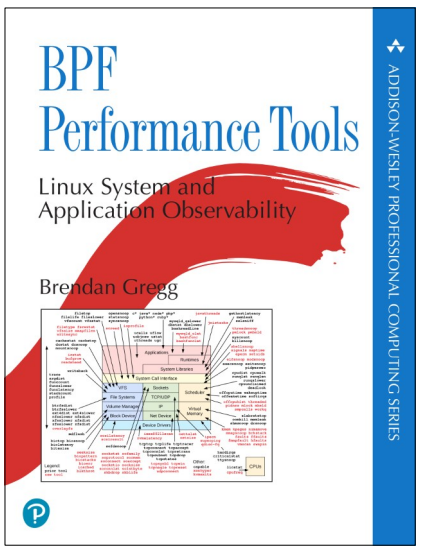
The tracing ponies were created by a tech marketing professional from Sun Microsystems, Deirdre Straughan (now my wife)

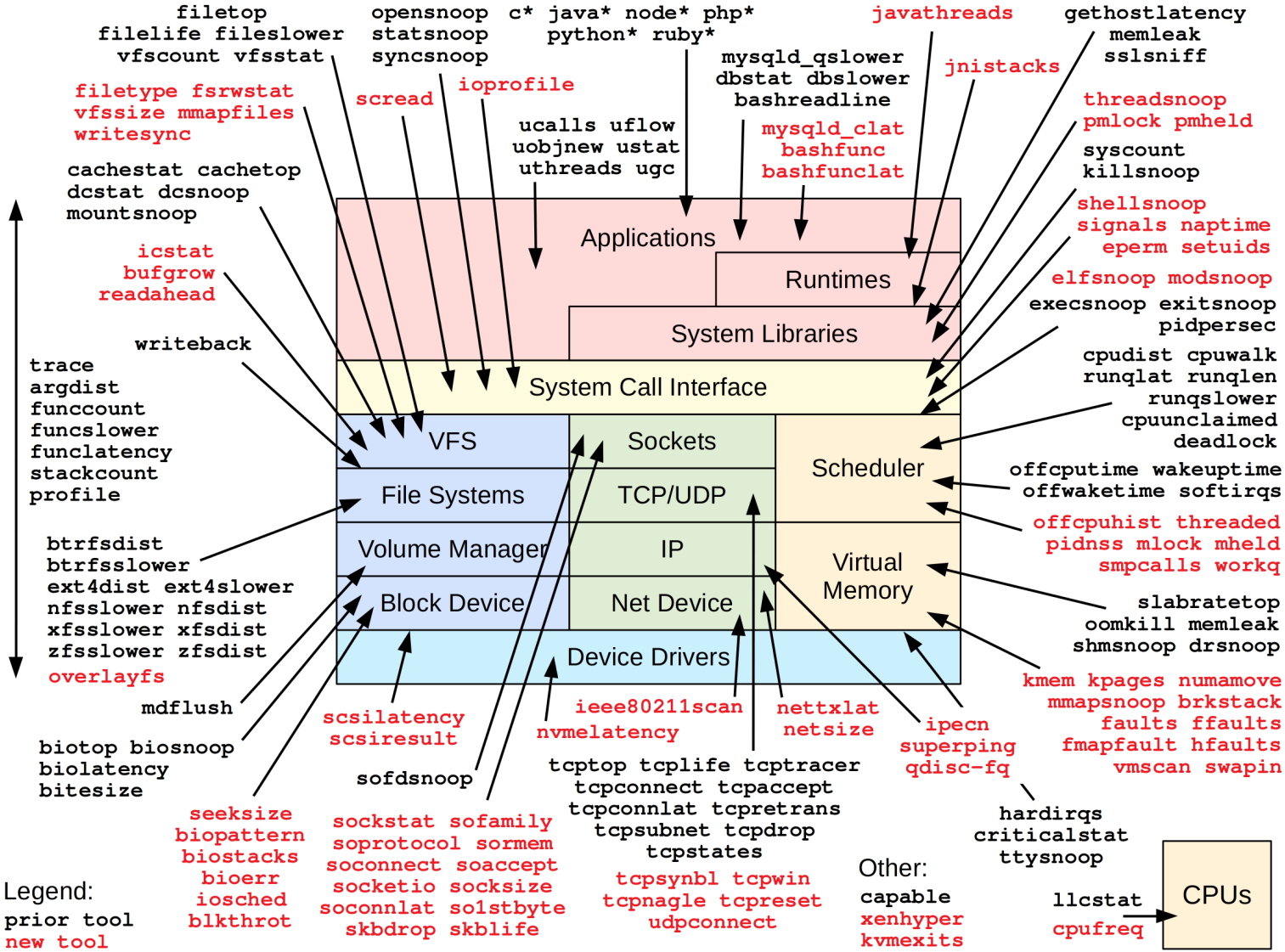
Linux Tracing Present and Future

bcc libbpf

bpftrace

eBPF Perf Tools





Example: BCC tcplife

Which processes are connecting to which port?

Example: BCC tcplife

Which processes are connecting to which port?

```
# ./tcplife
PID   COMM       LADDR           LPORT RADDR           RPORT TX_KB RX_KB MS
22597 recordProg 127.0.0.1       46644 127.0.0.1       28527     0     0 0.23
3277  redis-serv 127.0.0.1       28527 127.0.0.1       46644     0     0 0.28
22598 curl       100.66.3.172    61620 52.205.89.26    80        0     1 91.79
22604 curl       100.66.3.172    44400 52.204.43.121   80        0     1 121.38
22624 recordProg 127.0.0.1       46648 127.0.0.1       28527     0     0 0.22
3277  redis-serv 127.0.0.1       28527 127.0.0.1       46648     0     0 0.27
22647 recordProg 127.0.0.1       46650 127.0.0.1       28527     0     0 0.21
3277  redis-serv 127.0.0.1       28527 127.0.0.1       46650     0     0 0.26
[...]
```

Example: BCC tcplife

```
# tcplife -h
./usage: tcplife.py [-h] [-T] [-t] [-w] [-s] [-p PID] [-L LOCALPORT]
                    [-D REMOTEPORT]

Trace the lifespan of TCP sessions and summarize

optional arguments:
  -h, --help            show this help message and exit
  -T, --time            include time column on output (HH:MM:SS)
  -t, --timestamp       include timestamp on output (seconds)
  -w, --wide            wide column output (fits IPv6 addresses)
  -s, --csv             comma separated values output
  -p PID, --pid PID     trace this PID only
  -L LOCALPORT, --localport LOCALPORT
                        comma-separated list of local ports to trace.
  -D REMOTEPORT, --remoteport REMOTEPORT
                        comma-separated list of remote ports to trace.

examples:
    ./tcplife           # trace all TCP connect()s
    ./tcplife -t        # include time column (HH:MM:SS)
[...]
```

Example: BCC execsnoop

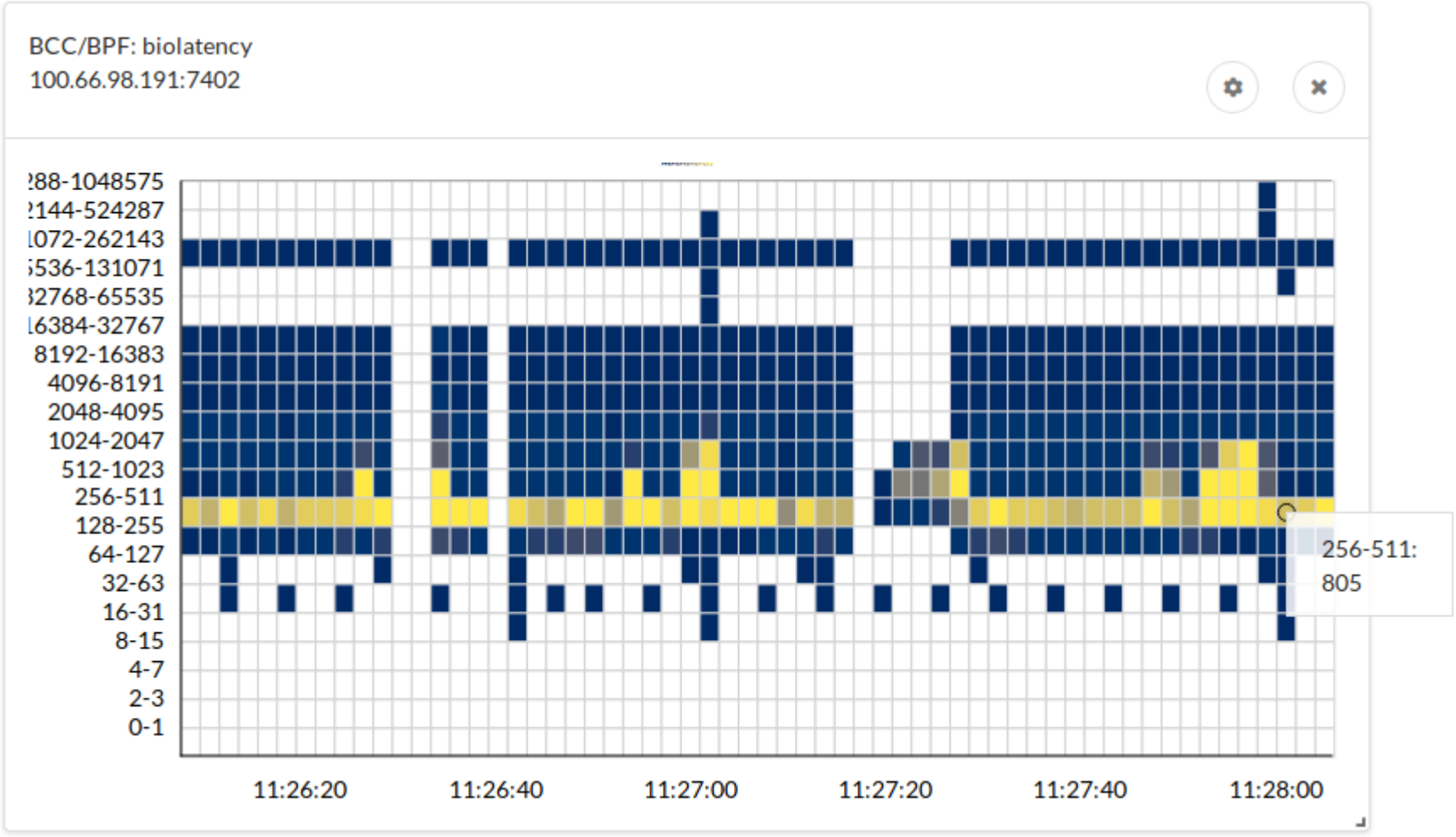
What processes are launching?

```
# execsnoop.py -T
TIME(s) PCOMM            PID    PPID   RET ARGS
0.506   run              8745   1828     0 ./run
0.507   bash             8745   1828     0 /bin/bash
0.511   svstat           8747   8746     0 /command/svstat /service/httpd
0.511   perl             8748   8746     0 /usr/bin/perl -e $l=<>;$l=~/(\d+) sec/;p...
0.514   ps               8750   8749     0 /bin/ps --ppid 1 -o pid,cmd,args
0.514   grep             8751   8749     0 /bin/grep org.apache.catalina
0.514   sed              8752   8749     0 /bin/sed s/^ *//;
0.515   xargs            8754   8749     0 /usr/bin/xargs
0.515   cut              8753   8749     0 /usr/bin/cut -d  -f 1
0.523   echo             8755   8754     0 /bin/echo
0.524   mkdir            8756   8745     0 /bin/mkdir -v -p /data/tomcat
[...]
1.533   svstat           8787   8786     0 /command/svstat /service/httpd
1.533   perl             8788   8786     0 /usr/bin/perl -e $l=<>;$l=~/(\d+) sec/;p...
[...]
```

Example: BCC biolatency

What is the distribution of disk I/O latency? Per second?

```
# ./biolatency -mT 1 5
Tracing block device I/O... Hit Ctrl-C to end.

06:20:16
     msecs               : count     distribution
       0 -> 1            : 36       |****************************************|
       2 -> 3            : 1        |*                                       |
       4 -> 7            : 3        |***                                     |
       8 -> 15           : 17       |*****************                       |
      16 -> 31           : 33       |*********************************       |
      32 -> 63           : 7        |*******                                 |
      64 -> 127          : 6        |******                                  |

06:20:17
     msecs               : count     distribution
       0 -> 1            : 96       |****************************************|
       2 -> 3            : 25       |*********                               |
       4 -> 7            : 29       |***********                             |
[...]
```


BCC/BPF: biolatency
100.66.98.191:7402
288-1048575
2144-524287
1072-262143
536-131071
32768-65535
16384-32767
8192-16383
4096-8191
2048-4095
1024-2047
512-1023
256-511
128-255
64-127
32-63
16-31
8-15
4-7
2-3
0-1
11:26:20
11:26:40
11:27:00
11:27:20
11:27:40
11:28:00
256-511:
805

Example: bpftrace readahead

Is readahead polluting the cache?

```
# readahead.bt
Attaching 5 probes...
^C
Readahead unused pages: 128

Readahead used page age (ms):
@age_ms:
[1]                2455 |@@@@@@@@@@@@@@@@                                    |
[2, 4)             8424 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@|
[4, 8)             4417 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@                        |
[8, 16)            7680 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@     |
[16, 32)           4352 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@                        |
[32, 64)              0 |                                                    |
[64, 128)             0 |                                                    |
[128, 256)          384 |@@                                                  |
```

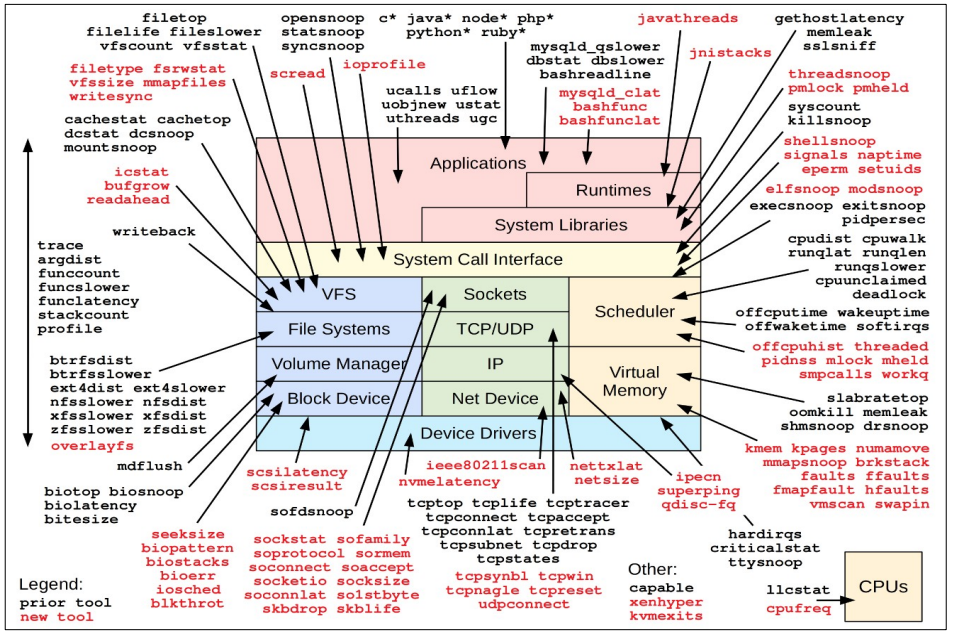
```
#!/usr/local/bin/bpftrace

kprobe:__do_page_cache_readahead    { @in_readahead[tid] = 1; }
kretprobe:__do_page_cache_readahead { @in_readahead[tid] = 0; }

kretprobe:__page_cache_alloc
/@in_readahead[tid]/
{
    @birth[retval] = nsecs;
    @rapages++;
}

kprobe:mark_page_accessed
/@birth[arg0]/
{
    @age_ms = hist((nsecs - @birth[arg0]) / 1000000);
    delete(@birth[arg0]);
    @rapages--;
}

END
{
    printf("\nReadahead unused pages: %d\n", @rapages);
    printf("\nReadahead used page age (ms):\n");
    print(@age_ms); clear(@age_ms);
    clear(@birth); clear(@in_readahead); clear(@rapages);
}
```

Entire readahead.bt bpftrace source

eBPF for Developers

Think like a
sysadmin

Not like a
programmer




```
# define BPF program
prog = """
int hello(void *ctx) {
    bpf_trace_printk("Hello, World!\\n");
    return 0;
}
"""

# load BPF program
b = BPF(text=prog)
b.attach_kprobe(event=b.get_syscall_fnname("clone"), f
```

Think like a **sysadmin**

Get it installed everywhere and use it.

```
# apt-get install bcc-tools bpftrace
# PATH=$PATH:/usr/share/bcc/tools
# execsnoop
# opensnoop
# tcplife
# ext4slower
# biosnoop
[...]
```

These are installed by default at Netflix, Meta, etc.

Think like a **sysadmin**

Get it installed everywhere and use it.

```
# apt-get install bcc-tools bpftrace
# PATH=$PATH:/usr/share/bcc/tools
# execsnoop
# opensnoop
# tcplife
# ext4slower
# biosnoop
[...]
```

Anything periodic running? crontab?

Any misconfigurations? File not found?

Any unexpected TCP sessions?

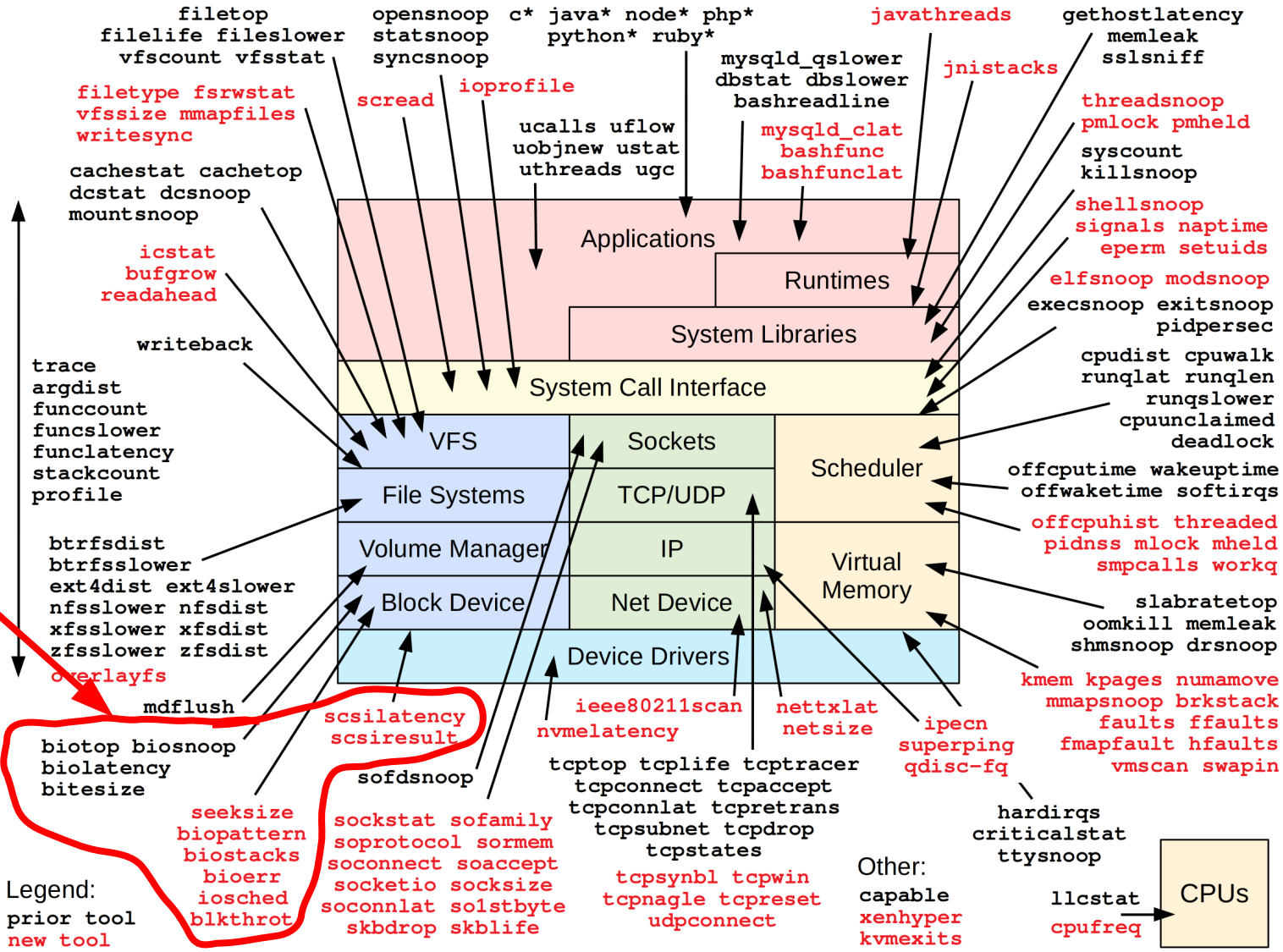
Any file system I/O slower than 10ms?

Any unusual disk access patterns? Outliers?

Print for your office wall, use as a checklist

Suspected disk issue?
Try these first:

https://
www.brendangregg.com/
Perf/bpf_book_tools.png



Recommended tracing front-ends

I want to run some tools

- bcc, bpftrace

I want to hack up some *new* tools

- bpftrace

I want to spend weeks developing a BPF product

- bcc libbpf C, bcc Python (maybe), gobpf, libbpf-rs

New, lightweight,
CO-RE & BTF based

Requires LLVM; becoming
obsolete / special-use only

Recommended tracing front-ends

I want to run some tools — Unix analogies

- bcc, bpftrace — /usr/bin/*

I want to hack up some *new* tools

- bpftrace — bash, awk

I want to spend weeks developing a BPF product

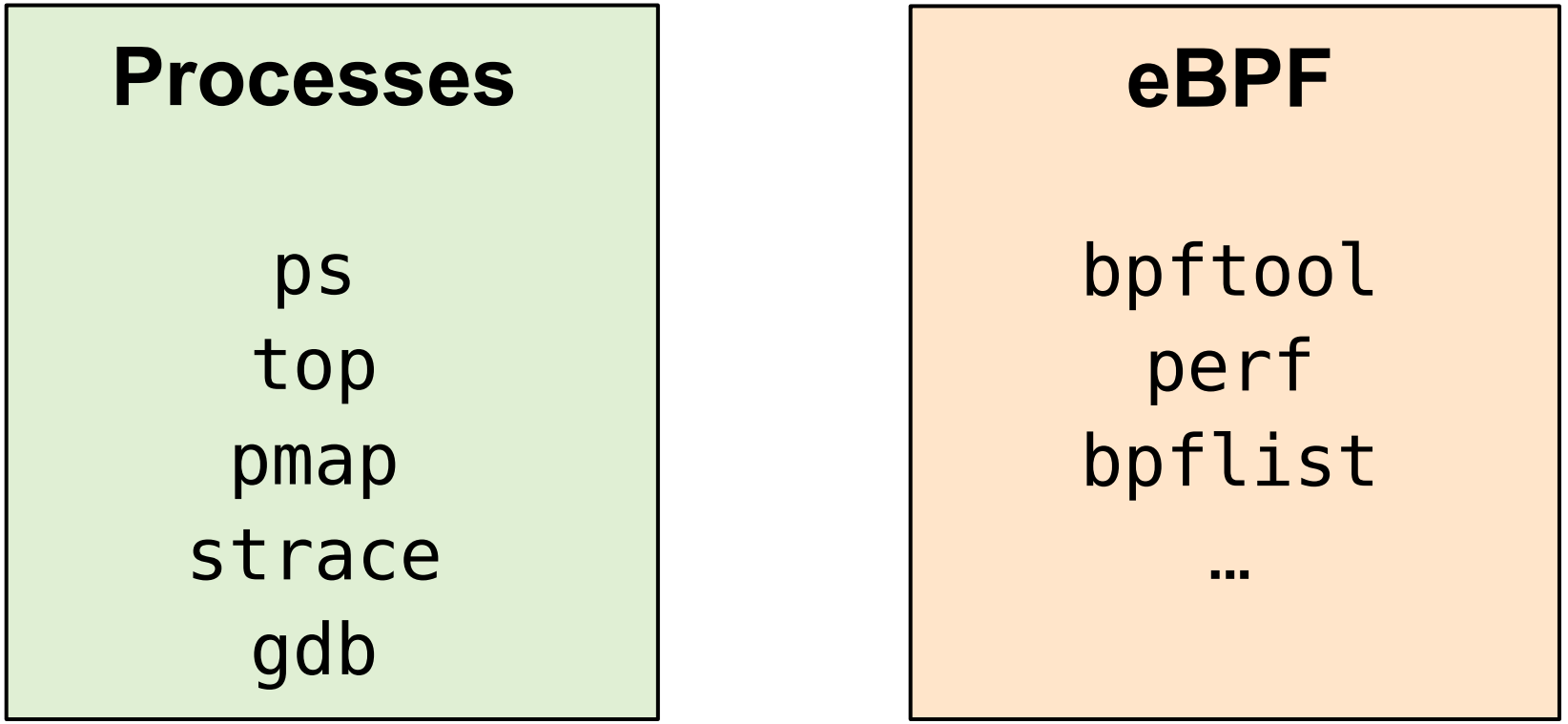
- bcc libbpf C, bcc Python (maybe), gobpf, libbpf-rs — C, C++, Rust

New, lightweight,
CO-RE & BTF based

Requires LLVM; becoming
obsolete / special-use only

Observability *of* eBPF

Observability *of* eBPF (WIP)



bpftool

PID

BPF ID

Event

```
# bpftool perf
pid 1765  fd 6: prog_id 26  kprobe  func blk_account_io_start  offset 0
pid 1765  fd 8: prog_id 27  kprobe  func blk_account_io_done  offset 0
pid 1765  fd 11: prog_id 28  kprobe  func sched_fork  offset 0
pid 1765  fd 15: prog_id 29  kprobe  func ttwu_do_wakeup  offset 0
pid 1765  fd 17: prog_id 30  kprobe  func wake_up_new_task  offset 0
pid 1765  fd 19: prog_id 31  kprobe  func finish_task_switch  offset 0
pid 1765  fd 26: prog_id 33  tracepoint  inet_sock_set_state
pid 21993  fd 6: prog_id 232  uprobe  filename /proc/self/exe  offset 1781927
pid 21993  fd 8: prog_id 233  uprobe  filename /proc/self/exe  offset 1781920
pid 21993  fd 15: prog_id 234  kprobe  func blk_account_io_done  offset 0
pid 21993  fd 17: prog_id 235  kprobe  func blk_account_io_start  offset 0
pid 25440  fd 8: prog_id 262  kprobe  func blk_mq_start_request  offset 0
pid 25440  fd 10: prog_id 263  kprobe  func blk_account_io_done  offset 0
```

```
# bpftool prog dump jited id 263
int trace_req_done(struct pt_regs * ctx):
0xffffffffc082dc6f:
; struct request *req = ctx->di;
   0:   push   %rbp
   1:   mov    %rsp,%rbp
   4:   sub    $0x38,%rsp
   b:   sub    $0x28,%rbp
   f:   mov    %rbx,0x0(%rbp)
  13:   mov    %r13,0x8(%rbp)
  17:   mov    %r14,0x10(%rbp)
  1b:   mov    %r15,0x18(%rbp)
  1f:   xor    %eax,%eax
  21:   mov    %rax,0x20(%rbp)
  25:   mov    0x70(%rdi),%rdi
; struct request *req = ctx->di;
  29:   mov    %rdi,-0x8(%rbp)
; tsp = bpf_map_lookup_elem((void *)bpf_pseudo_fd(1, -1), &req);
  2d:   movabs $0xffff96e680ab0000,%rdi
  37:   mov    %rbp,%rsi
  3a:   add    $0xfffffffffffffff8,%rsi
; tsp = bpf_map_lookup_elem((void *)bpf_pseudo_fd(1, -1), &req);
  3e:   callq  0xffffffffc39a49c1
```

LPC 2019, Arnaldo Carvalho de Melo
CPU profiling of BPF programs

“We should be able to single-step execution...
We should be able to take a core dump of all state.”

– David S. Miller, LSFMM 2019

UNIVAC 1
1951

eBPF Future Predictions

eBPF Future Predictions

More device drivers, incl. USB on BPF

Monitoring agents

Intrusion detection systems

TCP congestion controls

CPU & container schedulers

FS readahead policies

CDN accelerator

Reality Check

More perf wins come from CPU flame graphs
not CLI tracing

3. eBPF Flame Graphs

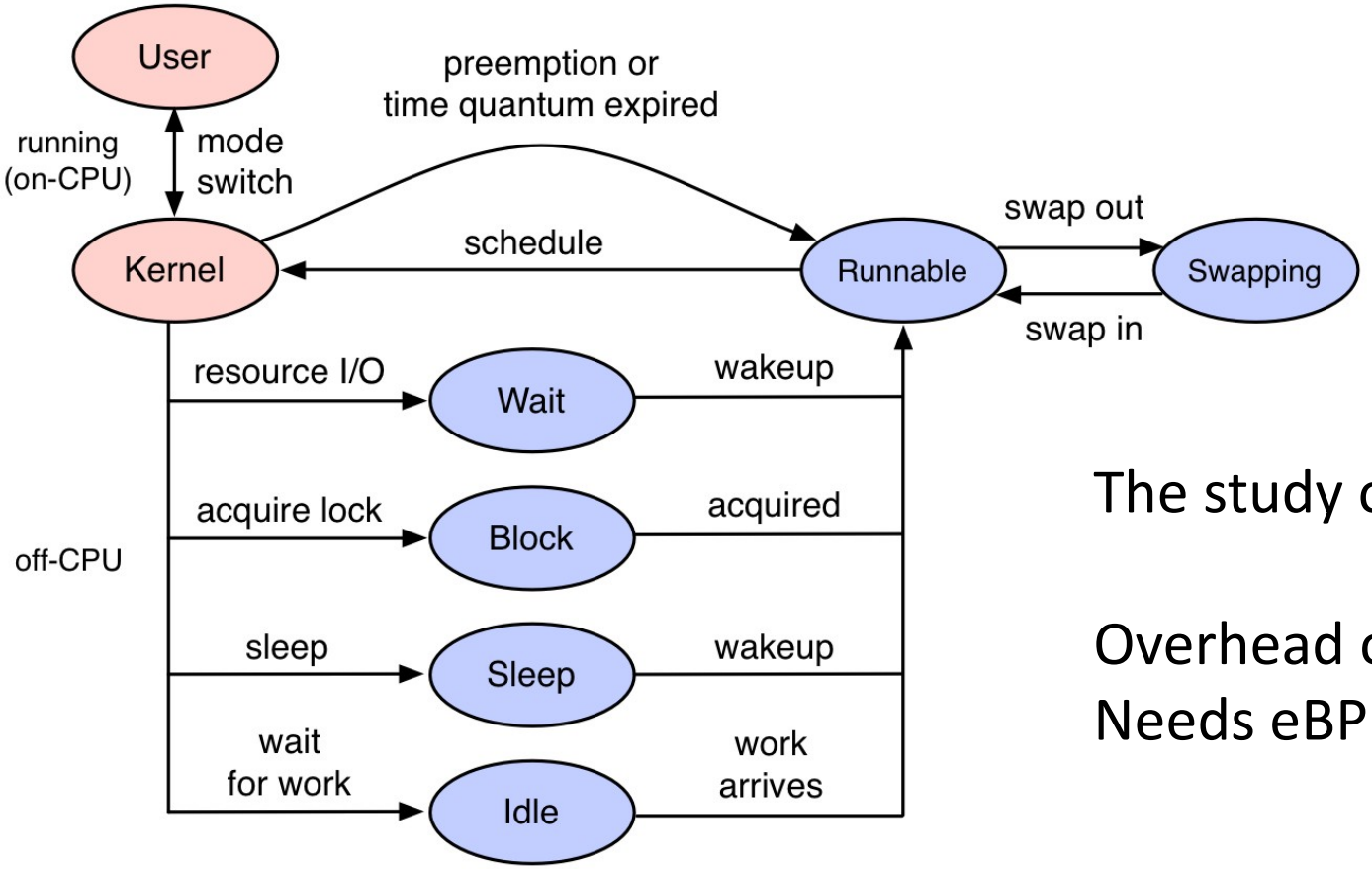
Linux eBPF CPU Flame Graphs

```
# profile -af -F 49 30 | ./flamegraph.pl > out.svg
```

Lower overhead profiling

Make continuous profiling more practical

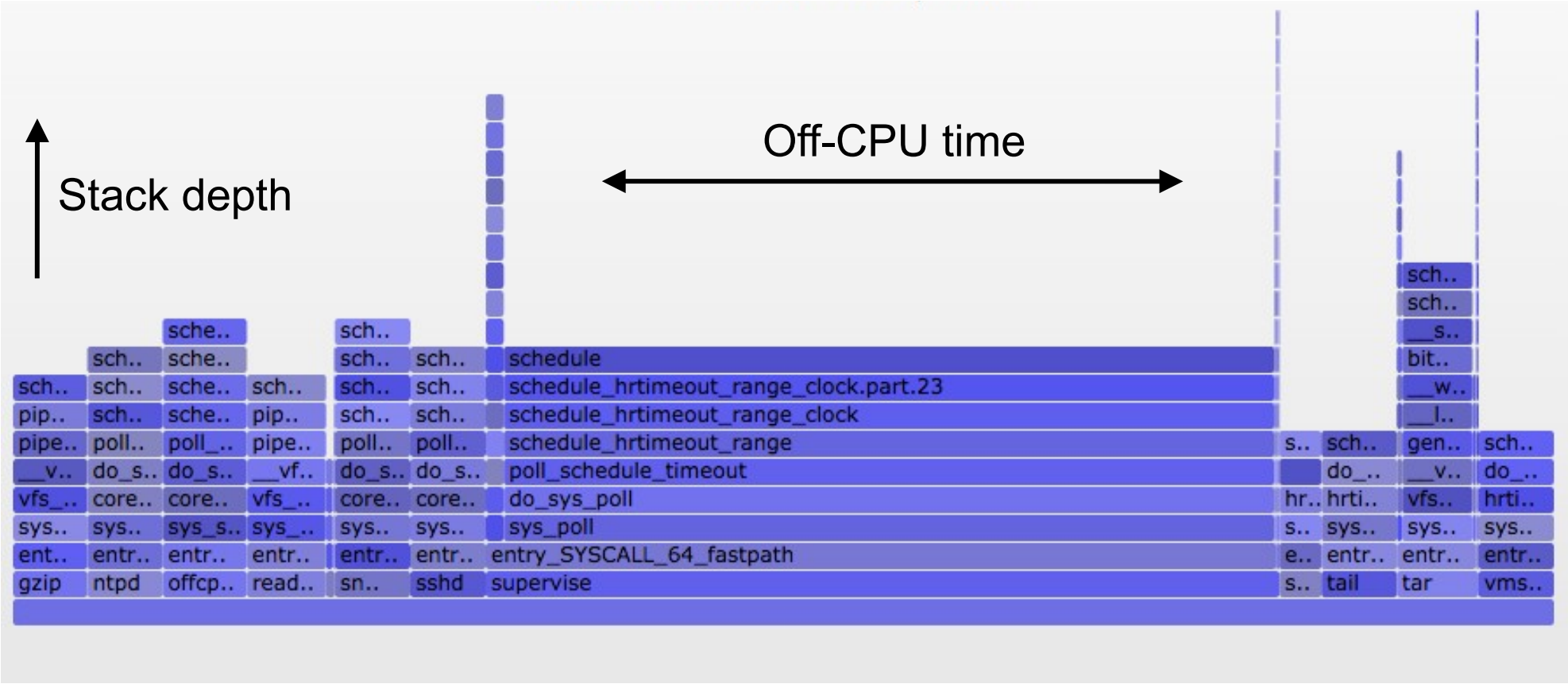
Off-CPU Analysis



The study of blocking states

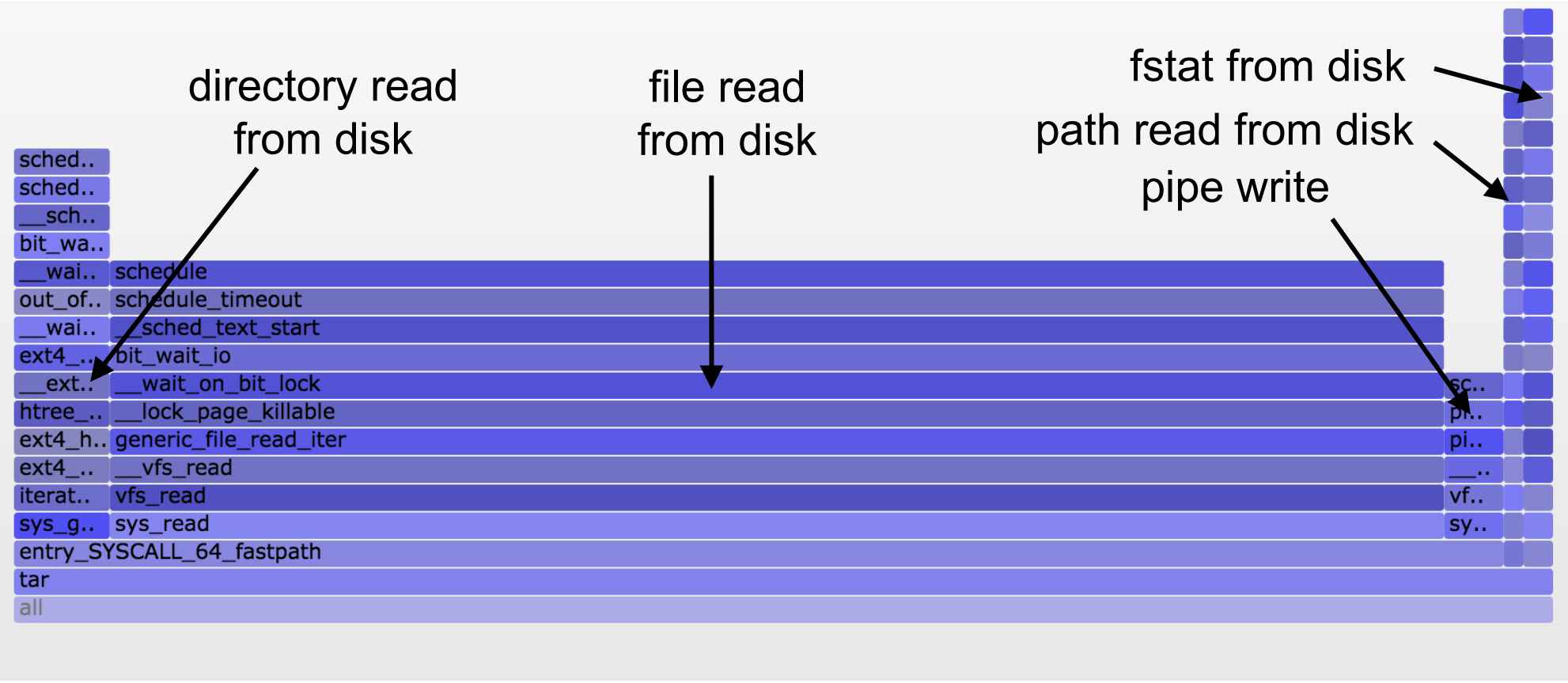
Overhead often prohibitive
Needs eBPF!

Off-CPU Time Flame Graph



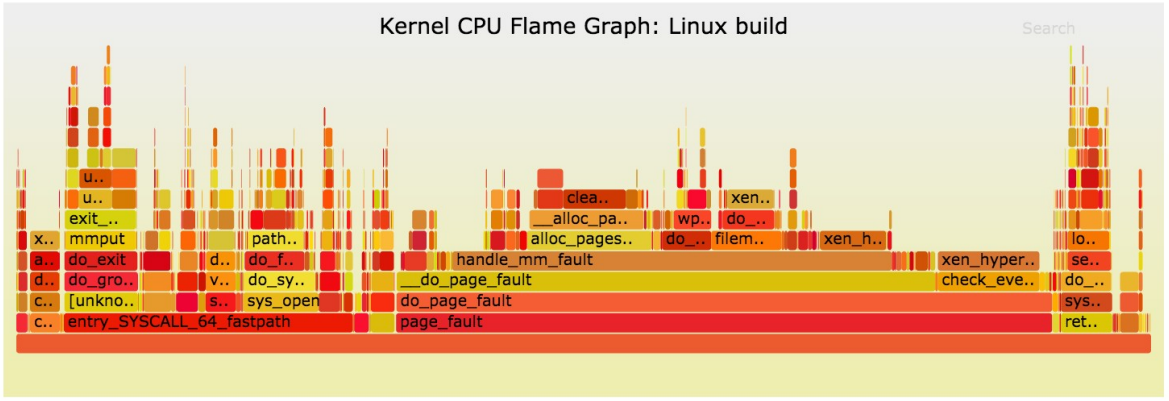
http://www.brendangregg.com/blog/2016-02-01/linux-wakeup-offwake-profiling.html

Off-CPU Time (zoomed): tar(1)

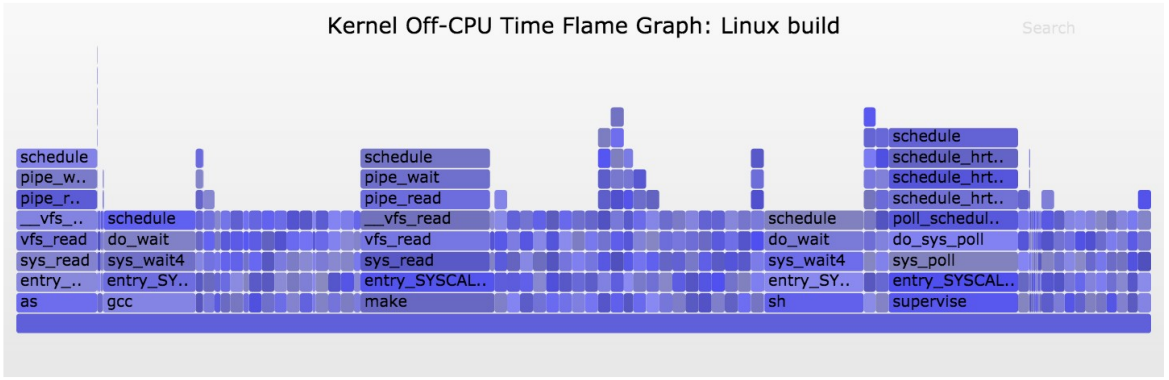


Only showing kernel stacks in this example

CPU + Off-CPU Flame Graphs: See Everything

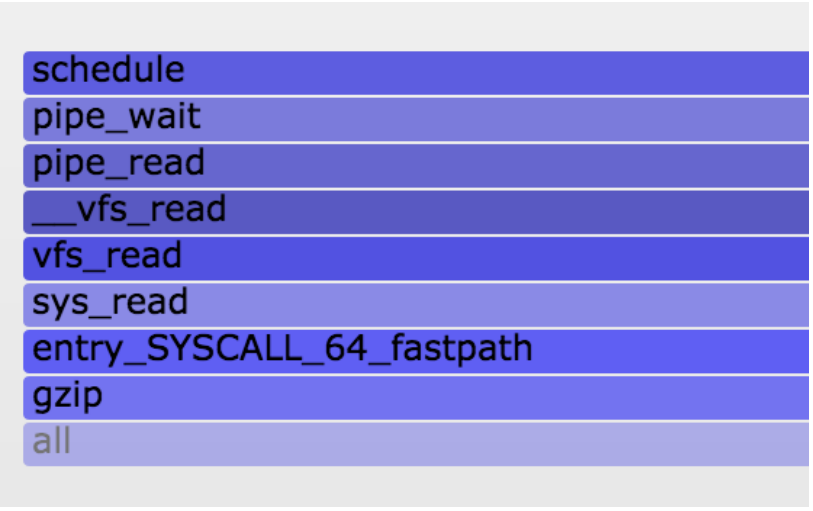


CPU



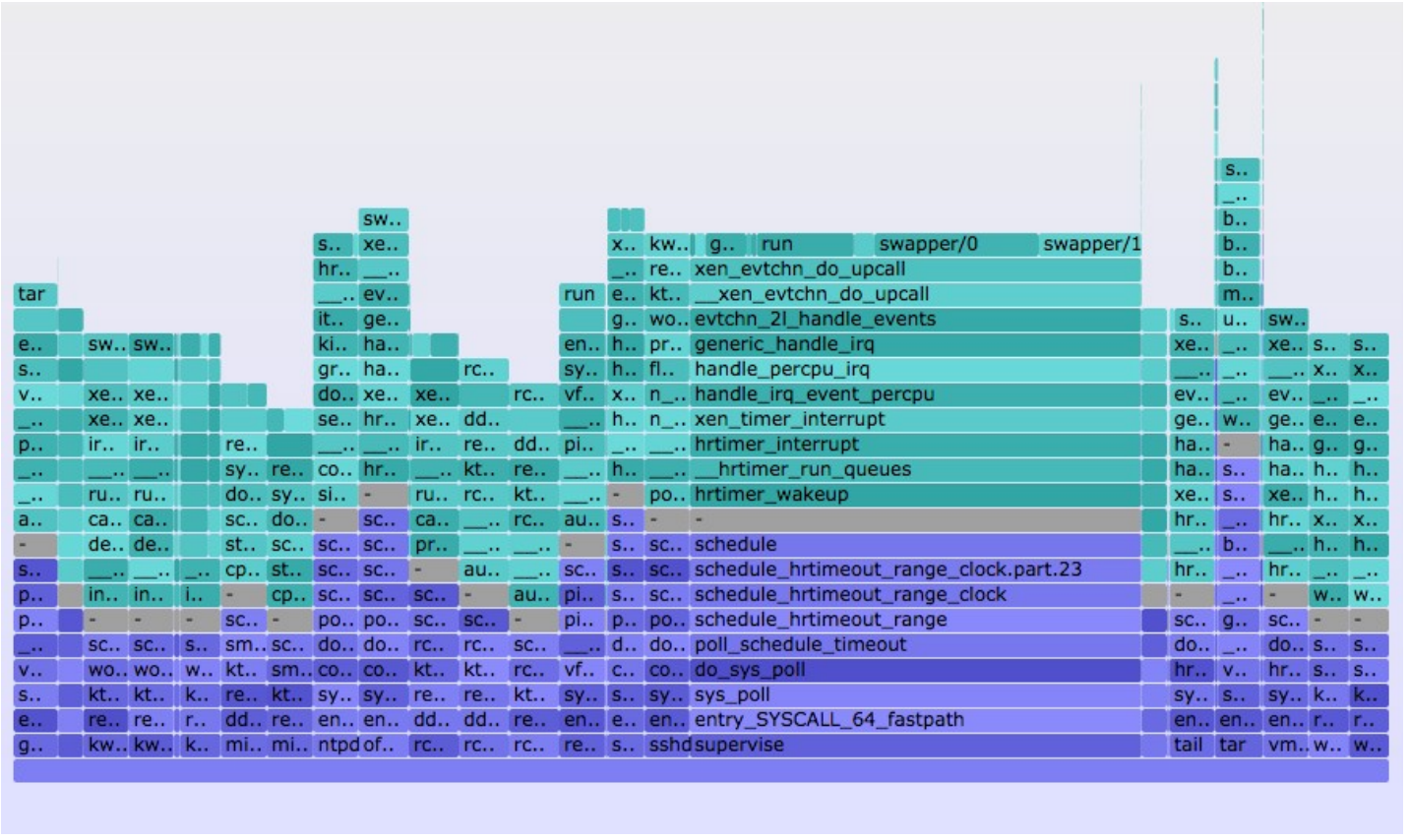
Off-CPU

Off-CPU Time (zoomed): gzip(1)



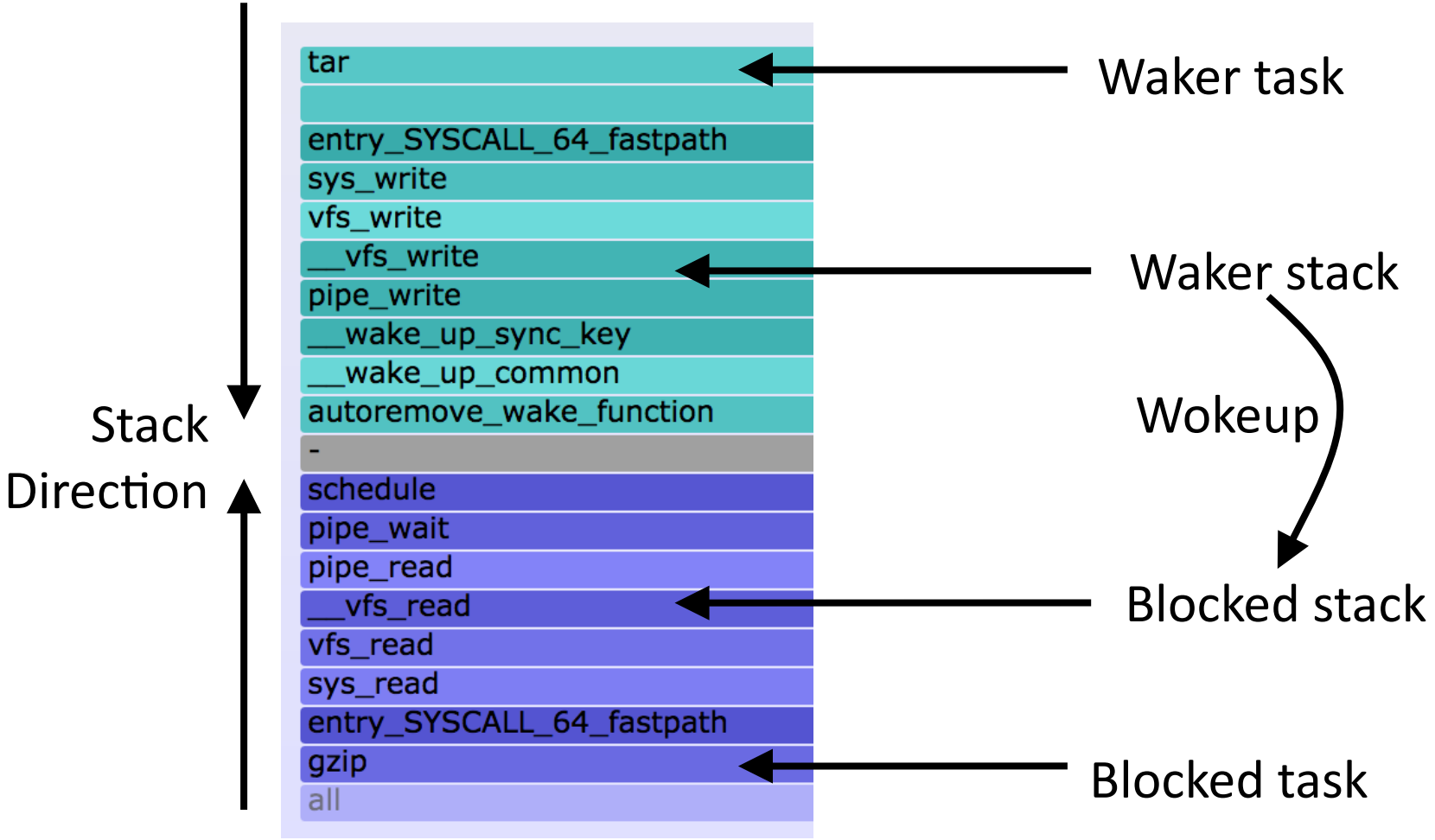
The off-CPU stack trace often doesn't show the root cause of latency.
What is gzip blocked on?

Off-Wake Time Flame Graph



Uses eBPF to merge off-CPU and waker stack in kernel context

Off-Wake Time Flame Graph (zoomed)



eBPF Flame Graph Futures

Practical off-CPU flame graphs

Other types: disk, network, malloc, etc.

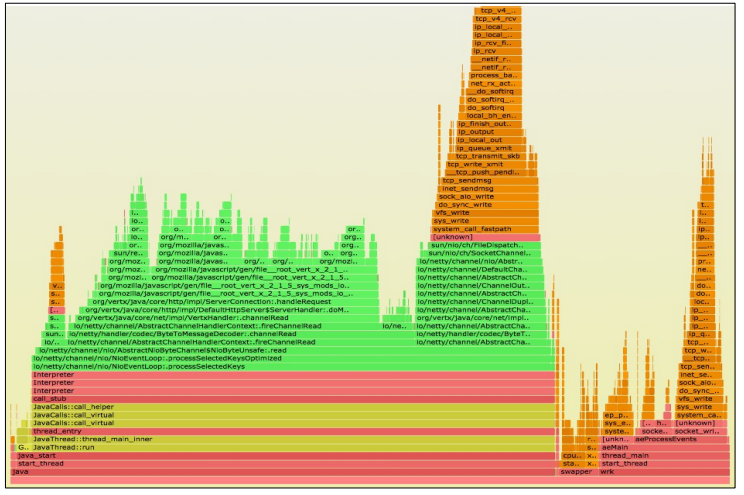
Custom stack walking

- Frame pointers not needed
- Include other app context

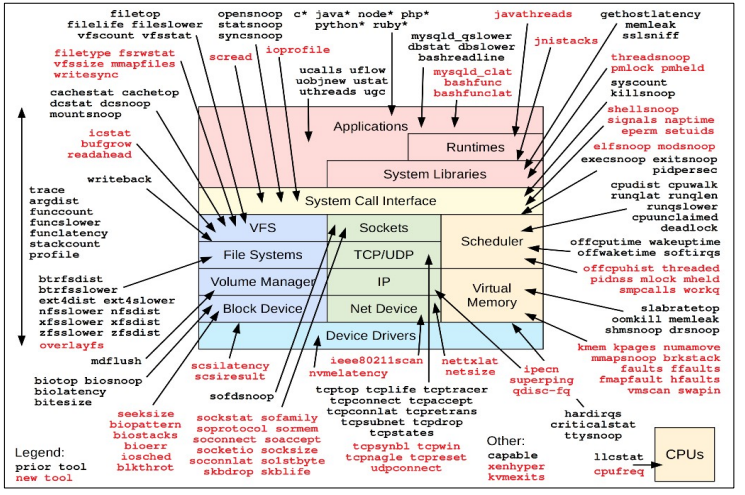
And/or frame pointers everywhere

Take Aways

Print these for your office wall:

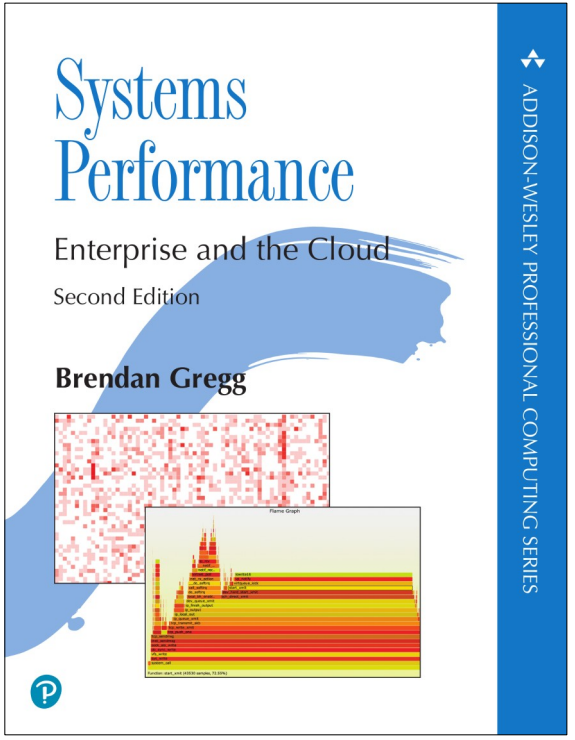


A CPU flame graph of your software



Open source eBPF tools you can run

Books



Volume 1

Volume 2

References/URLs

"The Flame Graph" Communications of the ACM, Vol. 56, No. 6 (June 2016)
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http://www.brendangregg.com/perf.html
https://github.com/iovisor/bcc
https://github.com/iovisor/bpftrace

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Canonical: BPF support, and libc-prof

brendan@intel.com

All photos credit myself; except slide 42 (KernelRecipes) and 43 (UbuntuMasters)