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Flame Graphs
on
FreeBSD

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Google
"flame graph"
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Web
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Blazing Performance
with
Flame Graphs
Brendan Gregg
Performance Profile Index
Off-CPU Time Flame Graph

Agenda

1. Genesis
2. Generation
3. CPU
4. Memory
5. Disk I/O
6. Off-CPU
7. Chain

1. Genesis

The Problem

- The same MySQL load on one host runs at 30% higher CPU than another. Why?
- CPU profiling should answer this easily

```
# dtrace -x ustackframes=100 -n 'profile-997 /execname == "mysqld"/ {
    @[ustack()] = count(); } tick-60s { exit(0); }'
dtrace: description 'profile-997 ' matched 2 probes
CPU     ID                    FUNCTION:NAME
  1  75195                        :tick-60s
[...]
            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
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           5530
```

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            mysqld`handle_one_connection+0x1a6
```

this stack

was sampled this many times

Only unique stacks are shown, with their counts.
This compresses the output.

```
# dtrace -x ustackframes=100 -n 'profile-997 /execname == "mysqld"/ {
    @[ustack()] = count(); } tick-60s { exit(0); }'
dtrace: description 'profile-997 ' matched 2 probes
CPU     ID                    FUNCTION:NAME
  1  75195                        :tick-60s
[...]
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            libc.so.1`pthread_setschedprio+0x1f
            mysqld`_Z16dispatch_command19enum_server_commandP3THDPcj+0x[illegible]
            mysqld`_Z10do_commandP3THD+0x198
            mysqld`handle_one_connection+0x1a6
            libc.so.1`_thrp_setup+0x8d
            libc.so.1`_lwp_start
           4884
```

This stack – the most frequent – is <2% of the samples

```
            mysqld`_Z13add_to_statusP17system_status_varS0_+0x47
            mysqld`_Z22calc_sum_of_all_statusP17system_status_var+0x67
            mysqld`_Z16dispatch_command19enum_server_commandP3THDPcj+0x1222
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            mysqld`_Z10do_commandP3THD+0x198
            mysqld`handle_one_connection+0x1a6
```

Despite the terse output, I elided over *500,000 lines*
Here is what all the output looks like…

Size of
one stack

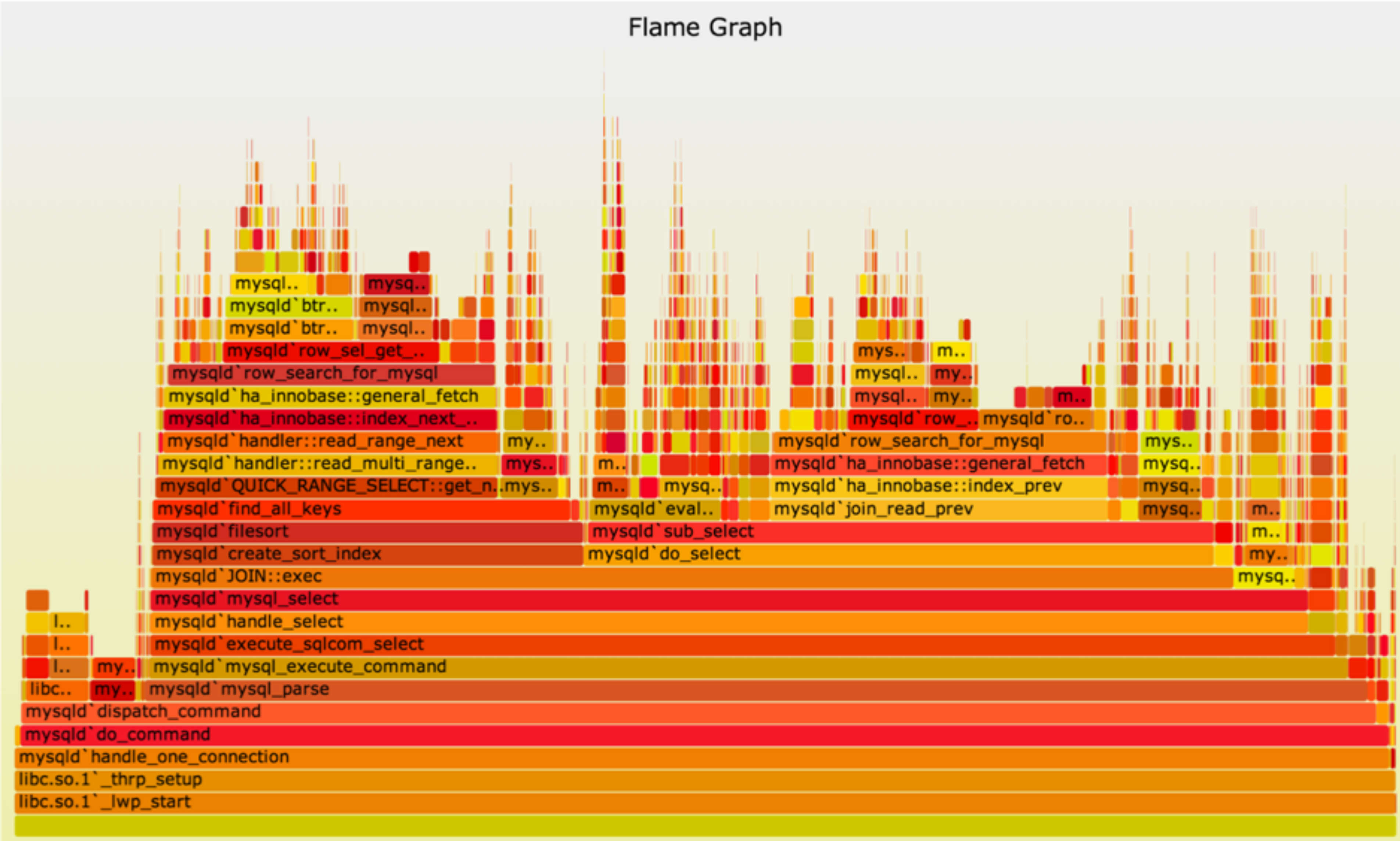
Last two
stacks

These are just the unique stacks.

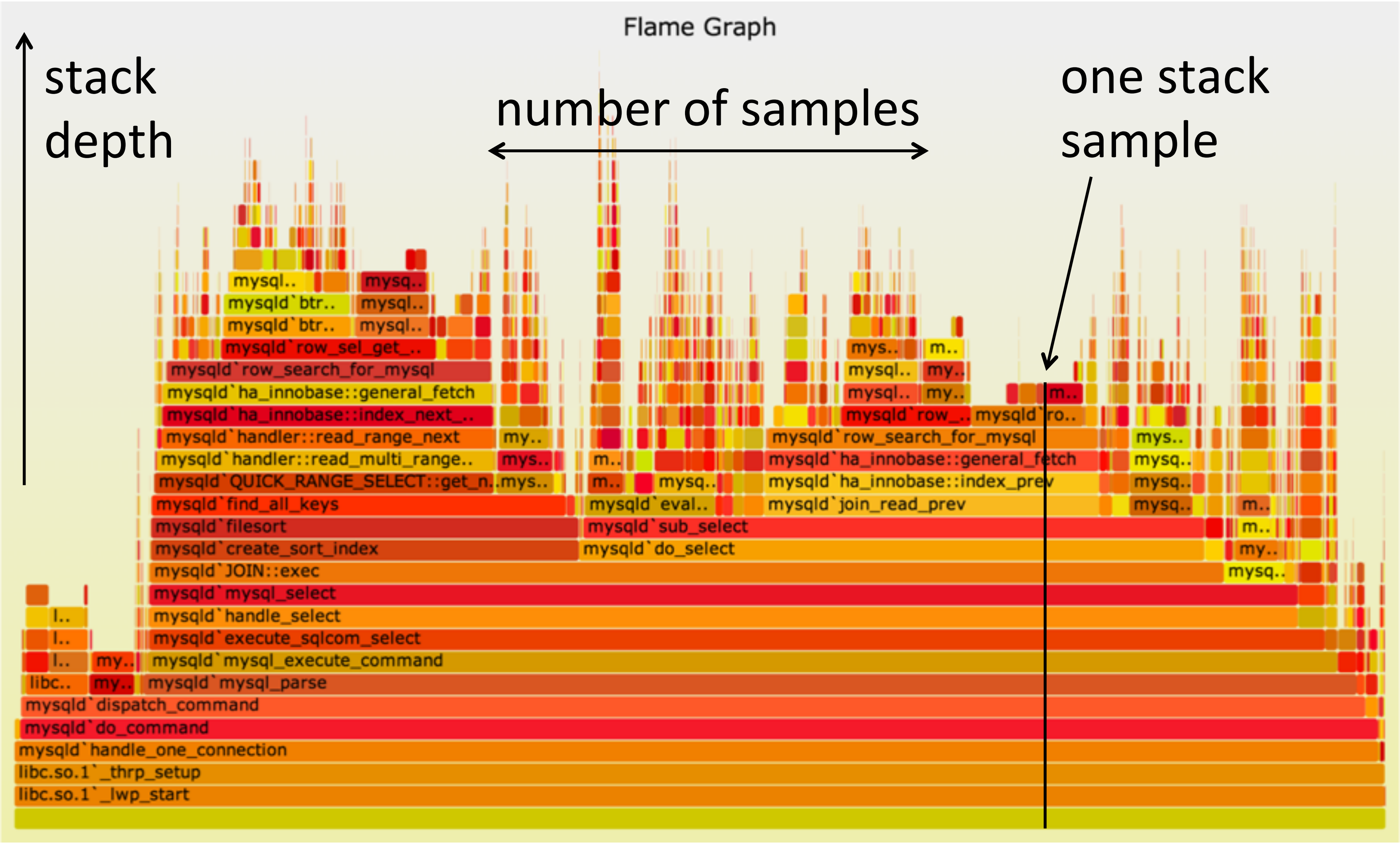
I have to compare this grey featureless square,
with a grey square from the other host,
and explain the 30% CPU difference.

And I need to do this by Friday.

Flame Graph of the same data



Flame Graph of the same data



Problem Solved

- Comparing two flame graphs was trivial
  - MySQL codepath difference suggested different compiler optimizations, which was confirmed
- Flame graph needed in this case
  - Profile data was too large to consume otherwise
  - Not always the case: the profiler output might be small enough to read directly. For CPU profiles, it often isn't.

Flame Graphs: Definition

- Boxes: are functions
  - Visualizes a frame of a stack trace
- y-axis: stack depth
  - The top function led to the profiling event, everything beneath it is ancestry: explains why
- x-axis: spans samples, sorted alphabetically
  - Box width shows sample count: bigger for more
  - Alphabetical sort improves merging of like-frames
- Colors: either random or a dimension
  - Random helps separate columns

Flame Graphs: Presentation

- All threads can be shown in the same graph
  - So can multiple distributed systems
- Can be interactive
  - Mouse over for details
  - Click to zoom
- Can be invented
  - Eg, Facebook's icicle-like flame graphs
- Uses for color:
  - Differentials
  - Modes: user/library/kernel

2. Generation

Examples

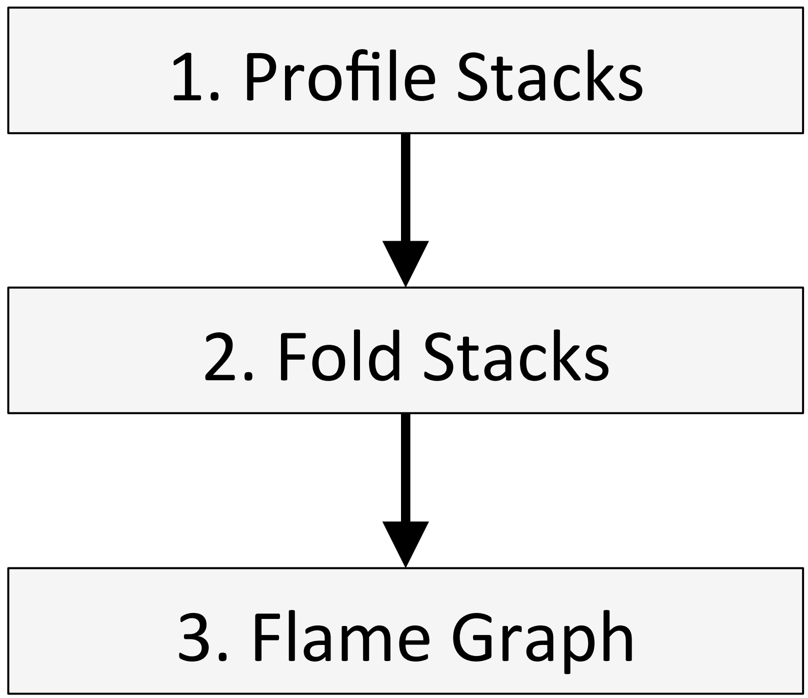
- Using DTrace to profile kernel CPU usage:

```
# git clone https://github.com/brendangregg/FlameGraph
# cd FlameGraph
# kldload dtraceall     # if needed
# dtrace -x stackframes=100 -n 'profile-197 /arg0/ {
    @[stack()] = count(); } tick-60s { exit(0); }' -o out.stacks
# ./stackcollapse.pl out.stacks | ./flamegraph.pl > out.svg
```

- Using pmcstat to profile stall cycles:

```
…
# pmcstat –S RESOURCE_STALLS.ANY -O out.pmcstat sleep 10
# pmcstat -R out.pmcstat -z100 -G out.stacks
# ./stackcollapse-pmc.pl out.stacks | ./flamegraph.pl > out.svg
```

Steps



Step 1. Profile Stacks

- FreeBSD data sources:
  - DTrace stack() or ustack()
  - pmcstat -G stacks
  - Application profilers
  - Anything that can gather full stacks

Step 2. Fold Stacks

- Profiled stacks are "folded" to 1 line per stack:

```
func1;func2;func3;… count
…
```

- Many converters exist (usually Perl). Eg:

Format	Program
DTrace	stackcollapse.pl
FreeBSD pmcstat	stackcollapse-pmc.pl
Linux perf_events	stackcollapse-perf.pl
OS X Instruments	stackcollapse-instruments.pl
Lightweight Java Profiler	stackcollapse-ljp.awk

Step 3. Flame Graph

- flamegraph.pl converts folded stacks into an interactive SVG Flame Graph
  - Uses JavaScript. Open in a browser.

```
USAGE: ./flamegraph.pl [options] infile > outfile.svg
    --title         # change title text
    --width         # width of image (default 1200)
    --height        # height of each frame (default 16)
    --minwidth      # omit smaller functions (default 0.1 pixels)
    --fonttype      # font type (default "Verdana")
    --fontsize      # font size (default 12)
    --countname     # count type label (default "samples")
    --nametype      # name type label (default "Function:")
    --colors        # "hot", "mem", "io" palette (default "hot")
    --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)
```

Extra Step: Filtering

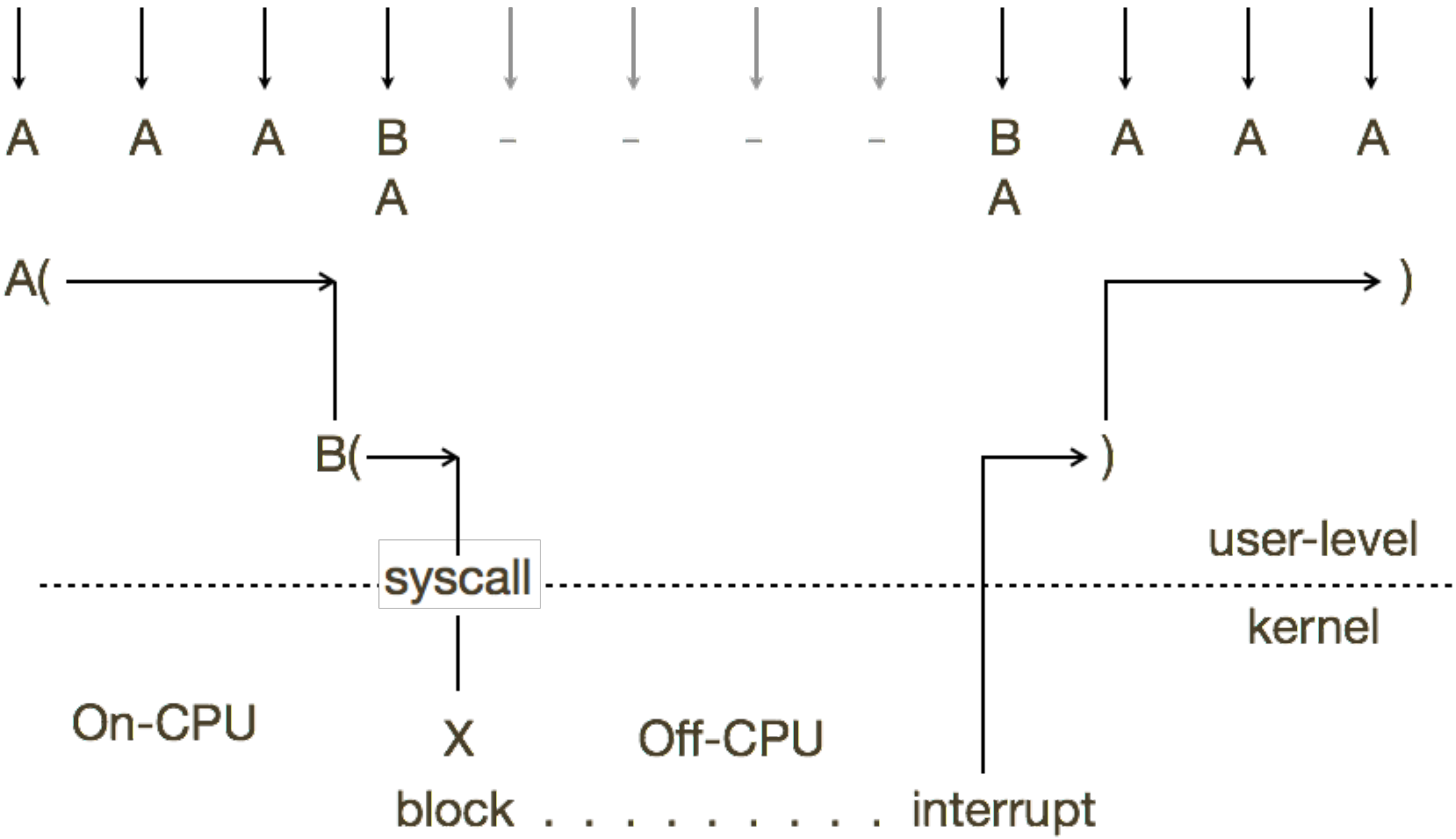
- Folded stacks (single line records) are easy to process with grep/sed/awk
- For CPU profiles, I commonly exclude cpu_idle():

```
# ./stackcollapse.pl out.stacks | grep –v cpu_idle | \
    ./flamegraph.pl out.folded > out.svg
```

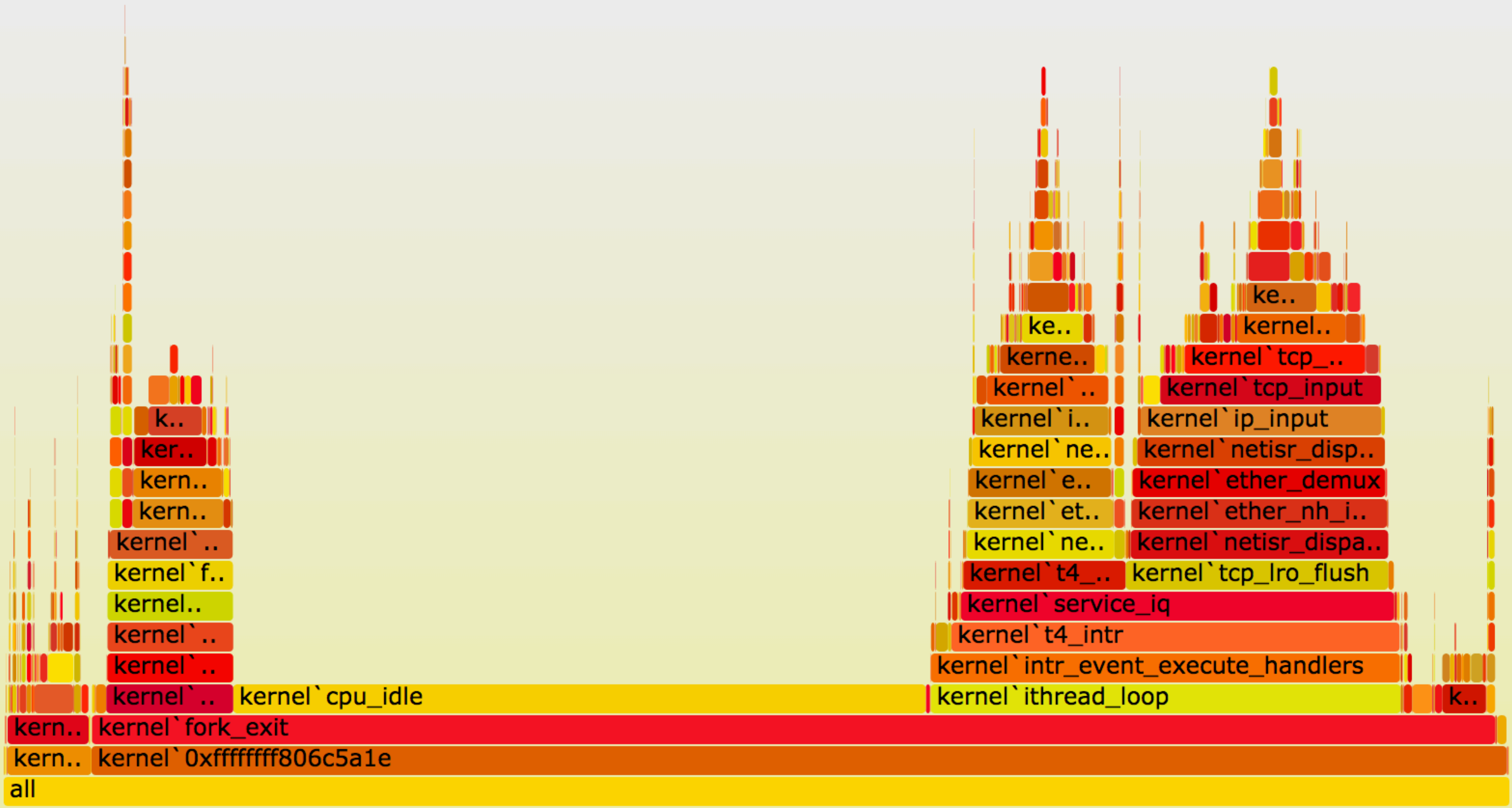
- Or click-to-zoom

3. CPU

CPU: Stack Sampling

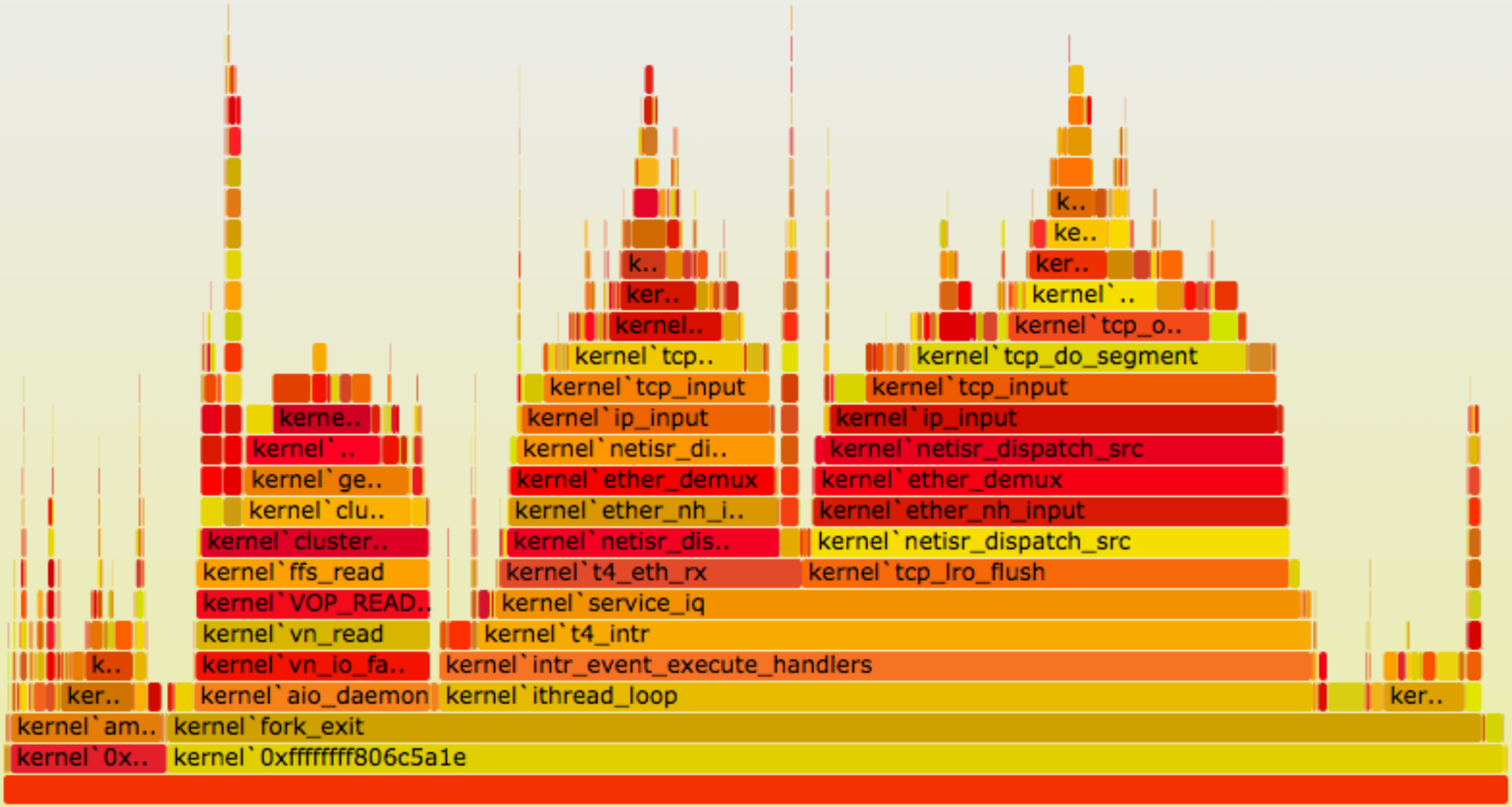


FreeBSD CPU Flame Graph



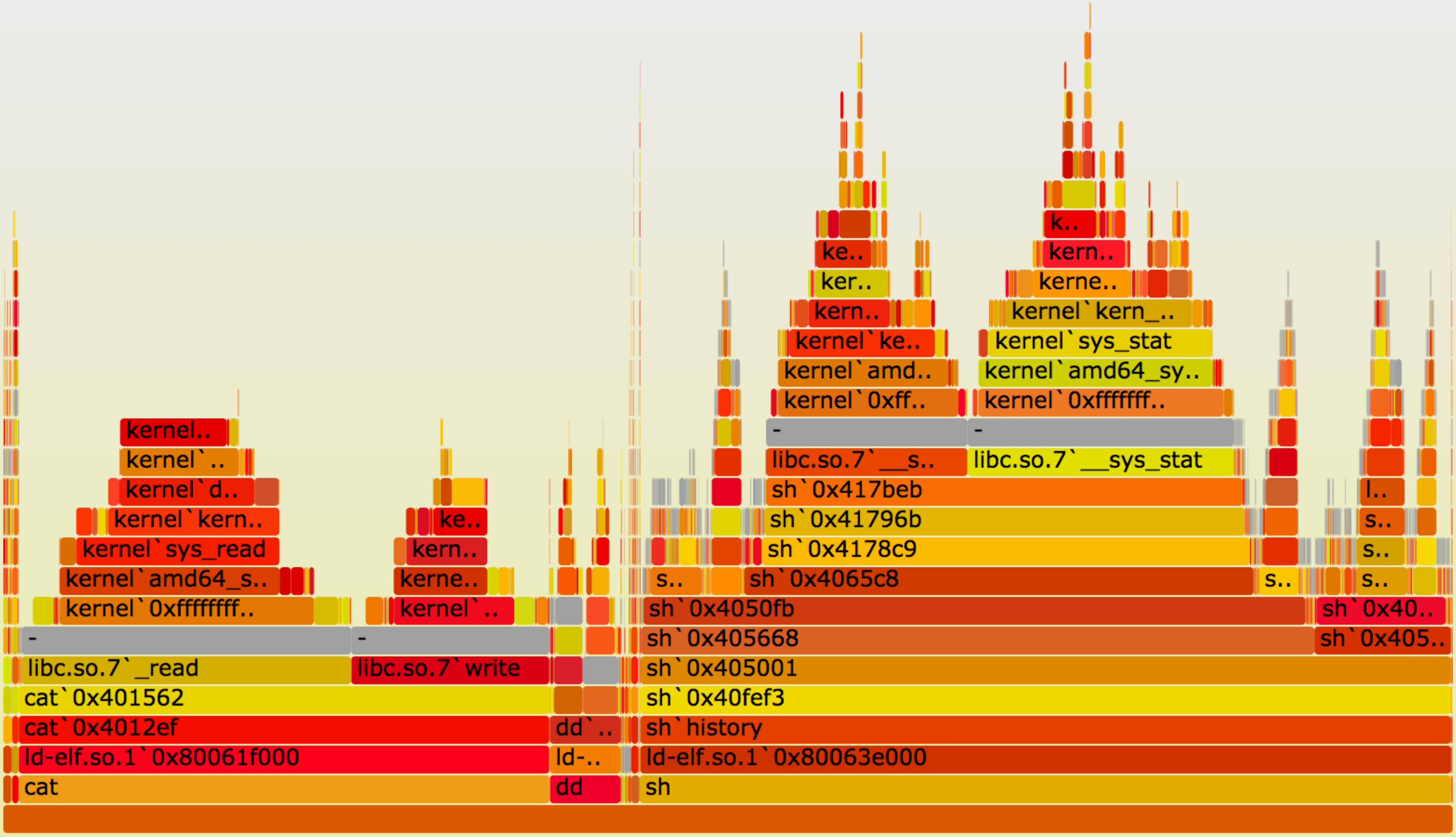
cpu-freebsd01.svg

FreeBSD Kernel CPU Flame Graph (no cpu_idle)



cpu-freebsd02.svg

FreeBSD Kernel and User CPU Flame Graph



cpu-freebsd03.svg

DEMO

CPU: Commands

- DTrace kernel stack sampling at 199 Hertz, 60 s:

```
# dtrace -x stackframes=100 -n 'profile-199 /arg0/ {
    @[stack()] = count(); } tick-60s { exit(0); }' -o out.stacks
```

- DTrace user stack sampling at 99 Hertz, 60 s:

```
# dtrace -x ustackframes=100 -n 'profile-99 /arg1/ {
    @[ustack()] = count(); } tick-60s { exit(0); }' -o out.stacks
```

- Warnings:
  - ustack() more expensive
  - Short-lived processes will miss symbol translation

CPU: Commands

- DTrace both stack sampling at 99 Hertz, 30 s:

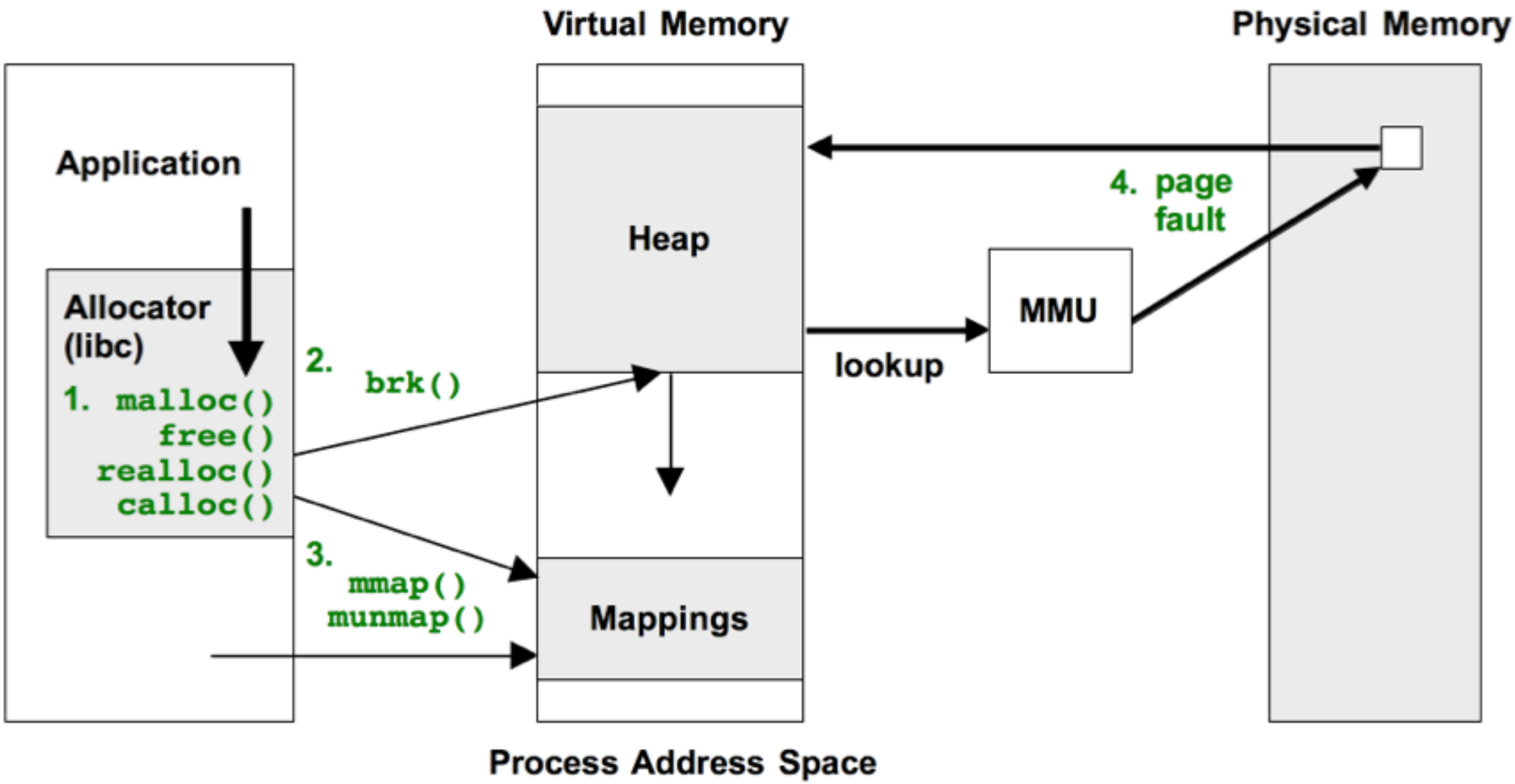
```
# dtrace -x stackframes=100 -x ustackframes=100 -n '
    profile-99 { @[stack(), ustack(), execname] = count(); }
    tick-30s { printa("%k-%k%s\n%@d\n", @); exit(0); }
    ' -o out.stacks
```

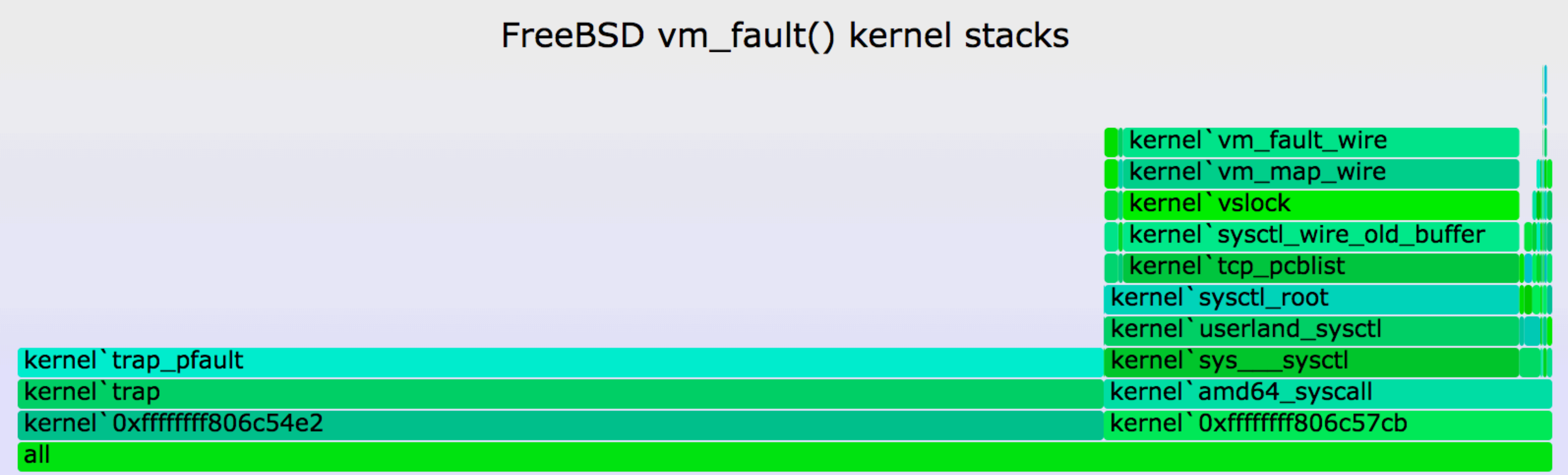
  – This prints kernel then user stacks, separated by a "-" line. flamegraph.pl makes "-" lines grey (separators)

- pmcstat for everything beyond sampling

4. Memory

Memory: 4 Targets





vm_faults-kernel01.svg

DEMO

Memory: Commands

- DTrace page fault profiling of kernel stacks, 30 s:

```
# dtrace –x stackframes=100 -n 'fbt::vm_fault:entry {
    @[stack()] = count(); } tick-30s { exit(0) }' -o out.stacks
```

- Flame graphs generated with --colors=mem

```
# cat out.stacks | ./stackcollapse.pl | ./flamegraph.pl \
    --title="FreeBSD vm_fault() kernel stacks" --colors=mem \
    --countname=pages --width=800 > vm_faults-kernel01.svg
```

- See earlier diagram for other targets

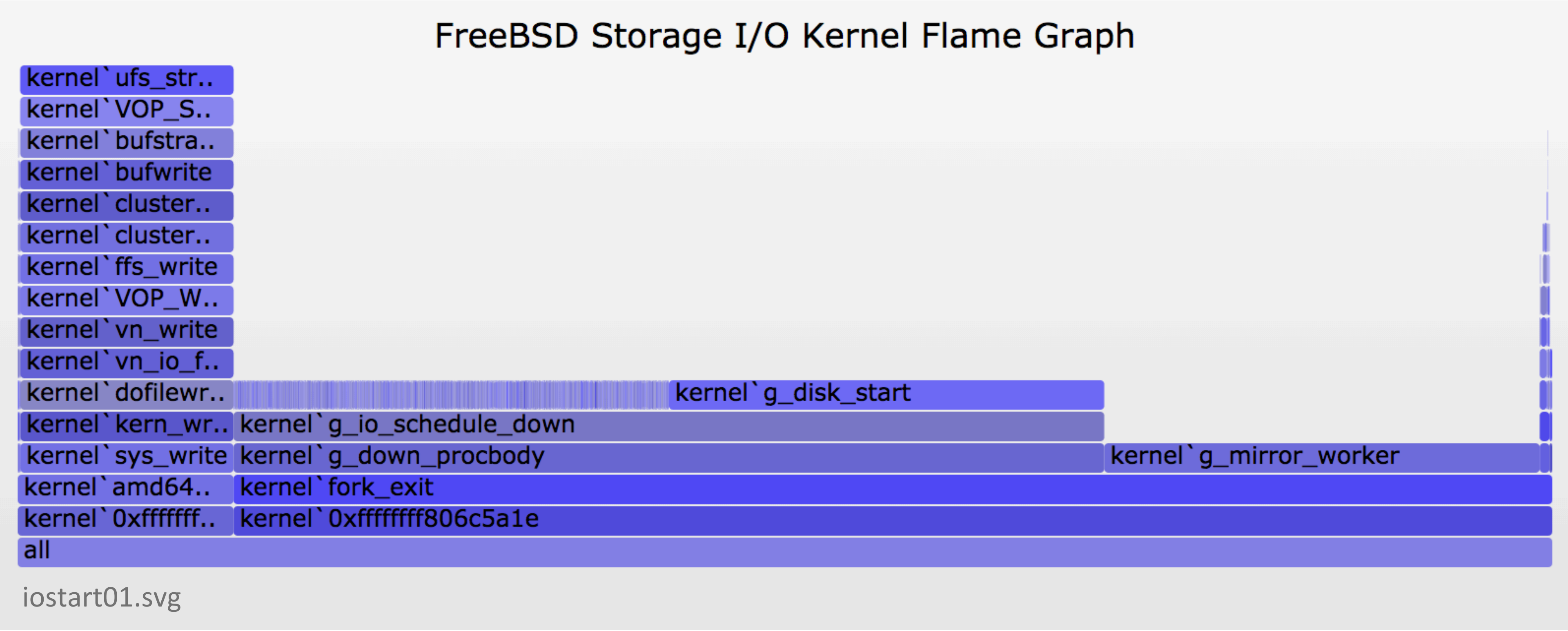
Memory: Commands

- DTrace page fault profiling of user stacks, 5 s:

```
# dtrace -x ustackframes=100 -n 'fbt::vm_fault:entry {
    @[ustack(), execname] = count(); } tick-5s { exit(0) }
    ' -o out.stacks
```

- Warnings:
  – Overhead for user-level stack translation relative to number of unique stacks, and might be significant
  – Stacks for short-lived processes may be hex, as translation is performed after the process has exited
- See also other memory target types (earlier pic)

5. Disk I/O


FreeBSD Storage I/O Kernel Flame Graph
kernel`ufs_str..
kernel`VOP_S..
kernel`bufstra..
kernel`bufwrite
kernel`cluster..
kernel`cluster..
kernel`ffs_write
kernel`VOP_W..
kernel`vn_write
kernel`vn_io_f..
kernel`dofilewr..
kernel`g_disk_start
kernel`kern_wr..
kernel`g_io_schedule_down
kernel`sys_write
kernel`g_down_procbody
kernel`g_mirror_worker
kernel`amd64..
kernel`fork_exit
kernel`0xfffffff..
kernel`0xffffffff806c5a1e
all
iostart01.svg

DEMO

Disk I/O: Commands

- Device I/O issued with kernel stacks, 30 s:

```
# dtrace –x stackframes=100 -n 'io:::start {
    @[stack()] = count(); } tick-10s { exit(0) }' -o out.stacks
```

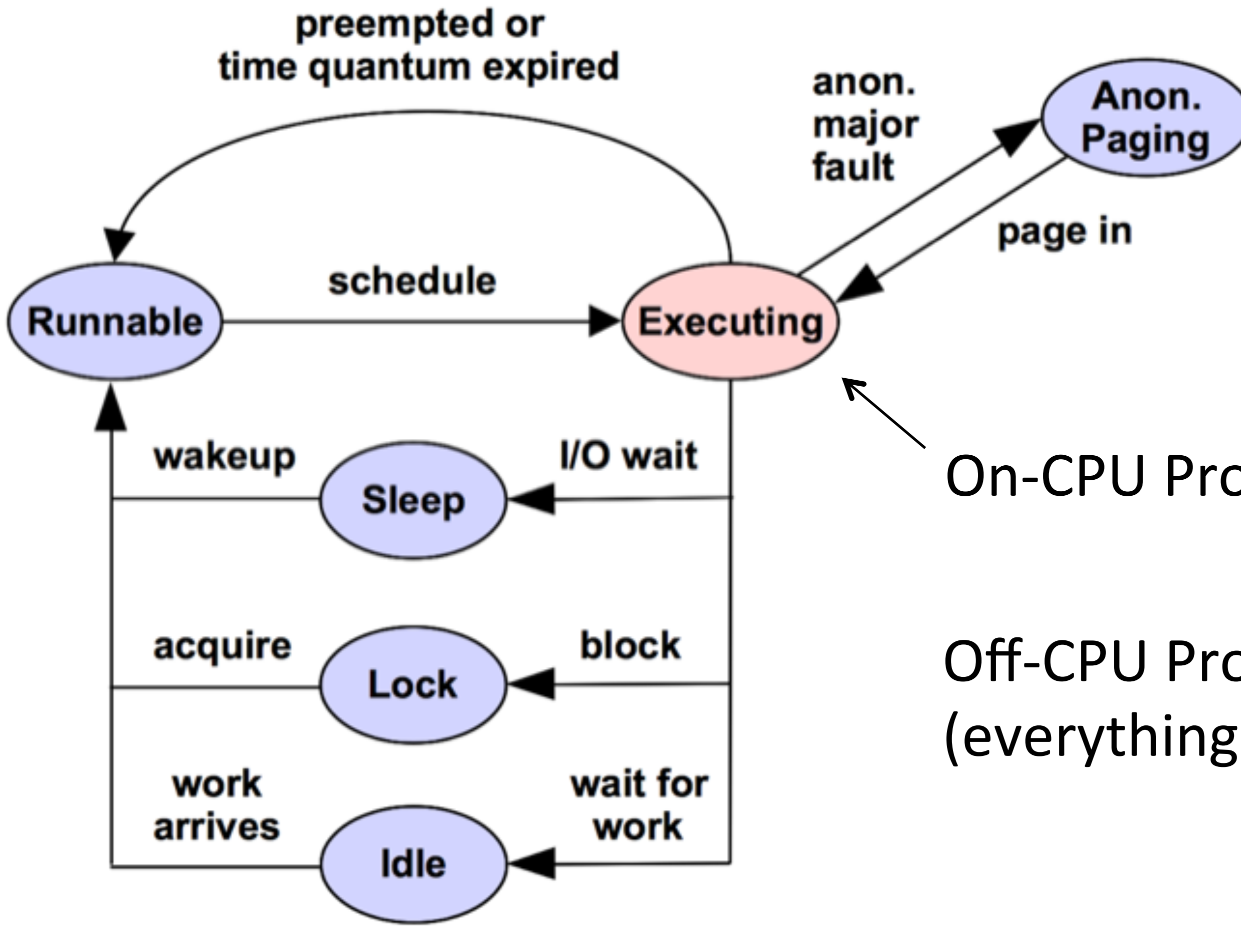
- Flame graphs generated with --colors=io

```
# cat out.stacks | ./stackcollapse.pl | ./flamegraph.pl \
    --title="FreeBSD Storage I/O Kernel Flame Graph" --colors=io\
    --countname=io--width=800 > iostart01.svg
```

- Note that this shows IOPS; would be better to measure and show latency

6. Off-CPU

Off-CPU Profiling

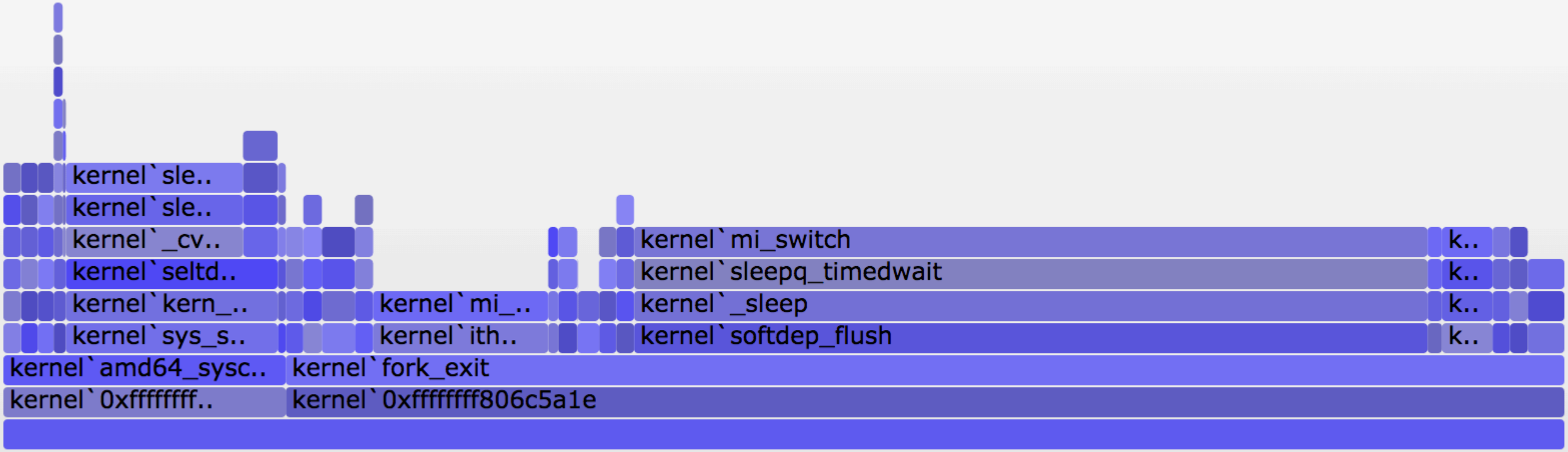


On-CPU Profiling

Off-CPU Profiling
(everything else)

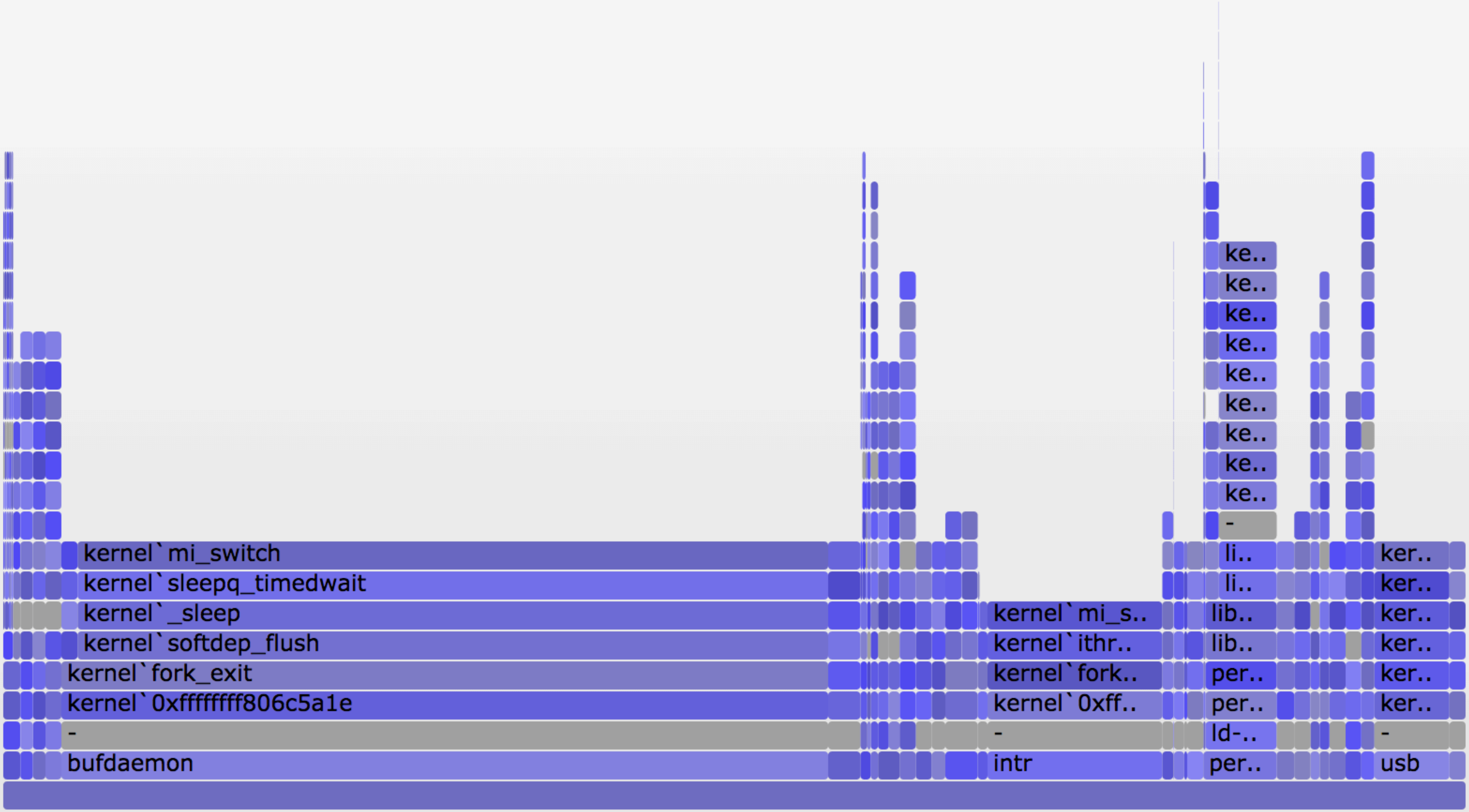
Thread State Transition Diagram

FreeBSD Off-CPU Time Kernel Flame Graph



off-kernel01.svg

FreeBSD Off-CPU Time Flame Graph



off-both01.svg

DEMO

Off-CPU: Commands

- DTrace off-CPU time kernel stacks, 10 s:

```
# dtrace -x dynvarsize=8m -x stackframes=100 –n ‘
    sched:::off-cpu { self->ts = timestamp; }
    sched:::on-cpu /self->ts/ { @[stack()] =
        sum(timestamp - self->ts); self->ts = 0; }
    tick-10s { normalize(@, 1000000); exit(0); }' -o out.stacks
```

- Flame graph: countname=ms
- Warning: Often high overhead. DTrace will drop:

```
dtrace: 886 dynamic variable drops with non-empty dirty list
```

- User-level stacks more interesting, and expensive

Off-CPU: Commands

- DTrace off-CPU time kernel & user stacks, 10 s:

```
# dtrace -x dynvarsize=8m -x stackframes=100 -x ustackframes=100 –n '
    sched:::off-cpu { self->ts = timestamp; }
    sched:::on-cpu /self->ts/ {
        @[stack(), ustack(), execname] = sum(timestamp - self->ts);
        self->ts = 0; }
    tick-10s { normalize(@, 1000000);
        printa("%k-%k%s\n%@d\n", @); exit(0); }
    ' -o out.offcpu
```

- Beware overheads
- Real reason for blocking often obscured
  – Need to trace the wakeups, and examine *their* stacks

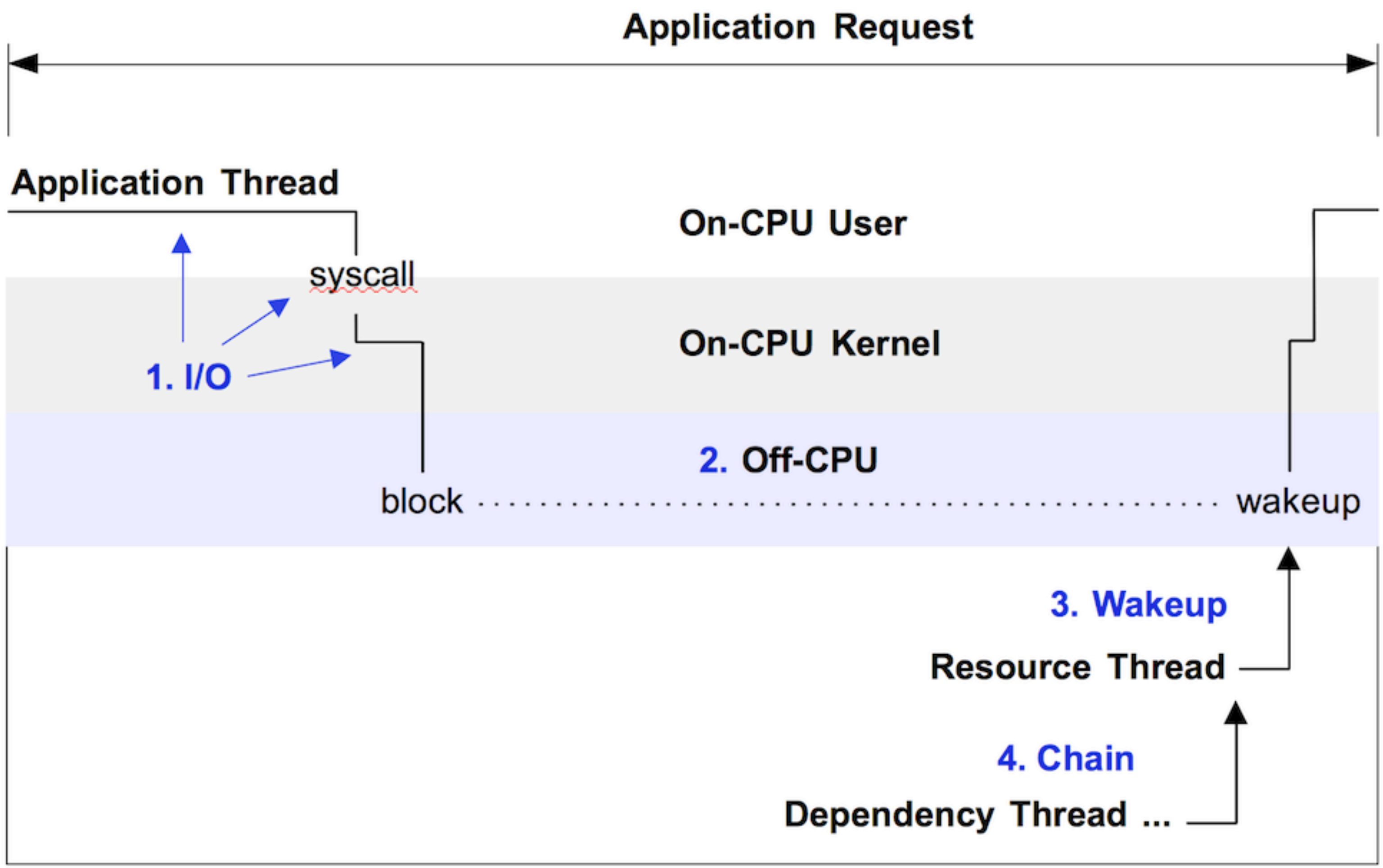
Solve ALL The Issues

- Tantalizingly close to solving all perf issues:

On-CPU Issues	Off-CPU Issues
Common	Common
Some solved using top alone	Some solved using iostat/systat
Many solved using CPU (Sample) Flame Graphs	Some solved using lock profiling
Most of the remainder solved using CPU performance counters	Some solved using Off-CPU Flame Graphs
Usually a solved problem	**Many not straightforward**

7. Chain Graphs

Walking the Wakeups…



chain-sshd.svg

DEMO

Chain Graphs: Commands

- This may be too advanced for current DTrace
  - Can't save stacks as variables
  - Overheads for tracing everything can become serious
- My prototype involved workarounds
  - Aggregating off-CPU->on-CPU time by:
    - execname, pid, blocking CV address, and stacks
  - Aggregating sleep->wakeup time by the same
  - Perl post-processing to connect the dots
  - Assuming that CV addrs aren't reused during tracing

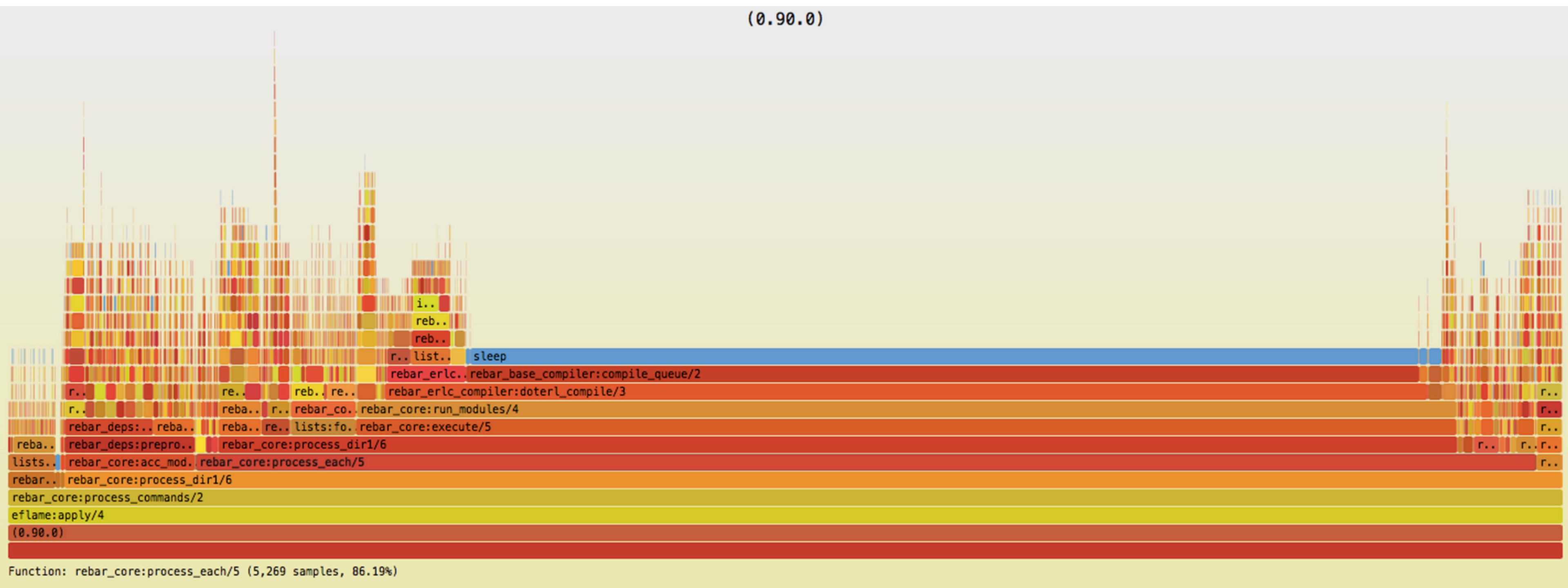
Grand Unified Analysis

- There are two types of performance issues:
  - On-CPU: Usually solved using CPU flame graphs
  - Off-CPU: Can be solved using chain graphs
- Combining CPU & chain graphs would provide a unified visualization for all perf issues
- Similar work to chain graphs:
  - Francis Giraldeau (École Polytechnique de Montréal), wakeup graph using LTTng, + distributed systems: http://www.tracingsummit.org/w/images/0/00/TracingSummit2014-Why-App-Waiting.pdf

Other Topics

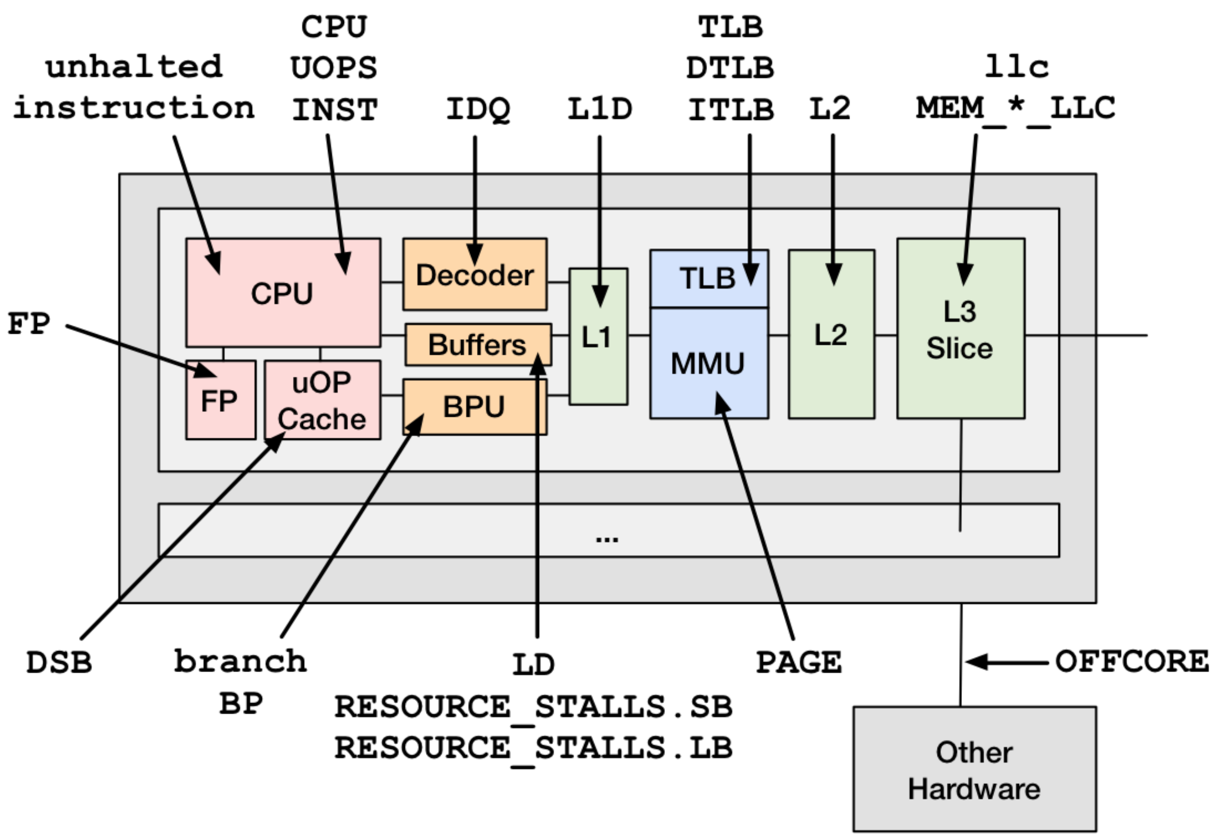
Hot/Cold Flame Graphs

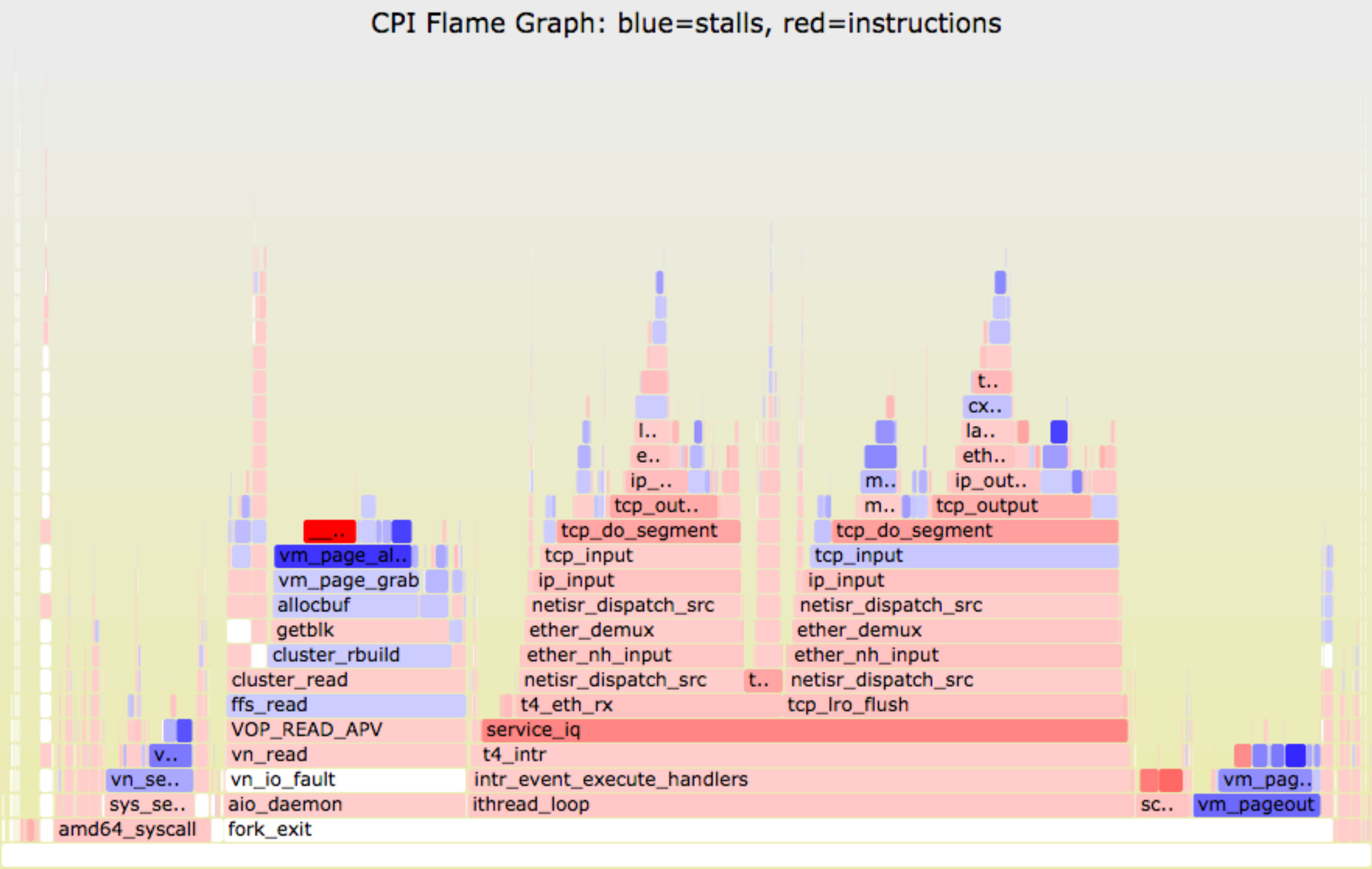
- CPU samples & off-CPU time in one flame graph
  - Off-CPU time often dominates & compresses CPU time too much. By-thread flame graphs helps.
- Example by Vladimir Kirillov, adding a blue frame:



CPU Counters

- Use pmcstat to make flame graphs for cycles, instructions, cache misses, stall cycles, CPI, …





cpi-flamegraph-01.svg

Differential Flame Graphs

- Just added (used to make the CPI flame graph)
- Useful for non-regression testing: hue shows difference between profile1 and profile2

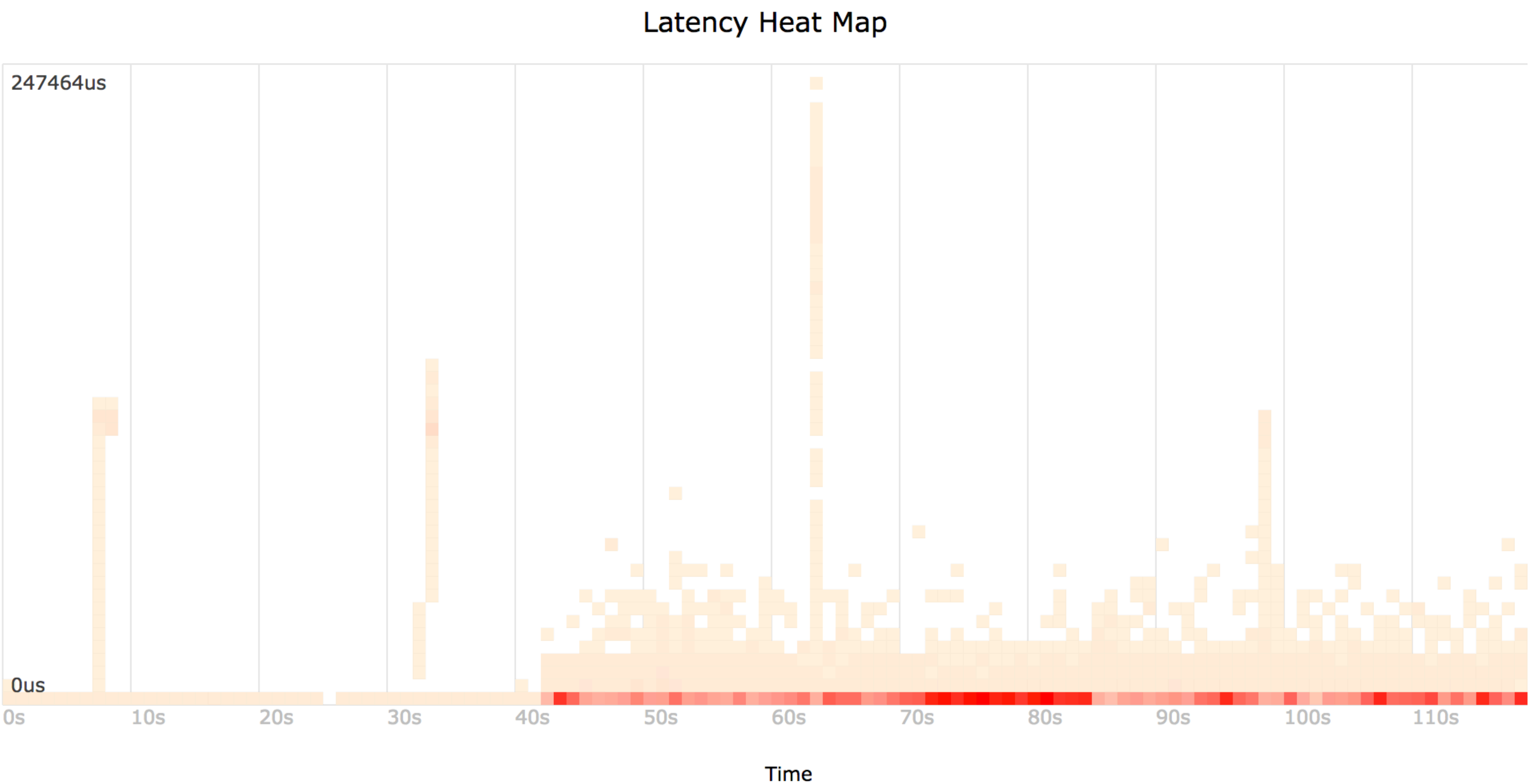
Flame Charts

- Similar to flame graphs, but different x-axis
- x-axis: passage of time
- Created by Google for Chrome/v8, inspired by flame graphs
- Needs timestamped stacks
  - Flame graphs just need stacks & counts, which is usually much less data

Other Implementations/Uses

- See http://www.brendangregg.com/flamegraphs.html#Updates
- Some use application profile sources, which should work on FreeBSD
- Thanks everyone who has contributed!

Other Text -> Interactive SVG Tools



https://github.com/brendangregg/HeatMap

References & Links

- Flame Graphs:
  - http://www.brendangregg.com/flamegraphs.html
  - http://www.brendangregg.com/FlameGraphs/cpuflamegraphs.html
  - http://www.brendangregg.com/FlameGraphs/memoryflamegraphs.html
  - http://www.brendangregg.com/FlameGraphs/offcpuflamegraphs.html
  - http://www.brendangregg.com/FlameGraphs/hotcoldflamegraphs.html
  - http://www.slideshare.net/brendangregg/blazing-performance-with-flame-graphs and https://www.youtube.com/watch?v=nZfNehCzGdw
  - https://github.com/brendangregg/FlameGraph
  - http://agentzh.org/misc/slides/off-cpu-flame-graphs.pdf
- Netflix Open Connect Appliance (FreeBSD):
  - https://openconnect.itp.netflix.com/
- Systems Performance, Prentice Hall:
  - http://www.brendangregg.com/sysperfbook.html

Thanks

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