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BPF Performance Tools Workshop

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Welcome to BPF Performance Tools

1. https://github.com/brendangregg/bpf-perf-workshop has these slides and the labs. Open it in a browser.
2. SSH to a lab instance (see bit of paper)
   - Or setup your own system. Instructions are at that URL.
3. Check BCC and bpftrace tools work. On the lab instance:

```
$ sudo bash
# opensnoop-bpfcc
[...]
# opensnoop.bt
[...]
```

BCC (Ubuntu naming scheme)

bpftrace

Press Ctrl-C to end each of these

4. Begin lab 1. You have 15 minutes.

Learning Objectives

1. Understand BPF, BCC, and bpftrace
2. Follow different analysis methodologies
3. Use BCC tools to analyze disk I/O issues
4. “ “ short-lived process issues
5. “ “ runq latency issues
6. Develop at least one new bpftrace tool

This was developed as a 90-minute workshop for USENIX LISA 2019

URLs

- https://github.com/brendangregg/bpf-perf-workshop
- https://github.com/iovisor/bcc Labs 1-3
  - https://github.com/iovisor/bcc/blob/master/docs/tutorial.md
- https://github.com/iovisor/bpftrace Labs 4-5
  - https://github.com/iovisor/bpftrace/blob/master/docs/tutorial_one_liners.md
  - https://github.com/iovisor/bpftrace/blob/master/docs/reference_guide.md
- https://github.com/brendangregg/bpf-perf-tools-book

Lab 1 Discussion

BPF

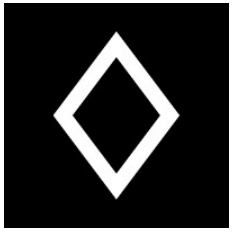
BPF 1992: Berkeley Packet Filter

```
# 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

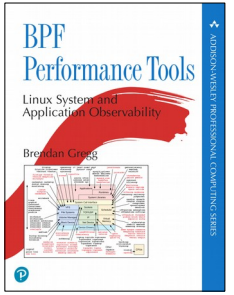
BPF 2019: aka extended BPF

bpftrace



XDP

BPF microconference

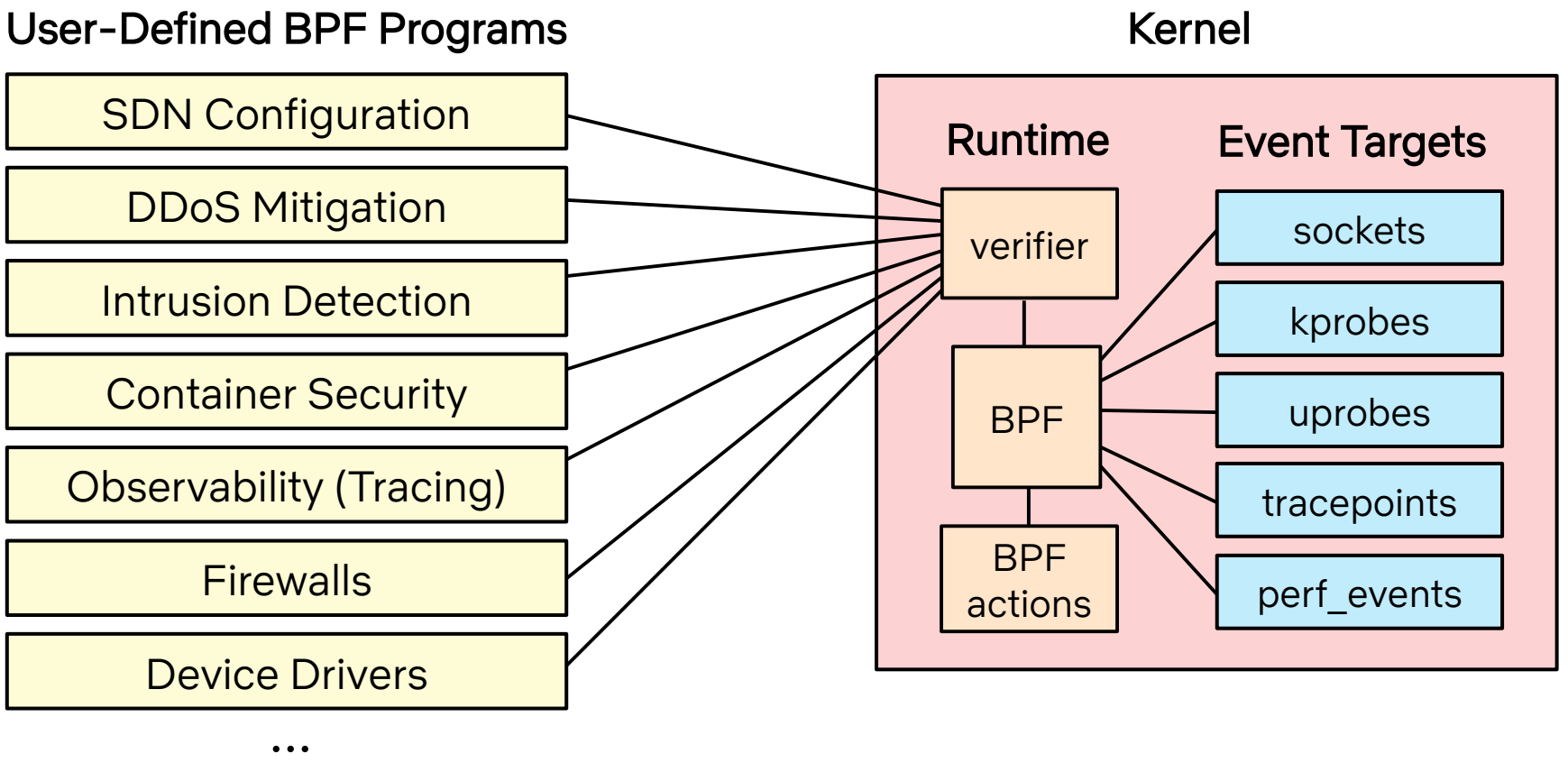


cilium

bpfconf

& Facebook Katran, Google KRSI, Netflix flowsrus, and many more

BPF 2019


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

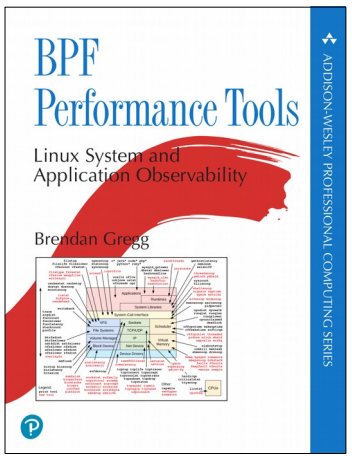
BPF Recommended Tracing Front Ends

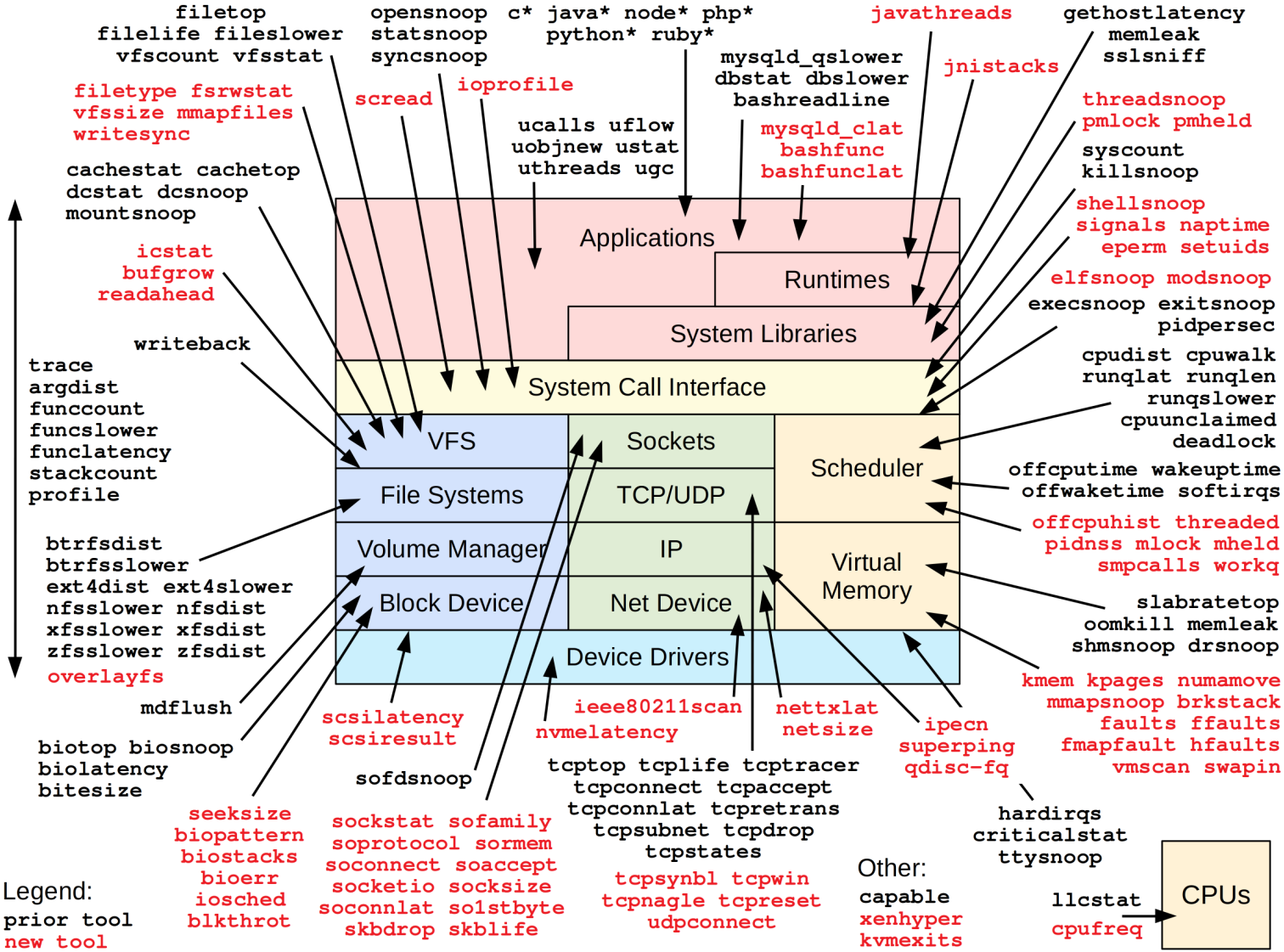
- BCC
  - Great for canned tools & daemons
  - https://github.com/iovisor/bcc
- bpftrace
  - Great for developing new short tools & one-liners
  - https://github.com/iovisor/bpftrace

The difference is like C vs shell
Polished products are better in C (BCC)
Custom one-offs are better in shell (bpftrace)

BPF Perf Tools (2019)

BCC & bpftrace repos contain those in black; the book repo has extras in red





BPF Tool Examples

CPUs: execsnoop

New process trace

```
# 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/nflx-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
[...]
1.528   run              8785   1828     0 ./run
1.529   bash             8785   1828     0 /bin/bash
1.533   svstat           8787   8786     0 /command/svstat /service/nflx-httpd
1.533   perl             8788   8786     0 /usr/bin/perl -e $l=<>;$l=~/(\d+) sec/;p...
[...]
```

CPUs: runqlat

Scheduler latency (run queue latency)

```
# runqlat.py 10 1
Tracing run queue latency... Hit Ctrl-C to end.

     usecs               : count     distribution
         0 -> 1          : 1906     |***                                     |
         2 -> 3          : 22087    |****************************************|
         4 -> 7          : 21245    |**************************************  |
         8 -> 15         : 7333     |*************                           |
        16 -> 31         : 4902     |********                                |
        32 -> 63         : 6002     |**********                              |
        64 -> 127        : 7370     |*************                           |
       128 -> 255        : 13001    |************************                |
       256 -> 511        : 4823     |********                                |
       512 -> 1023       : 1519     |**                                      |
      1024 -> 2047       : 3682     |******                                  |
      2048 -> 4095       : 3170     |*****                                   |
      4096 -> 8191       : 5759     |**********                              |
      8192 -> 16383      : 14549    |**************************              |
     16384 -> 32767      : 5589     |**********                              |
```

CPUs: runqlen

Run queue length

```
# runqlen.py 10 1
Sampling run queue length... Hit Ctrl-C to end.

     runqlen       : count     distribution
        0          : 47284    |****************************************|
        1          : 211      |                                        |
        2          : 28       |                                        |
        3          : 6        |                                        |
        4          : 4        |                                        |
        5          : 1        |                                        |
        6          : 1        |                                        |
```

Memory: ffaults (book)

Page faults by filename

```
# ffaults.bt
Attaching 1 probe...
^C

[...]
@[dpkg]: 18
@[sudoers.so]: 19
@[ld.so.cache]: 27
@[libpthread-2.27.so]: 29
@[ld-2.27.so]: 32
@[locale-archive]: 34
@[system.journal]: 39
@[libstdc++.so.6.0.25]: 43
@[libapt-pkg.so.5.0.2]: 47
@[BrowserMetrics-5D8A6422-77F1.pma]: 86
@[libc-2.27.so]: 168
@[i915]: 409
@[pkgcache.bin]: 860
@[]: 25038
```

Disks: biolatency

Disk I/O latency histograms, per second

```
# biolatency.py -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       |***********                             |
[...]
```

File Systems: xfsslower

XFS I/O slower than a threshold (variants for ext4, btrfs, zfs)

```
# xfsslower.py 50
Tracing XFS operations slower than 50 ms
TIME     COMM           PID    T BYTES   OFF_KB   LAT(ms) FILENAME
21:20:46 java           112789 R 8012    13925      60.16 file.out
21:20:47 java           112789 R 3571    4268      136.60 file.out
21:20:49 java           112789 R 5152    1780       63.88 file.out
21:20:52 java           112789 R 5214    12434     108.47 file.out
21:20:52 java           112789 R 7465    19379      58.09 file.out
21:20:54 java           112789 R 5326    12311      89.14 file.out
21:20:55 java           112789 R 4336    3051       67.89 file.out
[...]
22:02:39 java           112789 R 65536   1486748   182.10 shuffle_6_646_0.data
22:02:39 java           112789 R 65536   872492     30.10 shuffle_6_646_0.data
22:02:39 java           112789 R 65536   1113896   309.52 shuffle_6_646_0.data
22:02:39 java           112789 R 65536   1481020   400.31 shuffle_6_646_0.data
22:02:39 java           112789 R 65536   1415232   324.92 shuffle_6_646_0.data
22:02:39 java           112789 R 65536   1147912   119.37 shuffle_6_646_0.data
[...]
```

File Systems: xfsdist

XFS I/O latency histograms by operation

```
# xfsdist.py 60
Tracing XFS operation latency... Hit Ctrl-C to end.

22:41:24:

operation = 'read'
     usecs               : count     distribution
         0 -> 1          : 382130   |****************************************|
         2 -> 3          : 85717    |********                                |
         4 -> 7          : 23639    |**                                      |
         8 -> 15         : 5668     |                                        |
        16 -> 31         : 3594     |                                        |
        32 -> 63         : 21387    |**                                      |
[...]
operation = 'write'
     usecs               : count     distribution
         0 -> 1          : 12925    |*****                                   |
         2 -> 3          : 83375    |**********************************      |
[...]
```

Networking: tcplife

TCP session lifespans with connection details

```
# tcplife.py
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
[...]
```

Networking: tcpsynbl (book)

TCP SYN backlogs as histograms

```
# tcpsynbl.bt
Attaching 4 probes...
Tracing SYN backlog size. Ctrl-C to end.
^C
@backlog[backlog limit]: histogram of backlog size

@backlog[128]:
[0]                    2 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@|

@backlog[500]:
[0]                 2783 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@|
[1]                    9 |                                                    |
[2, 4)                 4 |                                                    |
[4, 8)                 1 |                                                    |
```

Languages: funccount

Count native function calls (C, C++, Go, etc)

```
# funccount.py 'tcp_s*'
Tracing 50 functions for "tcp_s*"... Hit Ctrl-C to end.
^C
FUNC                                    COUNT
[...]
tcp_setsockopt                           1839
tcp_shutdown                             2690
tcp_sndbuf_expand                        2862
tcp_send_delayed_ack                     9457
tcp_set_state                           10425
tcp_sync_mss                            12529
tcp_sendmsg_locked                      41012
tcp_sendmsg                             41236
tcp_send_mss                            42686
tcp_small_queue_check.isra.29           45724
tcp_schedule_loss_probe                 64067
tcp_send_ack                            66945
tcp_stream_memory_free                 178616
Detaching...
```

Applications: mysqld_qslower

MySQL queries slower than a threshold

```
# mysqld_qslower.py $(pgrep mysqld)
Tracing MySQL server queries for PID 9908 slower than 1 ms...
TIME(s)    PID         MS QUERY
0.000000   9962  169.032 SELECT * FROM words WHERE word REGEXP '^bre.*n$'
1.962227   9962  205.787 SELECT * FROM words WHERE word REGEXP '^bpf.tools$'
9.043242   9962   95.276 SELECT COUNT(*) FROM words
23.723025  9962  186.680 SELECT count(*) AS count FROM words WHERE word REGEXP
'^bre.*n$'
30.343233  9962  181.494 SELECT * FROM words WHERE word REGEXP '^bre.*n$' ORDER BY
word
[...]
```

Coping with so many BPF tools

- On Netflix servers, **/apps/nflx-bpf-alltools** has all tools
  - BCC, bpftrace, my book, Netflix internal
- Latest tools are fetched & put in a hierarchy: cpu, disk, ...

```
bgregg@lgud-bgregg:~> ls --color ~/Git/nflx-bpf-alltools/root/apps/nflx-bpf-alltools/
applications/         disk/                  funcslower.py*  stackcount_example.txt
argdist_example.txt   filesystems/           hypervisors/    stackcount.py*
argdist.py*           funccount_example.txt  kernel/         tplist_example.txt
bpflist_example.txt   funccount.py*          languages/      tplist.py*
bpflist.py*           funclatency_example.txt memory/        trace_example.txt
containers/           funclatency.py*        networking/     trace.py*
cpu/                  funcslower_example.txt security/
```

  - An employee can look in “disk” for all disk tools.
- We are also building **GUIs** to front these tools

We may open source nflx-bpf-alltools at some point

Performance Analysis with BPF

Start With Basics

- From my BCC tutorial: https://github.com/iovisor/bcc/blob/master/docs/tutorial.md

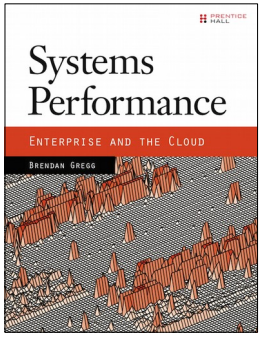
1. uptime
2. dmesg | tail
3. vmstat 1
4. mpstat -P ALL 1
5. pidstat 1
6. iostat -xz 1
7. free -m
8. sar -n DEV 1
9. sar -n TCP,ETCP 1
10. top

BCC Checklist

- ...continuing the BCC tutorial:
  1. execsnoop
  2. opensnoop
  3. ext4slower
     (or btrfs*, xfs*, zfs*)
  4. biolatency
  5. biosnoop
  6. cachestat
  7. tcpconnect
  8. tcpaccept
  9. tcpretrans
  10. runqlat
  11. profile

The **most important** skill to learn

- It's not the tools or the languages (bpftrace, BCC)
  - Analogy: good golf clubs don't make you a great golfer.
- It's the **know how**. It's years of experience and wisdom gained from practicing performance engineering.
- I've taught tracing to >1000 students as a professional instructor. What I found most effective was develop and teach performance analysis **methodologies**.
  - I documented many in my last book.
    Look out for 2nd ed.

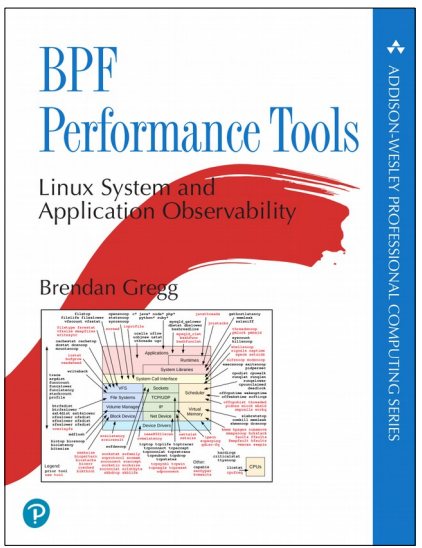


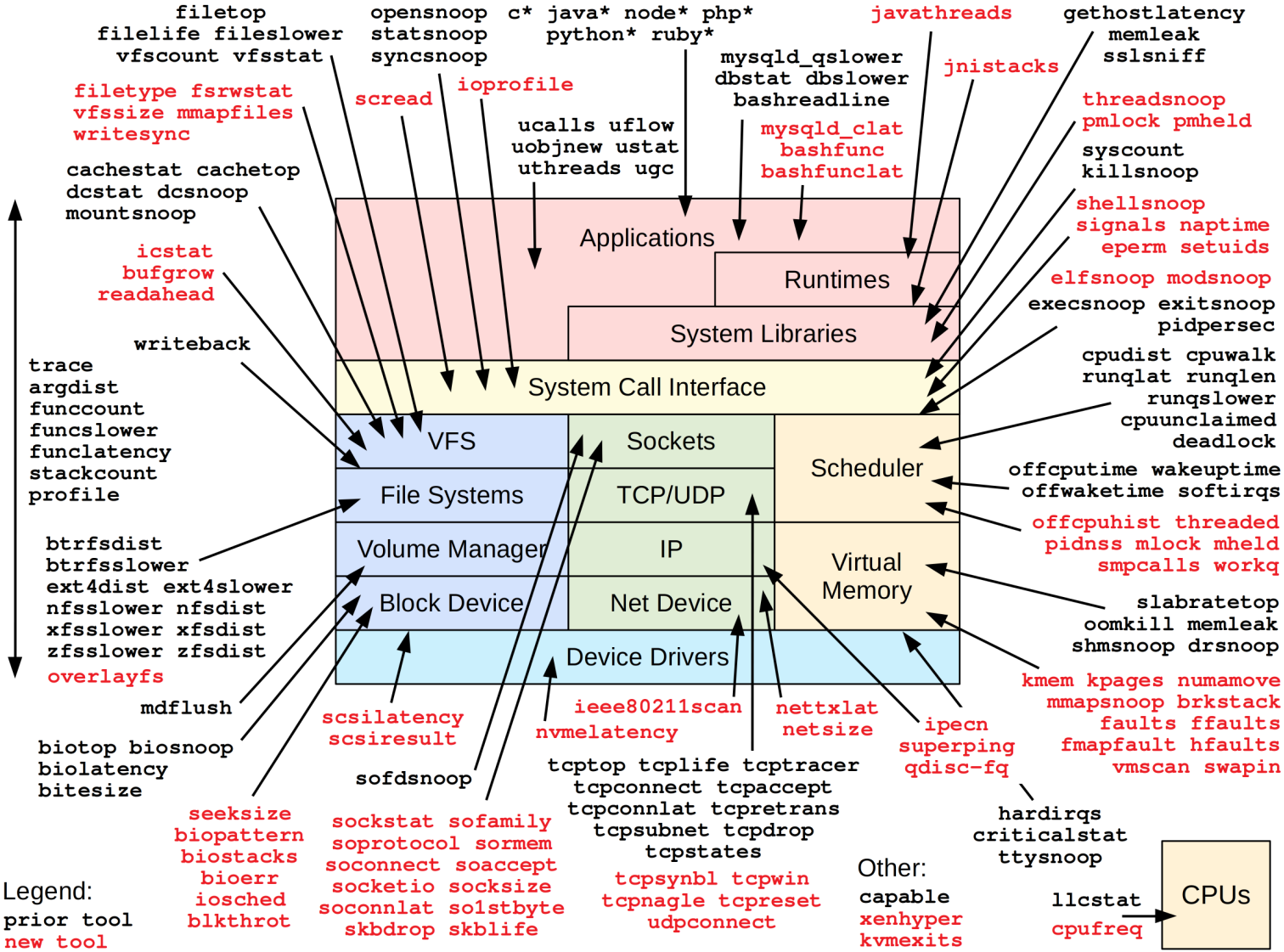
Methodologies

- Checklists
- Thread state analysis
- Workload characterization
- Reverse diagnosis
- Drill-down analysis
- Process of elimination
- 5 Whys
- (etc)

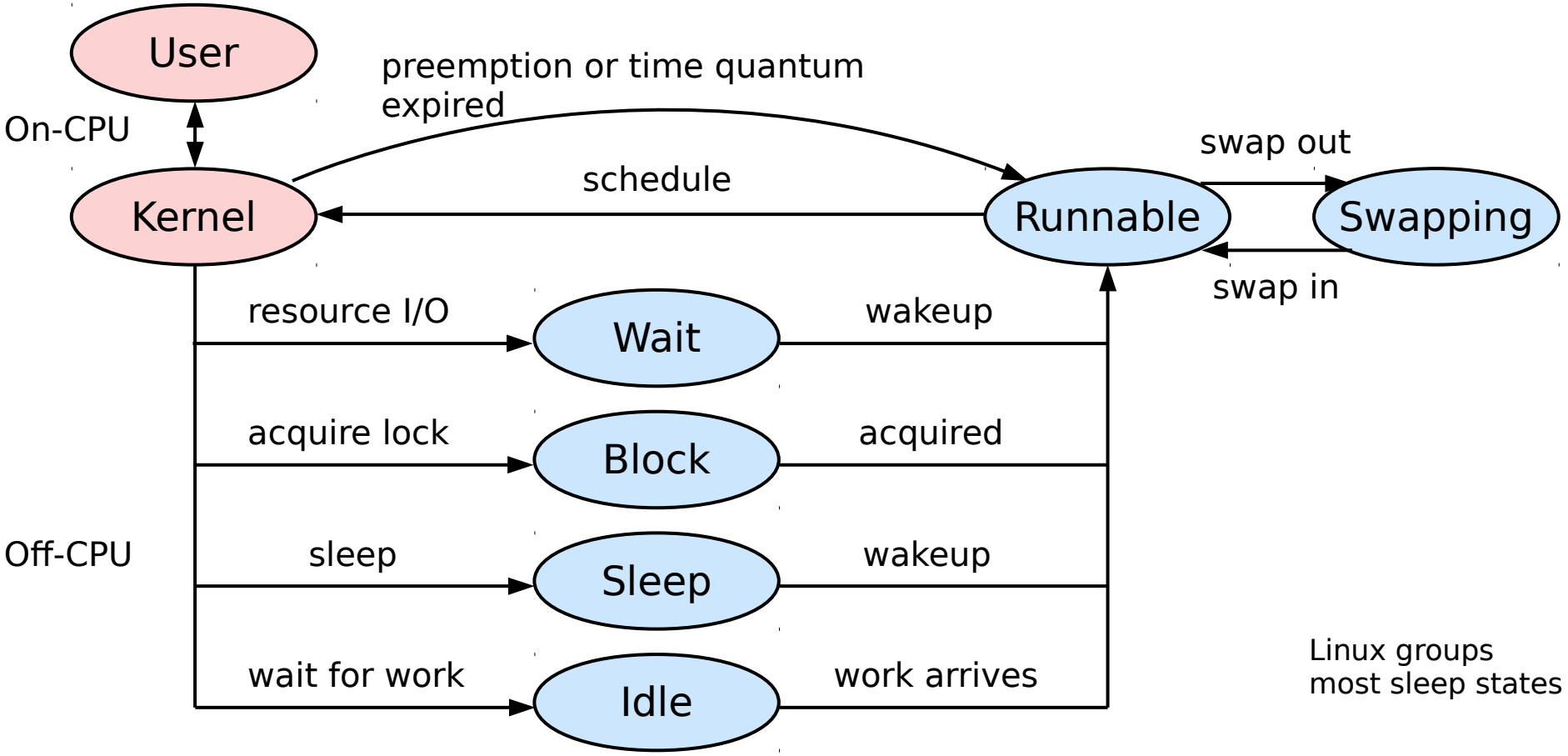
Checklists

BPF Perf Tools: my diagram can be a checklist





Thread State Analysis

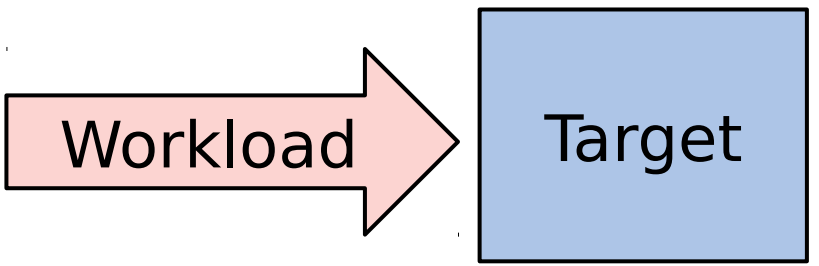


Workload Characterization

Analyze workload characteristics, not resulting performance

For example, CPUs:

1. **Who**: which PIDs, programs, users
2. **Why**: code paths, context
3. **What**: CPU instructions, cycles
4. **How**: changing over time



Reverse Diagnosis

- Performance problems can have multiple causes and solutions. List them then find the metrics.
- Example: disk I/O bounded workload:
  - A) buy faster disks
  - B) change filesystem tuning to reduce I/O
  - C) change application config to improve I/O (e.g., more I/O threads)
  - D) change application to do I/O later (e.g., sync→async)
  - E) change application to cache I/O
  - F) change application to eliminate I/O (e.g., logic change)
- What metrics would identify each of these solutions?

Other Methodologies

- Drill down analysis
- Process of elimination
- 5 Whys

Lab 2

- bpf-perf-workshop/lab2.md

Lab 2 Discussion

Lab 3

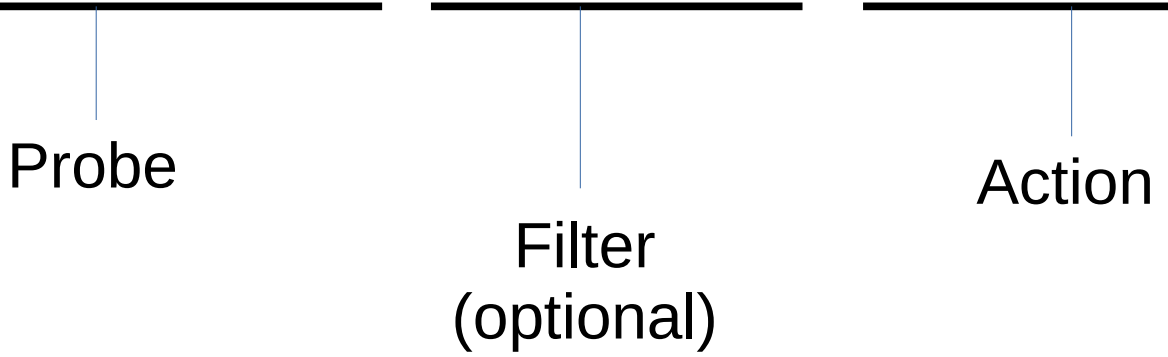
- bpf-perf-workshop/lab3.md

Lab 3 Discussion

bpftrace

bpftrace Syntax

```
bpftrace -e 'k:do_nanosleep /pid > 100/ { @[comm]++ }'
```



Probe Type Shortcuts

`tracepoint`	`t`	Kernel static tracepoints
`usdt`	`U`	User-level statically defined tracing
`kprobe`	`k`	Kernel function tracing
`kretprobe`	`kr`	Kernel function returns
`uprobe`	`u`	User-level function tracing
`uretprobe`	`ur`	User-level function returns
`profile`	`p`	Timed sampling across all CPUs
`interval`	`i`	Interval output
`software`	`s`	Kernel software events
`hardware`	`h`	Processor hardware events

Filters

- **`/pid == 181/`**
- **`/comm != “sshd”/`**
- **`/@ts[tid]/`**

Actions

- Per-event output
  - **`printf()`**
  - **`system()`**
  - **`join()`**
  - **`time()`**
- Map Summaries
  - **`@ = count()`** or **`@++`**
  - **`@ = hist()`**
  - …

The following is in the https://github.com/iovisor/bpftrace/blob/master/docs/reference_guide.md

Functions

- **`hist(n)`** Log2 histogram
- **`lhist(n, min, max, step)`** Linear hist.
- **`count()`** Count events
- **`sum(n)`** Sum value
- **`min(n)`** Minimum value
- **`max(n)`** Maximum value
- **`avg(n)`** Average value
- **`stats(n)`** Statistics
- **`str(s)`** String
- **`ksym(p)`** Resolve kernel addr
- **`usym(p)`** Resolve user addr
- **`kaddr(n)`** Resolve kernel symbol
- **`uaddr(n)`** Resolve user symbol

- **`printf(fmt, ...)`** Print formatted
- **`print(@x[, top[, div]])`** Print map
- **`delete(@x)`** Delete map element
- **`clear(@x)`** Delete all keys/values
- **`reg(n)`** Register lookup
- **`join(a)`** Join string array
- **`time(fmt)`** Print formatted time
- **`system(fmt)`** Run shell command
- **`cat(file)`** Print file contents
- **`exit()`** Quit bpftrace

Variable Types

- Basic Variables
  - **`@global`**
  - **`@thread_local[tid]`**
  - **`$scratch`**
- Associative Arrays
  - **`@array[key] = value`**
- Buitins
  - **`pid`**
  - **`...`**

Builtin Variables

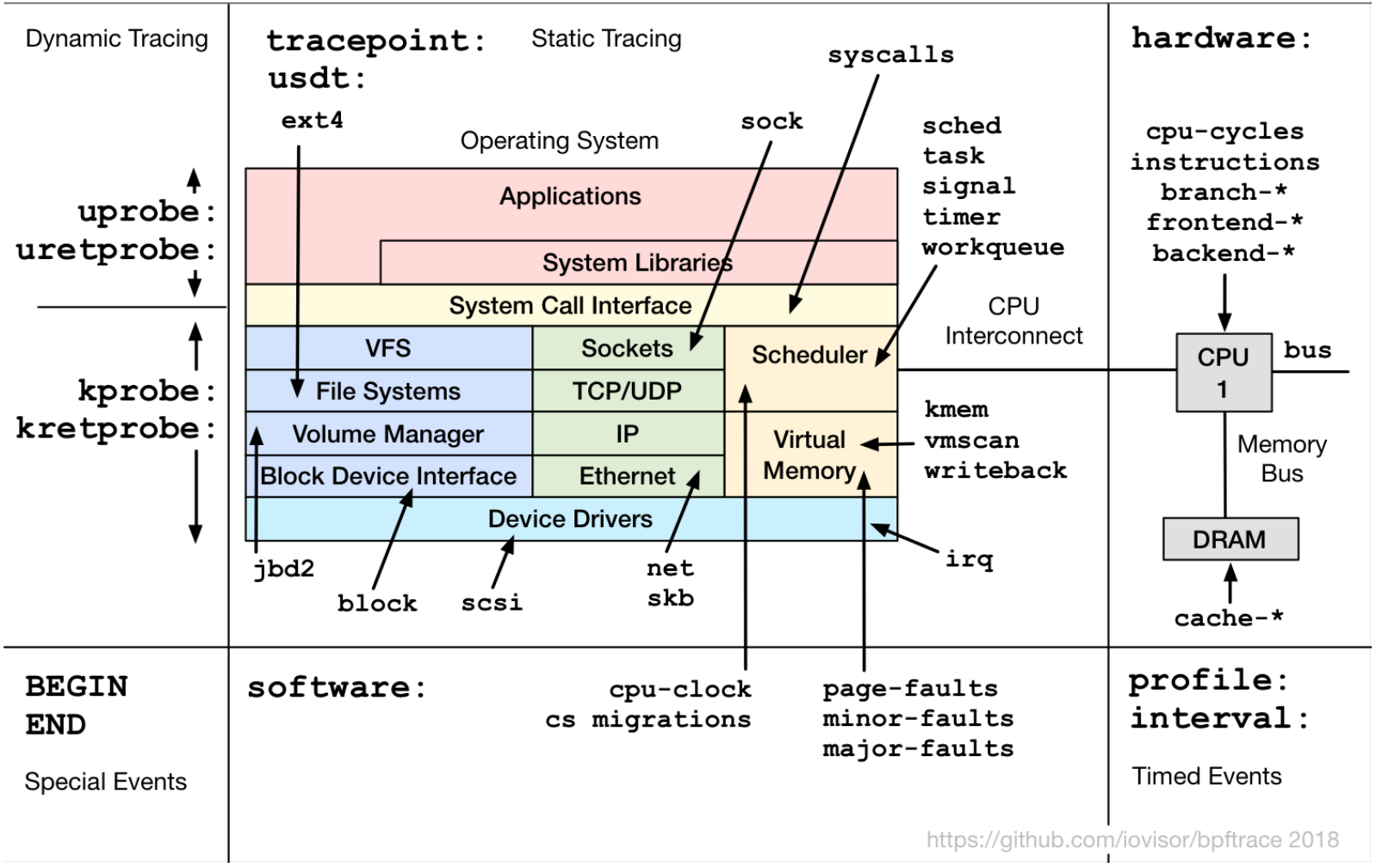
- **`pid`** Process ID (kernel tgid)
- **`tid`** Thread ID (kernel pid)
- **`cgroup`** Current Cgroup ID
- **`uid`** User ID
- **`gid`** Group ID
- **`nsecs`** Nanosecond timestamp
- **`cpu`** Processor ID
- **`comm`** Process name
- **`kstack`** Kernel stack trace
- **`ustack`** User stack trace

- **`arg0`**, **`arg1`**, … Function args
- **`retval`** Return value
- **`args`** Tracepoint args
- **`func`** Function name
- **`probe`** Full probe name
- **`curtask`** Curr task_struct (u64)
- **`rand`** Random number (u32)

bpftrace: BPF observability front-end

```
# Files opened by process
bpftrace -e 't:syscalls:sys_enter_open { printf("%s %s\n", comm,
    str(args->filename)) }'

# Read size distribution by process
bpftrace -e 't:syscalls:sys_exit_read { @[comm] = hist(args->ret) }'

# Count VFS calls
bpftrace -e 'kprobe:vfs_* { @[func]++ }'

# Show vfs_read latency as a histogram
bpftrace -e 'k:vfs_read { @[tid] = nsecs }
    kr:vfs_read /@[tid]/ { @ns = hist(nsecs - @[tid]); delete(@tid) }’

# Trace user-level function
bpftrace -e 'uretprobe:bash:readline { printf(“%s\n”, str(retval)) }’
...
```

Probes


Dynamic Tracing
tracepoint:
usdt:
Static Tracing
hardware:
syscalls
ext4
sock
Operating System
sched
task
signal
timer
workqueue
cpu-cycles
instructions
branch-*
frontend-*
backend-*
uprobe:
uretprobe:
Applications
System Libraries
System Call Interface
CPU
Interconnect
VFS
Sockets
Scheduler
CPU
1
bus
kprobe:
kretprobe:
File Systems
TCP/UDP
kmem
vmscan
writeback
Volume Manager
IP
Virtual
Memory
Memory
Bus
Block Device Interface
Ethernet
Device Drivers
DRAM
irq
jbd2
block
scsi
net
skb
cache-*
BEGIN
END
Special Events
software:
cpu-clock
cs migrations
page-faults
minor-faults
major-faults
profile:
interval:
Timed Events
https://github.com/iovisor/bpftrace 2018

biolatency

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

BEGIN
{
    printf("Tracing block device I/O... Hit Ctrl-C to end.\n");
}

kprobe:blk_account_io_start
{
    @start[arg0] = nsecs;
}

kprobe:blk_account_io_completion
/@start[arg0]/

{
    @usecs = hist((nsecs - @start[arg0]) / 1000);
    delete(@start[arg0]);
}
```

>120 code examples

```
bpftrace/tools> ls *.bt
bashreadline.bt  dcsnoop.bt         oomkill.bt      swapin.bt        tcpretrans.bt
biolatency.bt    execsnoop.bt       opensnoop.bt    syncsnoop.bt     tcpsynbl.bt
biosnoop.bt      gethostlatency.bt  pidpersec.bt    syscount.bt      threadsnoop.bt
biostacks.bt     killsnoop.bt       runqlat.bt      tcpaccept.bt     vfscount.bt
bitesize.bt      loads.bt           runqlen.bt      tcpconnect.bt    vfsstat.bt
capable.bt       mdflush.bt         setuids.bt      tcpdrop.bt       writeback.bt
cpuwalk.bt       naptime.bt         statsnoop.bt    tcplife.bt       xfsdist.bt
bpf-perf-tools-book/originals> ls */*.bt
Ch06_CPUs/cpufreq.bt          Ch10_Networking/skblife.bt
Ch06_CPUs/execsnoop.bt        Ch10_Networking/so1stbyte.bt
Ch06_CPUs/offcputime.bt       Ch10_Networking/soaccept.bt
Ch06_CPUs/runqlat.bt          Ch10_Networking/socketio.bt
Ch06_CPUs/runqlen.bt          Ch10_Networking/socksize.bt
Ch06_CPUs/smpcalls.bt         Ch10_Networking/sockstat.bt
Ch07_Memory/brkstack.bt       Ch10_Networking/soconnect.bt
Ch07_Memory/faults.bt         Ch10_Networking/soconnlat.bt
Ch07_Memory/ffaults.bt        Ch10_Networking/sofamily.bt
Ch07_Memory/hfaults.bt        Ch10_Networking/soprotocol.bt
[...]
```

Lab 4

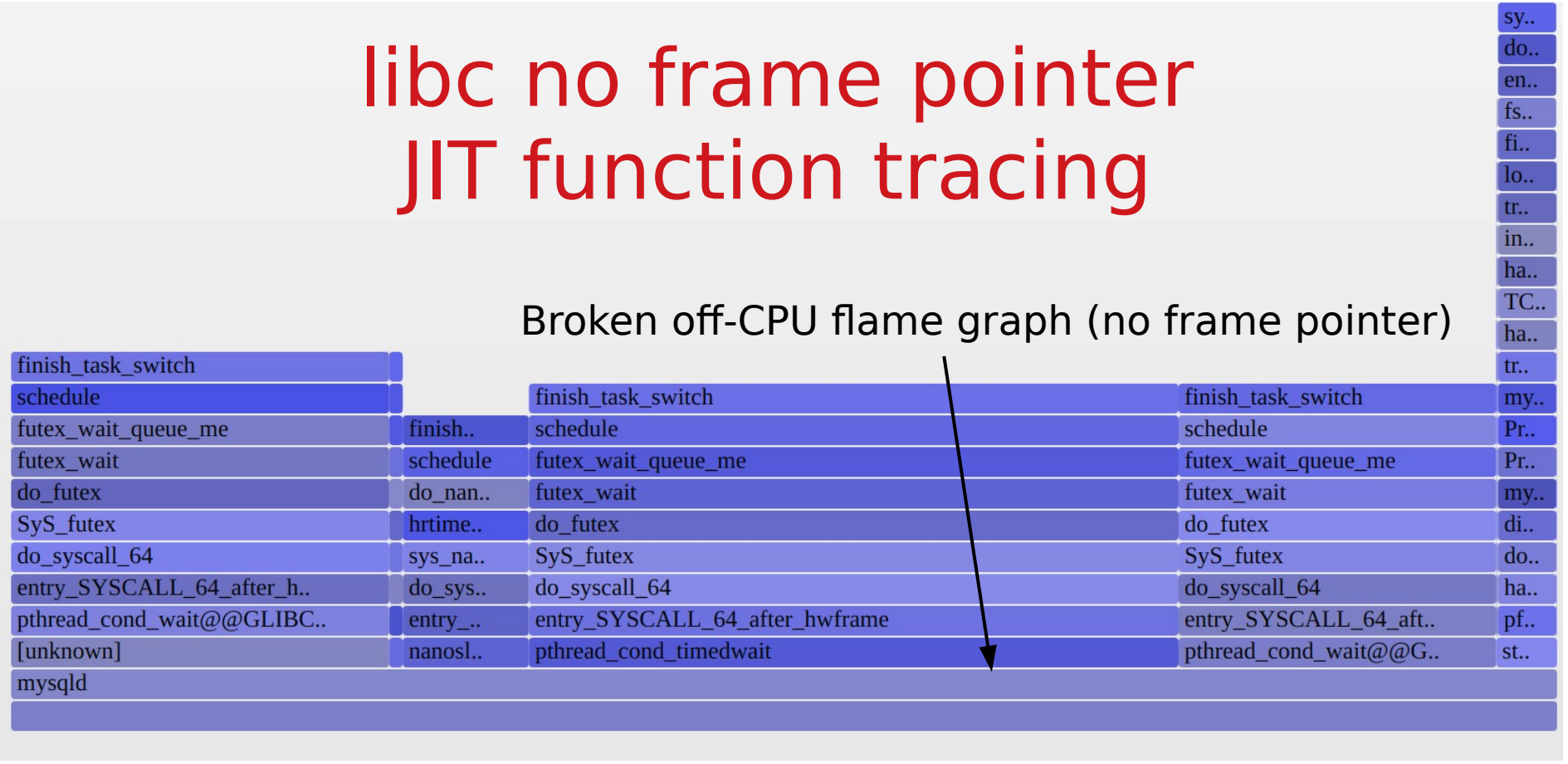
- bpf-perf-workshop/lab4.md

Lab 5 is optional advanced exercises

Lab 4 & 5 Discussion

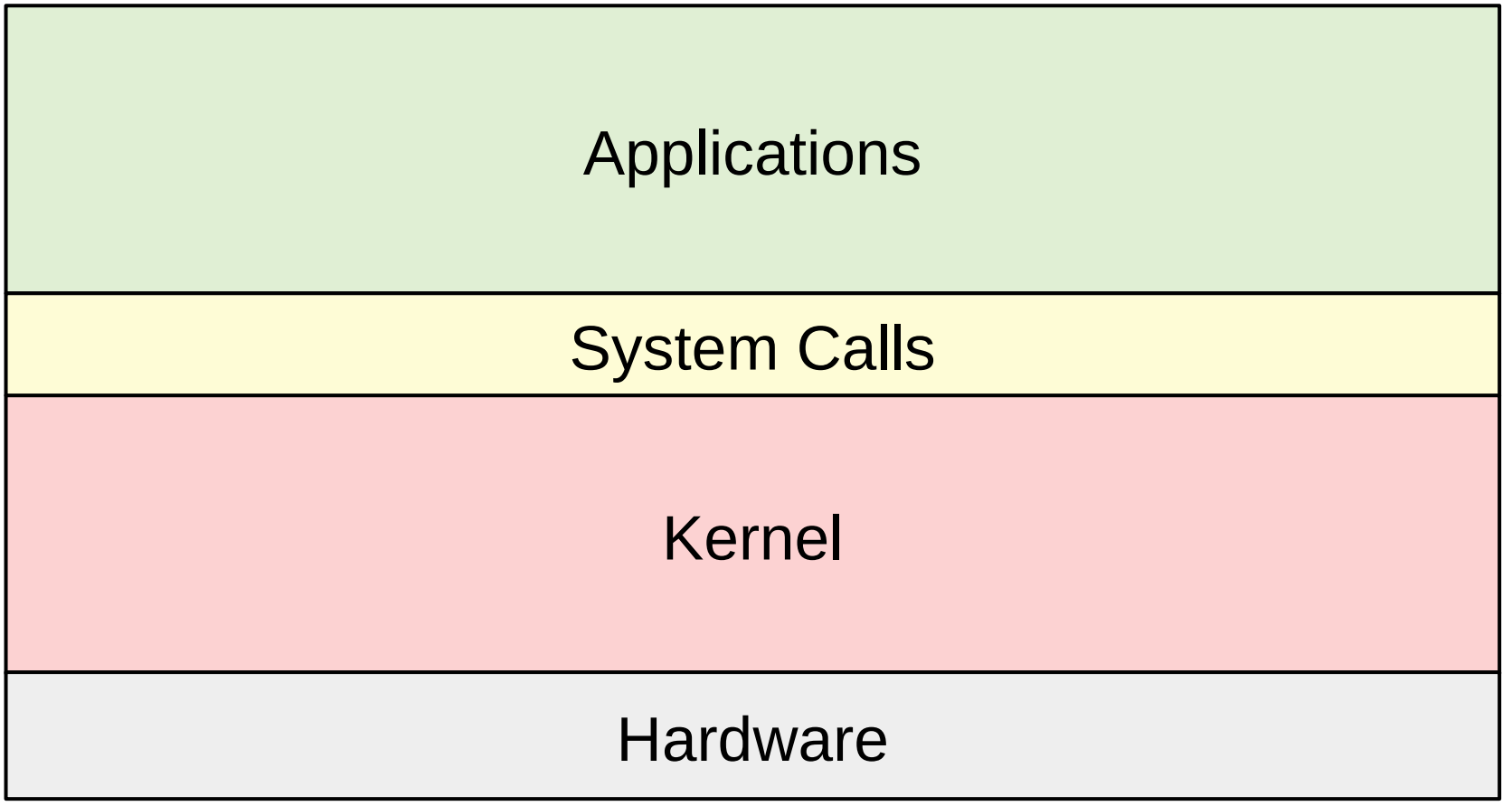
Challenges

Observability Challenges

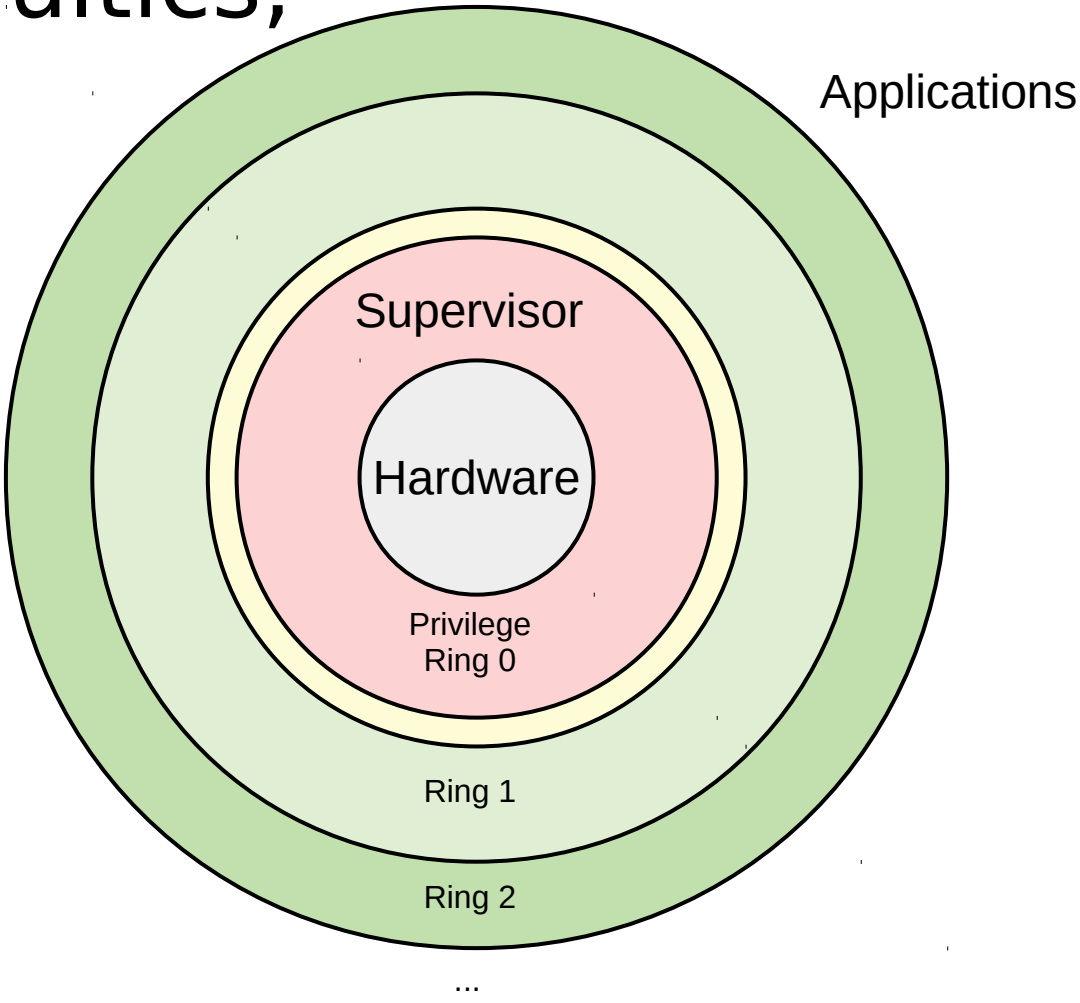


Future

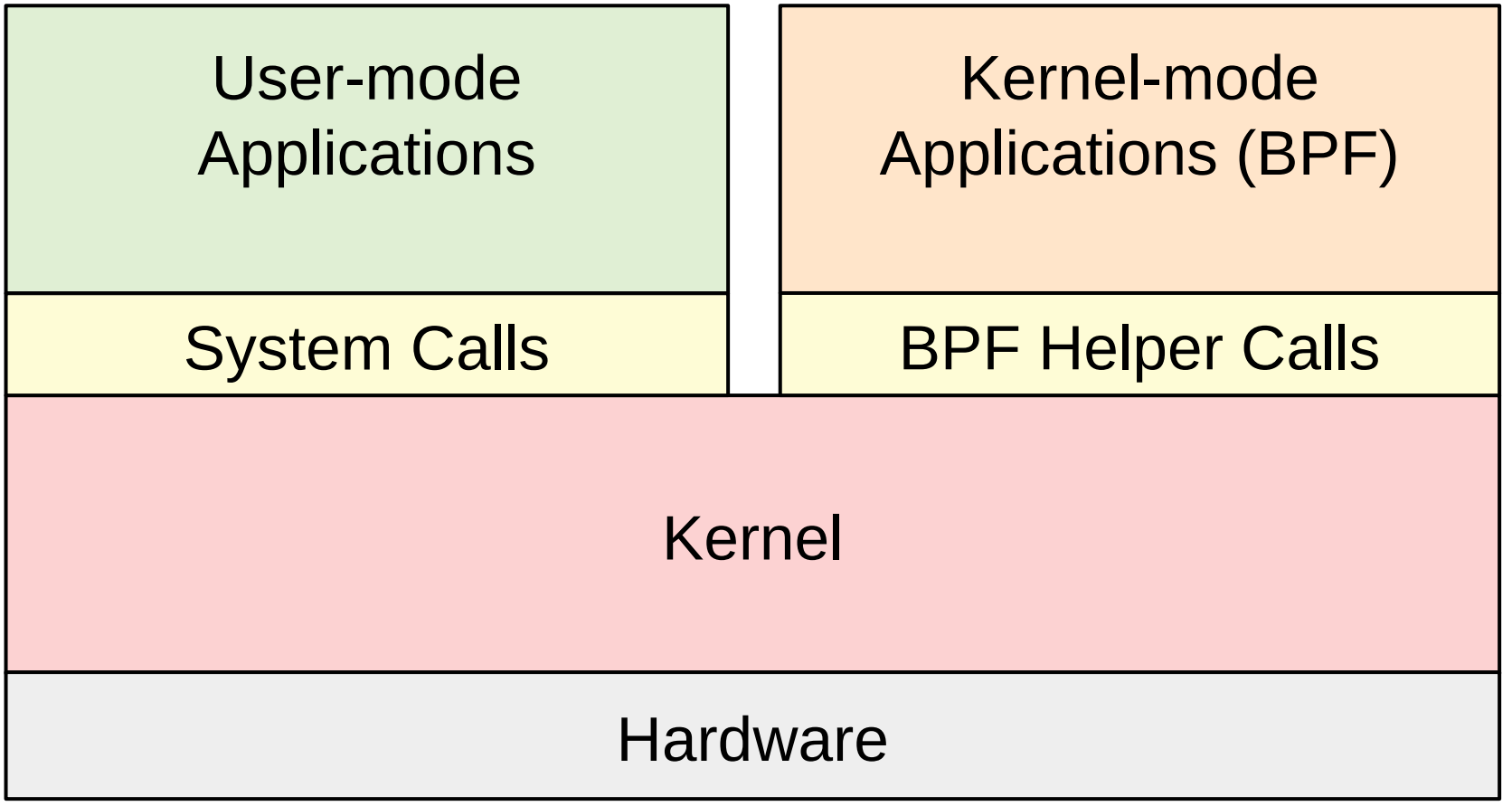
50 Years, one (dominant) OS model



Origins: Multics, 1960s



Modern Linux: A new OS model



Predictions

Recap

Learning Objectives

1. slides: Understand BPF, BCC, and bpftrace
2. slides & discussion: Follow different analysis methodologies
3. lab1: Use BCC tools to analyze disk I/O issues
4. lab2: “ “ short-lived process issues
5. lab3: “ “ runq latency issues
6. lab4-5: Develop at least one new bpftrace tool

Thanks

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BPF: Alexei Starovoitov, Daniel Borkmann, David S. Miller, Linus Torvalds, BPF community

BCC: Brenden Blanco, Yonghong Song, Sasha Goldsthein (who also does great workshops), BCC community

bpftrace: Alastair Robertson, Matheus Marchini, Dan Xu, bpftrace community

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http://jpetazzo.github.io/2015/09/10/how-to-deliver-great-tech-tutorials/