THE MAGICAL THINGS YOU CAN DO WITH LINUX'S KERNEL TRACING

eBPF

ORIGINALLY JUST FOR FILTERING PACKETS

BERKLEY PACKET FILTERS

by Julia Evans

WHAT ARE THOSE COMPUTERS SAYING TO EACH OTHER?

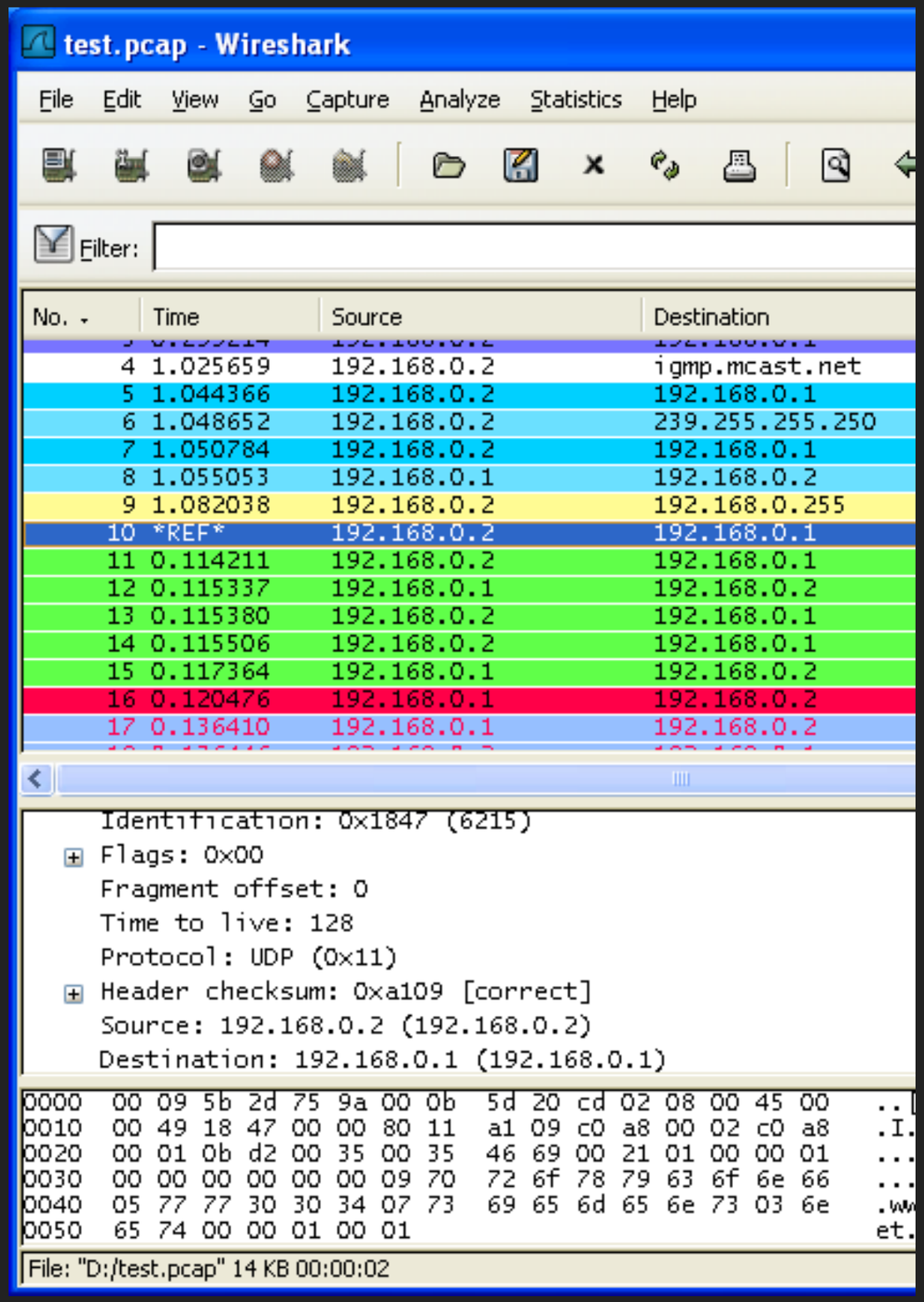
WITH TCPDUMP, YOU CAN FIND OUT!

Source: https://jvns.ca/zines/

TCPDUMP

```
tcpdump -i any port 80 or 443
```

- One of the first tools that used BPF
- Limited
- Layer 3 and 4 filtering at kernel level, but working with packets has to be in userspace



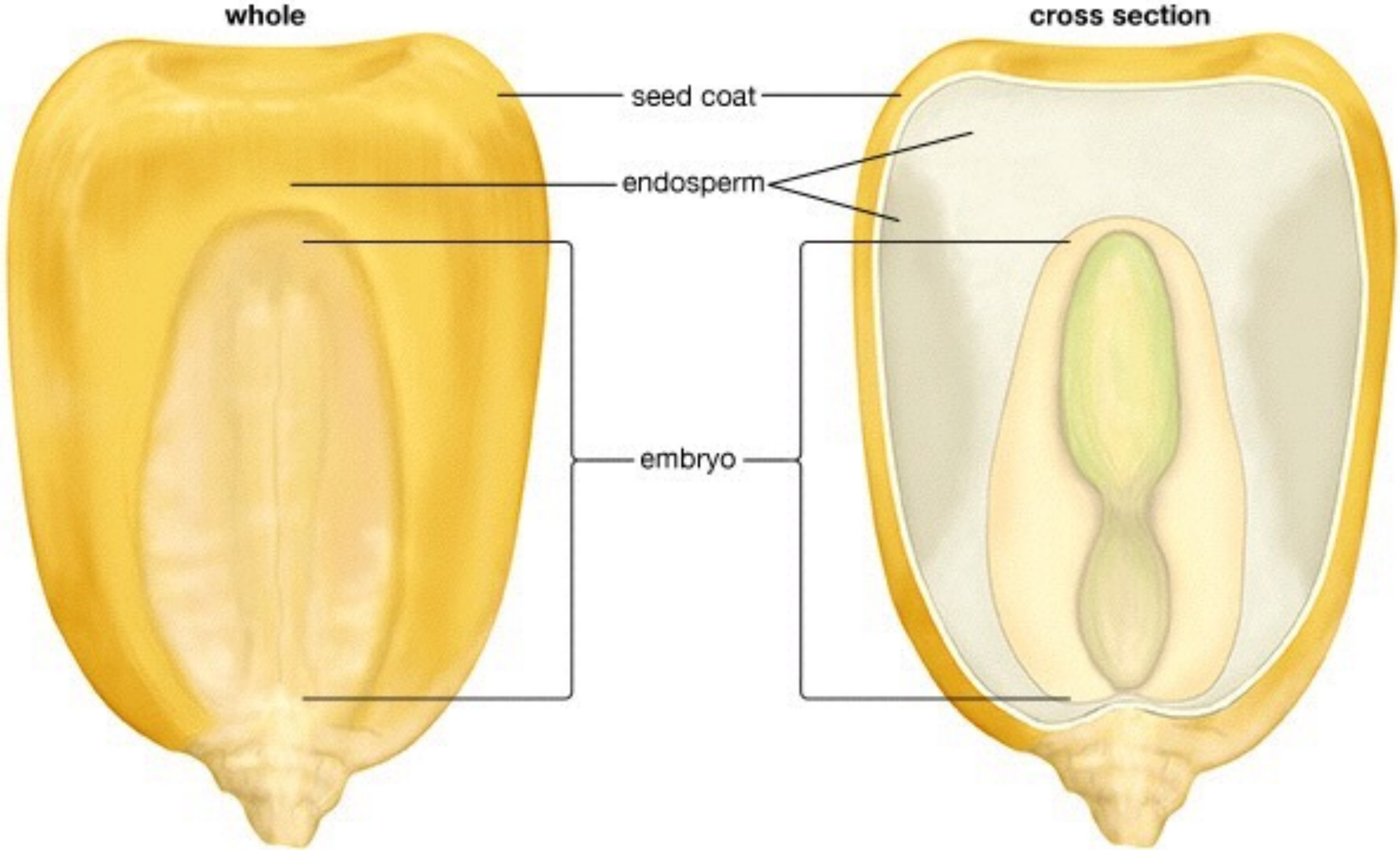
TRACING, NETWORKING, AND SECURITY

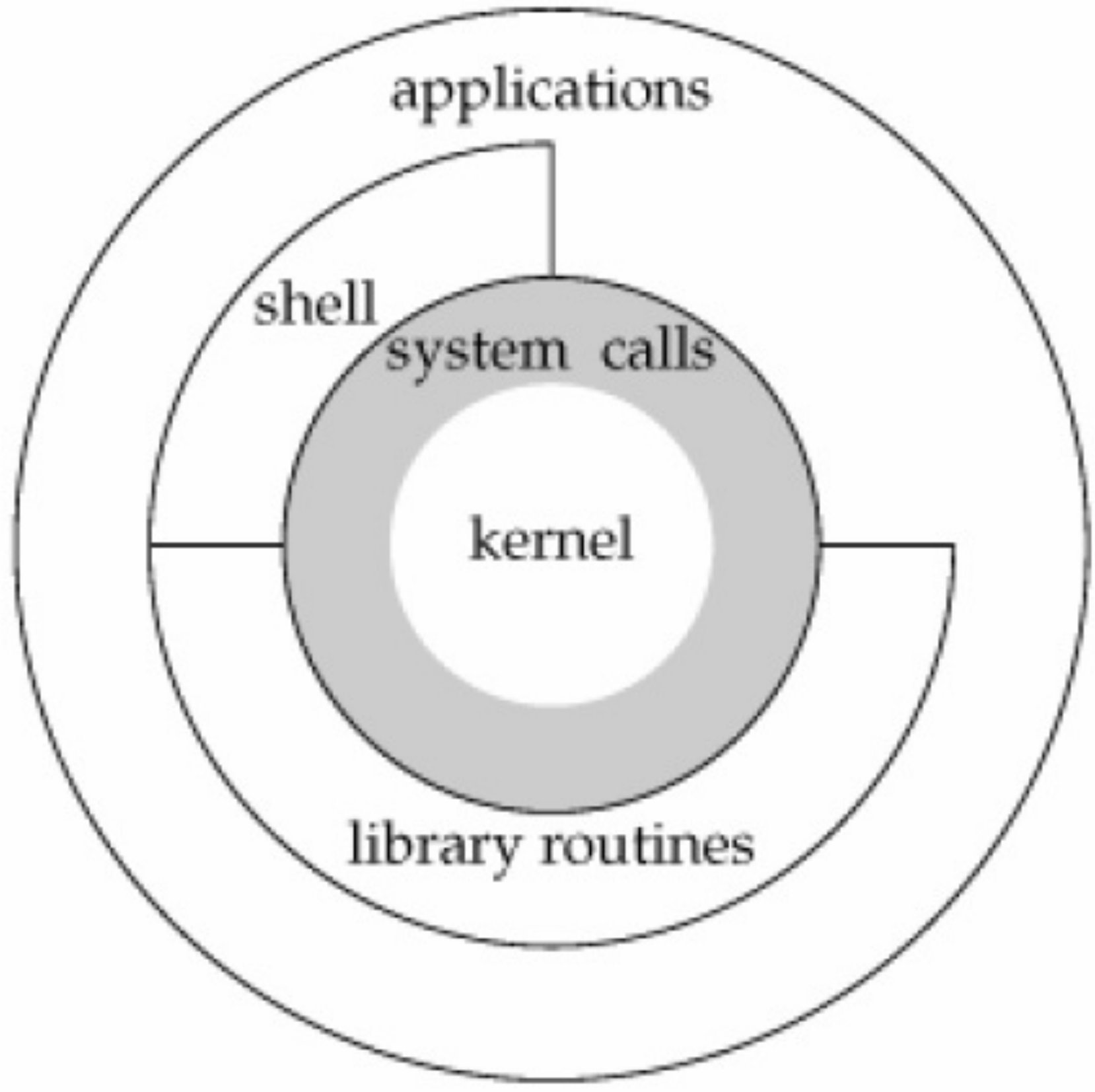
WHAT NOW?

extended Berkley Packet Filters and the BPF Compiler Collection

- Linux 4.1+, building on features from Linux 3.15
- BCC Kernel Version Features
- iovisor project
- Bindings for lua, Python, and Go.

Corn kernel



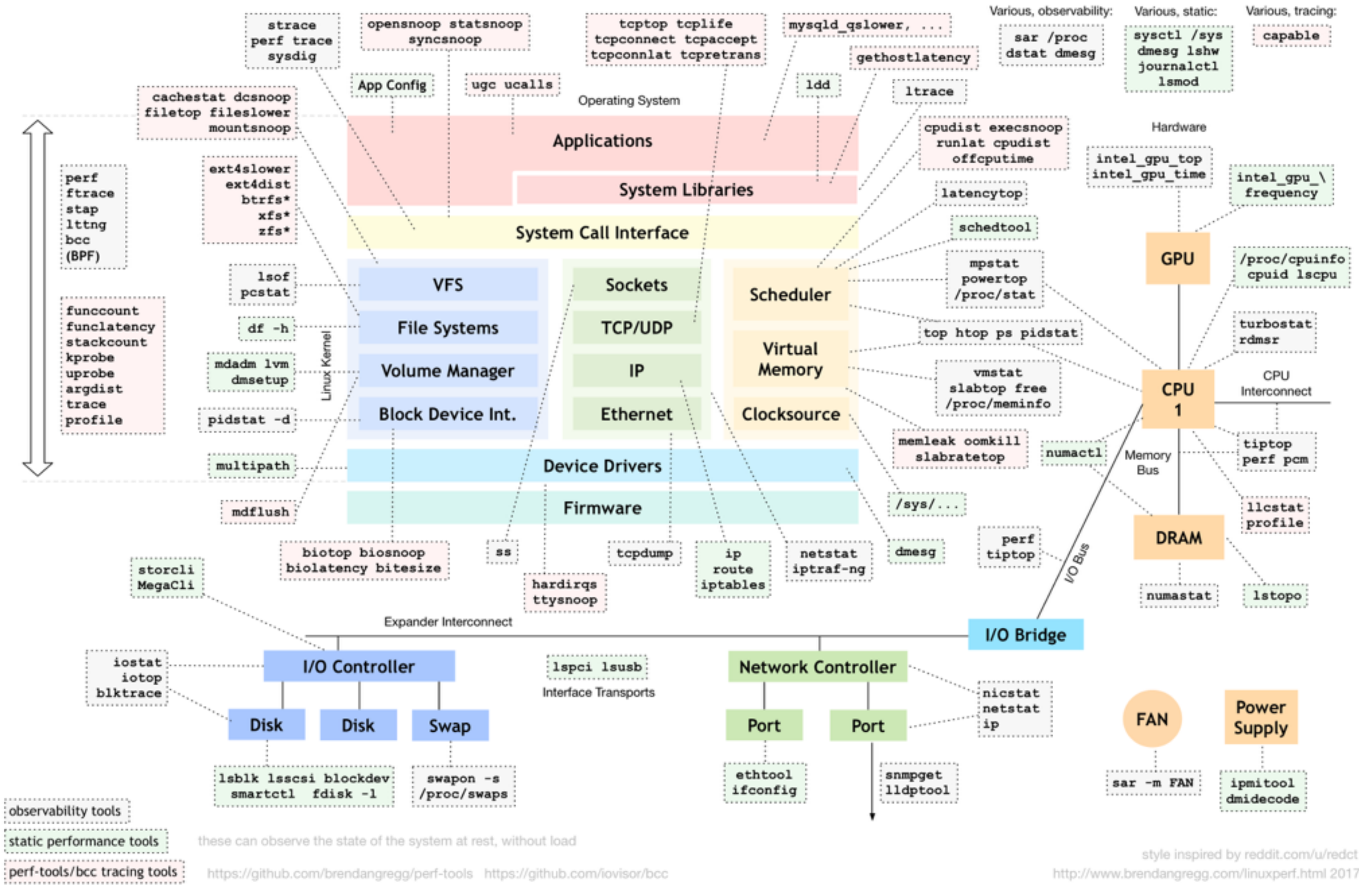

applications
shell
system calls
kernel
library routines

PERFORMANCE MONITORING AND TRACING

SPYING ON YOUR SYSTEM

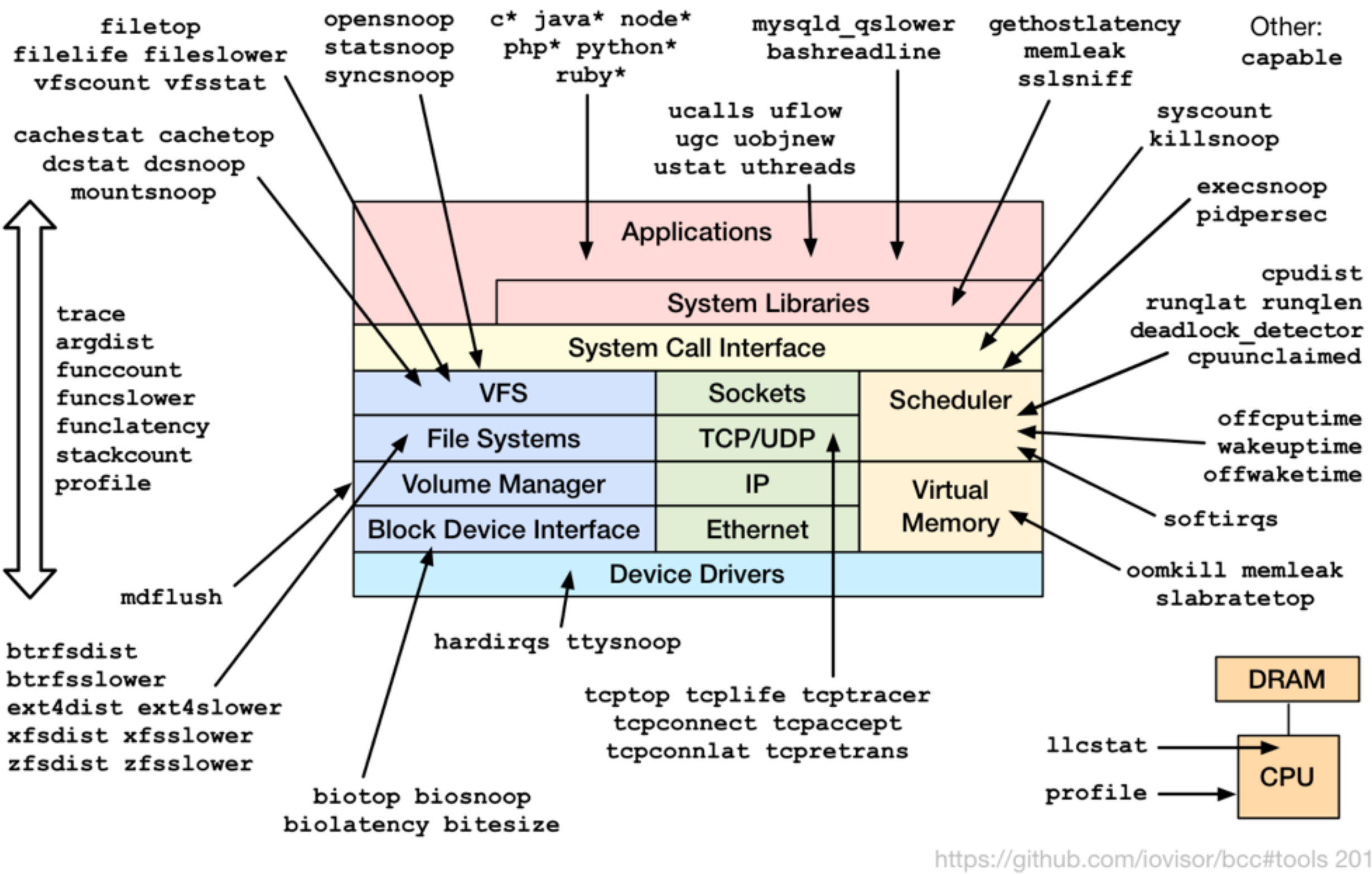
LINUX PERFORMANCE ANALYSIS IN 60,000 MILLISECONDS

```
# uptime
# dmesg | tail
# vmstat 1
# mpstat -P ALL 1
# pidstat 1
# iostat -xz 1
# free -m
# sar -n DEV 1
# sar -n TCP,ETCP 1
# top
```



Source: http://www.brendangregg.com/Perf/linux_perf_tools_full.png

Linux bcc/BPF Tracing Tools



https://github.com/iovisor/bcc#tools 2017

Source: http://www.brendangregg.com/Perf/bcc_tracing_tools.png

STRACE

- Hard to customise
- Impacts performance heavily

```
# /usr/share/bcc/tools/opensnoop -n python3
PID    COMM               FD ERR PATH
20526  python3             3   0 /etc/ld.so.cache
20526  python3             3   0 /lib/x86_64-linux-gnu/libpthread.so.
20526  python3             3   0 /lib/x86_64-linux-gnu/libc.so.6
20526  python3             3   0 /lib/x86_64-linux-gnu/libdl.so.2
20526  python3             3   0 /lib/x86_64-linux-gnu/libutil.so.1
20526  python3             3   0 /lib/x86_64-linux-gnu/libexpat.so.1
20526  python3             3   0 /lib/x86_64-linux-gnu/libz.so.1
20526  python3             3   0 /lib/x86_64-linux-gnu/libm.so.6
20526  python3             3   0 /usr/lib/locale/locale-archive
20526  python3             3   0 /usr/lib/x86_64-linux-gnu/gconv/
gconv-modules.cache
```

```
# strace python3 --version
execve("/usr/bin/python3", ["python3", "--version"], [/* 20 vars */]) = 0
brk(NULL)                               = 0x27d5000
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f698a5f1000
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=26515, ...}) = 0
mmap(NULL, 26515, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7f698a5ea000
close(3)                                = 0
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
open("/lib/x86_64-linux-gnu/libpthread.so.0", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\0\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0\260`\0\0\0\0\0\0"..., 832) = 832
fstat(3, {st_mode=S_IFREG|0755, st_size=138696, ...}) = 0
mmap(NULL, 2212904, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7f698a1b1000
mprotect(0x7f698a1c9000, 2093056, PROT_NONE) = 0
mmap(0x7f698a3c8000, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x17000) = 0x7f698a3c8000
mmap(0x7f698a3ca000, 13352, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0x7f698a3ca000
close(3)                                = 0
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\0\0\0"..., 832) = 832
fstat(3, {st_mode=S_IFREG|0755, st_size=1868984, ...}) = 0
mmap(NULL, 3971488, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7f6989de7000
mprotect(0x7f6989fa7000, 2097152, PROT_NONE) = 0
mmap(0x7f698a1a7000, 24576, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x1c0000) = 0x7f698a1a7000
mmap(0x7f698a1ad000, 14752, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0x7f698a1ad000
close(3)                                = 0
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
open("/lib/x86_64-linux-gnu/libdl.so.2", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\0\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0\240\r\0\0\0\0\0\0"..., 832) = 832
fstat(3, {st_mode=S_IFREG|0644, st_size=14608, ...}) = 0
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f698a5e9000
mmap(NULL, 2109680, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7f6989be3000
mprotect(0x7f6989be6000, 2093056, PROT_NONE) = 0
mmap(0x7f6989de5000, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x2000) = 0x7f6989de5000
close(3)                                = 0
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
open("/lib/x86_64-linux-gnu/libutil.so.1", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\0\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0`\16\0\0\0\0\0\0"..., 832) = 832
fstat(3, {st_mode=S_IFREG|0644, st_size=10656, ...}) = 0
mmap(NULL, 2105608, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7f69899e0000
mprotect(0x7f69899e2000, 2093056, PROT_NONE) = 0
mmap(0x7f6989be1000, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x1000) = 0x7f6989be1000
close(3)                                = 0
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
open("/lib/x86_64-linux-gnu/libexpat.so.1", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\0\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0;\0\0\0\0\0\0"..., 832) = 832
fstat(3, {st_mode=S_IFREG|0644, st_size=166032, ...}) = 0
mmap(NULL, 2261096, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7f69897b7000
mprotect(0x7f69897dd000, 2097152, PROT_NONE) = 0
mmap(0x7f69899dd000, 12288, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x26000) = 0x7f69899dd000
close(3)                                = 0
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
open("/lib/x86_64-linux-gnu/libz.so.1", O_RDONLY|O_CLOEXEC) = 3
```

```
#!/usr/bin/python
from __future__ import print_function
from bcc import BPF
import argparse
from socket import inet_ntop, ntohs, AF_INET, AF_INET6
from struct import pack
import ctypes as ct
from time import strftime

bpf_text = """
#include <uapi/linux/ptrace.h>
#define KBUILD_MODNAME "foo"
#include <linux/tcp.h>
#include <net/sock.h>
#include <bcc/proto.h>

BPF_HASH(birth, struct sock *, u64);

// separate data structs for ipv4 and ipv6
struct ipv4_data_t {
    // XXX: switch some to u32's when supported
    u64 ts_us;
    u64 pid;
    u64 saddr;
    u64 daddr;
    u64 ports;
    u64 rx_b;
    u64 tx_b;
    u64 span_us;
    char task[TASK_COMM_LEN];
};
BPF_PERF_OUTPUT(ipv4_events);

struct ipv6_data_t {
    u64 ts_us;
    u64 pid;
    unsigned __int128 saddr;
    unsigned __int128 daddr;
    u64 ports;
    u64 rx_b;
    u64 tx_b;
    u64 span_us;
    char task[TASK_COMM_LEN];
};
BPF_PERF_OUTPUT(ipv6_events);

struct id_t {
    u32 pid;
    char task[TASK_COMM_LEN];
};
BPF_HASH(whoami, struct sock *, struct id_t);

int kprobe__tcp_set_state(struct pt_regs *ctx, struct sock *sk, int state)
{
    u32 pid = bpf_get_current_pid_tgid() >> 32;

    // lport is either used in a filter here, or later
    u16 lport = sk->__sk_common.skc_num;
    FILTER_LPORT

    // dport is either used in a filter here, or later
    u16 dport = sk->__sk_common.skc_dport;
    FILTER_DPORT

    /*
     * This tool includes PID and comm context. It's best effort, and may
     * be wrong in some situations. It currently works like this:
     * - record timestamp on any state < TCP_FIN_WAIT1
     * - cache task context on:
```

THIS IS WHERE THINGS START GETTING MORE MAGICAL

perf

PERF

```
perf record -F 99 -a -g -- sleep 60

perf report --sort comm,dso
```

FLAME GRAPHS

```
perf record -F 99 -a -g -- sleep 60

perf script > out.perf

./stackcollapse-perf.pl out.perf > out.folded

./flamegraph.pl out.folded > perf.svg
```

Example: http://www.brendangregg.com/FlameGraphs/example-perf.svg

```
#!/usr/bin/python
from __future__ import print_function
from bcc import BPF
import argparse
from socket import inet_ntop, ntohs, AF_INET, AF_INET6
from struct import pack
import ctypes as ct
from time import strftime

bpf_text = """
#include <uapi/linux/ptrace.h>
#define KBUILD_MODNAME "foo"
#include <linux/tcp.h>
#include <net/sock.h>
#include <bcc/proto.h>

BPF_HASH(birth, struct sock *, u64);

// separate data structs for ipv4 and ipv6
struct ipv4_data_t {
    // XXX: switch some to u32's when supported
    u64 ts_us;
    u64 pid;
    u64 saddr;
    u64 daddr;
    u64 ports;
    u64 rx_b;
    u64 tx_b;
    u64 span_us;
    char task[TASK_COMM_LEN];
};
BPF_PERF_OUTPUT(ipv4_events);

struct ipv6_data_t {
    u64 ts_us;
    u64 pid;
    unsigned __int128 saddr;
    unsigned __int128 daddr;
    u64 ports;
    u64 rx_b;
    u64 tx_b;
    u64 span_us;
    char task[TASK_COMM_LEN];
};
BPF_PERF_OUTPUT(ipv6_events);

struct id_t {
    u32 pid;
    char task[TASK_COMM_LEN];
};
BPF_HASH(whoami, struct sock *, struct id_t);

int kprobe__tcp_set_state(struct pt_regs *ctx, struct sock *sk, int state)
{
    u32 pid = bpf_get_current_pid_tgid() >> 32;

    // lport is either used in a filter here, or later
    u16 lport = sk->__sk_common.skc_num;
    FILTER_LPORT

    // dport is either used in a filter here, or later
    u16 dport = sk->__sk_common.skc_dport;
    FILTER_DPORT

    /*
     * This tool includes PID and comm context. It's best effort, and may
     * be wrong in some situations. It currently works like this:
     * - record timestamp on any state < TCP_FIN_WAIT1
     * - cache task context on:
```

AND THEN IT GETS EVEN MORE MAGICAL

eBPF

Tools for Witchcraft

- BPF_HASH
- BPF_ARRAY
- BPF_HISTOGRAM
- BPF_PERF_OUTPUT
- BPF_STACK_TRACE
- BPF_TABLE

Hello World

```
#!/usr/bin/env python
from bcc import BPF
from time import sleep

b = BPF(text="""
int kprobe__sys_clone(void *ctx) {
    bpf_trace_printk("Hello, World!\\n");
    return 0;
}
""")

# tail /sys/kernel/debug/tracing/trace_pipe
bpf.trace_print()
```

```
# ./examples/hello_world.py
World!      sshd-1708  [001] d... 48979.876007: : Hello,
World!     <...>-23754 [001] d... 48979.895665: : Hello,
World!      sshd-23754 [001] d... 48981.184813: : Hello,
World!        sh-23757 [001] d... 48981.187325: : Hello,
World! run-parts-23758 [000] d... 48981.190149: : Hello,
World! 00-header-23759 [001] d... 48981.191524: : Hello,
World! 00-header-23759 [001] d... 48981.192774: : Hello,
World! 00-header-23759 [001] d... 48981.194310: : Hello,
World! run-parts-23758 [000] d... 48981.196453: : Hello,
World! run-parts-23758 [000] d... 48981.198322: : Hello,
World! run-parts-23758 [000] d... 48981.200000: : Hello,
World! 90-updates-avai-23765 [000] d... 48981.201821: : Hello,
World! run-parts-23758 [000] d... 48981.203598: : Hello,
World! 91-release-upgr-23767 [000] d... 48981.205087: : Hello,
World!     <...>-23768 [001] d... 48981.205652: : Hello,
World! 91-release-upgr-23768 [001] d... 48981.205895: : Hello,
World! 91-release-upgr-23767 [001] d... 48981.347179: : Hello,
World!      sshd-23754 [001] d... 48981.184813: : Hello,
World!        sh-23757 [001] d... 48981.187325: : Hello,
World! run-parts-23758 [000] d... 48981.190149: : Hello,
```

Hello More Fields

```
#!/usr/bin/env python

from bcc import BPF

b = BPF(text="""
int kprobe__sys_clone(void *ctx) {
    bpf_trace_printk("Hello, World!\\n");
    return 0;
}
""")

print("%-18s %-16s %-6s %s" % ("TIME(s)", "COMM", "PID", "MESSAGE"))

while True:
    try:
        (task, pid, cpu, flags, ts, msg) = b.trace_fields()
    except ValueError:
        continue
    print("%-18.9f %-16s %-6d %s" % (ts, task, pid, msg))
```

```
# examples/tracing/hello_fields.py
TIME(s)            COMM             PID    MESSAGE
50770.163158000    sshd             1708   Hello, World!
50770.171591000    <...>            24194  Hello, World!
50771.414130000    sshd             24194  Hello, World!
50771.415548000    sh               24199  Hello, World!
50771.416817000    sshd             1708   Hello, World!
50771.417001000    run-parts        24200  Hello, World!
50771.417860000    <...>            24201  Hello, World!
50771.418627000    00-header        24201  Hello, World!
50771.419441000    00-header        24201  Hello, World!
50771.420249000    run-parts        24200  Hello, World!
50771.421026000    run-parts        24200  Hello, World!
50771.421918000    run-parts        24200  Hello, World!
50771.422607000    90-updates-avai  24208  Hello, World!
50771.423555000    run-parts        24200  Hello, World!
50771.424070000    91-release-upgr  24210  Hello, World!
50771.424206000    91-release-upgr  24211  Hello, World!
```

Hello BPF_PERF_OUTPUT

```
#!/usr/bin/env python
from bcc import BPF
import ctypes as ct

b = BPF(text="""
#include <linux/sched.h>

// define output data structure in C
struct data_t {
    u32 pid;
    u64 ts;
    char comm[TASK_COMM_LEN];
};
BPF_PERF_OUTPUT(events);

int hello(struct pt_regs *ctx) {
    struct data_t data = {};
    data.pid = bpf_get_current_pid_tgid();
    data.ts = bpf_ktime_get_ns();
    bpf_get_current_comm(&data.comm, sizeof(data.comm));

    events.perf_submit(ctx, &data, sizeof(data));

    return 0;
}
""")

TASK_COMM_LEN = 16    # linux/sched.h
class Data(ct.Structure):
    _fields_ = [("pid", ct.c_uint),
                ("ts", ct.c_ulonglong),
                ("comm", ct.c_char * TASK_COMM_LEN)]

print("%-18s %-16s %-6s %s" % ("TIME(s)", "COMM", "PID", "MESSAGE"))

start = 0
def print_event(cpu, data, size):
    global start
    event = ct.cast(data, ct.POINTER(Data)).contents
    if start == 0:
            start = event.ts
    time_s = (float(event.ts - start)) / 1000000000
    print("%-18.9f %-16s %-6d %s" % (time_s, event.comm, event.pid,
        "Hello, perf_output!"))

b["events"].open_perf_buffer(print_event)
```

```
# ./examples/tracing/hello_perf_output.py
TIME(s)            COMM             PID    MESSAGE
0.000000000        sshd             1708   Hello, perf_output!
0.020348293        sshd             23934  Hello, perf_output!
1.709378491        sshd             23934  Hello, perf_output!
1.710825313        sh               23939  Hello, perf_output!
1.712730637        run-parts        23940  Hello, perf_output!
1.713539655        00-header        23941  Hello, perf_output!
1.714276330        00-header        23941  Hello, perf_output!
1.714813753        00-header        23941  Hello, perf_output!
1.715577598        run-parts        23940  Hello, perf_output!
1.716294354        run-parts        23940  Hello, perf_output!
1.717268885        run-parts        23940  Hello, perf_output!
1.718018553        90-updates-avai  23947  Hello, perf_output!
1.719002588        run-parts        23940  Hello, perf_output!
1.719772776        91-release-upgr  23949  Hello, perf_output!
1.720038403        91-release-upgr  23950  Hello, perf_output!
1.720197178        91-release-upgr  23950  Hello, perf_output!
1.792543698        release-upgrade  23949  Hello, perf_output!
1.794060920        release-upgrade  23949  Hello, perf_output!
1.795520303        release-upgrade  23949  Hello, perf_output!
1.796643253        run-parts        23940  Hello, perf_output!
1.797447438        97-overlayroot   23956  Hello, perf_output!
1.797651202        97-overlayroot   23957  Hello, perf_output!
1.797803991        97-overlayroot   23957  Hello, perf_output!
1.800281656        run-parts        23940  Hello, perf_output!
1.801679488        update-motd-fsc  23960  Hello, perf_output!
1.803061663        update-motd-fsc  23960  Hello, perf_output!
1.803530425        update-motd-fsc  23962  Hello, perf_output!
1.810352576        update-motd-fsc  23960  Hello, perf_output!
1.811627500        update-motd-fsc  23960  Hello, perf_output!
1.812744521        run-parts        23940  Hello, perf_output!
2.129480732        sshd             23934  Hello, perf_output!
2.134354001        bash             23967  Hello, perf_output!
2.136230270        bash             23968  Hello, perf_output!
```

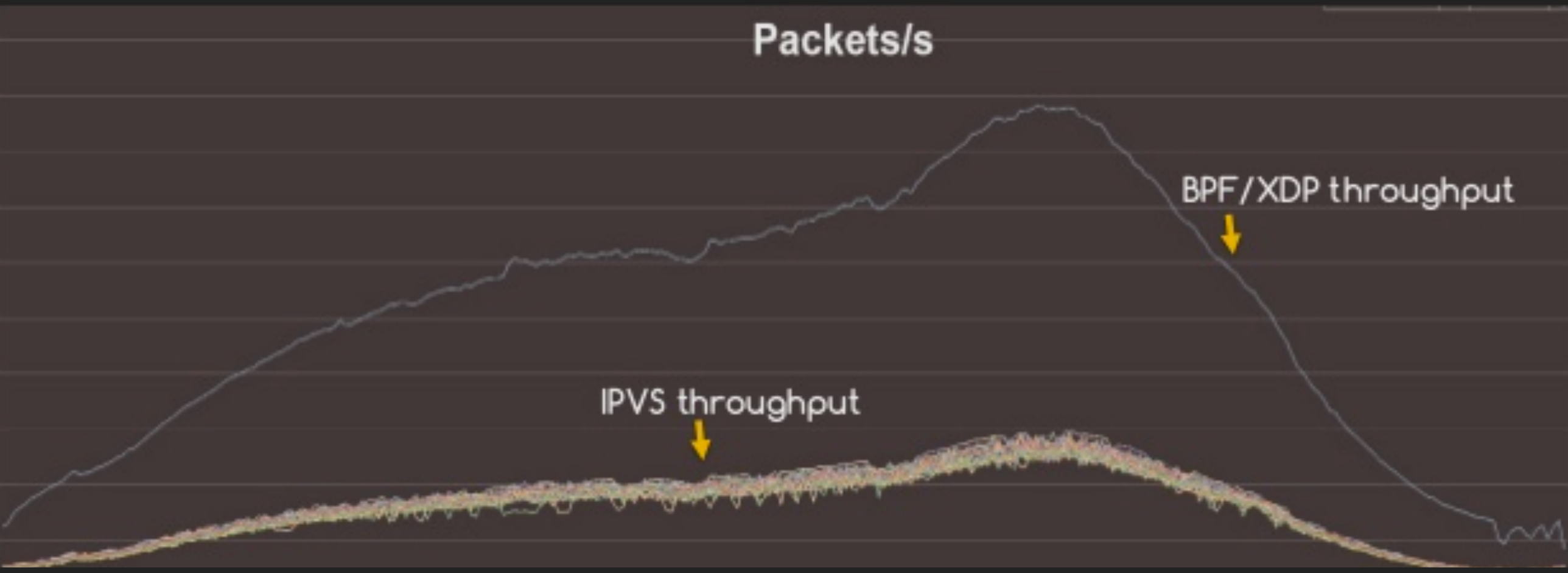
THE FUTURE AND BEYOND, BUT ALSO THE PRESENT

GOING FORWARD

Ply, inspired by dtrace, and therefore awk

```
ply -c 'kretprobe:SyS_read { @.quantize(retval()) }'

ply -c 'kprobe:SyS_read / (arg(2) > 1024) / { @[pid()].quantize(arg(2)); }'

ply -c 'kprobe:SyS_open { printf("%16s(%5d): %s\n", comm(), pid(), mem(arg(0), "128s")) }'

ply -c 'kprobe:SyS_* { @[func()].count() }'

ply -c 'kprobe:SyS_* { @[comm(), pid()].count() }'

ply -c 'kprobe:schedule { @[stack()].count() }'
```

Facebook published BPF/XDP numbers for L3/L4 LB at Netdev 2.1



Source of annotations: https://www.slideshare.net/ThomasGraf5/cilium-network-security-for-microservices/9

Original Source: https://www.netdevconf.org/2.1/slides/apr6/zhou-netdev-xdp-2017.pdf

CILIUM

```
[{
    "endpointSelector": {"matchLabels":{"id.empire.deathstar":""}},
    "ingress": [{
        "fromEndpoints": [
          {"matchLabels":{"id.spaceship":""}},
          {"matchLabels":{"reserved:host":""}}
        ]
    }]
},{
    "endpointSelector": {"matchLabels":{"id.spaceship":""}},
    "egress": [{
    "toPorts": [{
        "ports": [
                {"port": "80", "protocol": "tcp"}
            ],
        "rules": {
                "HTTP": [
                    {
                        "method": "GET",
                        "path": "/v1/"
                    },{
                        "method": "POST",
                        "path": "/v1/request-landing/"
                    },{
                        "method": "PUT",
                        "path": "/v1/exhaust-port/",
                        "headers": ["X-Has-Force: true"]
```

WEAVEWORKS' SCOPE