Efficient System Monitoring in Cloud Native Environments

gergely.szabo@origoss.com

About Myself

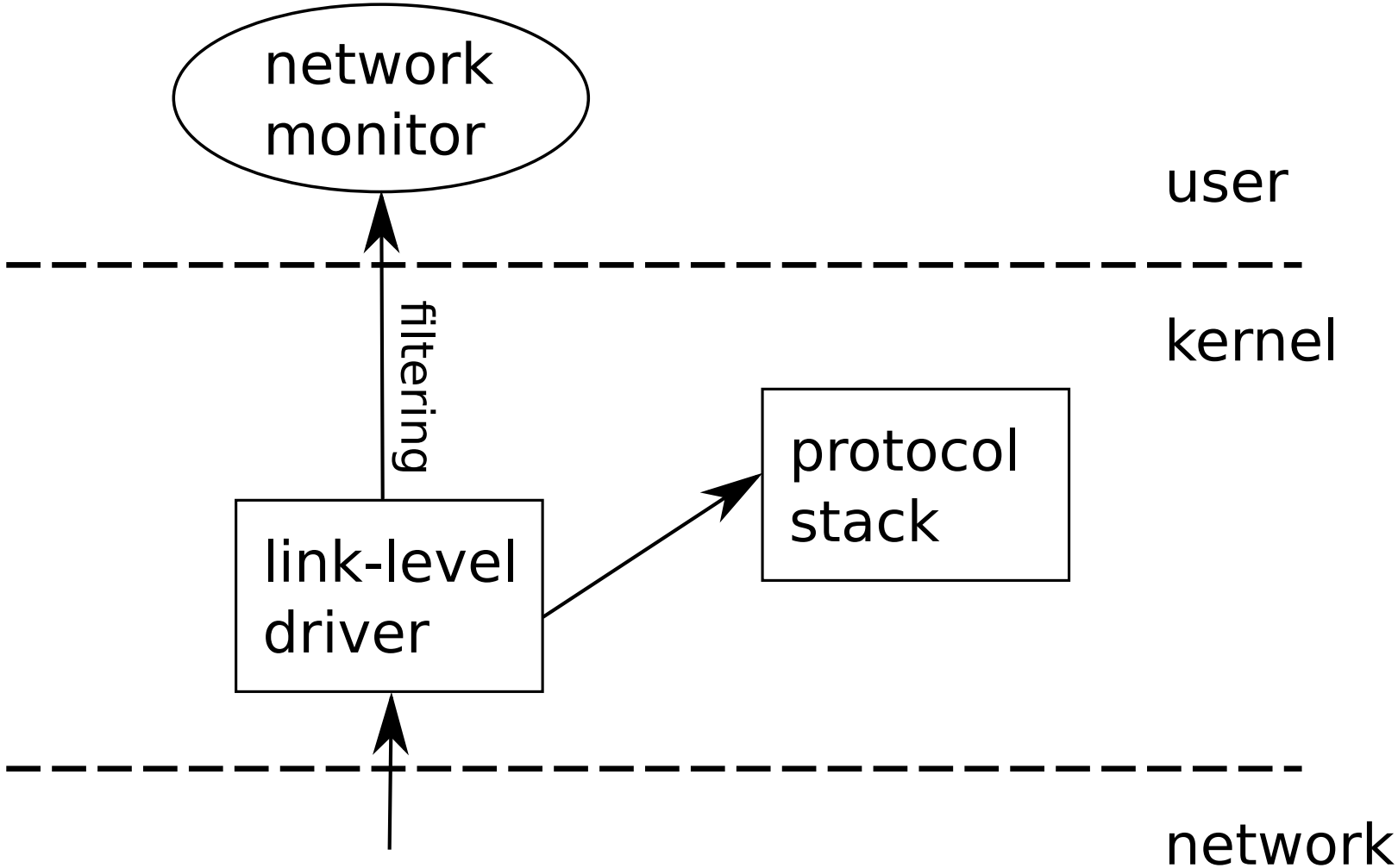
- more than 15 years in the industry
- research, development, system architect, etc...
- currently at Origoss Solutions
  - Cloud Native
  - Kubernetes
  - Prometheus

Agenda

- BPF
- Linux kernel tracing
- EBPF
- EBPF-based in monitoring in the cloud

BPF

Packet Filtering Problem



Filtering Requirements

- Efficient
- Flexible filter rules
- Safe

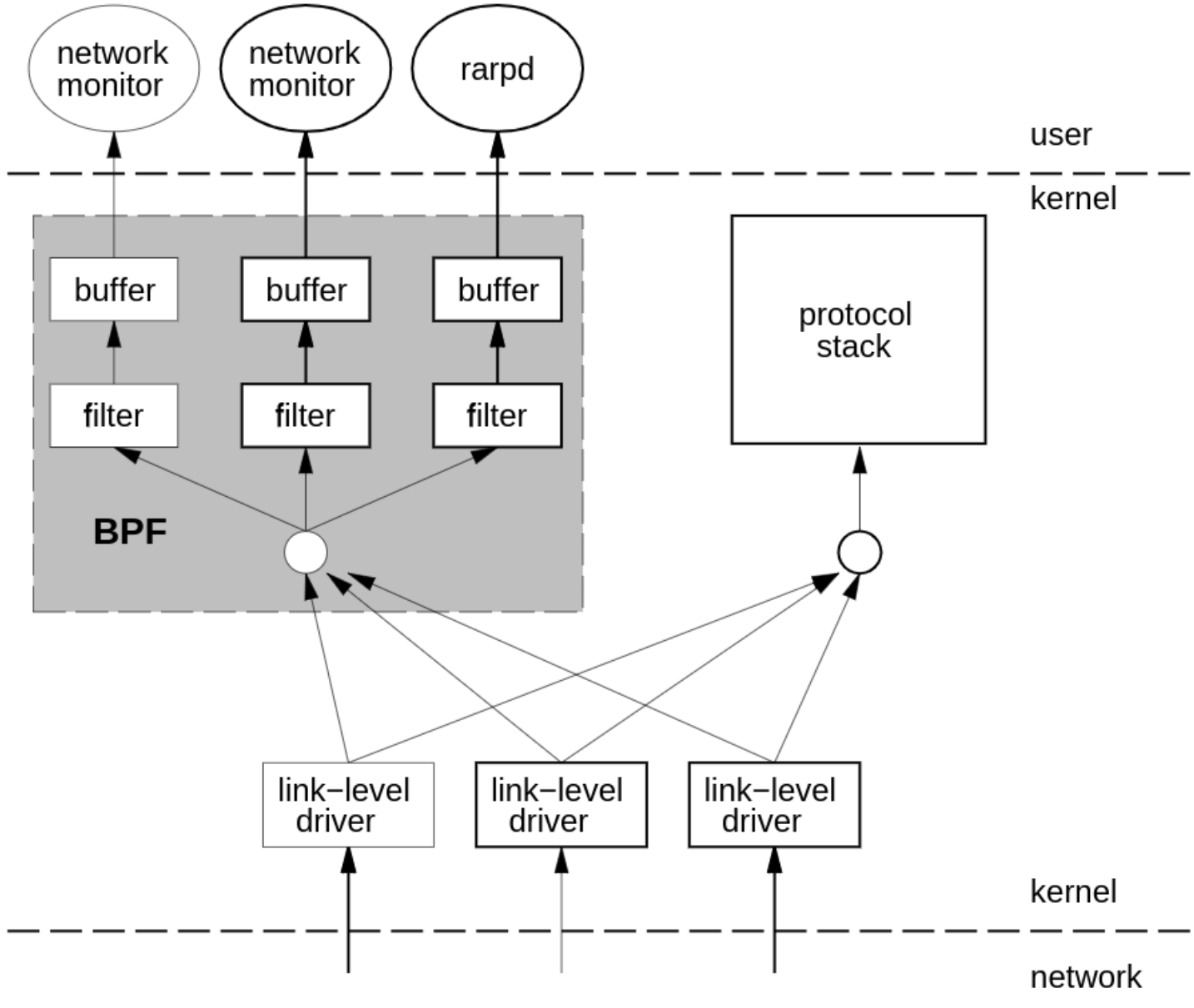
BPF

Steven McCanne and Van Jacobson:

The BSD Packet Filter: A New Architecture for User-level Packet Capture, 1992

http://www.tcpdump.org/papers/bpf-usenix93.pdf
(http://www.tcpdump.org/papers/bpf-usenix93.pdf)

BPF Architecture


network monitor
network monitor
rarpd
user
kernel
buffer
buffer
buffer
filter
filter
filter
BPF
protocol stack
link−level driver
link−level driver
link−level driver
kernel
network

Capturing without Filtering

In [ ]:
```
%%bash
sudo tcpdump -nc 4
```

Simple Filtering Rule

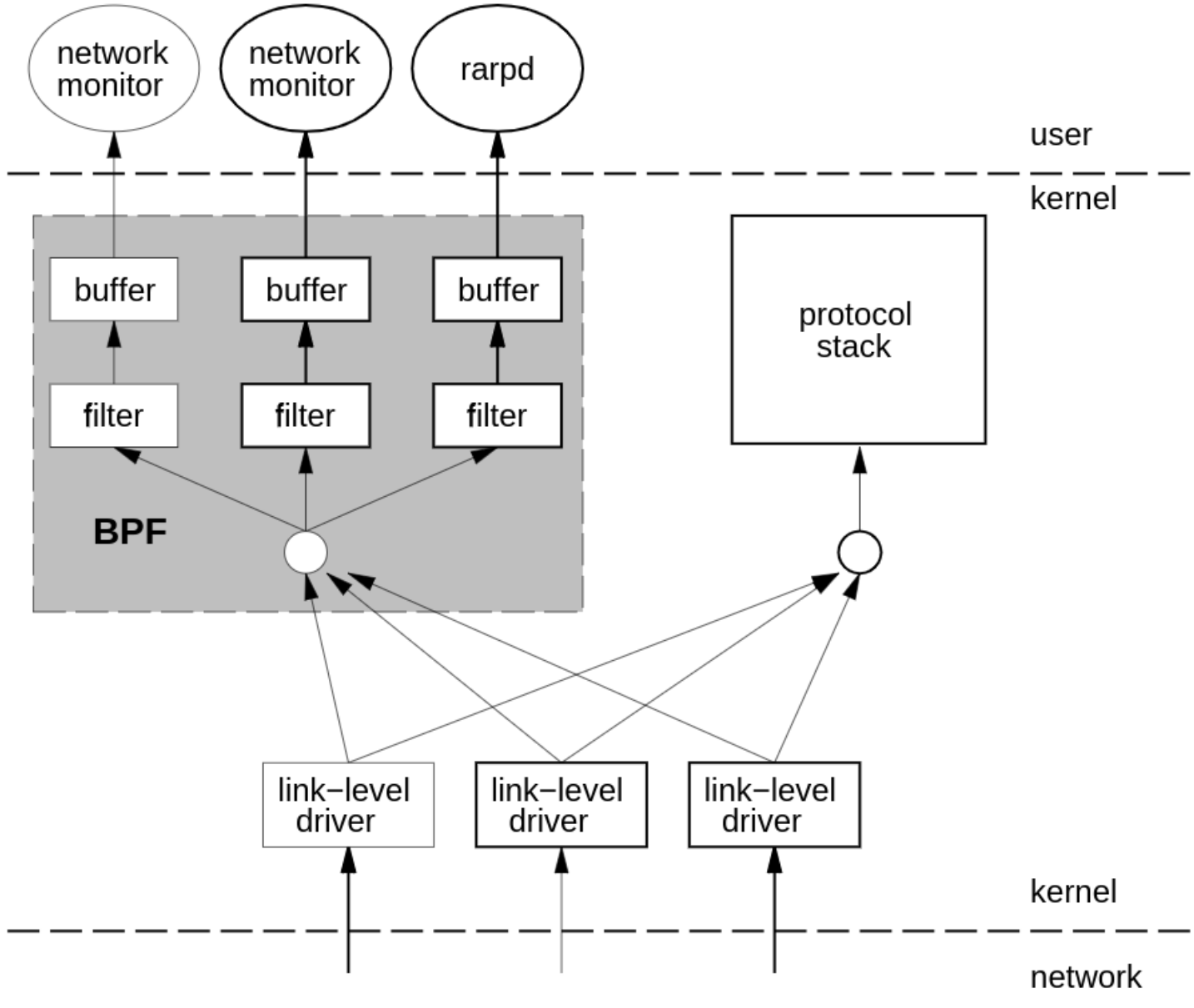
In [ ]:
```
%%bash
sudo tcpdump -nc 4 tcp and port 80
```

Complex Rule

To print all IPv4 HTTP packets to and from port 80, i.e. print only packets that contain data, not, for example, SYN and FIN packets and ACK-only packets.

In [ ]:
```
%%bash
sudo tcpdump -nc 4 'tcp port 80 and (((ip[2:2] - ((ip[0]&0xf)<<2)) - ((tcp[12]&0
xf0)>>2)) != 0)'
```

How Does This Work?


network monitor
network monitor
rarpd
user
kernel
buffer
buffer
buffer
filter
filter
filter
BPF
protocol stack
link−level driver
link−level driver
link−level driver
kernel
network

BPF VM Instruction Set

opcodes	*addr modes*				
ldb ldh	[k] [k]			[x+k] [x+k]	
ld	#k	#len	M[k]	[k]	[x+k]
ldx	#k	#len	M[k]	4*([k]&0xf)	
st stx	M[k] M[k]				
jmp	L				
jeq jgt jge jset	#k, Lt, Lf #k, Lt, Lf #k, Lt, Lf #k, Lt, Lf				
add sub mul div and or lsh rsh	#k #k #k #k #k #k #k #k			x x x x x x x x	
ret	#k			a	
tax txa					

Simple Filtering Rule

In [ ]:
```
%%bash
tcpdump -d tcp and port 80
```

Complex Rule

In [ ]:
```
%%bash
tcpdump -d 'tcp port 80 and (((ip[2:2] - ((ip[0]&0xf)<<2)) - ((tcp[12]&0xf0)>>
2)) != 0)'
```

Linux Kernel Tracepoints

- A tracepoint placed in code provides a hook to call a function (probe) that you can provide at runtime.
- A tracepoint can be "on" or "off"
  - When a tracepoint is "on", the function you provide is called each time the tracepoint is executed
- They can be used for tracing and performance accounting.

Adding Tracepoints

```
void blk_requeue_request(struct request_queue *q, struct request *rq)
{
    blk_delete_timer(rq);
    blk_clear_rq_complete(rq);
    trace_block_rq_requeue(q, rq);   // <- Tracepoint hook

    if (rq->cmd_flags & REQ_QUEUED)
        blk_queue_end_tag(q, rq);

    BUG_ON(blk_queued_rq(rq));

    elv_requeue_request(q, rq);
}
```

List of Tracepoints

In [ ]:
```
%%bash
perf list tracepoint
```

Tracepoints in Action

In [ ]:
```
%%bash
sudo perf stat -a -e kmem:kmalloc sleep 10
```

Linux Kernel KProbes

- dynamically break into any kernel routine and collect debugging and performance information non-disruptively.
  - some parts of the kernel code can not be trapped
- two types of probes: kprobes, and kretprobes
- A kprobe can be inserted on virtually any instruction in the kernel.
- A return probe fires when a specified function returns.

List of KProbes

In [ ]:
```
%%bash
sudo cat /sys/kernel/debug/kprobes/list
```

Probing a Linux Function

```
void blk_delete_timer(struct request *req)
{
    list_del_init(&req->timeout_list);
}
```

In [ ]:

```
%%bash
sudo sh -c 'echo p:demo_probe blk_delete_timer >> /sys/kernel/debug/tracing/kpro
be_events'
```

List of KProbes

In [ ]:
```
%%bash
sudo cat /sys/kernel/debug/kprobes/list
```

In [ ]:
```
%%bash
sudo perf list | grep demo
```

KProbes in Action

In [ ]:
```
%%bash
sudo perf stat -a -e kprobes:demo_probe sleep 10
```

Removing KProbe

In [ ]:
```
%%bash
sudo sh -c 'echo "-:demo_probe" >> /sys/kernel/debug/tracing/kprobe_events'
```

In [ ]:
```
%%bash
sudo cat /sys/kernel/debug/kprobes/list
```

In [ ]:
```
%%bash
sudo perf list | grep demo
```

EBPF

Recent Developments: eBPF

- v3.15: BPF machine upgrade (64bit registers, more registers, new instruction)
- v3.16: JIT compiling
- v3.18: BPF maps
- v4.1: attach BPF programs to kprobes
- v4.7: attach BPF programs to tracepoints
- v4.8: XDP (https://www.iovisor.org/technology/xdp)
- ...

eBPF Maps

- 15+ map types: `BPF_MAP_TYPE_HASH`, `BPF_MAP_TYPE_ARRAY`, `BPF_MAP_TYPE_PROG_ARRAY`, `BPF_MAP_TYPE_PERF_EVENT_ARRAY`, ...
- associated to a userspace process
- read/written by userspace process, eBPF programs

eBPF Map Operations

```
int bpf_create_map(enum bpf_map_type map_type, unsigned int key_size, unsigned
 int value_size, unsigned int max_entries)
int bpf_lookup_elem(int fd, const void *key, void *value)
int bpf_update_elem(int fd, const void *key, const void *value, uint64_t flags
)
int bpf_delete_elem(int fd, const void *key)
int bpf_get_next_key(int fd, const void *key, void *next_key)
```

eBPF Programs

- 20+ program types: `BPF_PROG_TYPE_SOCKET_FILTER`, `BPF_PROG_TYPE_KPROBE`, `BPF_PROG_TYPE_TRACEPOINT`, `BPF_PROG_TYPE_XDP`, ...
- associated to a userspace process
- event-based execution (e.g. tracepoint hooks)
- executed by BPF VM
  - safe
  - efficient

eBPF Program Operations

```
int bpf_prog_load(enum bpf_prog_type type, const struct bpf_insn *insns, int i
nsn_cnt, const char *license)
```

eBPF Program as C struct

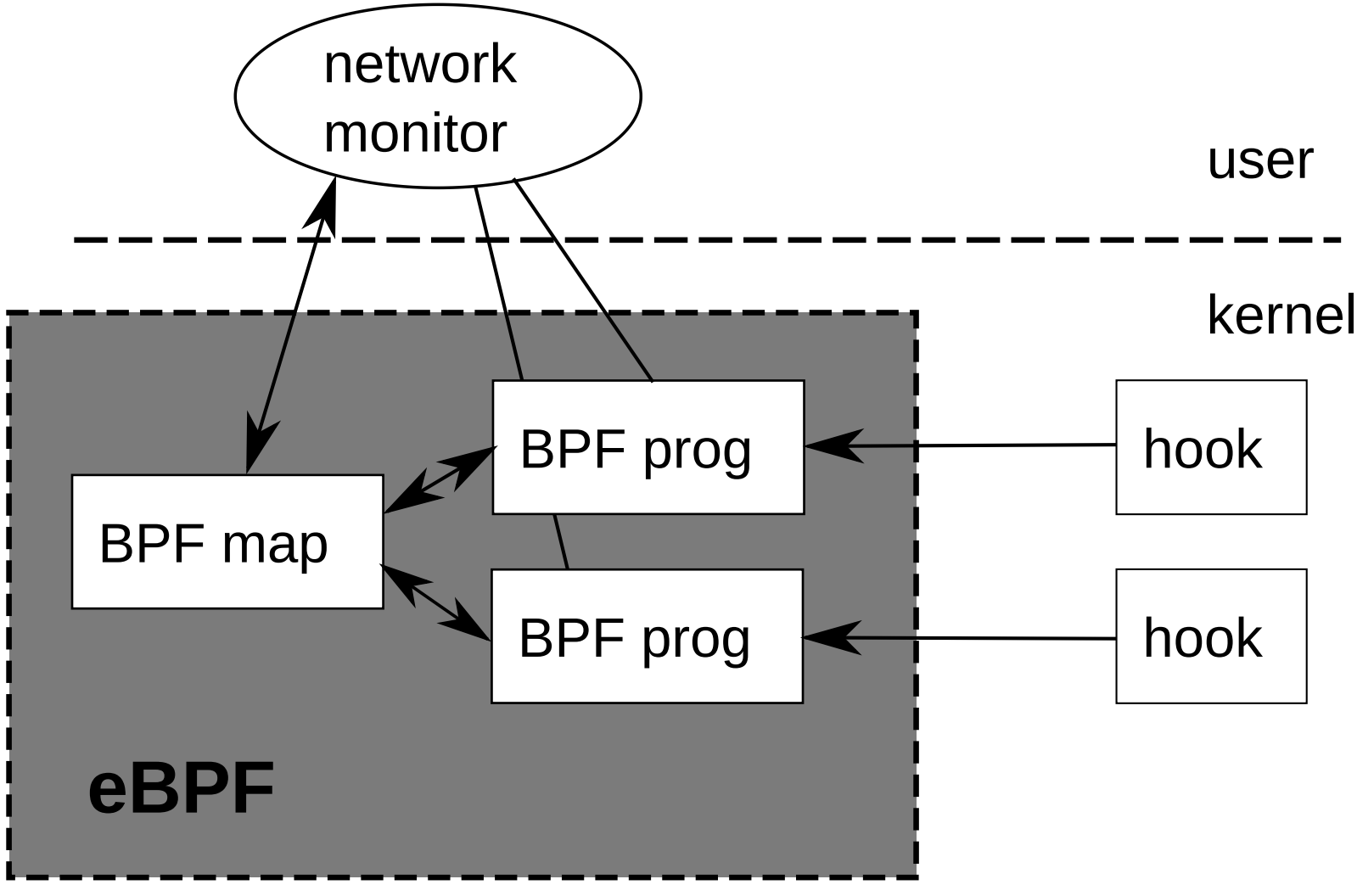
```
struct bpf_insn prog[] = {
     BPF_MOV64_REG(BPF_REG_6, BPF_REG_1),        /* r6 = r1 */
     BPF_LD_ABS(BPF_B, ETH_HLEN + offsetof(struct iphdr, protocol)),
                                        /* r0 = ip->proto */
     BPF_STX_MEM(BPF_W, BPF_REG_10, BPF_REG_0, -4),
                                        /* *(u32 *)(fp - 4) = r0 */
     BPF_MOV64_REG(BPF_REG_2, BPF_REG_10),       /* r2 = fp */
     BPF_ALU64_IMM(BPF_ADD, BPF_REG_2, -4),      /* r2 = r2 - 4 */
     BPF_LD_MAP_FD(BPF_REG_1, map_fd),           /* r1 = map_fd */
     BPF_CALL_FUNC(BPF_FUNC_map_lookup_elem),
                                        /* r0 = map_lookup(r1, r2) */
     BPF_JMP_IMM(BPF_JEQ, BPF_REG_0, 0, 2),
                                        /* if (r0 == 0) goto pc+2 */
     BPF_MOV64_IMM(BPF_REG_1, 1),                /* r1 = 1 */
     BPF_XADD(BPF_DW, BPF_REG_0, BPF_REG_1, 0, 0),
                                        /* lock *(u64 *) r0 += r1 */
     BPF_MOV64_IMM(BPF_REG_0, 0),                /* r0 = 0 */
     BPF_EXIT_INSN(),                            /* return r0 */
};
```

eBPF Program as C Code

Can be compiled with LLVM/Clang using the BPF backend.

```
int bpf_prog1(struct pt_regs *ctx)
{
    /* attaches to kprobe netif_receive_skb,
     * looks for packets on loobpack device and prints them
     */
    char devname[IFNAMSIZ];
    struct net_device *dev;
    struct sk_buff *skb;
    int len;

    /* non-portable! works for the given kernel only */
    skb = (struct sk_buff *) PT_REGS_PARM1(ctx);
    dev = _(skb->dev);
    len = _(skb->len);

    bpf_probe_read(devname, sizeof(devname), dev->name);

    if (devname[0] == 'l' && devname[1] == 'o') {
        char fmt[] = "skb %p len %d\n";
        /* using bpf_trace_printk() for DEBUG ONLY */
        bpf_trace_printk(fmt, sizeof(fmt), skb, len);
    }

    return 0;
}
```

eBPF-based Monitoring



eBPF WorkFlow: Linux Kernel BPF Samples

- see `linux/samples/bpf`
- eBPF kernel part (.c)
  - contains map and program definitions
  - compiled with LLVM -> .o
- eBPF user part (.c)
  - compiles to executable
  - extracts maps and programs from kernel part (.o)
  - creates maps: `bpf_create_map`
  - relocates maps in program codes
  - loads programs: `bpf_prog_load`
  - reads maps and generates output

eBPF WorkFlow: `iovisor/bcc`

- see https://github.com/iovisor/bcc (https://github.com/iovisor/bcc)
- single Python script that contains:
  - definition of eBPF maps
  - definition of eBPF programs (as LLVM compatible C code)
  - code to read and process the maps
- C code is compiled when the script starts (LLVM)

eBPF Example

https://github.com/iovisor/bcc/blob/master/tools/filelife.py
(https://github.com/iovisor/bcc/blob/master/tools/filelife.py)

```
#!/usr/bin/python
# @lint-avoid-python-3-compatibility-imports
#
# filelife    Trace the lifespan of short-lived files.
#             For Linux, uses BCC, eBPF. Embedded C.
#
# This traces the creation and deletion of files, providing information
# on who deleted the file, the file age, and the file name. The intent is to
# provide information on short-lived files, for debugging or performance
# analysis.
#
# USAGE: filelife [-h] [-p PID]
#
# Copyright 2016 Netflix, Inc.
# Licensed under the Apache License, Version 2.0 (the "License")
#
# 08-Feb-2015   Brendan Gregg   Created this.
# 17-Feb-2016   Allan McAleavy updated for BPF_PERF_OUTPUT

from __future__ import print_function
from bcc import BPF
import argparse
from time import strftime
import ctypes as ct

# arguments
examples = """examples:
    ./filelife           # trace all stat() syscalls
    ./filelife -p 181    # only trace PID 181
"""
parser = argparse.ArgumentParser(
    description="Trace stat() syscalls",
    formatter_class=argparse.RawDescriptionHelpFormatter,
    epilog=examples)
parser.add_argument("-p", "--pid",
    help="trace this PID only")
parser.add_argument("--ebpf", action="store_true",
```

```
    help=argparse.SUPPRESS)
args = parser.parse_args()
debug = 0

# define BPF program
bpf_text = """
#include <uapi/linux/ptrace.h>
#include <linux/fs.h>
#include <linux/sched.h>
struct data_t {
    u32 pid;
    u64 delta;
    char comm[TASK_COMM_LEN];
    char fname[DNAME_INLINE_LEN];
};
BPF_HASH(birth, struct dentry *);
BPF_PERF_OUTPUT(events);
// trace file creation time
int trace_create(struct pt_regs *ctx, struct inode *dir, struct dentry *dentr
y)
{
    u32 pid = bpf_get_current_pid_tgid();
    FILTER
    u64 ts = bpf_ktime_get_ns();
    birth.update(&dentry, &ts);
    return 0;
};
// trace file deletion and output details
int trace_unlink(struct pt_regs *ctx, struct inode *dir, struct dentry *dentr
y)
{
    struct data_t data = {};
    u32 pid = bpf_get_current_pid_tgid();
    FILTER
    u64 *tsp, delta;
    tsp = birth.lookup(&dentry);
    if (tsp == 0) {
        return 0;   // missed create
```

```
    }
    delta = (bpf_ktime_get_ns() - *tsp) / 1000000;
    birth.delete(&dentry);
    struct qstr d_name = dentry->d_name;
    if (d_name.len == 0)
        return 0;
    if (bpf_get_current_comm(&data.comm, sizeof(data.comm)) == 0) {
        data.pid = pid;
        data.delta = delta;
        bpf_probe_read(&data.fname, sizeof(data.fname), d_name.name);
    }
    events.perf_submit(ctx, &data, sizeof(data));
    return 0;
}
"""

TASK_COMM_LEN = 16            # linux/sched.h
DNAME_INLINE_LEN = 255        # linux/dcache.h

class Data(ct.Structure):
    _fields_ = [
        ("pid", ct.c_uint),
        ("delta", ct.c_ulonglong),
        ("comm", ct.c_char * TASK_COMM_LEN),
        ("fname", ct.c_char * DNAME_INLINE_LEN)
    ]

if args.pid:
    bpf_text = bpf_text.replace('FILTER',
        'if (pid != %s) { return 0; }' % args.pid)
else:
    bpf_text = bpf_text.replace('FILTER', '')
if debug or args.ebpf:
    print(bpf_text)
    if args.ebpf:
        exit()

# initialize BPF
```

Prometheus eBPF Exporter

Motivation of this exporter is to allow you to write eBPF code and export metrics that are not otherwise accessible from the Linux kernel.

- *https://github.com/cloudflare/ebpf_exporter (https://github.com/cloudflare/ebpf_exporter)*

- leverages on tools made by `iovisor/bcc`
- written in go
- exported metrics are defined as yaml files

Prometheus eBPF Exporter - Example

https://github.com/cloudflare/ebpf_exporter/blob/master/examples/bio.yaml
(https://github.com/cloudflare/ebpf_exporter/blob/master/examples/bio.yaml)

```
programs:
  # See:
  # * https://github.com/iovisor/bcc/blob/master/tools/biolatency.py
  # * https://github.com/iovisor/bcc/blob/master/tools/biolatency_example.txt
  #
  # See also: bio-tracepoints.yaml
  - name: bio
    metrics:
      histograms:
        - name: bio_latency_seconds
          help: Block IO latency histogram
          table: io_latency
          bucket_type: exp2
          bucket_min: 0
          bucket_max: 26
          bucket_multiplier: 0.000001 # microseconds to seconds
          labels:
            - name: device
              size: 32
              decoders:
                - name: string
            - name: operation
              size: 8
              decoders:
                - name: uint
                - name: static_map
                  static_map:
                    1: read
                    2: write
            - name: bucket
              size: 8
              decoders:
                - name: uint
        - name: bio_size_bytes
          help: Block IO size histogram with kibibyte buckets
          table: io_size
          bucket_type: exp2
```

```
        bucket_min: 0
        bucket_max: 15
        bucket_multiplier: 1024 # kibibytes to bytes
        labels:
          - name: device
            size: 32
            decoders:
              - name: string
          - name: operation
            size: 8
            decoders:
              - name: uint
              - name: static_map
                static_map:
                  1: read
                  2: write
          - name: bucket
            size: 8
            decoders:
              - name: uint
    kprobes:
      blk_start_request: trace_req_start
      blk_mq_start_request: trace_req_start
      blk_account_io_completion: trace_req_completion
    code: |
      #include <linux/blkdev.h>
      #include <linux/blk_types.h>
      typedef struct disk_key {
          char disk[32];
          u8 op;
          u64 slot;
      } disk_key_t;
      // Max number of disks we expect to see on the host
      const u8 max_disks = 255;
      // 27 buckets for latency, max range is 33.6s .. 67.1s
      const u8 max_latency_slot = 26;
      // 16 buckets per disk in kib, max range is 16mib .. 32mib
      const u8 max_size_slot = 15;
```

```
      // Hash to temporily hold the start time of each bio request, max 10k in
-flight by default
      BPF_HASH(start, struct request *);
      // Histograms to record latencies
      BPF_HISTOGRAM(io_latency, disk_key_t, (max_latency_slot + 1) * max_disk
s);
      // Histograms to record sizes
      BPF_HISTOGRAM(io_size, disk_key_t, (max_size_slot + 1) * max_disks);
      // Record start time of a request
      int trace_req_start(struct pt_regs *ctx, struct request *req) {
          u64 ts = bpf_ktime_get_ns();
          start.update(&req, &ts);
          return 0;
      }
      // Calculate request duration and store in appropriate histogram bucket
      int trace_req_completion(struct pt_regs *ctx, struct request *req, unsig
ned int bytes) {
          u64 *tsp, delta;
          // Fetch timestamp and calculate delta
          tsp = start.lookup(&req);
          if (tsp == 0) {
              return 0; // missed issue
          }
          // There are write request with zero length on sector zero,
          // which do not seem to be real writes to device.
          if (req->__sector == 0 && req->__data_len == 0) {
            return 0;
          }
          // Disk that received the request
          struct gendisk *disk = req->rq_disk;
          // Delta in nanoseconds
          delta = bpf_ktime_get_ns() - *tsp;
          // Convert to microseconds
          delta /= 1000;
          // Latency histogram key
          u64 latency_slot = bpf_log2l(delta);
          // Cap latency bucket at max value
          if (latency_slot > max_latency_slot) {
```

Using eBPF for Monitoring in Cloud-Native Environment

Cloud Native:

- microservice architecture
- containerized
- orchestrated

Pitfall #1: Dependencies

- Linux Kernel headers
- bcc
- LLVM

Pitfall #2: KProbes and Kernel Version

```
static int bpf_prog_load(union bpf_attr *attr)
{
    enum bpf_prog_type type = attr->prog_type;
    struct bpf_prog *prog;
    int err;
    char license[128];
    bool is_gpl;

    if (CHECK_ATTR(BPF_PROG_LOAD))
        return -EINVAL;

    if (attr->prog_flags & ~BPF_F_STRICT_ALIGNMENT)
        return -EINVAL;

    /* copy eBPF program license from user space */
    if (strncpy_from_user(license, u64_to_user_ptr(attr->license),
                  sizeof(license) - 1) < 0)
        return -EFAULT;
    license[sizeof(license) - 1] = 0;

    /* eBPF programs must be GPL compatible to use GPL-ed functions */
    is_gpl = license_is_gpl_compatible(license);

    if (attr->insn_cnt == 0 || attr->insn_cnt > BPF_MAXINSNS)
        return -E2BIG;

    if (type == BPF_PROG_TYPE_KPROBE &&
        attr->kern_version != LINUX_VERSION_CODE)
        return -EINVAL;
    /* ... */
}
```

Pitfall #3: KProbes and Stability

- Kprobe can be created for any kernel function
- Most of the Linux kernel source code is subject to change
  - in-kernel APIs and ABIs are unstable
- Distribution-specific kernel modifications, propriatery kernels

Pitfall #4: Kernel Support

- v4.1: attach BPF programs to kprobes (21 June, 2015)
- v4.7: attach BPF programs to tracepoints (24 July, 2016)
- RHEL 7.6 (30 October, 2018) has `3.10.0-957`

Ongoing Activities

- eBPF-based Prometheus exporter, containerized
- run-time configurable eBPF metrics
- self contained
  - no dep on `iovisor/bcc`
  - no dep on Linux kernel headers
- supporting the major Linux distributions

Thank you!

Questions?