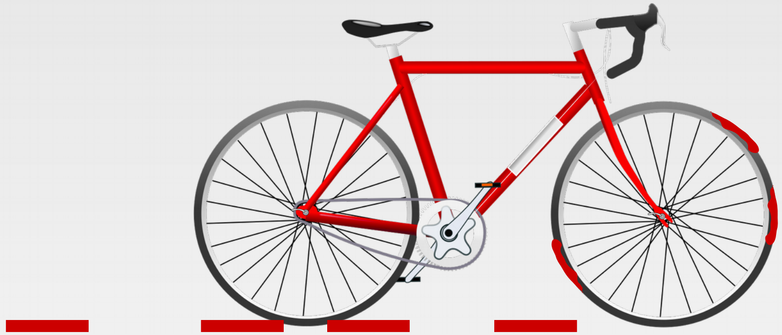


Trace Aggregation and Collection with eBPF

Suchakrapani Sharma

5th May 2017
Polytechnique Montréal

Agenda

Introduction

- Quick eBPF Intro
- Internals of eBPF

Usecases

- Networking, Tracing, Security
- IOVisor BPF Compiler Collection
- Tracing Examples

Trace Collection

- eBPF to CTF

What’s Next

eBPF

Stateful, programmable, in-kernel decisions for networking, tracing and security

"One Ring" by Yukatan (CC)

Berkeley Packet Filter

Classical BPF (cBPF)

- Network packet filtering [McCanne et al. 1993], Seccomp
- Filter Expressions → Bytecode → Interpret*
- Small, in-kernel VM. Register based, switch dispatch interpreter, few instructions

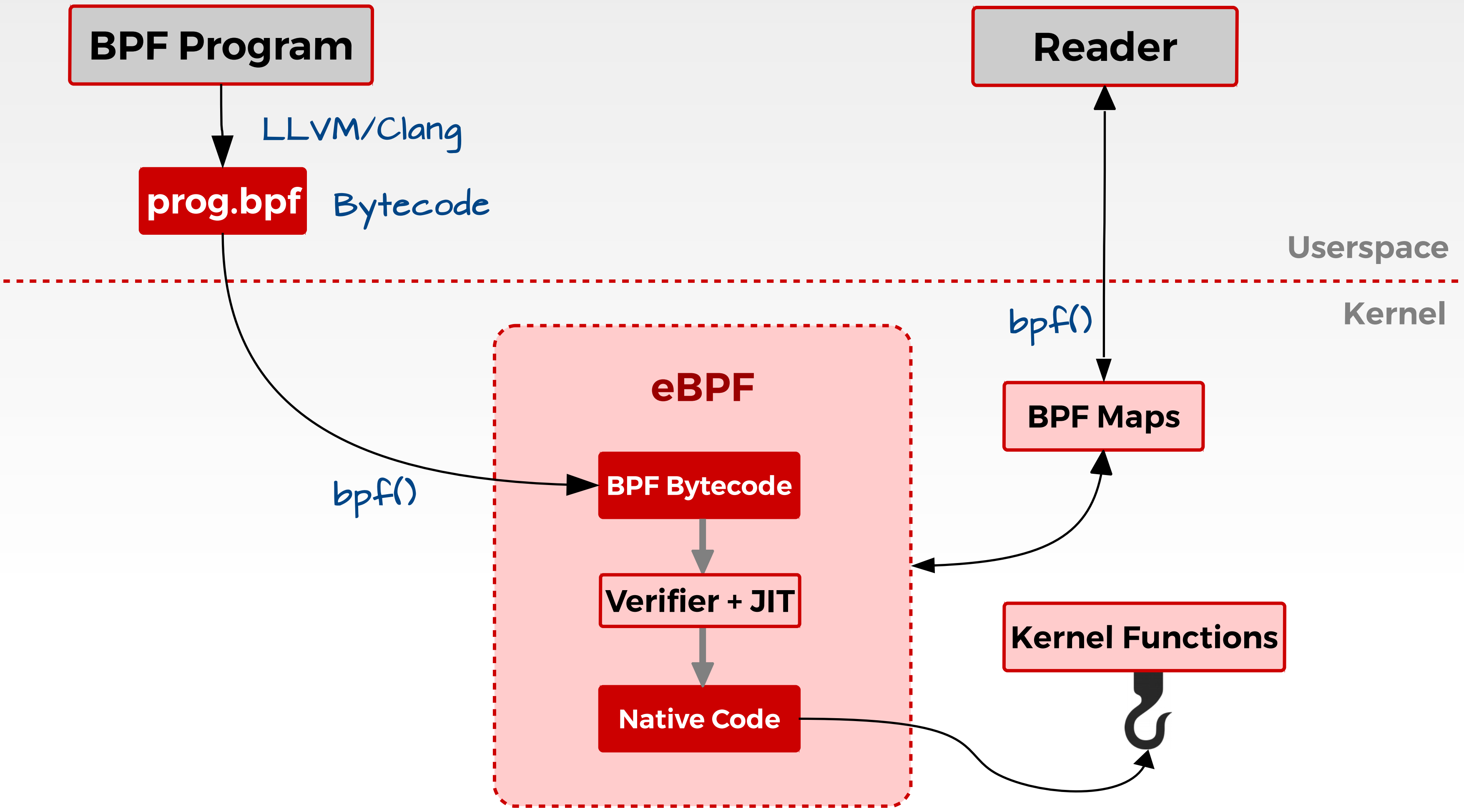
Extended BPF (eBPF) [Sharma et al. 2016] [Clément 2016]

- More registers, JIT compiler (flexible/faster), verifier
- Attach on Tracepoint/Kprobe/Uprobe/USDT
- In-kernel trace aggregation & filtering
- Control via ***`bpf()`***, trace collection via **BPF Maps**
- Upstream in Linux Kernel (`bpf()` syscall, v3.18+)
- Bytecode compilation upstream in LLVM/Clang

*JIT support eventually landed in kernel

Berkeley Packet Filter

Program Anatomy



BPF Program

LLVM/Clang

prog.bpf

Bytecode

Reader

Userspace

Kernel

bpf()

eBPF

BPF Bytecode

Verifier + JIT

Native Code

bpf()

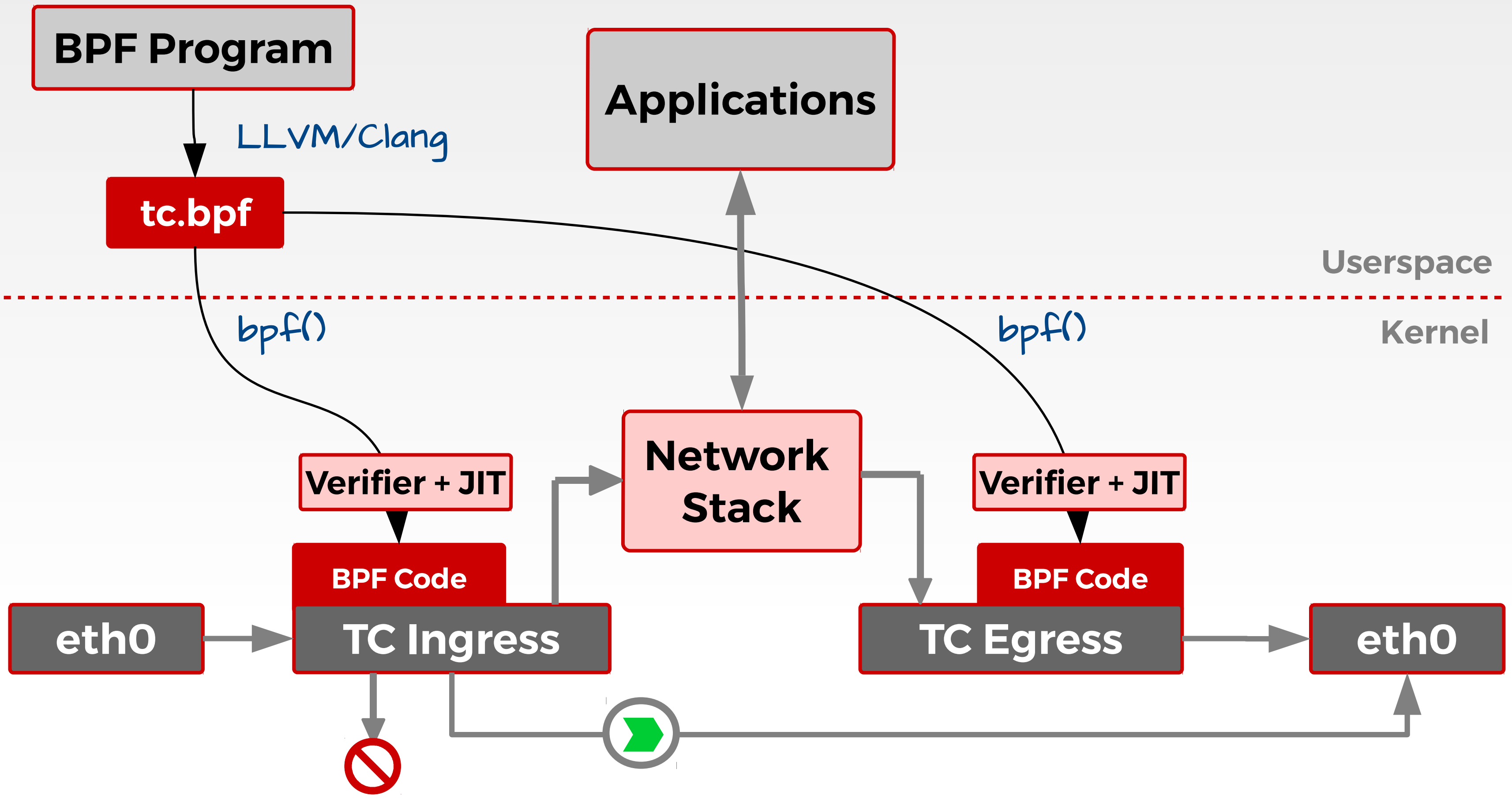
BPF Maps

Kernel Functions

eBPF for Networking

Traffic Control/XDP

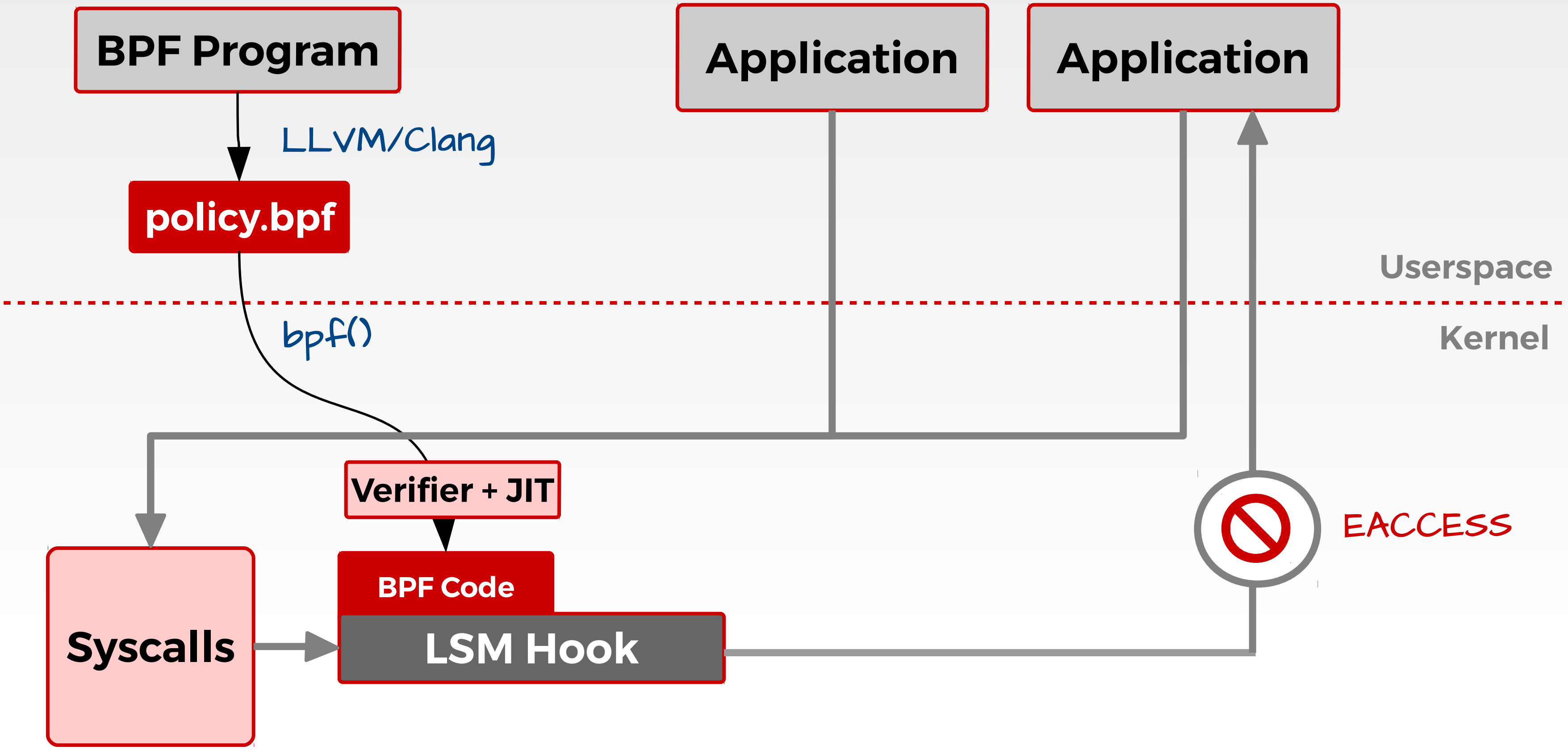
- TC with `cls_bpf` [Borkmann, 2016] `act_bpf` and XDP



Adapted from Thomas Graf's presentation "Cilium - BPF & XDP for containers"

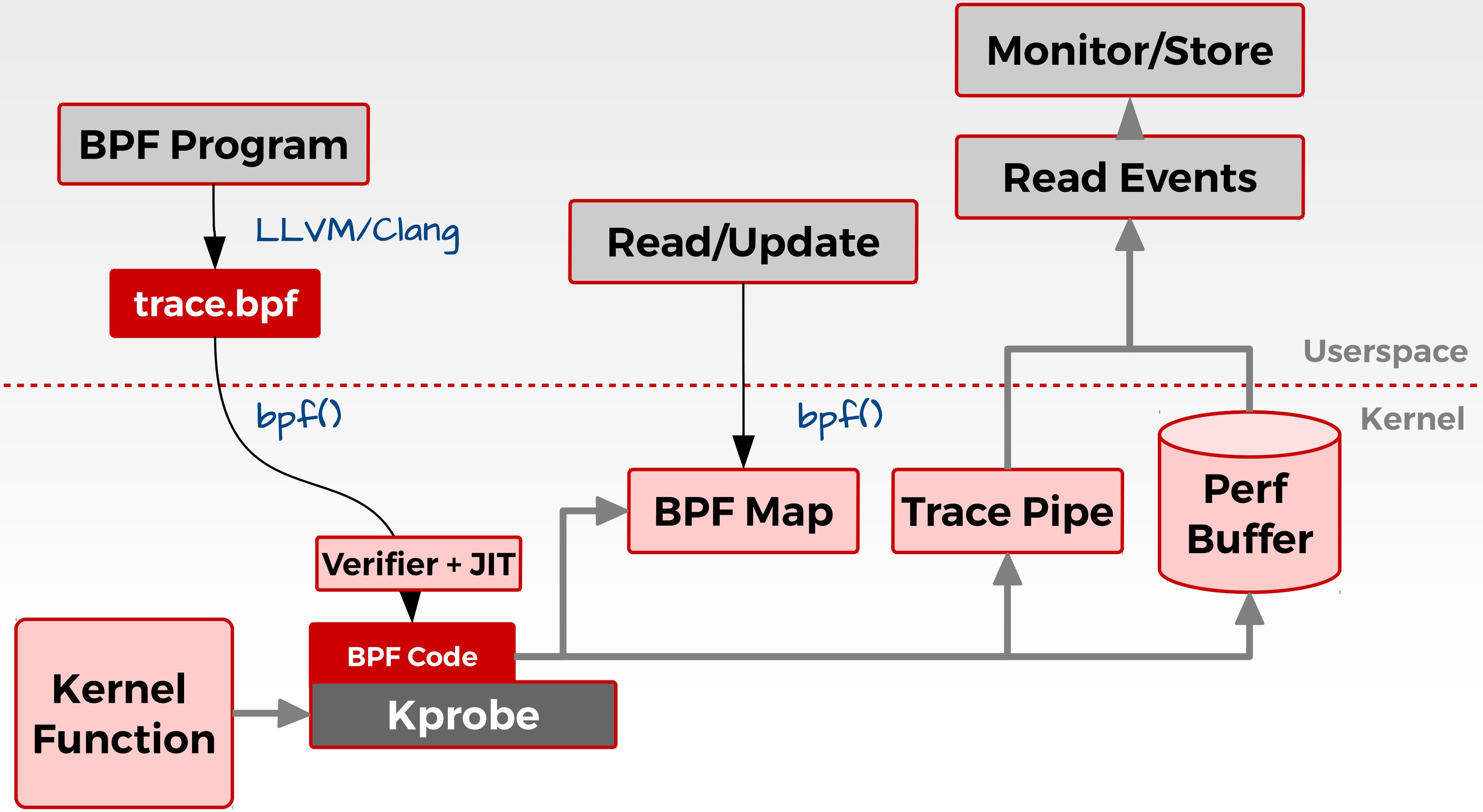
eBPF for Security

LSM Hooks



eBPF for Tracing

Kprobes/Kretprobes



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eBPF Features & Support

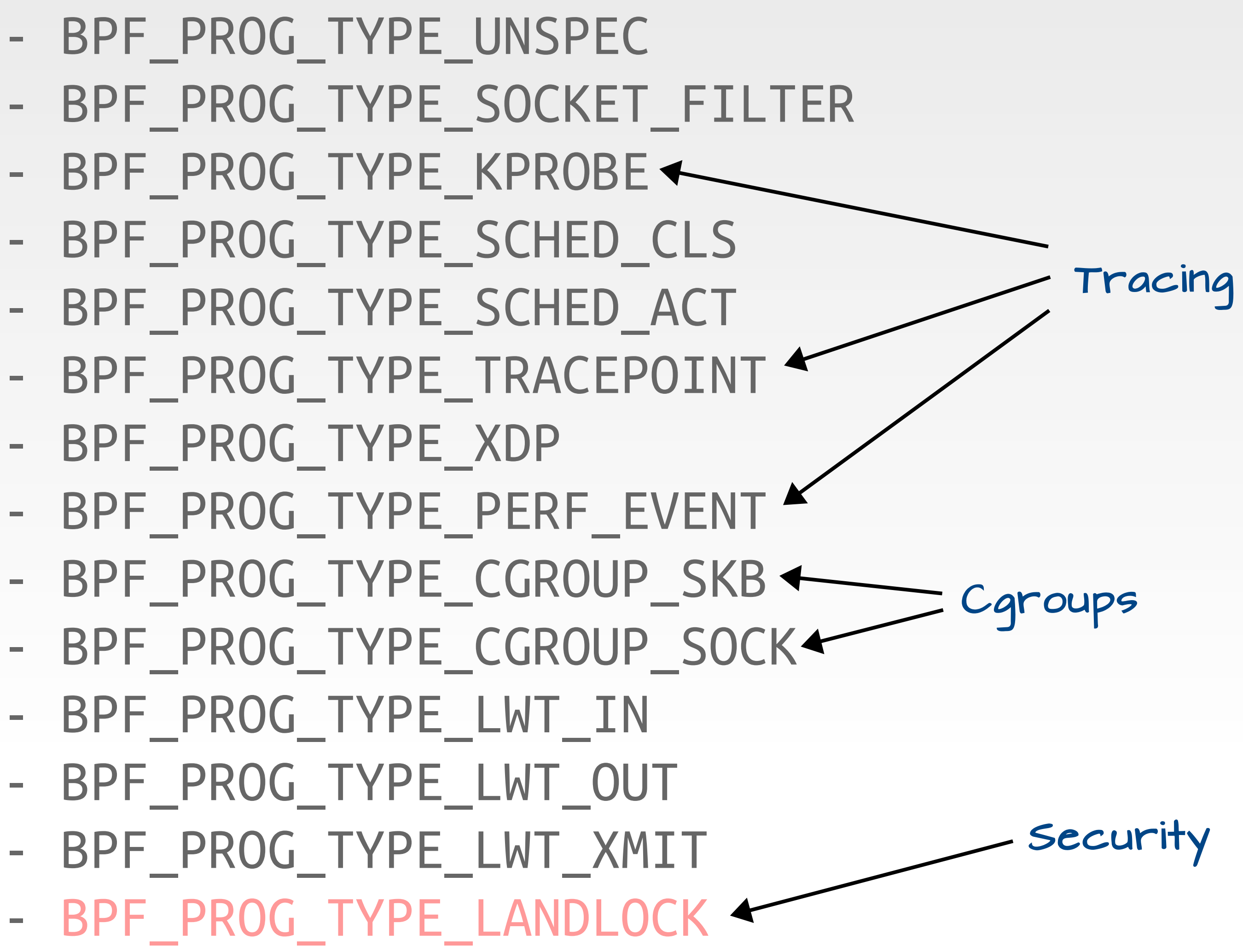
Major BPF Milestones by Kernel Version*

- 3.18 : `bpf()` syscall
- 3.19 : Sockets support, BPF Maps
- 4.1 : Kprobe support
- 4.4 : Perf events
- 4.6 : Stack traces, per-CPU Maps
- 4.7 : Attach on Tracepoints
- 4.8 : XDP core and act
- 4.9 : Profiling, attach to Perf events
- 4.10 : cgroups support (socket filters)
- 4.11 : *Tracerception* – tracepoints for eBPF debugging

*Adapted from “BPF: Tracing and More” by Brendan Gregg (Linux.Conf.au 2017)

eBPF Features & Support

Program Types



- BPF_PROG_TYPE_UNSPEC
- BPF_PROG_TYPE_SOCKET_FILTER
- BPF_PROG_TYPE_KPROBE
- BPF_PROG_TYPE_SCHED_CLS
- BPF_PROG_TYPE_SCHED_ACT
- BPF_PROG_TYPE_TRACEPOINT
- BPF_PROG_TYPE_XDP
- BPF_PROG_TYPE_PERF_EVENT
- BPF_PROG_TYPE_CGROUP_SKB
- BPF_PROG_TYPE_CGROUP_SOCK
- BPF_PROG_TYPE_LWT_IN
- BPF_PROG_TYPE_LWT_OUT
- BPF_PROG_TYPE_LWT_XMIT
- BPF_PROG_TYPE_LANDLOCK

http://lxr.free-electrons.com/source/include/uapi/linux/bpf.h

eBPF Features & Support

Map Types

- BPF_MAP_TYPE_UNSPEC
- BPF_MAP_TYPE_HASH
- BPF_MAP_TYPE_ARRAY
- BPF_MAP_TYPE_PROG_ARRAY
- BPF_MAP_TYPE_PERF_EVENT_ARRAY
- BPF_MAP_TYPE_PERCPU_HASH
- BPF_MAP_TYPE_PERCPU_ARRAY
- BPF_MAP_TYPE_STACK_TRACE
- BPF_MAP_TYPE_CGROUP_ARRAY
- BPF_MAP_TYPE_LRU_HASH
- BPF_MAP_TYPE_LRU_PERCPU_HASH

http://lxr.free-electrons.com/source/include/uapi/linux/bpf.h

eBPF for Tracing

Frontends

- IOVisor BCC – Python, C++, Lua, Go (gobpf) APIs
- Compile BPF programs directly via LLVM interface
- Helper functions to manage maps, buffers, probes

Kprobes Example

Complete Program
trace_fields.py

```
from bcc import BPF

prog = """
int hello(void *ctx) {
  bpf_trace_printk("Hello, World!\\n");
  return 0;
}
"""
b = BPF(text=prog)
b.attach_kprobe(event="sys_clone", fn_name="hello")
print "PID MESSAGE"
b.trace_print(fmt="{1} {5}")
```

prog compiled to BPF bytecode

Attach to Kprobe event

Print trace pipe

eBPF for Tracing

Tracepoint Example (v4.7+)

Program Excerpt

Attach to tracepoint

Filter on args

```
# define EXIT_REASON 18

prog = """
TRACEPOINT_PROBE(kvm, kvm_exit) {
    if (args->exit_reason == EXIT_REASON) {
        bpf_trace_printk("KVM_EXIT exit_reason : %d\\n", args->exit_reason);
    }
    return 0;
}

TRACEPOINT_PROBE(kvm, kvm_entry) {
    if (args->vcpu_id = 0) {
        bpf_trace_printk("KVM_ENTRY vcpu_id : %u\\n", args->vcpu_id);
    }
}
"""
```

Output

```
# ./kvm-test.py
2445.577129000     CPU 0/KVM        8896   KVM_ENTRY vcpu_id : 0
2445.577136000     CPU 0/KVM        8896   KVM_EXIT exit_reason : 18
```

eBPF for Tracing

Uprobes Example

Program Excerpt

```
bpf_text = """
#include <uapi/linux/ptrace.h>
#include <uapi/linux/limits.h>

int get_fname(struct pt_regs *ctx) {
    if (!ctx->si)
      return 0;
    char str[NAME_MAX] = {};
    bpf_probe_read(&str, sizeof(str), (void *)ctx->si);
    bpf_trace_printk("%s\\n", &str);
    return 0;
};
"""
b = BPF(text=bpf_text)
b.attach_uprobe(name="/usr/bin/vim", sym="readfile", fn_name="get_fname")
```

Get 2nd argument

Process

Symbol

Output

```
# ./vim-test.py
TASK   PID    FILENAME
vim    23707  /tmp/wololo
```

eBPF for Tracing

USDT Example

Program Excerpt
nodejs_http_server.py

```
from bcc import BPF, USDT
.
.
bpf_text = """
#include <uapi/linux/ptrace.h>
int do_trace(struct pt_regs *ctx) {
    uint64_t addr;
    char path[128]={0};
    bpf_usdt_readarg(6, ctx, &addr);
    bpf_probe_read(&path, sizeof(path), (void *)addr);
    bpf_trace_printk("path:%s\\n", path);
    return 0;
};
"""

u = USDT(pid=int(pid))
u.enable_probe(probe="http__server__request", fn_name="do_trace")
b = BPF(text=bpf_text, usdt_contexts=[u])
```

Get 6th Argument

Read to local variable

Target PID

Probe in Node

eBPF for Tracing

USDT Example

Output

```
# ./nodejs_http_server.py 24728
TIME(s)            COMM             PID    ARGS
24653324.561322998 node             24728  path:/index.html
24653335.343401998 node             24728  path:/images/welcome.png
24653340.510164998 node             24728  path:/images/favicon.png
```

Supported Frameworks

- MySQL : `--enable-dtrace` (Build)
- JVM : `-XX:+ExtendedDTraceProbes` (Runtime)
- Node : `--with-dtrace` (Build)
- Python : `--with-dtrace` (Build)
- Ruby : `--enable-dtrace` (Build)

eBPF for Tracing

BPF Maps – Filters, States, Counters

Program Excerpt
tcpv4connect.py

```
bpf_text = """
#include <uapi/linux/ptrace.h>
#include <net/sock.h>
#include <bcc/proto.h>

BPF_HASH(currsock, u32, struct sock *);

int kprobe__tcp_v4_connect(struct pt_regs *ctx, struct sock *sk)
{
    u32 pid = bpf_get_current_pid_tgid();
    // stash the sock ptr for lookup on return
    currsock.update(&pid, &sk);
    return 0;
};
.
.
.
```

Key

Value type

Update hash map

eBPF for Tracing

BPF Maps – Filters, States, Counters

Program Excerpt
tcpv4connect.py

```
int kretprobe__tcp_v4_connect(struct pt_regs *ctx)
{
    int ret = PT_REGS_RC(ctx);
    u32 pid = bpf_get_current_pid_tgid();
    struct sock **skpp;
    skpp = currsock.lookup(&pid);
    if (skpp == 0) {
        return 0;     // missed entry
    }
    if (ret != 0) {
        // failed to send SYNC packet, may not have populated
        currsock.delete(&pid);
        return 0;
    }

    struct sock *skp = *skpp;
    u32 saddr = 0, daddr = 0;
    u16 dport = 0;
    bpf_probe_read(&saddr, sizeof(saddr), &skp->__sk_common.skc_rcv_saddr);
    bpf_probe_read(&daddr, sizeof(daddr), &skp->__sk_common.skc_daddr);
    bpf_probe_read(&dport, sizeof(dport), &skp->__sk_common.skc_dport);
    bpf_trace_printk("trace_tcp4connect %x %x %d\\n", saddr, daddr, ntohs(dport));
    currsock.delete(&pid);
    return 0;
}
"""
```

ax reg

Get Key

Lookup

Delete

Read stuff from
sock ptr

Delete

Suchakrapani Datt Sharma

eBPF for Tracing

BPF Maps – Filters, States, Counters

Output

```
# ./tcpv4connect.py
PID    COMM         SADDR            DADDR            DPORT
1479   telnet       127.0.0.1        127.0.0.1        23
1469   curl         10.201.219.236   54.245.105.25    80
1469   curl         10.201.219.236   54.67.101.145    80
```

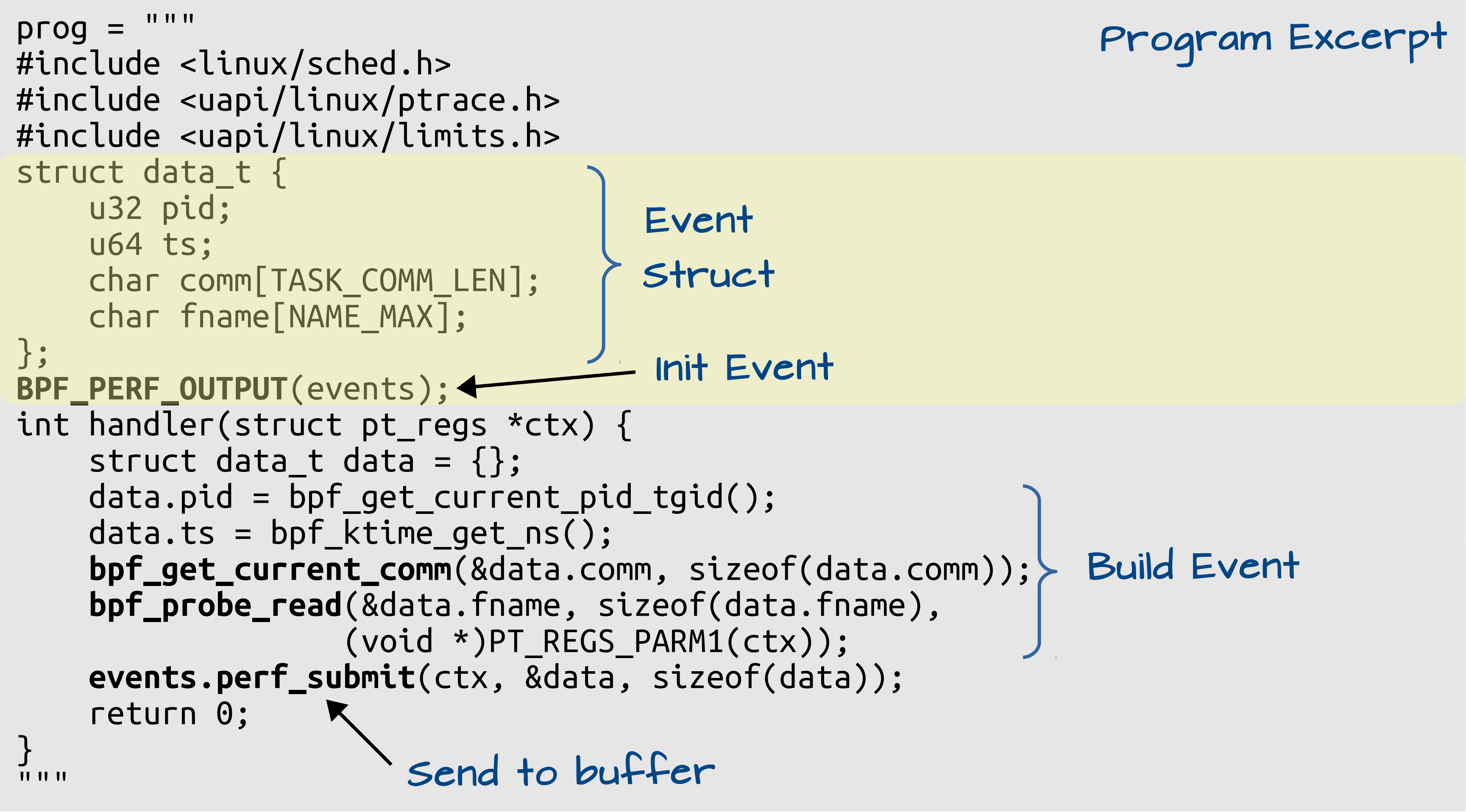
More Uses

- Record latency (Δt)
    - `biosnoop.py`
- Flags for keeping track of events
    - `kvm_hypercall.py`
- Counting events, histograms
    - `cachestat.py`
    - `cpudist.py`

eBPF for Tracing

BPF Perf Event Output

- Build perf events and save to per-cpu perf buffers



```
prog = """
#include <linux/sched.h>
#include <uapi/linux/ptrace.h>
#include <uapi/linux/limits.h>
struct data_t {
    u32 pid;
    u64 ts;
    char comm[TASK_COMM_LEN];
    char fname[NAME_MAX];
};
BPF_PERF_OUTPUT(events);
int handler(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));
    bpf_probe_read(&data.fname, sizeof(data.fname),
                   (void *)PT_REGS_PARM1(ctx));
    events.perf_submit(ctx, &data, sizeof(data));
    return 0;
}
"""
```

Program Excerpt

Event Struct

Init Event

Build Event

Send to buffer

eBPF Trace Visualization

Current State

- Using ASCII histograms, ASCII escape codes
- eBPF trace driven Flamegraphs

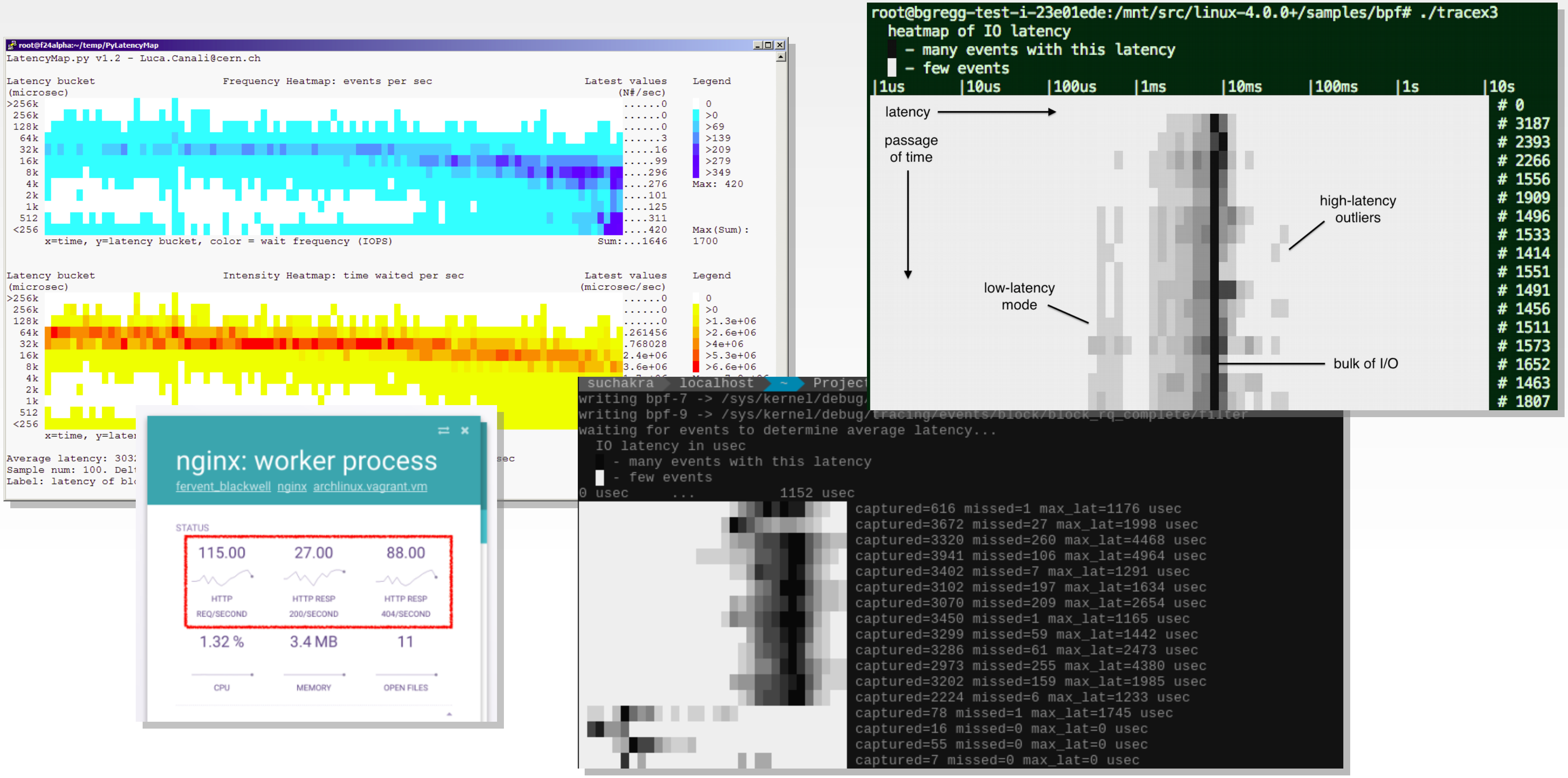
Output
argdist.py

```
# ./argdist -H 'p:c:write(int fd, void *buf, size_t len):size_t:len:fd==1'
[01:47:19]
p:c:write(int fd, void *buf, size_t len):size_t:len:fd==1
 len :  count    distribution
   0 -> 1    : 0    |                                        |
   2 -> 3    : 0    |                                        |
   4 -> 7    : 0    |                                        |
   8 -> 15   : 3    |*********                               |
  16 -> 31   : 0    |                                        |
  32 -> 63   : 5    |***************                         |
  64 -> 127  : 13   |****************************************|
```

eBPF Trace Visualization

Current State

- Using ASCII histograms, ASCII escape codes
- eBPF Flamegraphs, some web-based views



root@f24alpha:~/temp/PyLatencyMap

```
LatencyMap.py v1.2 - Luca.Canali@cern.ch

Latency bucket                Frequency Heatmap: events per sec                Latest values    Legend
(microsec)                                                                          (N#/sec)
>256k                                                                           ......0          0
 256k                                                                           ......0          >0
 128k                                                                           ......0          >69
  64k                                                                           ......3          >139
  32k                                                                           .....16          >209
  16k                                                                           .....99          >279
   8k                                                                           ....296          >349
   4k                                                                           ....276          Max: 420
   2k                                                                           ....101
   1k                                                                           ....125
  512                                                                           ....311
 <256                                                                           ....420          Max(Sum):
     x=time, y=latency bucket, color = wait frequency (IOPS)                   Sum:...1646      1700

Latency bucket                Intensity Heatmap: time waited per sec           Latest values    Legend
(microsec)                                                                     (microsec/sec)
>256k                                                                           ......0          0
 256k                                                                           ......0          >0
 128k                                                                           ......0          >1.3e+06
  64k                                                                           .261456          >2.6e+06
  32k                                                                           .768028          >4e+06
  16k                                                                           2.4e+06          >5.3e+06
   8k                                                                           3.6e+06          >6.6e+06
   4k
   2k
   1k
  512
 <256
     x=time, y=later

Average latency: 303                                                     sec
Sample num: 100. Del
Label: latency of bl
```

nginx: worker process

fervent_blackwell nginx archlinux.vagrant.vm

STATUS

115.00	27.00	88.00
HTTP REQ/SECOND	HTTP RESP 200/SECOND	HTTP RESP 404/SECOND
1.32 %	3.4 MB	11
CPU	MEMORY	OPEN FILES

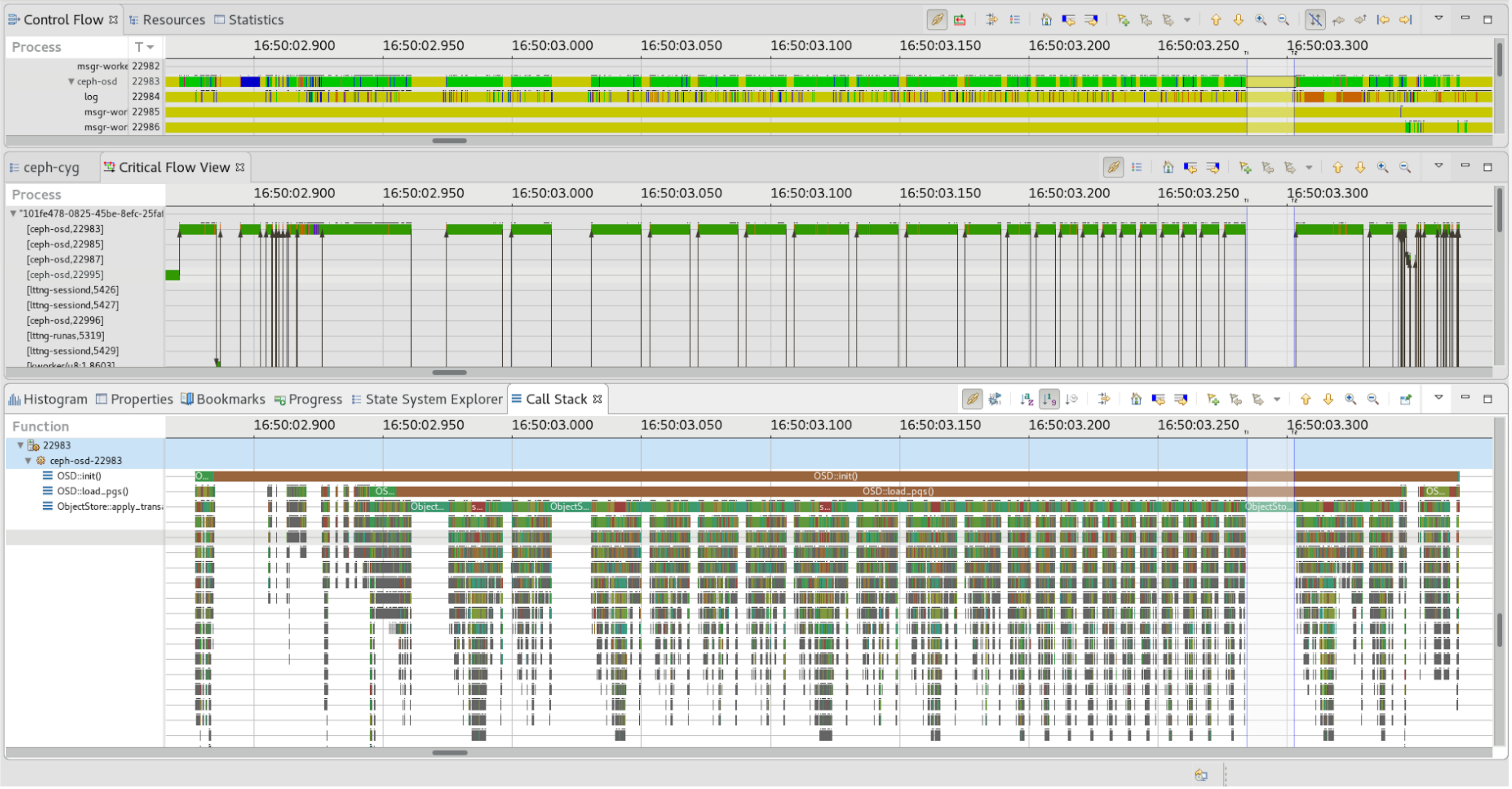
```
root@bgregg-test-i-23e01ede:/mnt/src/linux-4.0.0+/samples/bpf# ./tracex3
  heatmap of IO latency
  █ - many events with this latency
  █ - few events
|1us      |10us     |100us    |1ms      |10ms     |100ms    |1s       |10s
                                                                        # 0
                                                                        # 3187
                                                                        # 2393
                                                                        # 2266
                                                                        # 1556
                                                                        # 1909
                                                                        # 1496
                                                                        # 1533
                                                                        # 1414
                                                                        # 1551
                                                                        # 1491
                                                                        # 1456
                                                                        # 1511
                                                                        # 1573
                                                                        # 1652
                                                                        # 1463
                                                                        # 1807
```

```
 suchakra   localhost   ~   Project
writing bpf-7 -> /sys/kernel/debug/
writing bpf-9 -> /sys/kernel/debug/tracing/events/block/block_rq_complete/filter
waiting for events to determine average latency...
  IO latency in usec
  █ - many events with this latency
  █ - few events
0 usec     ...        1152 usec
                                 captured=616 missed=1 max_lat=1176 usec
                                 captured=3672 missed=27 max_lat=1998 usec
                                 captured=3320 missed=260 max_lat=4468 usec
                                 captured=3941 missed=106 max_lat=4964 usec
                                 captured=3402 missed=7 max_lat=1291 usec
                                 captured=3102 missed=197 max_lat=1634 usec
                                 captured=3070 missed=209 max_lat=2654 usec
                                 captured=3450 missed=1 max_lat=1165 usec
                                 captured=3299 missed=59 max_lat=1442 usec
                                 captured=3286 missed=61 max_lat=2473 usec
                                 captured=2973 missed=255 max_lat=4380 usec
                                 captured=3202 missed=159 max_lat=1985 usec
                                 captured=2224 missed=6 max_lat=1233 usec
                                 captured=78 missed=1 max_lat=1745 usec
                                 captured=16 missed=0 max_lat=0 usec
                                 captured=55 missed=0 max_lat=0 usec
                                 captured=7 missed=0 max_lat=0 usec
```

eBPF Trace Visualization

What We Need

- Modern visualizations, trace analysis, flame charts
- Data driven views, packaged with eBPF tools



Ceph traces from Mohamad Gebai (@mogeb88)

eBPF Trace Collection

Why collect traces?

- eBPF aggregates traces, no real trace storage
- Complement the live/snapshot usecase
- Fulfil long term analysis needs
- **Trace Compass** is a powerful visualization tool, we need to leverage its power!

Common Trace Format (CTF)

- Compact, binary format to save and store traces
- Very fast to write and read
- Well documented, stable, field-tested and used in industry-standard tools such as LTTng
- Easy to define trace streams and events
- Trace Compass supports CTF

eBPF Trace Collection

eBPF to CTF

- Currently uses `libbabeltrace` 2.0.0-pre Python APIs
- Just a PoC for now, **APIs will change for sure**

Program Excerpt

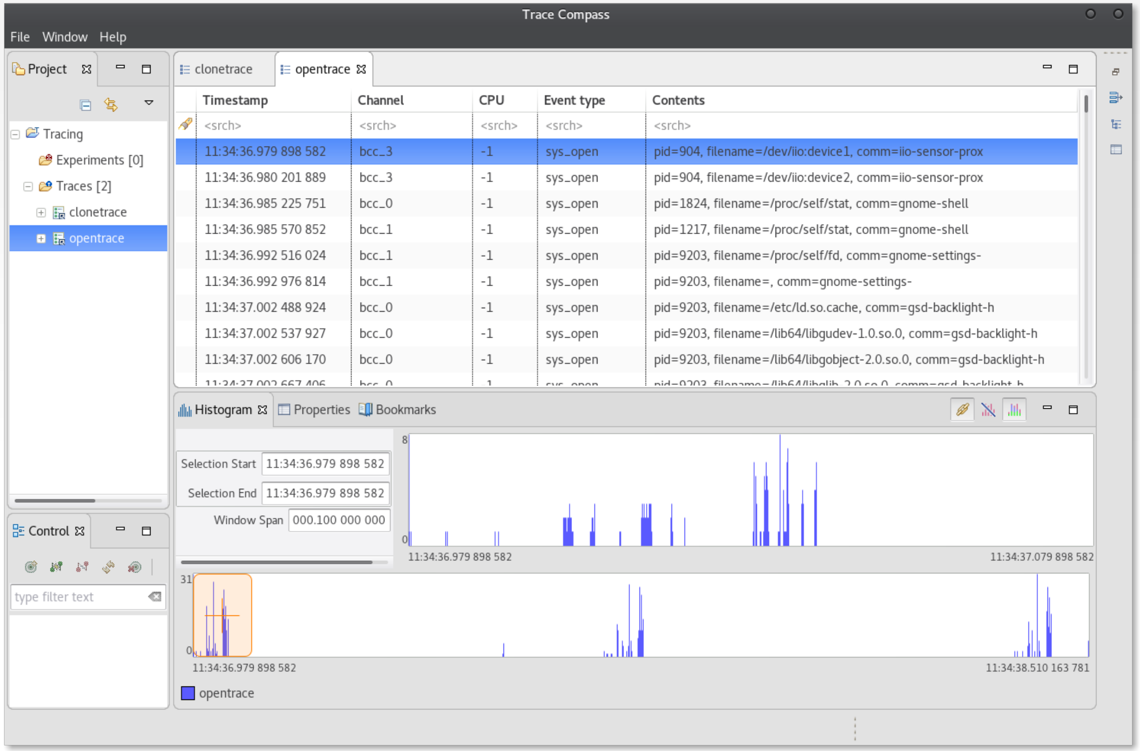
```
from bcc import BPF, CTF, CTFEvent
import ctypes as ct
.
.
fields = {"pid": CTF.Type.u32, "comm": CTF.Type.string,
          "filename": CTF.Type.string}
c = CTF("sys_open", "/tmp/opentrace", fields)

def write_event(cpu, data, size):
    event = ct.cast(data, ct.POINTER(Data)).contents
    ev = CTFEvent(c)
    ev.time(c, int(event.ts))
    ev.payload('pid', event.pid)
    ev.payload('comm', event.comm.decode())
    ev.payload('filename', event.fname.decode())
    ev.write(c, cpu)

b["events"].open_perf_buffer(write_event)
while 1:
    b.kprobe_poll()
```

https://github.com/iovisor/bcc/tree/ctf/examples/tracing/ctf

eBPF Trace Collection

eBPF to CTF

```
$ babeltrace /tmp/opentrace
[11:32:19.482715248] (+0.000068367) 0 sys_open: { },
{ comm = "java", filename = "/proc/self/stat", pid = 10912 }
[11:32:19.514412607] (+0.031697359) 0 sys_open: { },
{ comm = "iio-sensor-prox", filename = "/dev/iio:device1", pid = 904 }
[11:32:19.514569626] (+0.000157019) 0 sys_open: { },
{ comm = "iio-sensor-prox", filename = "/dev/iio:device2", pid = 904 }
```



Timestamp	Channel	CPU	Event type	Contents
<srch>	<srch>	<srch>	<srch>	<srch>
11:34:36.979 898 582	bcc_3	-1	sys_open	pid=904, filename=/dev/iio:device1, comm=iio-sensor-prox
11:34:36.980 201 889	bcc_3	-1	sys_open	pid=904, filename=/dev/iio:device2, comm=iio-sensor-prox
11:34:36.985 225 751	bcc_0	-1	sys_open	pid=1824, filename=/proc/self/stat, comm=gnome-shell
11:34:36.985 570 852	bcc_1	-1	sys_open	pid=1217, filename=/proc/self/stat, comm=gnome-shell
11:34:36.992 516 024	bcc_1	-1	sys_open	pid=9203, filename=/proc/self/fd, comm=gnome-settings-
11:34:36.992 976 814	bcc_1	-1	sys_open	pid=9203, filename=, comm=gnome-settings-
11:34:37.002 488 924	bcc_0	-1	sys_open	pid=9203, filename=/etc/ld.so.cache, comm=gsd-backlight-h
11:34:37.002 537 927	bcc_0	-1	sys_open	pid=9203, filename=/lib64/libgudev-1.0.so.0, comm=gsd-backlight-h
11:34:37.002 606 170	bcc_0	-1	sys_open	pid=9203, filename=/lib64/libgobject-2.0.so.0, comm=gsd-backlight-h
11:34:37.002 667 406	bcc_0	-1	sys_open	pid=9203, filename=/lib64/libglib-2.0.so.0, comm=gsd-backlight-h

Selection Start 11:34:36.979 898 582

Selection End 11:34:36.979 898 582

Window Span 000.100 000 000

eBPF Trace Collection

eBPF to CTF

```
$ babeltrace /tmp/opentrace
[11:32:19.482715248] (+0.000068367) 0 sys_open: { },
{ comm = "java", filename = "/proc/self/stat", pid = 10912 }
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{ comm = "iio-sensor-prox", filename = "/dev/iio:device2", pid = 904 }
```
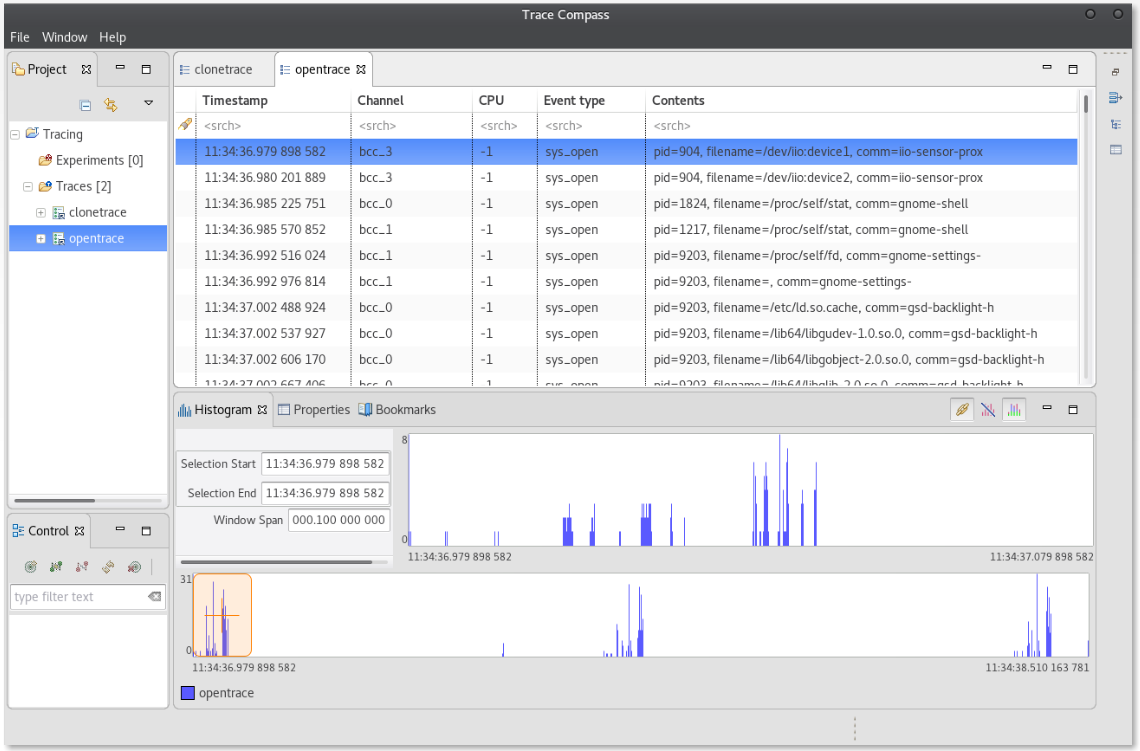
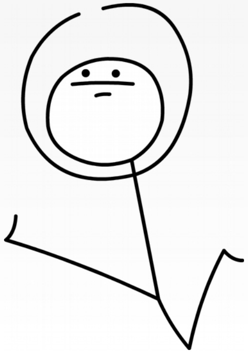



Timestamp	Channel	CPU	Event type	Contents
<srch>	<srch>	<srch>	<srch>	<srch>
11:34:36.979 898 582	bcc_3	-1	sys_open	pid=904, filename=/dev/iio:device1, comm=iio-sensor-prox
11:34:36.980 201 889	bcc_3	-1	sys_open	pid=904, filename=/dev/iio:device2, comm=iio-sensor-prox
11:34:36.985 225 751	bcc_0	-1	sys_open	pid=1824, filename=/proc/self/stat, comm=gnome-shell
11:34:36.985 570 852	bcc_1	-1	sys_open	pid=1217, filename=/proc/self/stat, comm=gnome-shell
11:34:36.992 516 024	bcc_1	-1	sys_open	pid=9203, filename=/proc/self/fd, comm=gnome-settings-
11:34:36.992 976 814	bcc_1	-1	sys_open	pid=9203, filename=, comm=gnome-settings-
11:34:37.002 488 924	bcc_0	-1	sys_open	pid=9203, filename=/etc/ld.so.cache, comm=gsd-backlight-h
11:34:37.002 537 927	bcc_0	-1	sys_open	pid=9203, filename=/lib64/libgudev-1.0.so.0, comm=gsd-backlight-h
11:34:37.002 606 170	bcc_0	-1	sys_open	pid=9203, filename=/lib64/libgobject-2.0.so.0, comm=gsd-backlight-h
11:34:37.002 667 406	bcc_0	-1	sys_open	pid=9203, filename=/lib64/libglib-2.0.so.0, comm=gsd-backlight-h

Selection Start: 11:34:36.979 898 582

Selection End: 11:34:36.979 898 582

Window Span: 000.100 000 000



It's Something...

What's Next

VM Analysis

- BCC tool to monitor and analyze VMs
- Currently supports vCPU usage report only

Trace Storage & Display

- Use Babeltrace directly or BareCTF to generate custom trace writing code
- Explore if we can package analysis/views and trace data together
- Other trace formats for storage/display (Catapult)

References

Papers

[McCanne et al. 1993] The BSD Packet Filter: A New Architecture for User-level Packet Capture, *Winter USENIX Conference (1993) San Diego*

[Sharma et al. 2016] Enhanced Userspace and In-Kernel Trace Filtering for Production Systems*, J. Comput. Sci. Technol. (2016), Springer US*

[Clément 2016] Linux Kernel packet transmission performance in high-speed networks, *Masters Thesis (2016), KTH, Stockholm*

[Borkmann 2016] Advanced programmability and recent updates with tc's cls_bpf, *NetDev 1.2 (2016) Tokyo*

References

Links

- IOVisor BPF Docs
- bcc Reference Guide
- bcc Python Developer Tutorial
- bcc/BPF Blog Posts
- Dive into BPF: a list of reading material (Quentin Monnet)
- Cilium - Network and Application Security with BPF and XDP (Thomas Graf)
- Landlock LSM Docs (Mickaël Salaün et al.)
- XDP for the Rest of Us (Jesper Brouer & Andy Gospodarek, Netdev 2.1)
- USDT/BPF Tracing Tools (Sasha Goldshtein)
- Linux 4.x Tracing : Performance Analysis with bcc/BPF (Brendan Gregg, SCALE 15X)
- The Common Trace Format (EfficiOS/Diamon Workgroup)
- babeltrace Library (EfficiOS/Diamon Workgroup)
- Trace Compass
- BPF/bcc for Oracle Tracing
- Weaveworks Scope HTTP Statistics Plugin

Ack

EfficiOS
Ericsson
DORSAL Lab, Polytechnique Montréal
IOVisor Project
LTTng Project
Eclipse Trace Compass Project

Fin!

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