eBPF Tutorial

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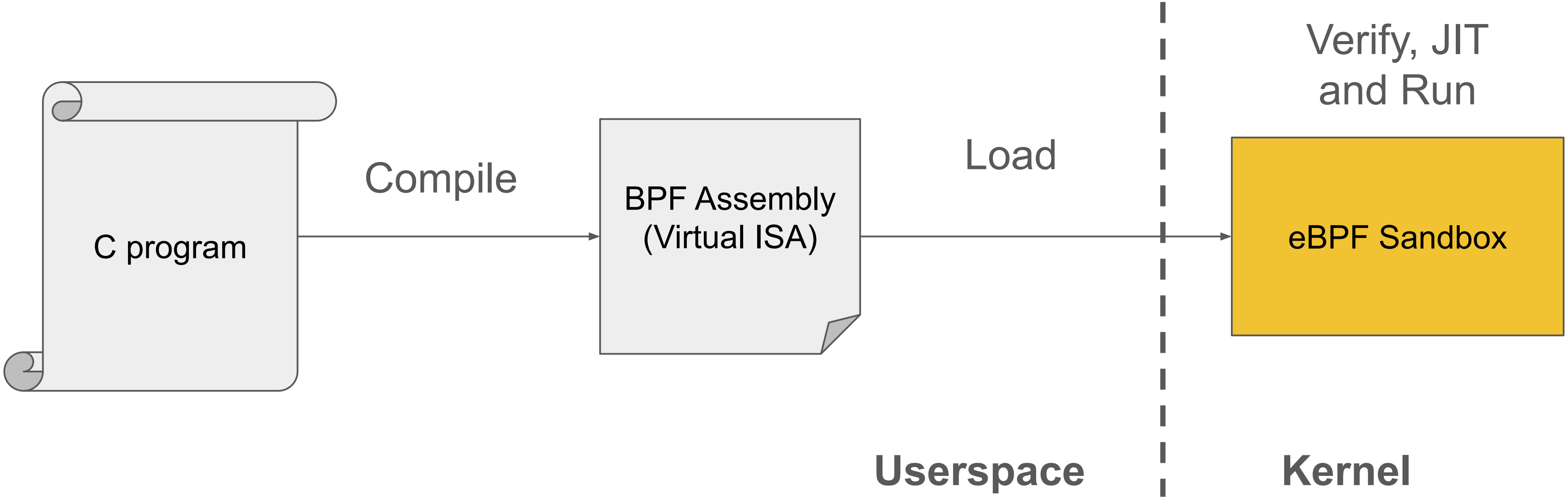
Lecture Goals

- Mental framework for eBPF
  - What is it fundamentally?
  - When does it run?
  - How do I get data in / out?
  - Practical examples with code for observability, networking, security.

What is eBPF?

- eBPF is a secure sandbox (executes arbitrary code) in the kernel!



How is eBPF secure?

- Secure == it doesn't crash and bring down the kernel.
- Method: Verification. Run all possible code paths and verify no crashes.
- General principles when writing code:
    - Bounded loops.
    - Check for NULLs.
    - Check buffer bounds.

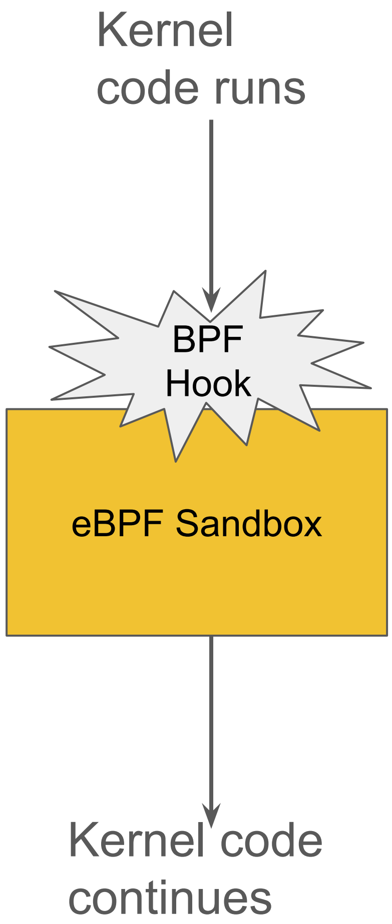
See more at:

https://www.kernel.org/doc/html/v6.1/bpf/verifier.html

When does it run?

Points where eBPF runs == BPF Hooks:

- Tracepoints
- Kprobes
- Networking hooks for inspecting / redirecting packets
- Security hooks for auditing / allowing access to files
- …



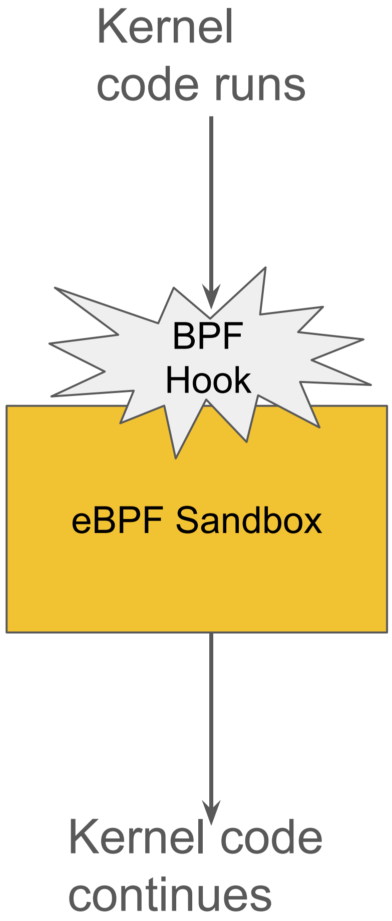
Example 1: Hello world

BPF Hook:

- Tracepoint syscalls/sys_enter

What are tracepoints?

- A tracepoint placed in code provides a hook to call a function (probe) that you can provide at runtime. Linux sprinkles them in interesting spots (e.g., syscalls, io start/end, …)
- Very stable interface to build on!
- Full list on your machine:
  ls /sys/kernel/debug/tracing/events/



Example 1: Hello world

```
// All linux kernel type definitions are in vmlinux.h
#include "vmlinux.h"
// BPF helpers
#include <bpf/bpf_helpers.h>

char LICENSE[] SEC("license") = "Dual BSD/GPL";

// SEC name is important! libbpf infers program type from it.
// See: https://docs.kernel.org/bpf/libbpf/program_types.html#program-types-and-elf
SEC("tracepoint")
int handle_tracepoint(void *ctx) {
    // bpf_get_current_pid_tgid is a helper function!
    int pid = bpf_get_current_pid_tgid() >> 32;
    bpf_printk("BPF triggered from PID %d.\n", pid);

    return 0;
}
```

Boilerplate

BPF helpers

First way of output!

Example 1: Hello world

Let’s compile it to BPF bytecode!

```
clang -O2 -target bpf -g -c hello_world.c -o hello_world.o
```

What does it look like?

```
llvm-objdump -d -S ./hello_world.bpf.o
```

Example 1: Hello world

```
./hello_world.bpf.o:     file format elf64-bpf

Disassembly of section tracepoint:

0000000000000000 <handle_tracepoint>:
;       int pid = bpf_get_current_pid_tgid() >> 32;
       0:	85 00 00 00 0e 00 00 00 call 14
       1:	77 00 00 00 20 00 00 00 r0 >>= 32
;       bpf_printk("BPF triggered from PID %d.\n", pid);
       2:	18 01 00 00 00 00 00 00 00 00 00 00 00 00 00 00 r1 = 0 ll
       4:	b7 02 00 00 1c 00 00 00 r2 = 28
       5:	bf 03 00 00 00 00 00 00 r3 = r0
       6:	85 00 00 00 06 00 00 00 call 6
;       return 0;
       7:	b7 00 00 00 00 00 00 00 r0 = 0
       8:	95 00 00 00 00 00 00 00 exit
```

This is BPF bytecode!

Assembly for a CPU that does not exist!

Example 1: Hello world

Let's load it in the kernel! Simplified loader program:

1. Load
2. Attach

```c
#include <bpf/libbpf.h>
#include <bpf/bpf.h>

int main() {
    struct bpf_object *obj;
    struct bpf_program *prog;
    struct bpf_link *link;
    int prog_fd;

    // Load and verify BPF application
    obj = bpf_object__open_file("hello_world.bpf.o", NULL);
    bpf_object__load(obj))

    // Attach BPF program
    prog = bpf_object__find_program_by_name(obj, "handle_tracepoint");
    prog_fd = bpf_program__fd(prog);
    link = bpf_program__attach_tracepoint(prog, "raw_syscalls",
"sys_enter");
    printf("BPF tracepoint program attached. Press ENTER to exit...\n");
    getchar();
}
```

Example 1: Hello world

Let's see the code the kernel JIT compiler generates for that program!

```
bpftool prog dump jited name handle_tracepoint
```

This is ARM64 assembly!

```
int handle_tracepoint(void * ctx):
bpf_prog_b36af1abfd77d74e_handle_tracepoint:
; int pid = bpf_get_current_pid_tgid() >> 32;
   0:   add x9, x30, #0x0
   4:   nop
   8:   paciasp
   c:   stp x29, x30, [sp, #-16]!
  10:   mov x29, sp
  14:   stp x19, x20, [sp, #-16]!
  18:   stp x21, x22, [sp, #-16]!
  1c:   stp x25, x26, [sp, #-16]!
  20:   stp x27, x28, [sp, #-16]!
  24:   mov x25, sp
  28:   mov x26, #0x0                       // #0
  2c:   sub x27, x25, #0x0
  30:   sub sp, sp, #0x0
  34:   mov x10, #0xffffffffffffb9b0        // #-18000
  ...
```

Example 1: Hello world

Let's view the output of **bpf_printk**!

It goes to the system tracing buffer.

```
sudo cat /sys/kernel/debug/tracing/trace_pipe
```

```
root@dev-vm:~# cat /sys/kernel/debug/tracing/trace_pipe
           <...>-13197   [000] d...1 14391.036697: bpf_trace_printk: BPF triggered from PID 13197.

           <...>-13197   [000] d...1 14391.036697: bpf_trace_printk: BPF triggered from PID 13197.

           <...>-13197   [000] d...1 14391.036698: bpf_trace_printk: BPF triggered from PID 13197.

           <...>-13197   [000] d...1 14391.036699: bpf_trace_printk: BPF triggered from PID 13197.
```

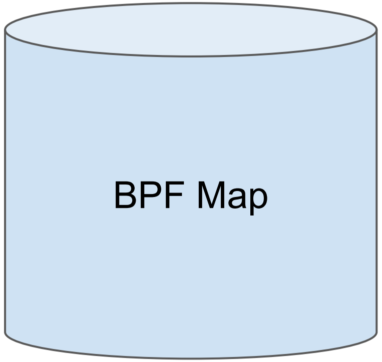
Example 1: Hello world

Conclusion:

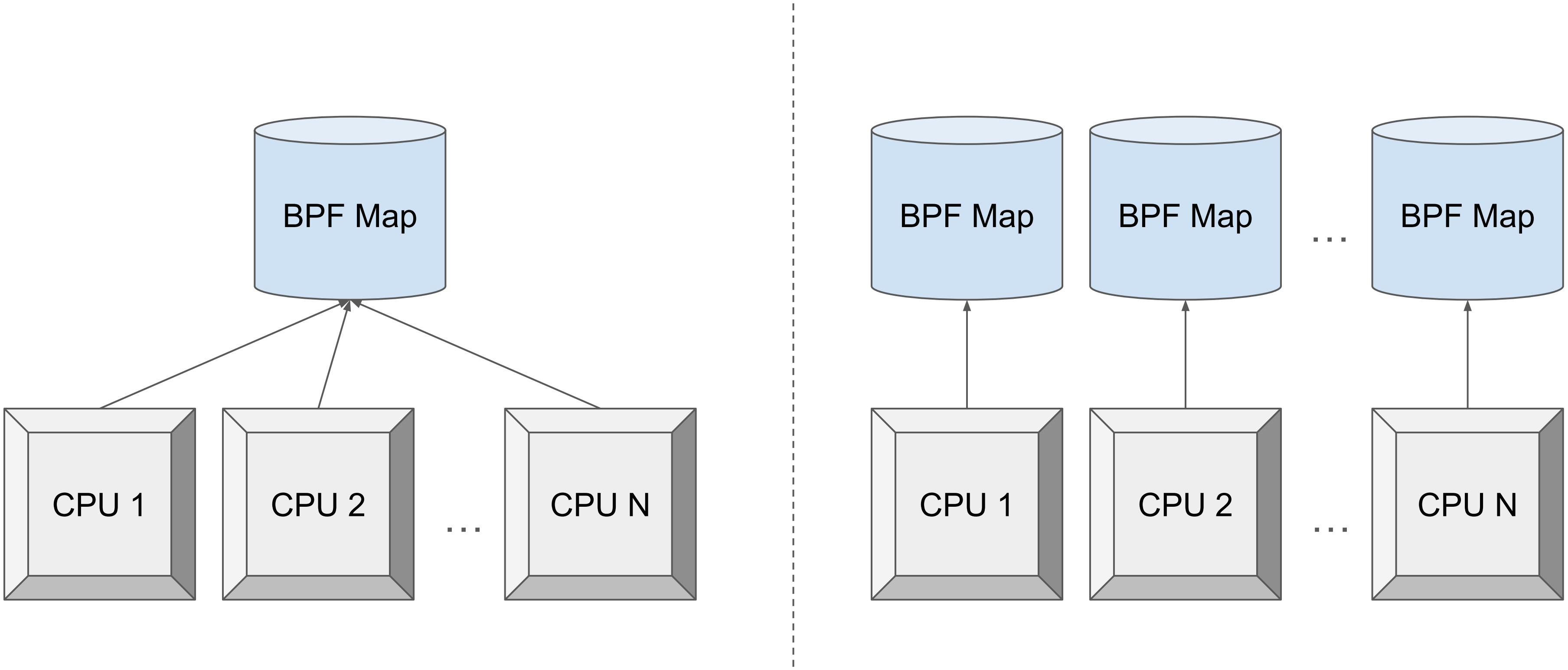
- See the essence of eBPF in action: code -> BPF bytecode -> assembly
- Learn to write / compile / attach a simple eBPF program.
- Learn to output and read logs with bpf_printk.

eBPF Maps - Maintaining state

- The simple hello world example is not very useful.
- Most useful programs need **STATE**.
- BPF Maps are how BPF programs **maintain state** and **get data in/out to userspace**!
- Maps persist and are not tied to eBPF program execution lifetime.
- Many types of maps:
  - Array
  - Hash (key-value store)
  - Global and per-cpu variants



eBPF Maps - Global and Per-CPU variants



BPF Helpers

Useful utilities to interact with the system. For example:

- What CPU am I running on?
- In what PID’s context is the eBPF program running right now?
    - We saw **bpf_get_current_pid_tgid** before!
- Get / set map key-values.
- …

BPF helpers are to eBPF what system calls are to userspace programs.

An interface to more privileged actions.

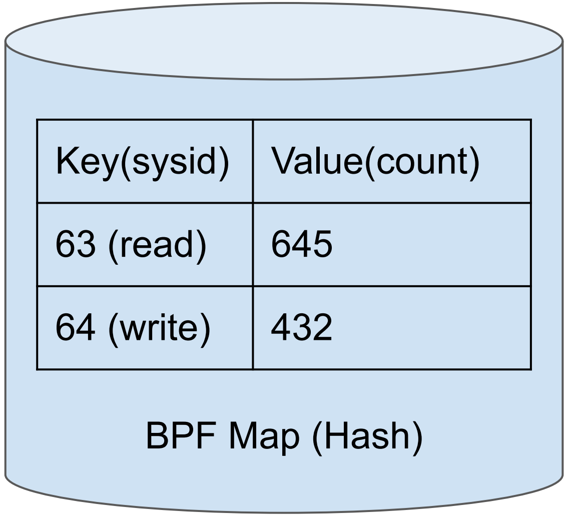
Example 2: syscount

Let’s extend hello world to do something more useful:

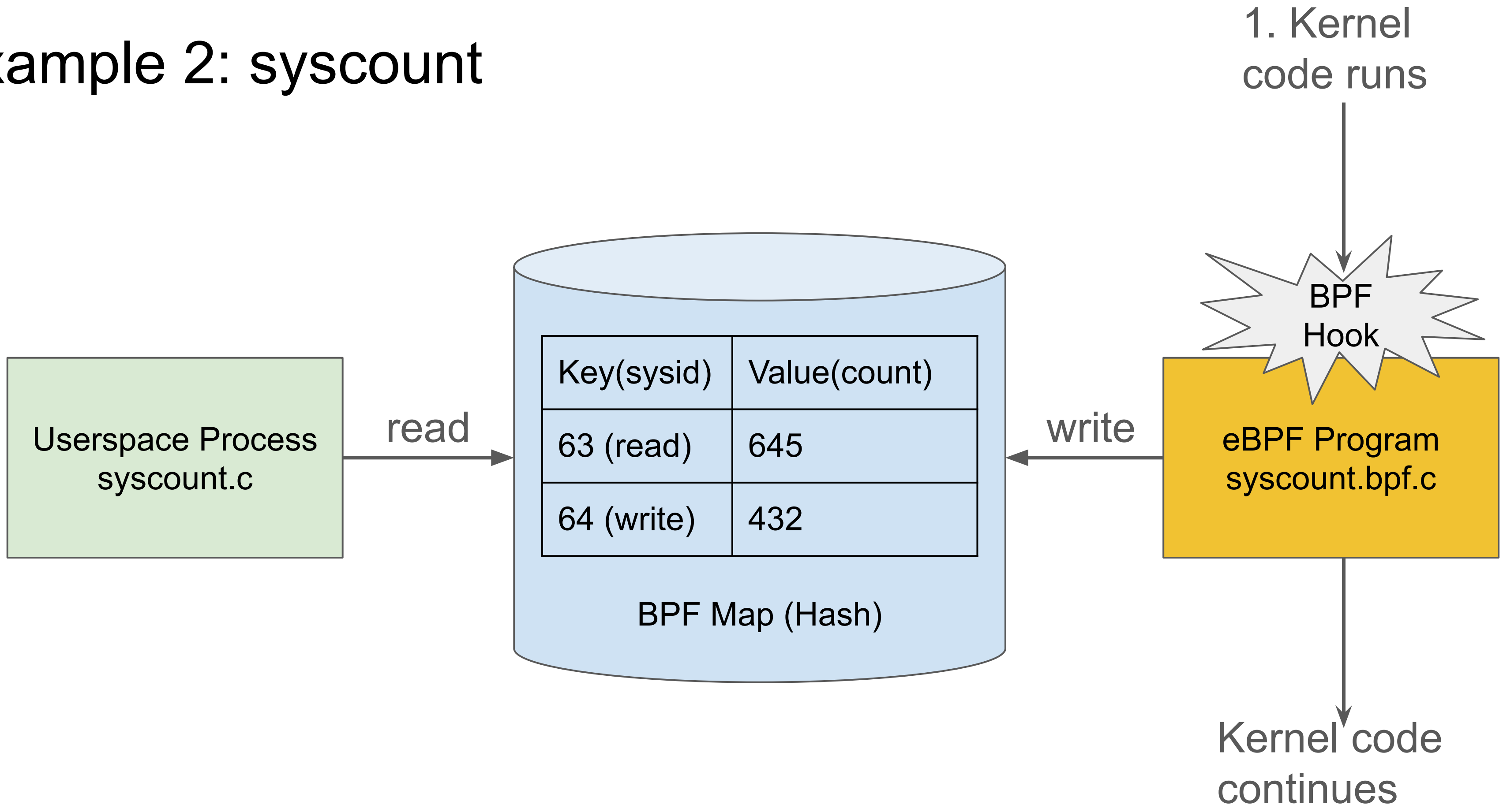
- Count how many times each syscall was used system-wide.
- I.e. **construct a key-value map of syscall-id to count**.

Introducing:

- BPF_MAP_TYPE_HASH
- See all here: https://docs.kernel.org/bpf/maps.html



Example 2: syscount



Example 2: syscount - BPF part

Let’s define the map in eBPF! Why do we use a per-cpu map?

```
// Map of type hash (essentially a key-value store)
// Key: syscall number
// Value: number of times the syscall was called
struct {
    __uint(type, BPF_MAP_TYPE_PERCPU_HASH);
    __type(key, u64);
    __type(value, u64);
    __uint(max_entries, 500);  // most linux systems have 300-400 syscalls
} syscall_id_to_count SEC(".maps");
```

- `__uint(type, BPF_MAP_TYPE_PERCPU_HASH);` → **Map Type**
- `__type(key, u64);` → **Key Type**
- `__type(value, u64);` → **Value Type**

Example 2: syscount - BPF part

```c
SEC("tracepoint/syscount")
int syscount(struct trace_event_raw_sys_enter *ctx) {
    // Interpret ctx
    u64 syscall_id = ctx->id;
    u64 *value;
    // Get the value from the map and increment
    value = bpf_map_lookup_elem(&syscall_id_to_count, &syscall_id);
    if (value) {
        *value += 1;
    } else {
        u64 zero = 0;
        bpf_map_update_elem(&syscall_id_to_count, &syscall_id, &zero, BPF_ANY);
    }
    return 0;
}
```

How do we know this?

Example 2: syscount - Userspace part

For each syscall id (key), add the values from all CPUs.

```
__u64 *curr_key = NULL;
__u64 next_key;
__u64 *values = (__u64 *)malloc(roundup(sizeof(__u64), 8) * num_cpus);
while (bpf_map_get_next_key(map_fd, curr_key, &next_key) == 0) {
    // Get value
    bpf_map_lookup_elem(map_fd, &next_key, values);
    // Calculate total from all CPUs
    __u64 total = 0;
    for (int i = 0; i < num_cpus; i++) {
        total += values[i];
    }
    printf("Syscall %s - Count %llu", syscall_id_to_name[next_key], total);
    // Update key
    curr_key = &next_key;
}
```

Example 2: syscount

Conclusion:

- Learn how to maintain state with BPF maps.
  - Syscall counts persist across invocations!
- Learn how to export state to userspace with BPF maps.

Taking actions with eBPF

- So far we’ve mainly focused on observability use-cases.
- However, many BPF program types can take **actions**.
- For example:
    - Networking: BPF programs can reject / forward a packet
    - Security: BPF programs can allow / block a filesystem operation

XDP: BPF for networking

Program type **BPF_PROG_TYPE_XDP**

```
int xdp_program(struct xdp_md *ctx) {
    return XDP_DROP;
}
```

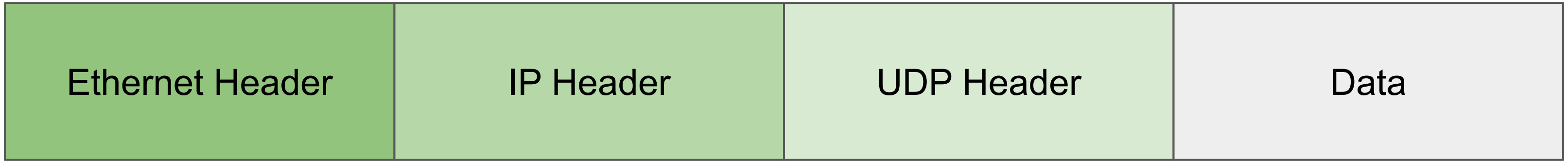
Takes action with return code:

- **XDP_DROP**: Drop the packet.
- **XDP_PASS**: Continue processing as normal.
- **XDP_TX / XDP_REDIRECT**: Redirect the package to the same / another NIC.

Example 3: Simple Firewall

- Let’s use XDP to make a simple firewall! It will just block UDP port 11111.
- XDP program see ethernet frames. Need to parse.

Message Buffer:



Example 3: Simple Firewall - BPF part

```c
SEC("xdp")
int xdp_firewall(struct xdp_md *ctx) {
    // We see the raw ethernet frame here.
    // To filter on higher-level protocols, we need to parse it.
    void *data = (void *)(long)ctx->data;
    void *data_end = (void *)(long)ctx->data_end;

    // Parse IP
    struct iphdr *ip = data + sizeof(struct ethhdr);
    // Verifier check.
    if ((void *)(ip + 1) > data_end) return XDP_PASS;
    if (ip->protocol != IPPROTO_UDP) {
        return XDP_PASS;
    }
```

Example 3: Simple Firewall - BPF part

```
    // Parse UDP
    struct udphdr *udp =
        (struct udphdr *)(data + sizeof(struct ethhdr) + sizeof(struct iphdr));
    // Verifier check.
    if ((void *)(udp + 1) > data_end) return XDP_PASS;

    // Block 11111
    if (udp->dest == bpf_htons(11111)) {
        bpf_printk("Dropping packet to port 11111\n");
        return XDP_DROP;
    }
    return XDP_PASS;
}
```

Example 3: Simple Firewall - Userspace part

Same as hello_world, just different attach function:

```
// Get ifindex of interface
char* ifname = "lo";
unsigned int ifindex = if_nametoindex(ifname);
link = bpf_program__attach_xdp(prog, ifindex);
if (libbpf_get_error(link)) {
    fprintf(stderr, "ERROR: Attaching BPF program to interface failed\n");
    return 1;
}
```

Example 3: Simple Firewall - Demo

Let’s see it running live!

Example 3: Simple Firewall

Conclusions:

- Learn how eBPF can route / drop packets using XDP.
- Implement a simple firewall.
- Food for thought: Think about what we could build by adding maps to our simple firewall. We can enable userspace to encode a great amount of complex rules that can change at runtime.
    - Facebook uses something similar for their firewall!
    - http://vger.kernel.org/lpc_net2018_talks/ebpf-firewall-LPC.pdf
- Why XDP?
    - Performance
    - Flexibity

BPF in Security - LSM Hooks

Linux Security Modules (LSM)

- Framework for implementing new security models in Linux.
- TLDR: It's a bunch of hooks in strategic locations (mainly file operations).
  - File open
  - File permission (read / write)
  - File mmap
  - …
- See: security/security.c in Linux kernel

BPF in Security - LSM Hooks

Linux Security Modules (LSM)

- Framework for implementing new security models in Linux.
- TLDR: It’s a bunch of hooks in strategic locations (mainly file operations).
    - File open
    - File permission (read / write)
    - File mmap
    - …
- See: security/security.c in Linux kernel
- Traditionally implemented with custom Linux Kernel Modules
- But now, we can also attach BPF programs!

Example 4: Simple file access control

Let’s build a simple access control system with eBPF.

- On each file operation, check if a user is possibly compromised.
- If they are, disallow all interactions with the filesystem.

Example 4: Simple file access control - BPF part

```c
// Map of type hash (essentially a key-value store)
// Key: user id
// Value: true if user is compromised, false otherwise
struct {
    __uint(type, BPF_MAP_TYPE_HASH);
    __type(key, u64);
    __type(value, bool);
    __uint(max_entries, 100);
} compromised_users SEC(".maps");

inline bool is_user_compromised() {
    u64 uid_gid = bpf_get_current_uid_gid();
    u64 uid = uid_gid & 0xFFFFFFFF;
    bool *is_compromised = bpf_map_lookup_elem(&compromised_users, &uid);
    if (is_compromised != NULL && *is_compromised) {
        // Yes, user is compromised.
        bpf_printk("User %d is compromised\n", uid);
        return true;
    }
    return false;
}
```

Example 4: Simple file access control - BPF part

```
SEC("lsm/file_open")
int BPF_PROG(lsm_access_control_open, struct file *file, int
ret) {
    // ret is the return value from the previous BPF program
    // or 0 if it's the first hook.
    if (ret != 0) {
        return ret;
    }
    // Is intrusion detected?
    if (is_user_compromised()) {
        return -EPERM;
    }
    return 0;
}
```

Example 4: Simple file access control - BPF part

```
SEC("lsm/file_permission")
int BPF_PROG(lsm_access_control_file_permission, struct file
*file, int mask,
             int ret) {
    // ret is the return value from the previous BPF program
    // or 0 if it's the first hook.
    if (ret != 0) {
        return ret;
    }
    // Is intrusion detected?
    if (is_user_compromised()) {
        return -EPERM;
    }
    return 0;
}
```

Example 4: Demo

Example 4: Conclusions

- One more use-case where eBPF can actually take decisions on behalf of the kernel.
- Again, think how this could be combined with a auditing and detection tool.
- Example eBPF security projects:
    - Falco
    - Tracee

Advanced Topics

Don’t really need to know any of them to do useful things, but you may see them in online resources and I want you to have an idea of what they are:

- BPF CO-RE (BTF)
- Libbpf - skeleton
- Iterators

Advanced Topics - BPF CO-RE

CORE == Compile Once Run Anywhere

- Aims to solve the problem of portability
- Imagine you had v1 code that accessed: **kernel_struct->b**
- What would happen if you ran it in v2?

v1

```
struct kernel_struct {
  int a;
  int b;
}
```

v2

```
struct kernel_struct {
  int a;
  int a1;
  int b;
}
```

Advanced Topics - BPF CO-RE

Solution: BPF Type Format (BTF)

- See: https://nakryiko.com/posts/bpf-portability-and-co-re/

Basically:

- Record all types for accessed kernel structs in BPF programs (object files), using the BTF format.
- When loading the BPF program, field accesses are matched based on **name** and **type**.

Advanced Topics - Libbpf Skeleton

- Generated helper code by libbpf: **bpftool gen skeleton**
- Quality of life improvement for working with BPF programs.
- See: https://docs.kernel.org/bpf/libbpf/libbpf_overview.html#bpf-object-skeleton-file

Features like:

- Easier interaction with global vars and maps.
- Bytecode embedded in skeleton, no need to load anything.

We didn’t use it for the examples as it was a bit too “magic”. But it is recommended for stuff that will hit production.

Advanced Topics - BPF Iterators

- So far, we've seen that BPF programs are triggered as part of the kernel control flow.
- We can also iterate through certain structures of the kernel (e.g., tasks) and trigger a BPF program for each one.
- These are called BPF iterators.

See: https://docs.kernel.org/bpf/bpf_iterators.html