eBPF inside-out

Extending kernel with ease

IndoSys 2025

Systems and Networking Research Group
IIT Bombay

https://github.com/cloudarxiv/ebpf-inside-out

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What is eBPF?

eBPF — extended Berkeley Packet Filter enables loading ***custom code*** into the kernel **dynamically** and **securely**

Why do we want to load custom code?

- Add new features
- Improve observability and security
- Reduce kernel overhead, etc.

Who is using eBPF?

Collects network insights at scale

Observability in K8s clusters

Load balancing at data centres

Networking for android phones

Uses for security monitoring

Kernel security monitoring

Detecting DDoS attacks

load balancing and tracing

and many more ...

More Info: [eBPF case studies]

eBPF application areas

1. **Tracing and Observability**

   system call trace, monitor network and disk IO activity
2. **Networking**

   Packet Filtering, load balancing, header processing, high speed packet processing
3. **Security**

   Syscall restriction (Seccomp), system-wide MAC (LSM), DDoS detection
4. **Reducing kernel overheads**

   Offloading code and short circuiting paths e.g. XRP
5. **Customizations**

   process scheduler, userspace extensions

More Info: eBPF case studies

(Hard) ways to add custom code to kernel

1. **Pushing your changes to Linux upstream**
   - Too hard and too long

2. **Change the kernel and Re-compile locally**
   - Need kernel knowledge, unfeasible to distribute

3. **Kernel Modules**
   - Need kernel knowledge, no safety guarantee

:(

Your PC ran into a problem and needs to restart. We're just collecting some error info, and then we'll restart for you.

20% complete

For more information about this issue and possible fixes, visit https://www.windows.com/stopcode

If you call a support person, give them this info:

Stop code: CRITICAL_PROCESS_DIED

What is eBPF?

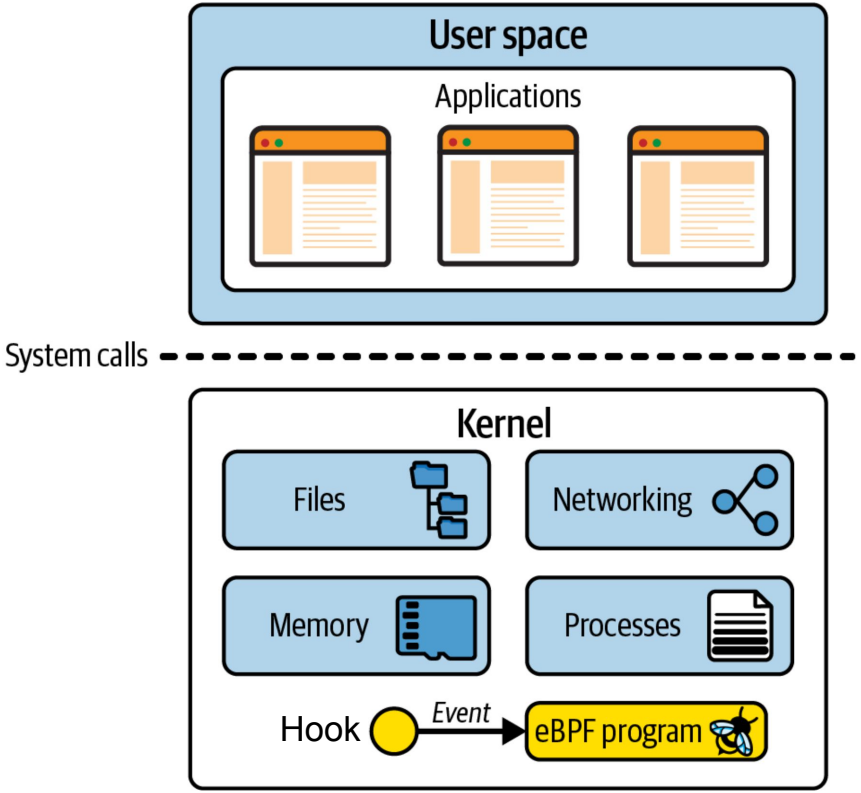
eBPF — extended Berkeley Packet Filter enables loading ***custom code*** into the kernel **dynamically** and **securely**.

The custom code is known as eBPF program.

No system reboot required!

No Kernel crash!

eBPF execution model



Event-driven execution

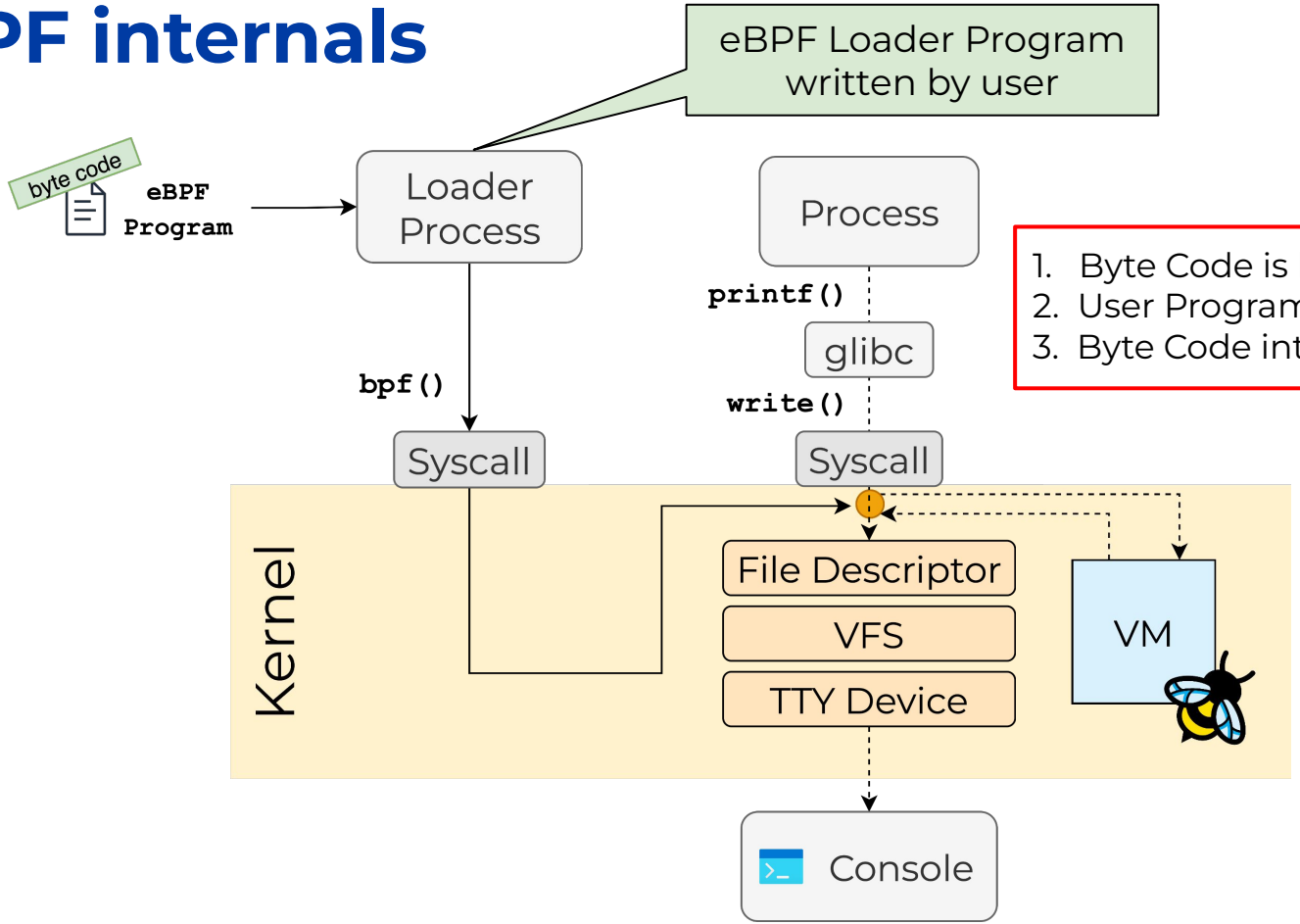
eBPF programs triggered when user/kernel code hits a hook point

hook is a location in user/kernel code

Examples of pre-defined hooks — system calls, kernel tracepoints, network events, files access ...

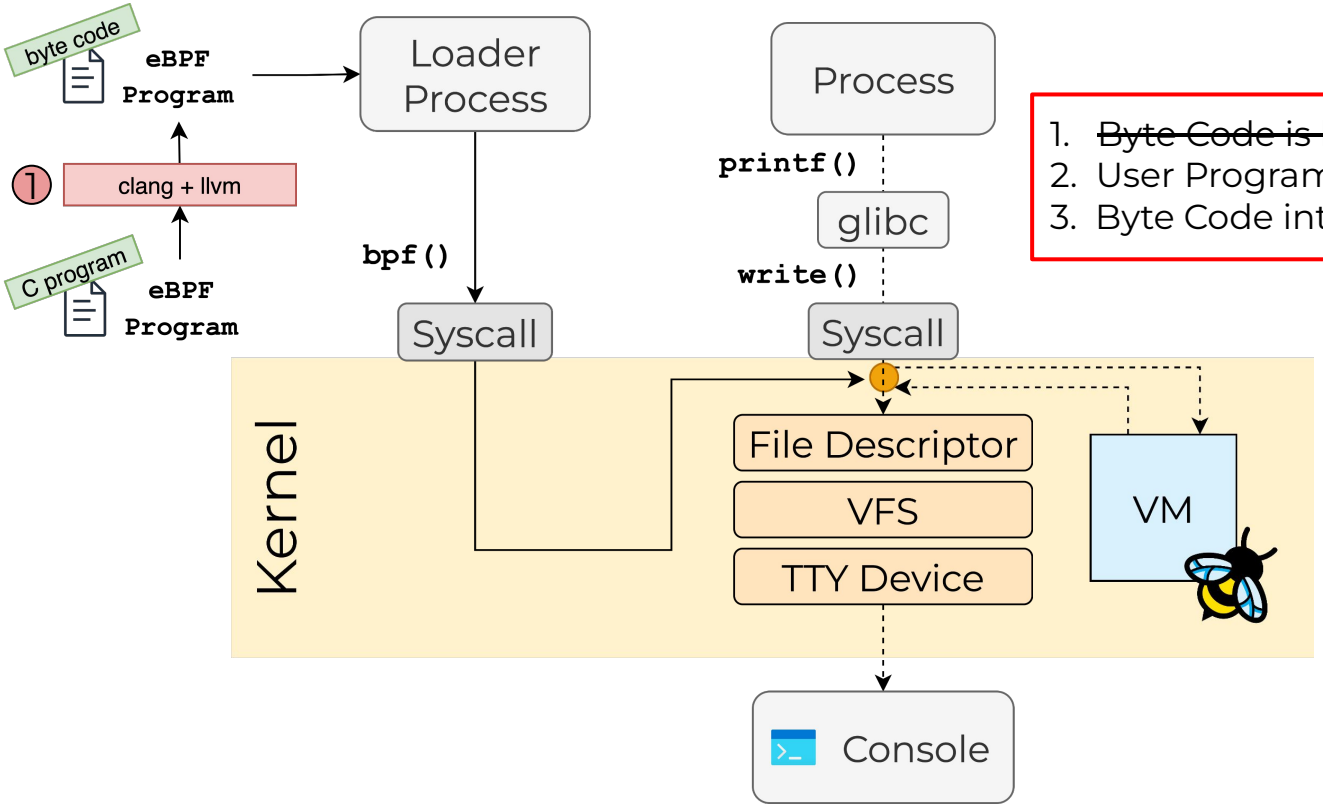
Source: Fig 1-1 from Learning eBPF by Liz Rice

eBPF internals



1. Byte Code is hard to write.
2. User Program can be unsafe.
3. Byte Code interpretation is slow.

eBPF internals - clang + llvm



1. ~~Byte Code is hard to write.~~
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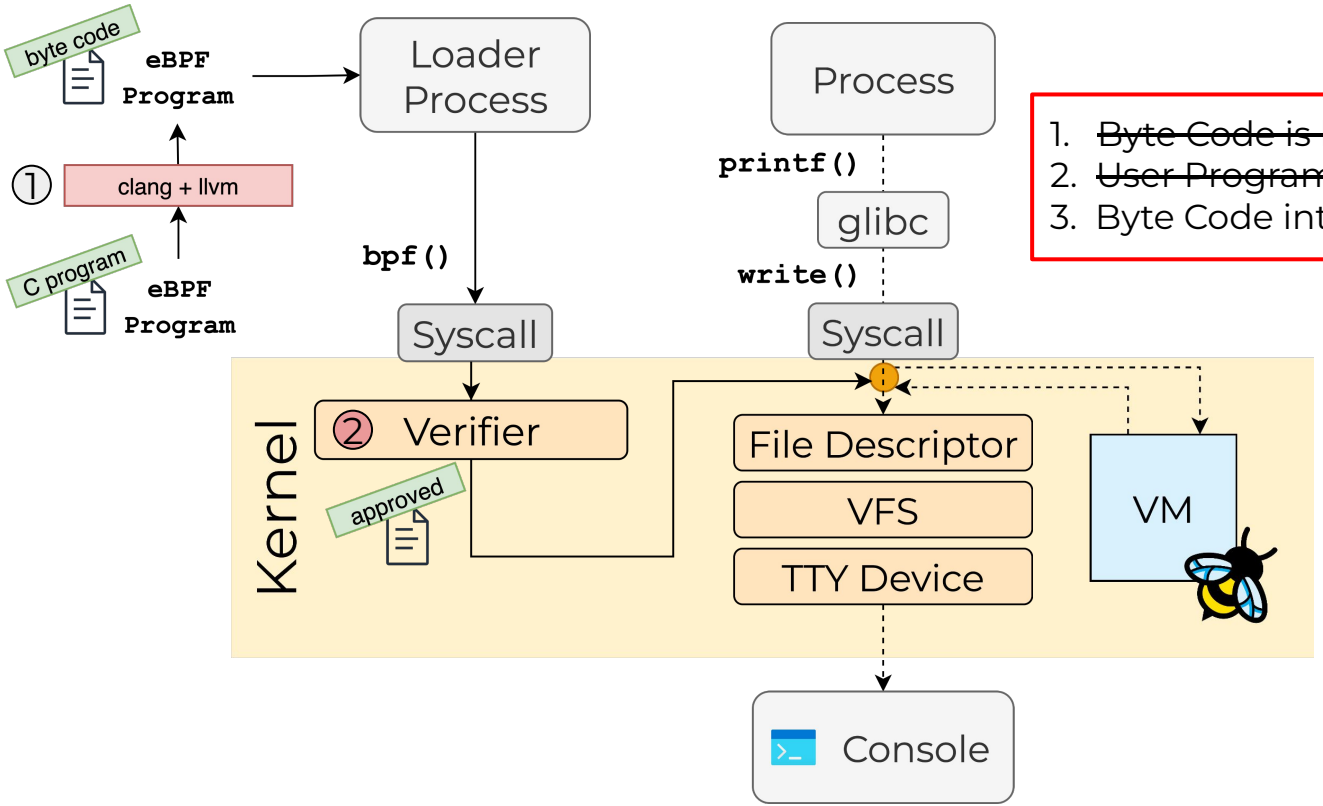
eBPF internals - the ebpf verifier



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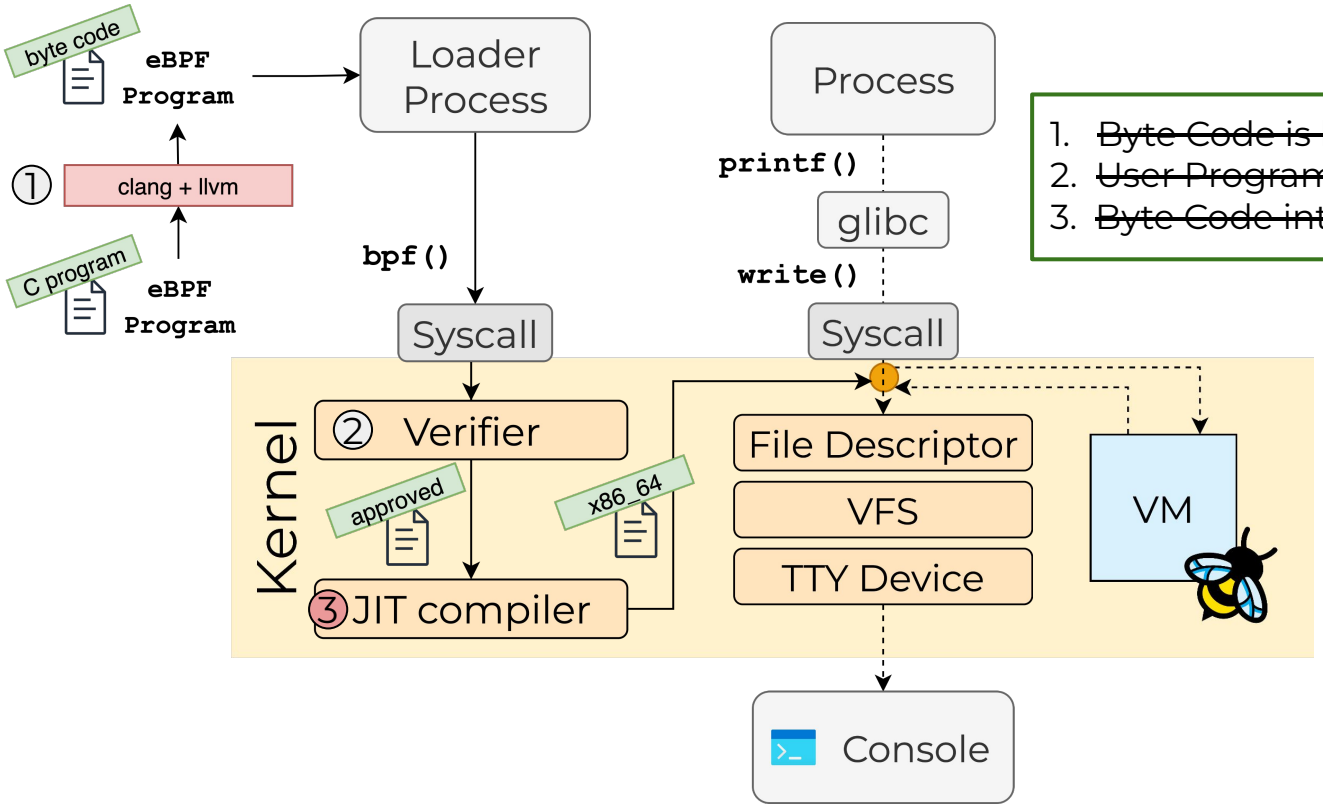
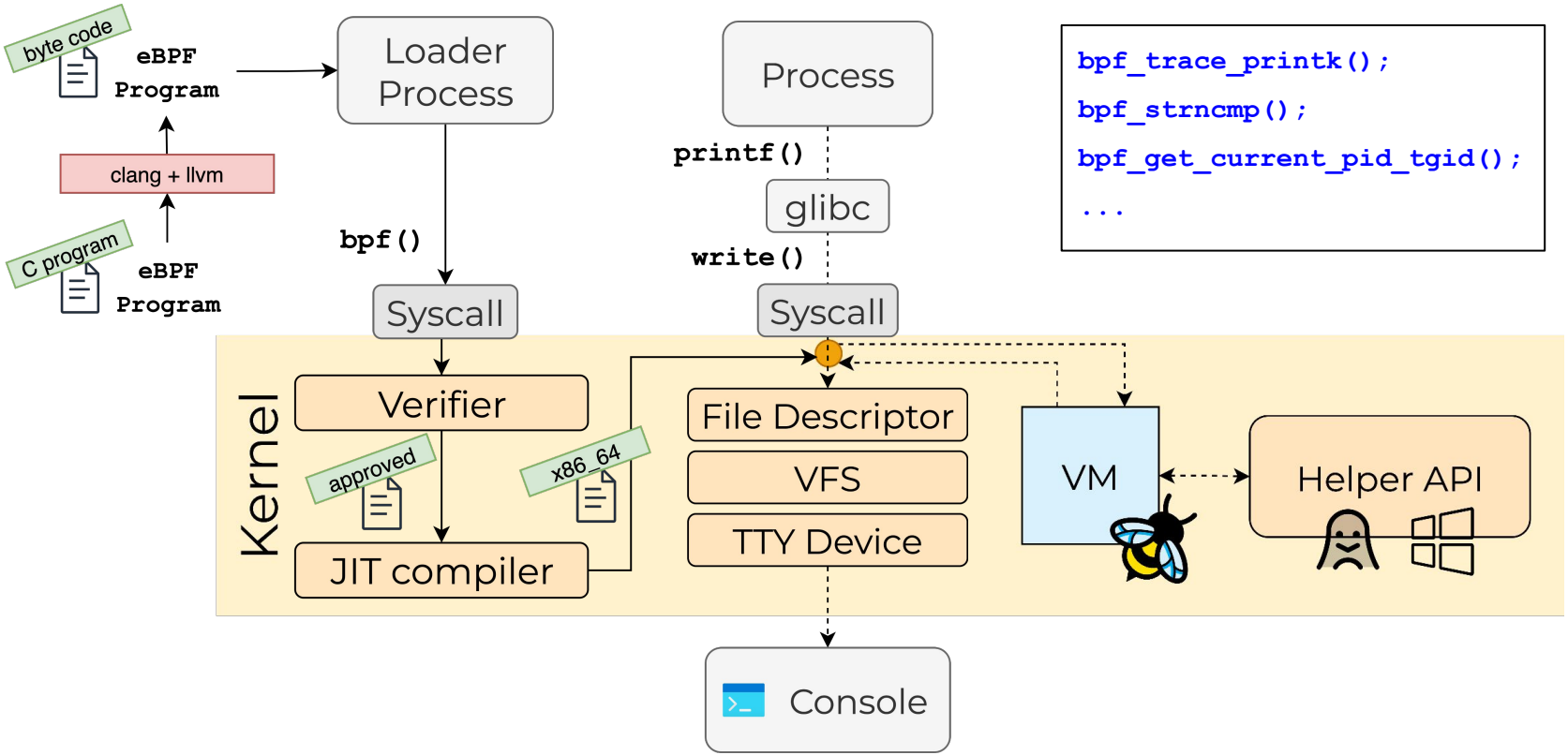
eBPF internals - JIT compilation



1. ~~Byte Code is hard to write.~~
2. ~~User Program can be unsafe.~~
3. ~~Byte Code interpretation is slow.~~

eBPF internals - helper functions



eBPF program types

Example eBPF program types —

`BPF_PROG_TYPE_TRACEPOINT`

`BPF_PROG_TYPE_KPROBE`

`BPF_PROG_TYPE_XDP`, etc.

A program type can have multiple compatible hookpoints.

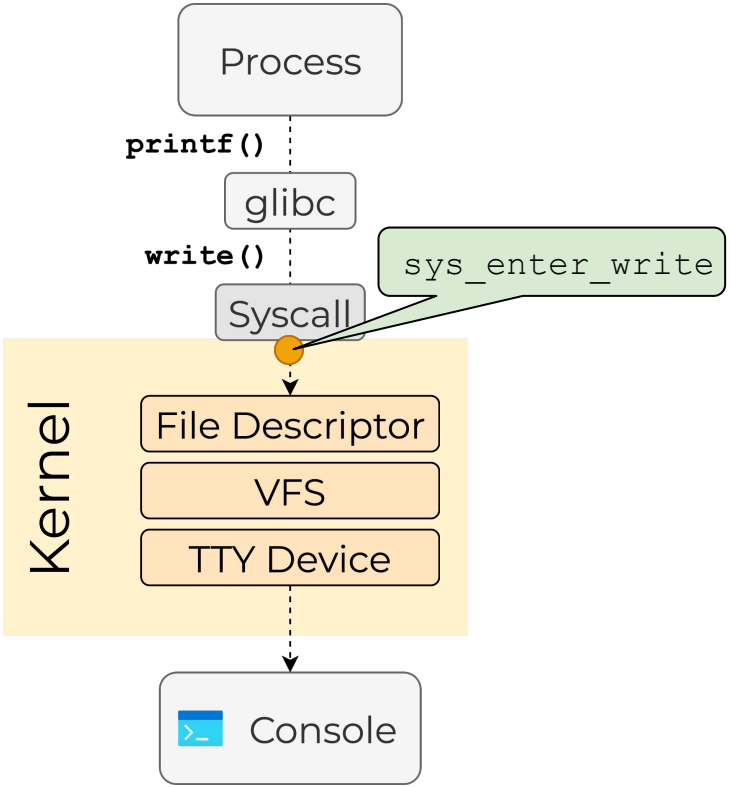
Hook points determine:

- Context provided (e.g. CPU registers)
- Helper functions and kfuncs available (e.g. bpf_trace_printk())
- Return code semantics

eBPF hookpoints

- **Kprobes and Kretprobes**
  - Used to attach to any instruction in kernel
- **Tracepoints**
  - Maintained stable hookpoints (locations) in kernel
- **XDP**
  - Intercept packets at driver level before skb is formed
- **Socket related types**
  - Hooks operating at socket level

Example



Example tracepoint *eBPF program* — **`BPF_PROG_TYPE_TRACEPOINT`**

Can be loaded to tracepoint *hookpoints*

hookpoints provide ***context*** to eBPF programs — `sys_enter_write` provides **`(fd, buffer, length)`**

Hands-on

Basic eBPF programs

https://github.com/cloudarxiv/ebpf-inside-out

Machine setup

- Load VM image in Workstation (Linux/Windows) or Fusion (MAC)
  (Double click on VM image / Drag and drop image in Fusion)

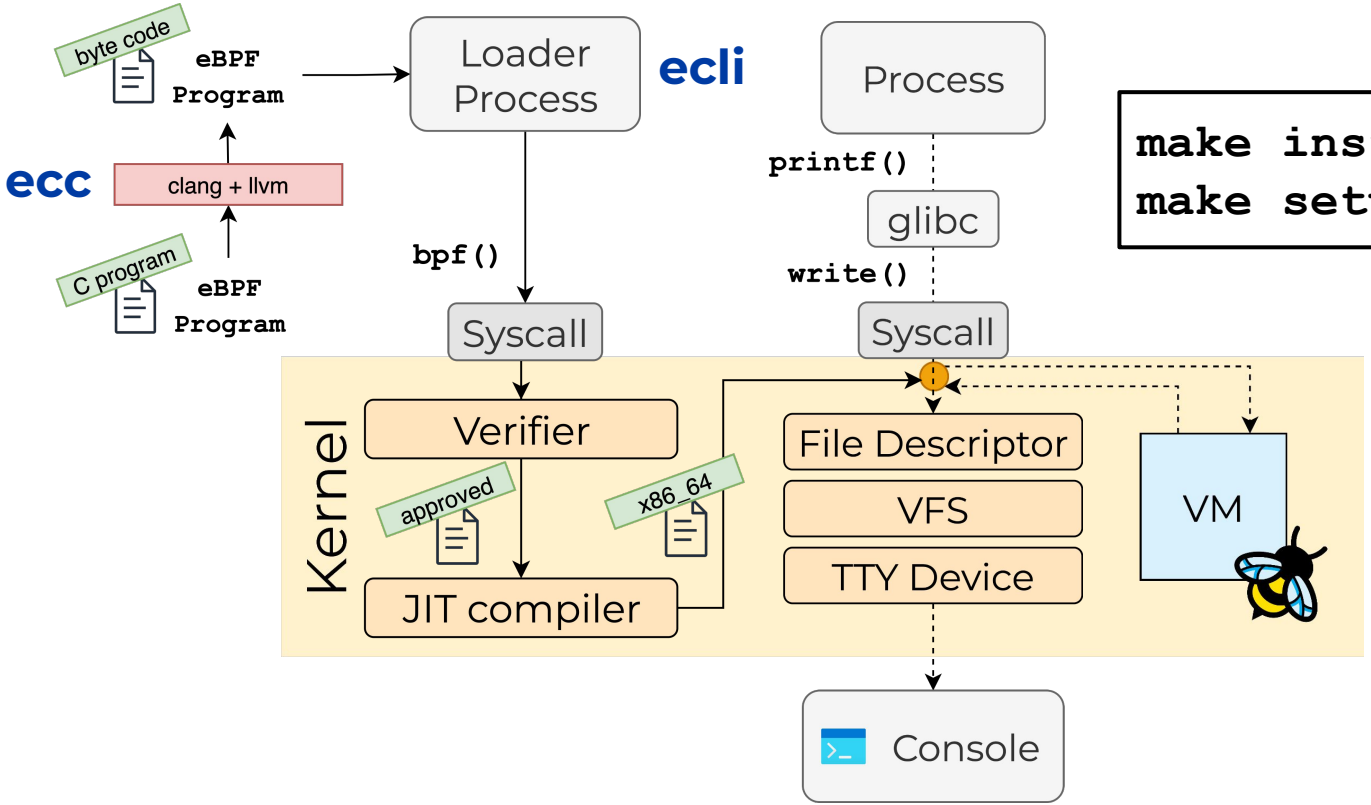
- Username: **vm** Password: **1234**

- No graphical interface in provided VM image.
  Use SSH based text editors (e.g. VSCode with “Remote - SSH” extension) if not comfortable with cli text editors

- Follow **Getting Started** instructions available on the repo —

  https://github.com/cloudarxiv/ebpf-inside-out

Task 0: ecc and ecli installation




```
make install-deps
make setup-tools
```

Task 1: Hello eBPF

```c
#define BPF_NO_GLOBAL_DATA
#include <linux/bpf.h>
#include <bpf/bpf_helpers.h>
#include <bpf/bpf_tracing.h>

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

SEC("tp/syscalls/sys_enter_write")
int handle_tp(void *ctx)
{
    pid_t pid = bpf_get_current_pid_tgid() >> 32;
    bpf_printk("Hello eBPF: sys_enter_write triggered BPF from PID %d.\n", pid);
    return 0;
}
```

Stores string passed to bpf_printk on stack

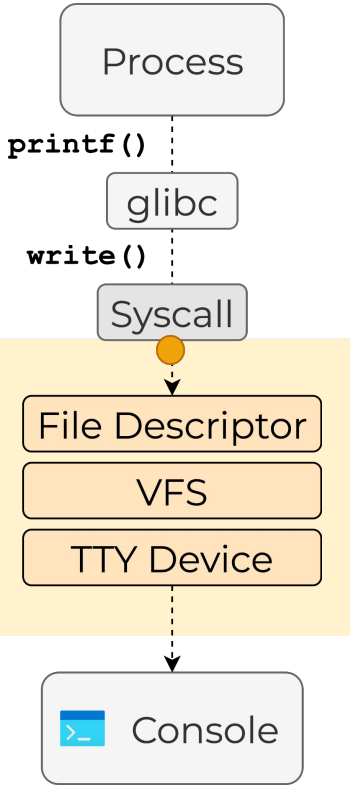
Context passed to the eBPF program. In this case, it will contain parameters passed to write syscall

Attach hookpoint

eBPF Program

eBPF helper function to get pid/tgid

Helper function to print into trace log of kernel



Prints “Hello eBPF” each time the **`write()`** system call is invoked

Task 1: Hello eBPF

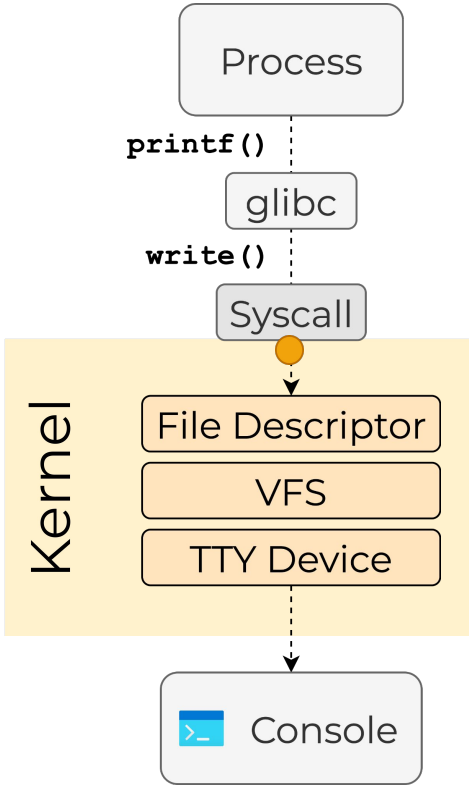
Now let's run it on our machine —

1. Change working directory to
   `ebpf-inside-out/basic/task1`

2. Compile hello.bpf.c
   ```
   $ ecc hello.bpf.c
   ```

3. Load ebpf program using ecli (needs root access)
   ```
   $ sudo ecli run package.json
   ```

4. Run following in another terminal to see output written to kernel trace log by eBPF program
   ```
   $ sudo cat /sys/kernel/debug/tracing/trace_pipe
   ```



Task 1: TODOs

eBPF Program Parameters

Global variables act argument passing mechanism in eBPF programs, allowing userspace programs to provide parameters during eBPF program loading.

To set a global variable using ecli:

```
$ sudo ecli run package.json -<global_var_name> <value>
```

Exercise

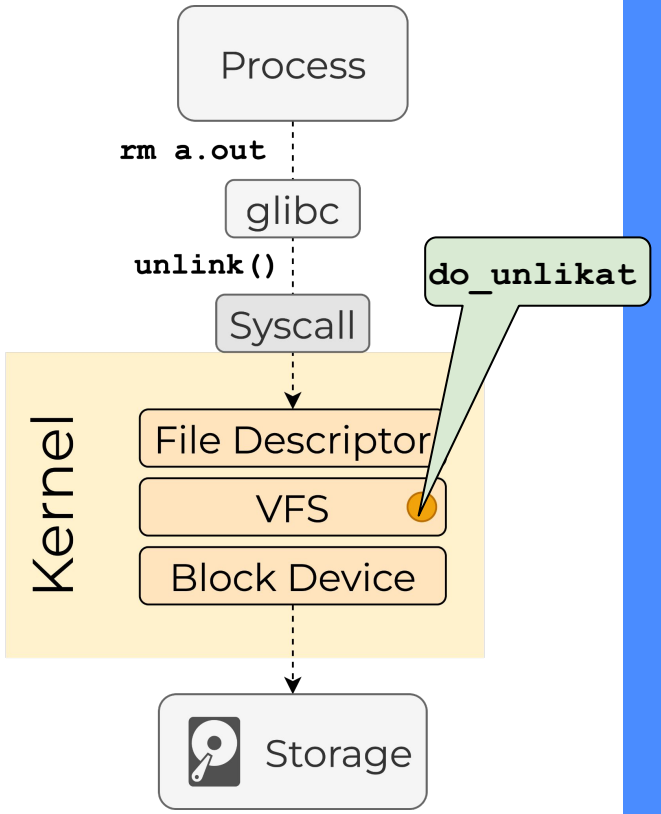
- Extend the eBPF program to print only when a specific process (e.g., `bash`) performs a write operation.
- Use global variable to pass pid of the the specific process.
- Steps have been provided in the program comments.

Task 2: Hello kProbes (Background)

Tracepoint → Allows probing at specific predefined locations in kernel

kProbe → Allows probing at almost any kernel instruction. Can be added using symbol name or address of the instruction.

kRetProbe → Probing when a kernel function returns



Task 2: Hello kProbes

```c
SEC("kprobe/do_unlinkat")
int BPF_KPROBE(probe_do_unlinkat_entry, int dfd, struct filename *f)
{
    pid_t pid;
    const char *filename;
    pid = bpf_get_current_pid_tgid() >> 32;
    filename = BPF_CORE_READ(f, name);
    bpf_printk("KPROBE ENTRY pid = %d, filename = %s\n", pid, filename);
    return 0;
}
SEC("kretprobe/do_unlinkat")
int BPF_KRETPROBE(probe_do_unlinkat_exit, long ret)
{
    pid_t pid;
    pid = bpf_get_current_pid_tgid() >> 32;
    bpf_printk("KPROBE EXIT: pid = %d, ret = %ld\n", pid, ret);
    return 0;
}
```

set kprobe at start of do_unlinkat function

eBPF helper MACRO to easily parse arguments passed to kprobed function.
Arg 1: name of the kprobe handler
Arg 2 - N: Arguments passed to the kprobed function

Helper MACRO to read value stored at *name* field of *struct filename* in an architecture agnostic manner.

eBPF helper MACRO to easily parse return value of kprobed function
Arg 1: name of the kprobe handler
Arg 2: value return by the kprobed function

Task 2: TODOs

Exercise

- Add more eBPF programs to trace other kernel functions using kprobes. Specifically, trace **`do_mkdirat`** and **`do_rmdir`** functions.

- You can follow the same pattern as shown in the **`do_unlinkat`** example.

- References are provided as comment in the program file.

- You can then try creating and removing directories to see the output in the kernel trace log:

```
$ mkdir test_dir1
$ rmdir test_dir1
$ mkdir test_dir2
$ rmdir test_dir2
```

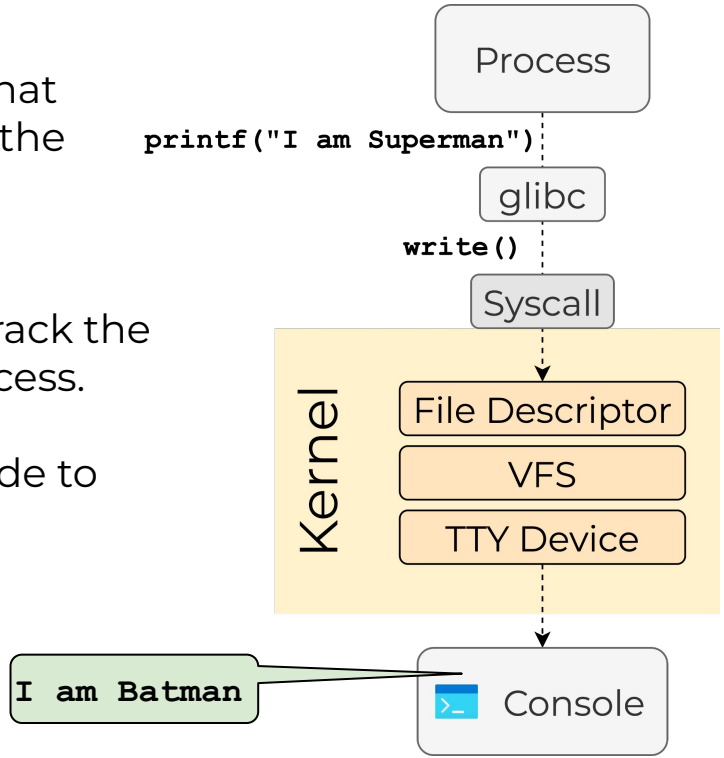
Task 3: Hijacking a system call

Exercise

- In this task, we will create an eBPF program that hijacks the **`write()`** system call and modifies the output to say "I am Batman" instead of "I am Superman

- First, add logic to the eBPF program to only track the **`write()`** system calls made by superman process.

- Then, follow steps outlined in the program code to modify the system call parameter.



eBPF maps

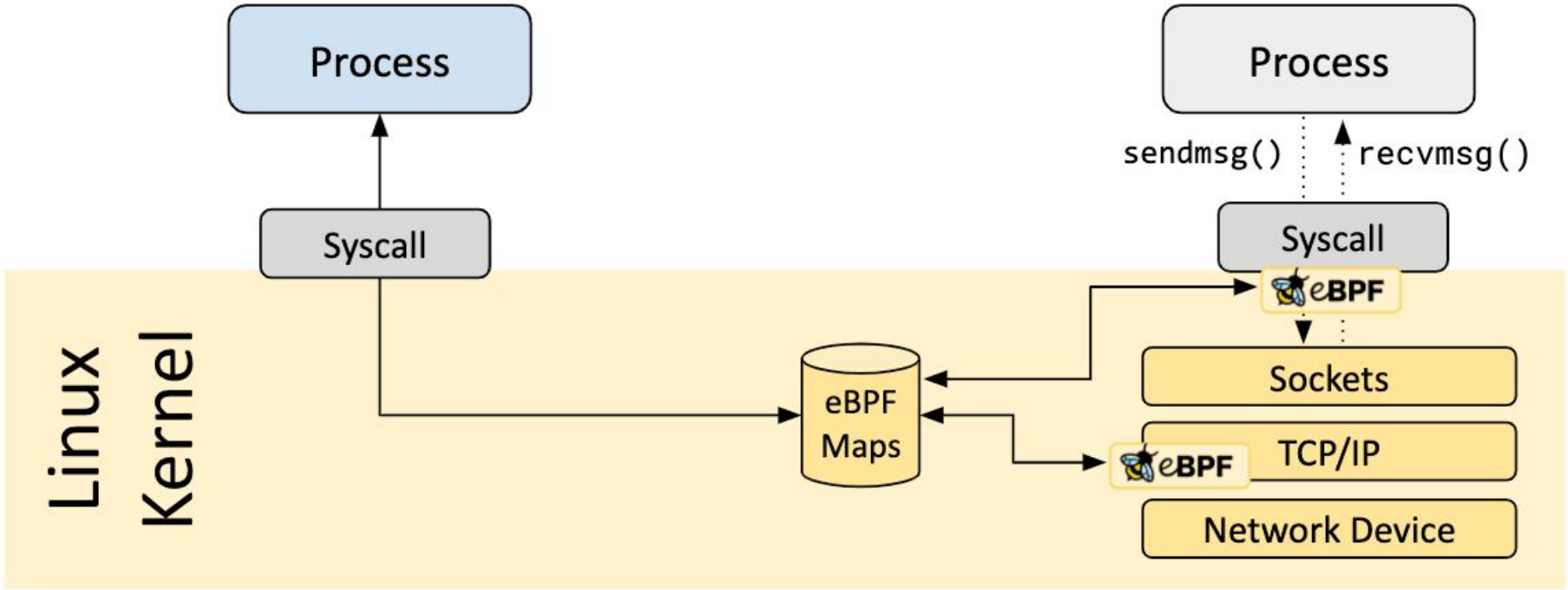
Used to share data between eBPF programs and userspace.

Examples data structures —

key value stores, array, ring buffer ...

BPF_MAP_TYPE_HASH, BPF_MAP_TYPE_ARRAY, BPF_MAP_TYPE_RINGBUF

Global variables are also stored as maps



Source: https://ebpf.io/what-is-ebpf/

eBPF maps

Typical use cases:

- Config information from userspace to eBPF program
- Storing state information to be used by next invocation
- Returning results and metrics back to userspace

Used Map helper functions:

- **`bpf_map_lookup_elem(void *map, const void *key):`** Returns pointer to the value in map associated with given key

- **`bpf_map_update_elem(void *map, const void *key, const void *value, __u64 flags):`** For flags = BPF_ANY updates / inserts key value in the map.

  `bpf_map_delete_elem(void *map, const void *key):` Deletes given key value from the map

Task 4: Using eBPF maps

We want to know how many reads and writes a process does in its lifetime

We will store this information in eBPF maps

Five eBPF programs attached to different hooks will maintain and update the eBPF map

Once the program exits we will print the information to the kernel trace

A simple eBPF map

```
struct counts {
    unsigned int rcount;
    unsigned int wcount;
    char comm[TASK_COMM_LEN];
};

struct {
    __uint(type, BPF_MAP_TYPE_HASH);
    __uint(max_entries, MAX_ENTRIES);
    __type(key, __u32);
    __type(value, struct counts);
} values SEC(".maps");
```

XDP (Xpress Data Path)

Intercepts packets at early on even before any kernel stack processing

Context:

```
struct xdp_md {
    __u32 data;
    __u32 data_end;
    ...
};
```

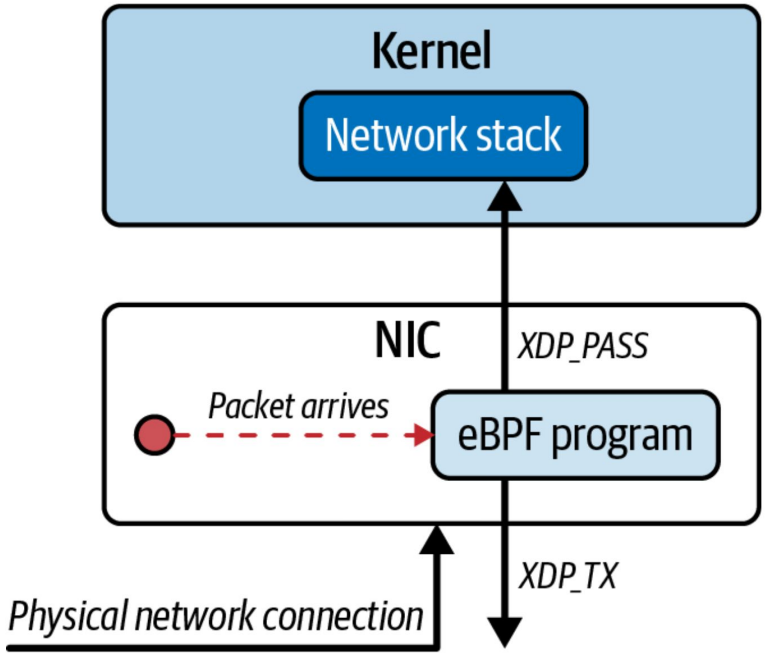
Return Values:

XDP_ABORTED, XDP_DROP,

XDP_PASS, XDP_TX,

XDP_REDIRECT

BPF_PROG_TYPE_XDP



Source: Fig 8-3 from Learning eBPF by Liz Rice

Task 5: Using XDP hook

```c
#include "vmlinux.h"
#include <bpf/bpf_helpers.h>

/// @ifindex 2
/// @flags 0
SEC("xdp")
int xdp_pass(struct xdp_md* ctx) {
   void* data = (void*)(long)ctx->data;
   void* data_end = (void*)(long)ctx->data_end;
   int pkt_sz = data_end - data;

   bpf_printk("packet size is %d", pkt_sz);
   return XDP_PASS;
}

char __license[] SEC("license") = "GPL";
```

Parameters to the bpf_xdp_attach
These parameters specify the interface on which the XDP program should be attached along with other flags and options.

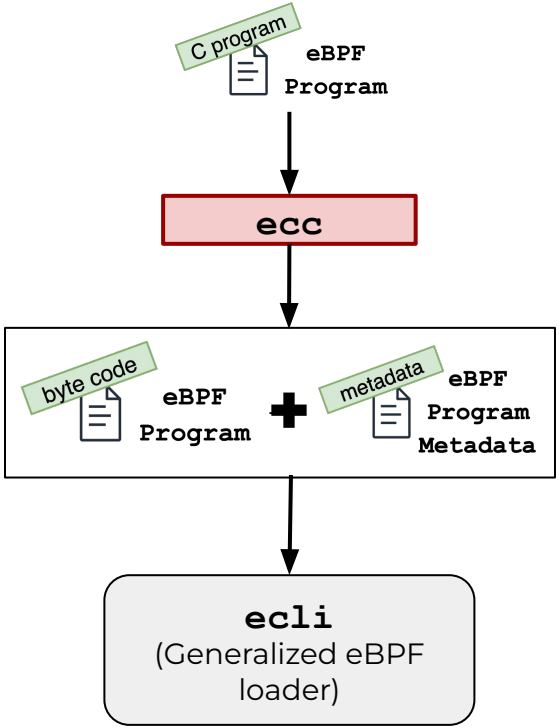
NOTE: This way of passing XDP options using `///` just before XDP function is specific to *ecli* and is not an standard eBPF feature.

ctx→data: pointer to the start of raw packet
ctx→data_end: pointer to the end of raw packet
pkt_sz: size of the raw packet

Hands-on

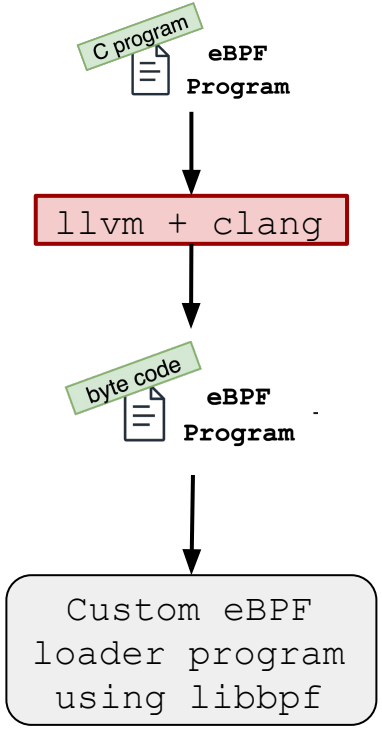
Advanced eBPF programs

Task 1: Generalized Loader



- Suited for simple use cases
- No specialized communication between eBPF and userspace agent

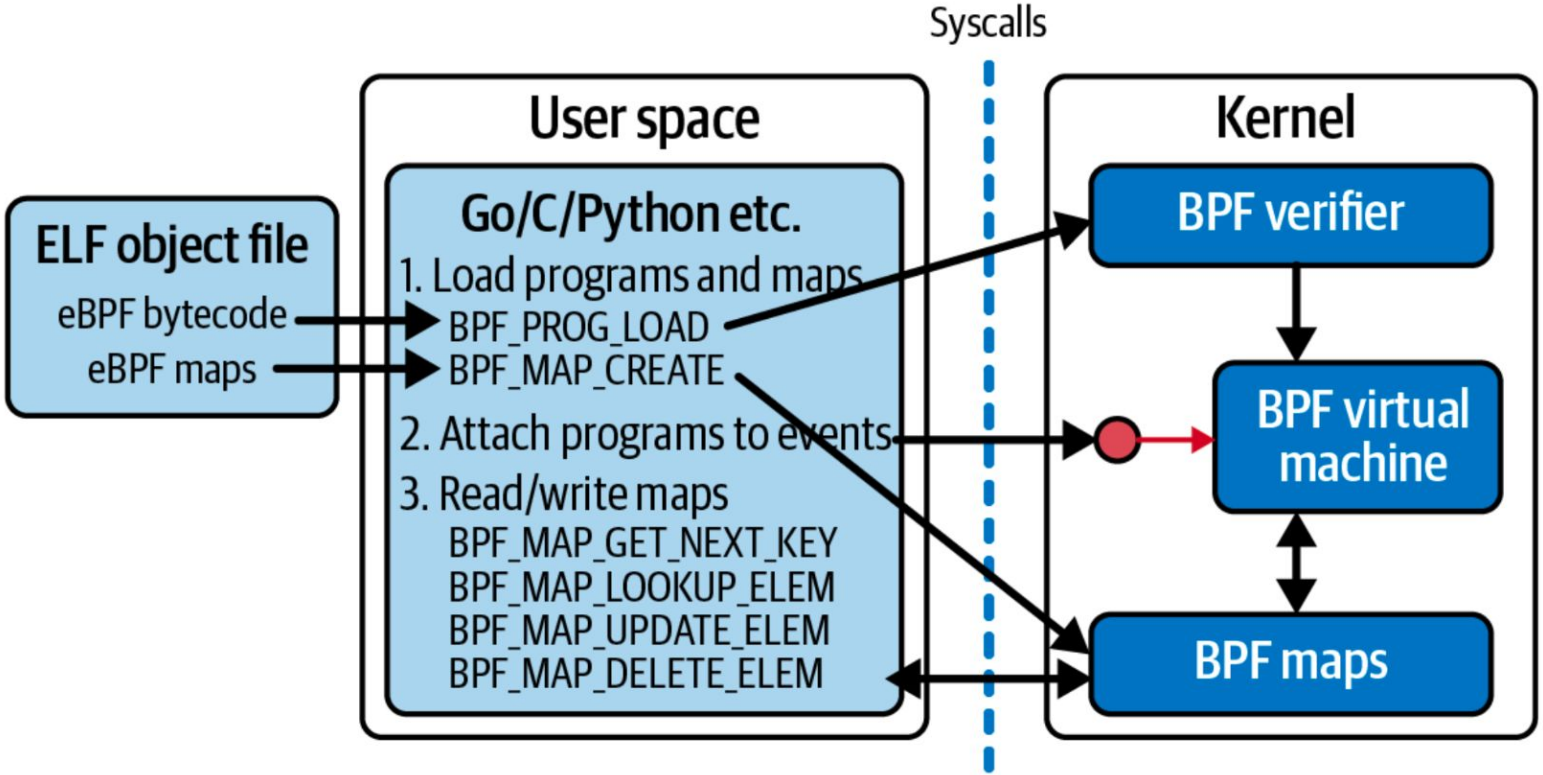
Task 1: Using libbpf for userspace programs



There are two ways to use **libbpf**

- First, directly using libbpf's C API and opening/loading ebpf objects manually.
- Second, using **`bpftool`** to generate convenient skeleton header file, which internally uses the libbpf API

Task 1: libbpf internals



Source: Figure 4-1 from Learning eBPF

Task 1: Hello libbpf

Now let's run it on our machine —

1. Change working directory to **`ebpf-inside-out/advanced/task1`**
2. Compile hello.bpf.c and load using Makefile
   `$ make`
3. Run the loader program
   `$ sudo ./hello`

Exercise

- Complete all steps mentioned in hello.bpf.c (Same as in `basic/task1`)
- Modify loader (**`hello.c`**) to accept an argument (pid) from command line and pass it to the eBPF program as argument (to track specific process) before loading

Task 2: Parsing and Dropping ping packets

In this task we will drop every odd ping (ICMP ECHO REQUEST) packets.

We have provided a partially implemented packet parser that parses ethernet and ipv4 headers.

Exercise

- Add **`parse_icmphdr()`** which should parse the ICMP header and return the ICMP type.

- Modify the main function, to check if the packet is an ICMP echo request.
  If ICMP echo request, check the sequence number of the ICMP packet, and
  if the sequence number is odd, drop the packet

Task 3: Network telemetry with eBPF

In this task we will track the throughput of our network link.

To accomplish this we will use a custom loader that will load the eBPF program and use eBPF maps to communicate the packets that has been received by the link to the loader.

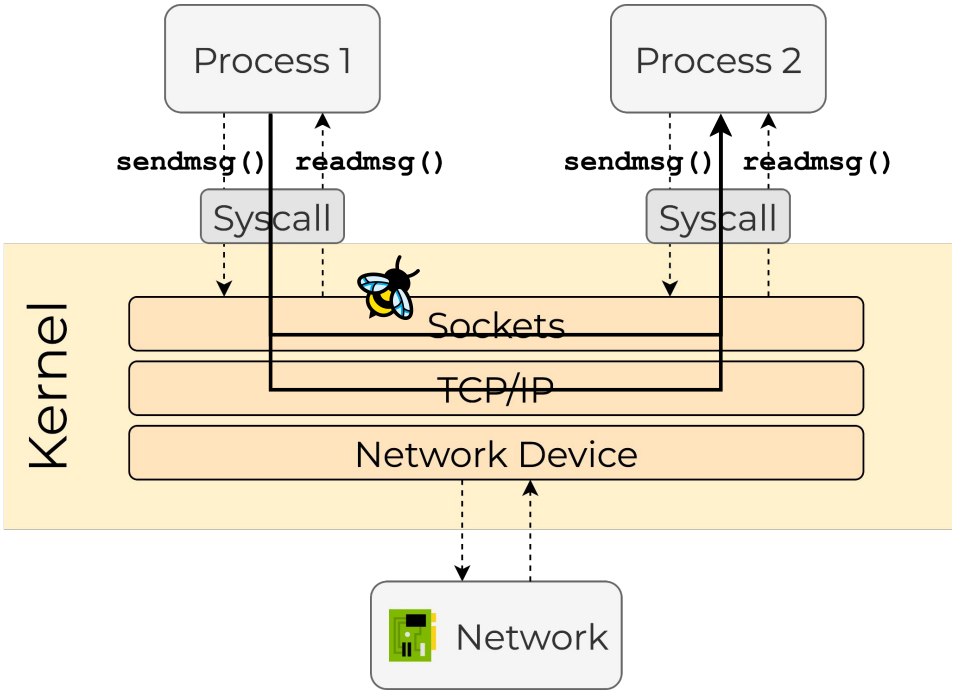
The loader will then print the statistics at regular intervals.

Exercise

- Currently the counter program only prints the throughput in packets per second.

- Add support for printing throughput in bytes per second.
  To accomplish this follow the steps given in comments in the file **`common_kern_user.h`**, **`counter.bpf.c`**, and **`counter.c`**.

Task 4: Packet forwarding using eBPF



- Communication of co-located processes traverse through multiple kernel layers.
- Using eBPF we can bypass some of the processing.

Task 4: Background

BPF_MAP_TYPE_SOCKHASH: Special map types use to socket objects.

BPF_PROG_TYPE_SOCK_OPS: eBPF programs are invoked when some socket operation occurs e.g. socket creation, connection etc. It can be used to keep track of all connected sockets.

BPF_PROG_TYPE_SK_MSG: eBPF programs attached to sockhash/sockmap maps. Invoked when a send operation is called on any socket in sockhash map.

bpf_msg_redirect_hash: Helper function. Redirects packet from one socket to another directly.

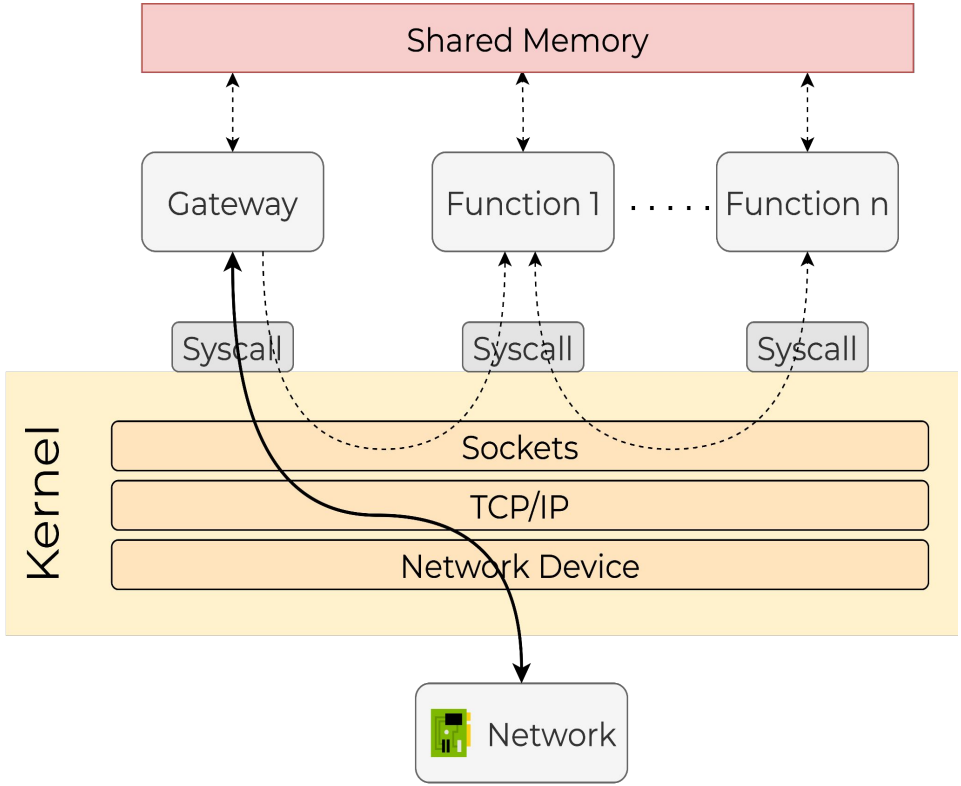
What can we do with eBPF?

- **Use eBPF for different interesting use cases:**
  Syrup (SOSP '21), BMC (NSDI '21), SPRIGHT (SIGCOMM '22), DINT (NSDI '24)

- **Extend eBPF functionalities in kernel:**
  XRP (OSDI '22), KFlex (SOSP '24), eTran (NSDI '25)

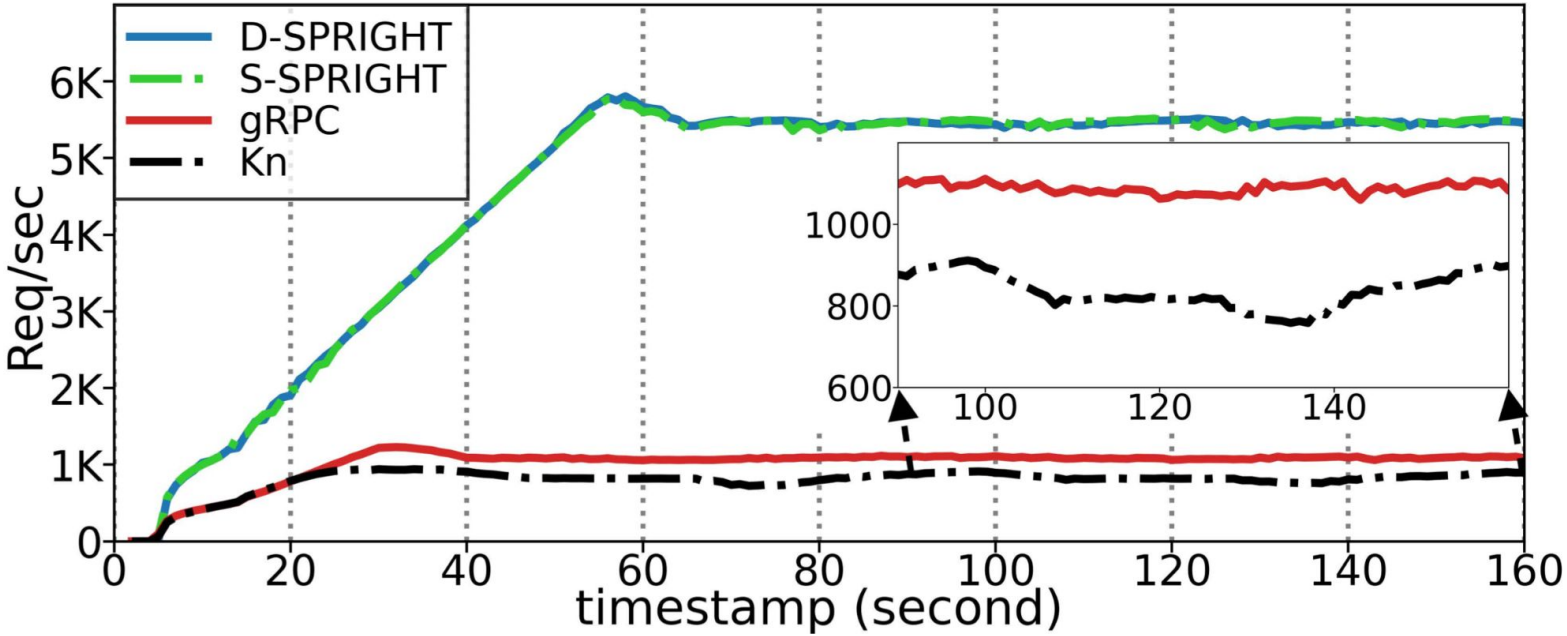
- **Find new use cases for eBPF technology:**
  JANUS (MobiCom '23), eGPU (HCDS '25), bpftime (OSDI '25)

Spright: extracting the server from serverless computing! (NSDI '22)



- A FaaS platform
- Reduces serialization and Deserialization
- Increased Throughput and Reduces latency using zero-copy

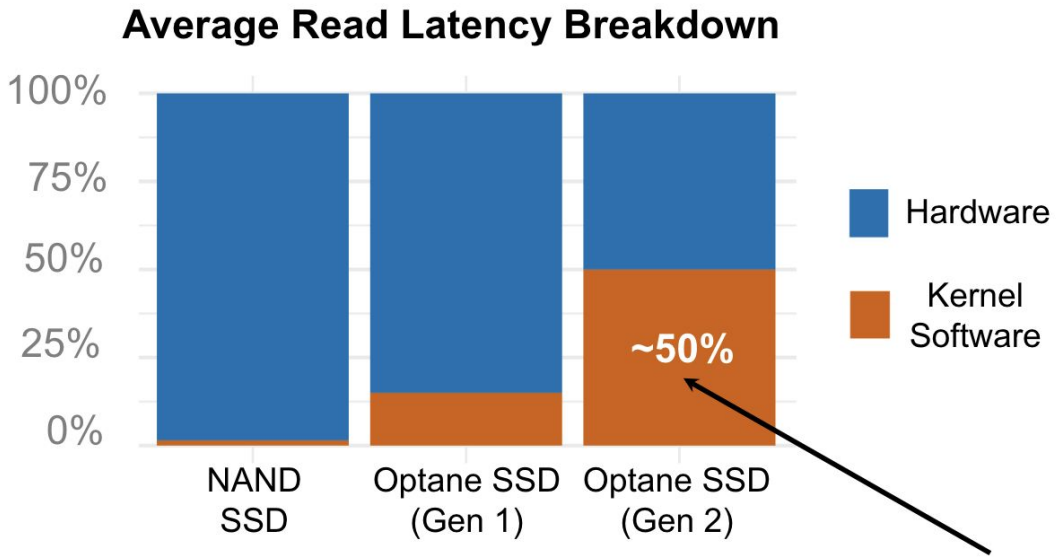
Spright: extracting the server from serverless computing! (NSDI '22)



XRP: In-Kernel Storage Functions with eBPF
(OSDI '22 Best Paper Award)

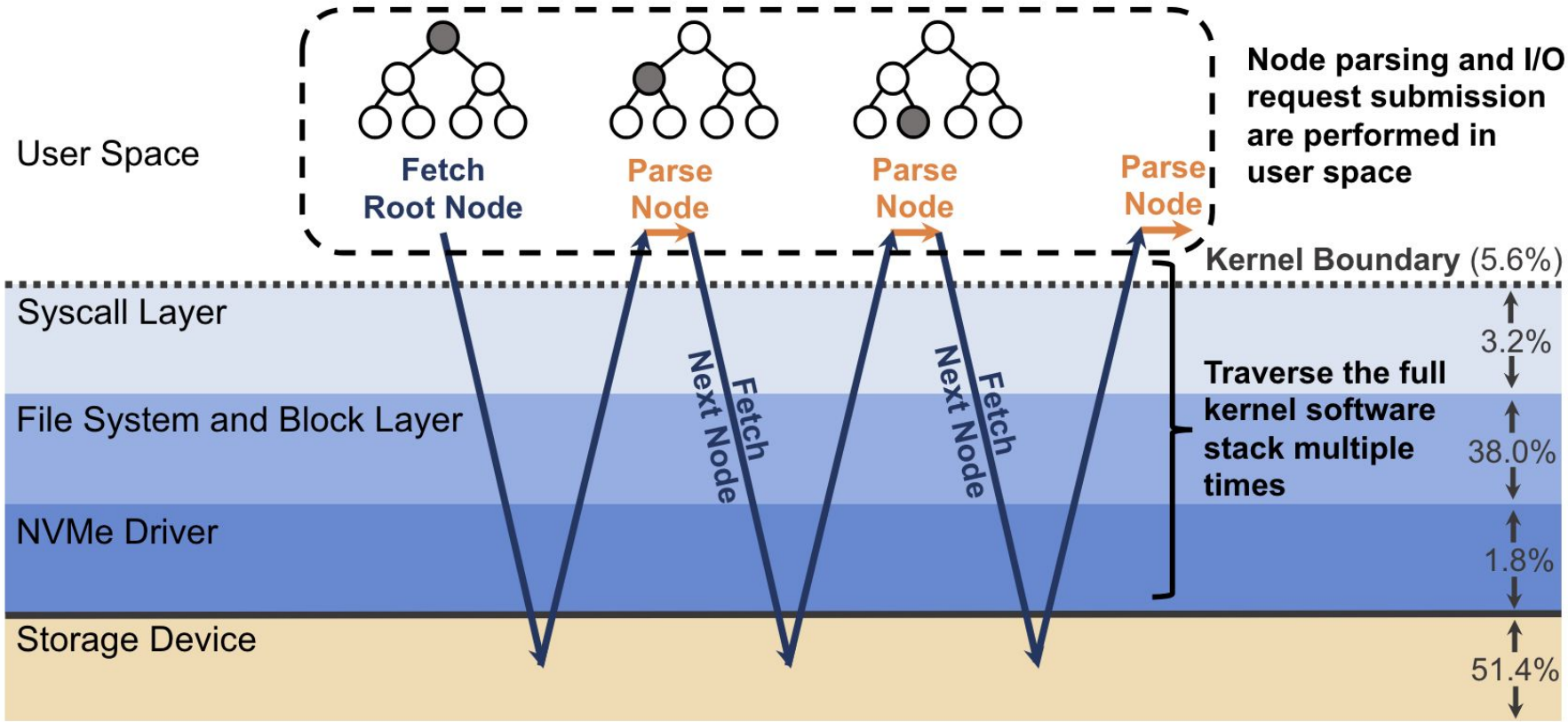
Kernel Software is Becoming the Bottleneck for Storage

XRP reduces the kernel software overhead using eBPF.



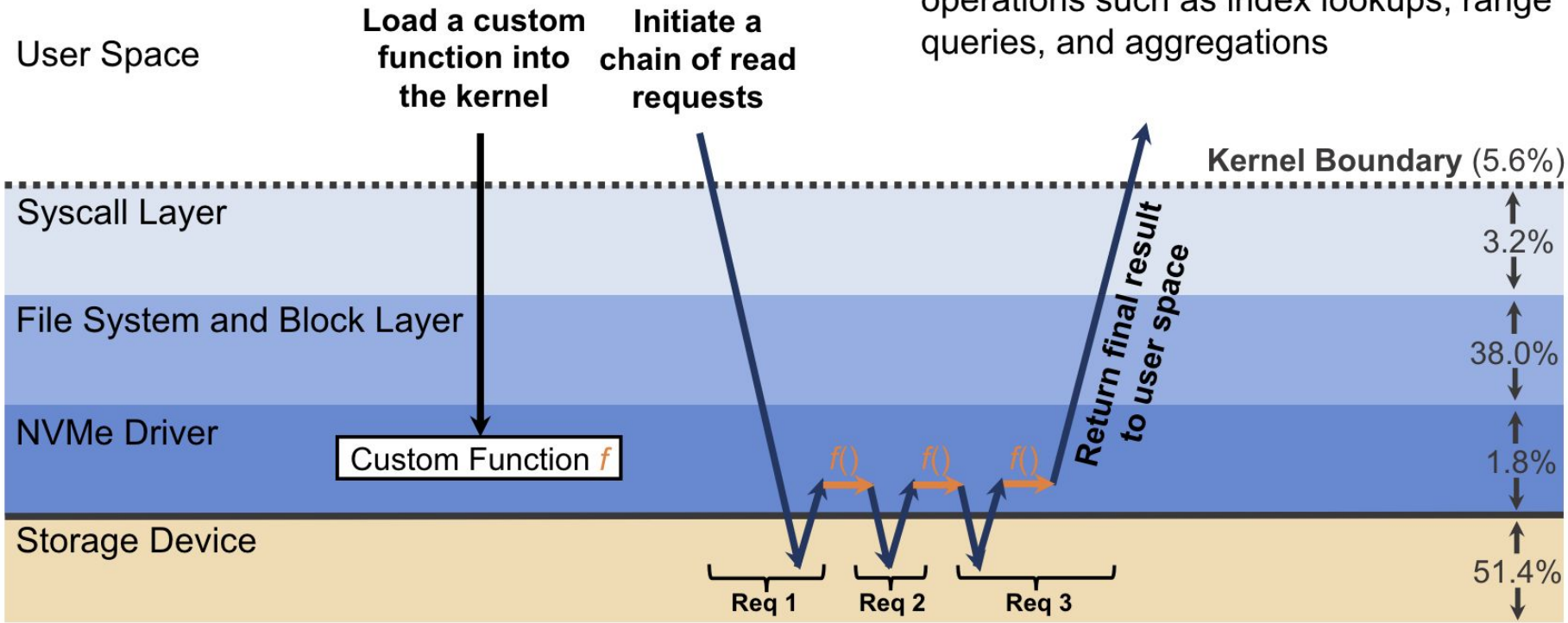
Kernel software overhead accounts for ~50% of read latency on Optane SSD Gen 2

B+ Tree Index Lookup from User Space

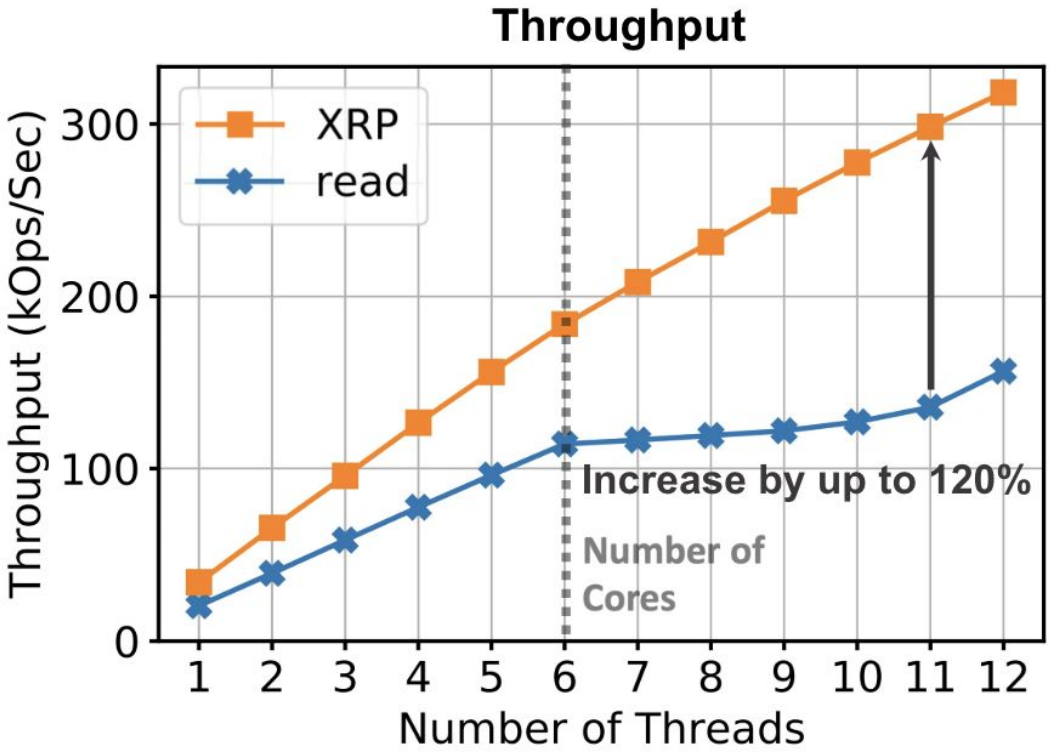


XRP: A Framework for In-Kernel Storage Functions

XRP can accelerate many types of operations such as index lookups, range queries, and aggregations



XRP: In-Kernel Storage Functions with eBPF



Load balancing in Kubernetes

K8s actions might include adding new pods or changing load balancing rules

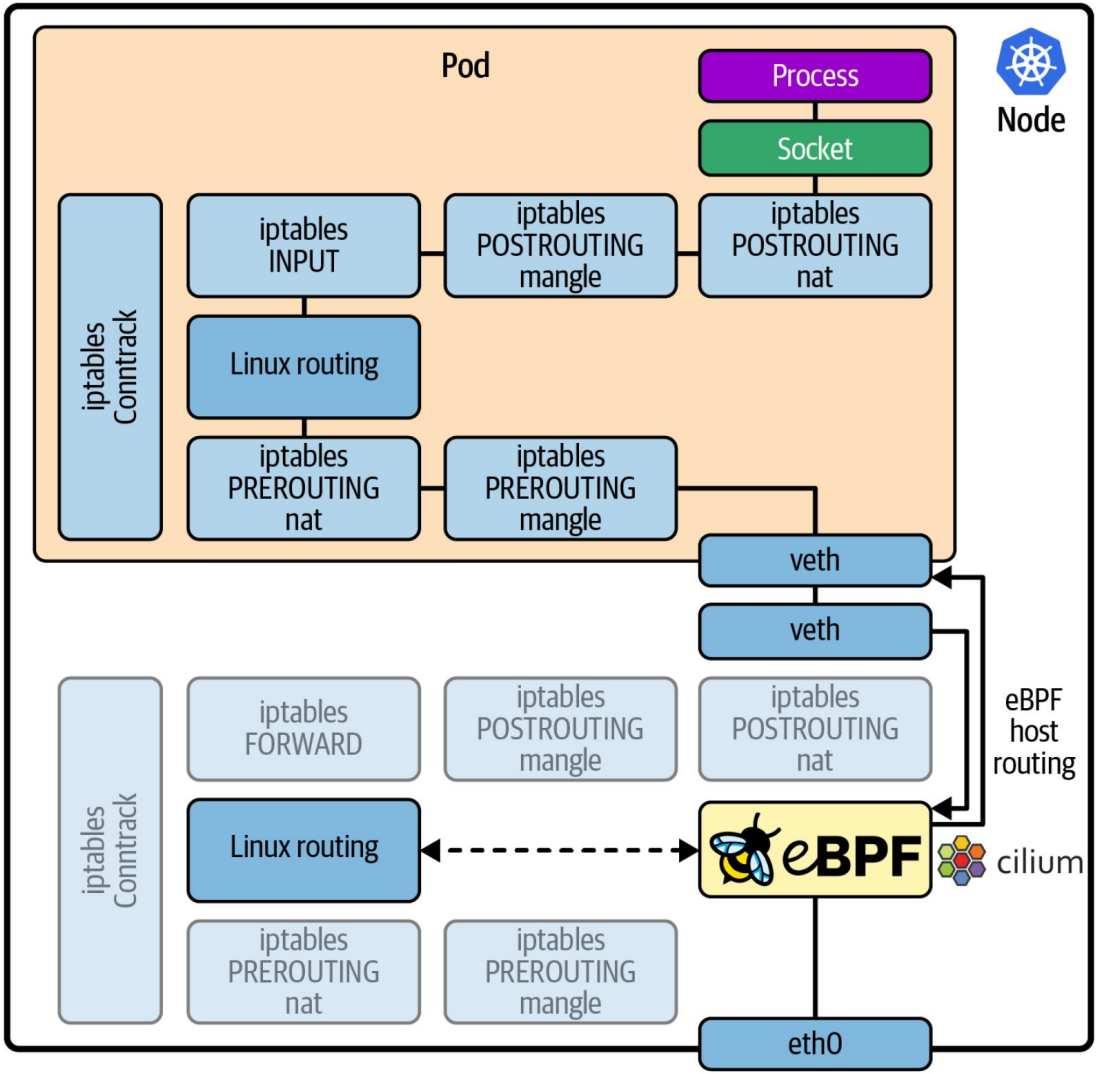
Kube proxy

- Implements load balancing through IP tables
- Requires iptable update when pod IP changes
- Slow O(n) lookup and addition

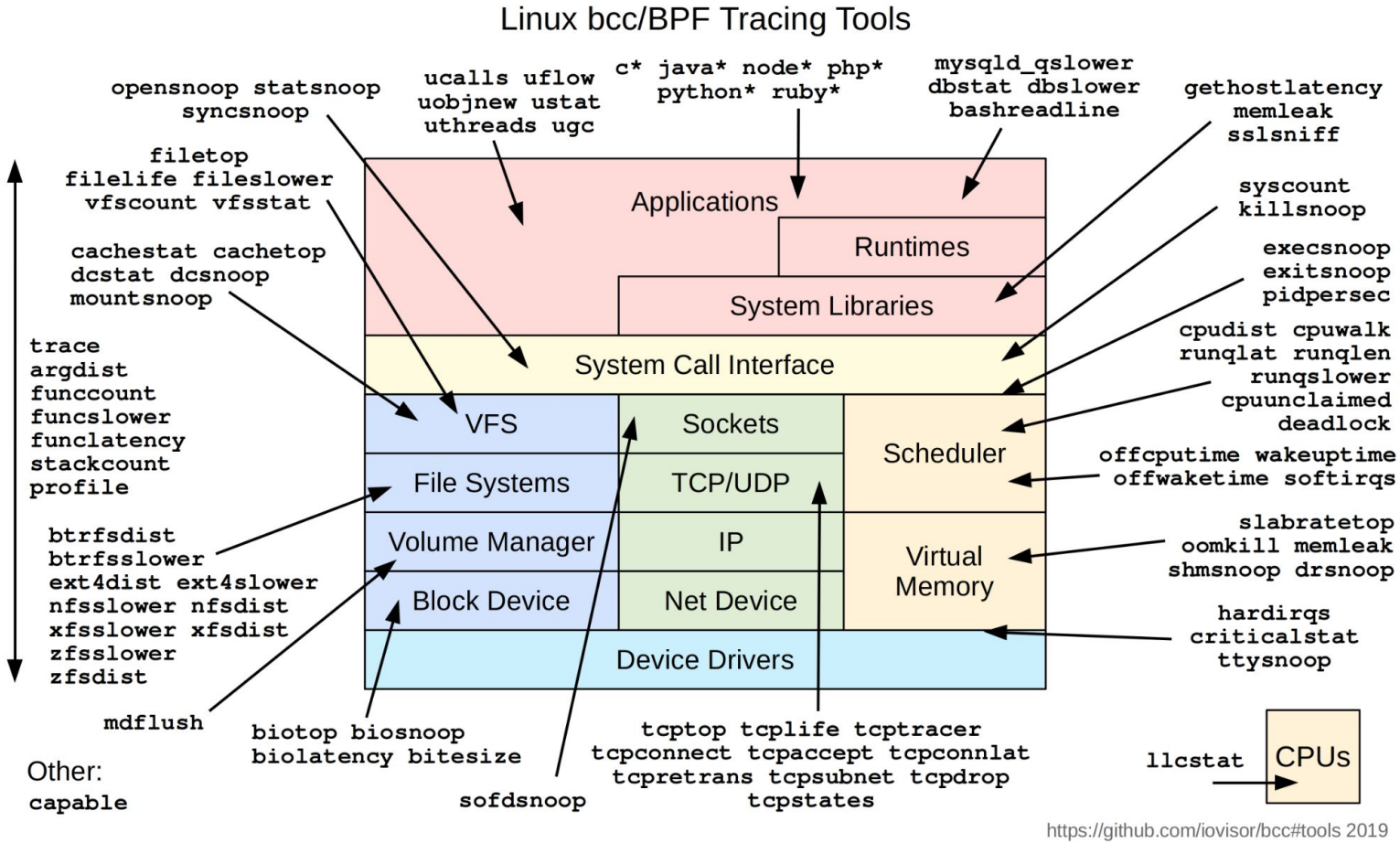
Cilium

Accelerates networking in K8s using eBPF

- Uses eBPF to encode routing logic
- Efficient O(1) logic lookup using eBPF hash maps



Source: Fig 8-6 from
Learning eBPF
by Liz Rice



Source: https://www.brendangregg.com/ebpf.html

Thanks

https://github.com/cloudarxiv/ebpf-inside-out

www.cse.iitb.ac.in/synerg

Links:

1. Learning eBPF by Liz Rice:
   https://www.oreilly.com/library/view/learning-ebpf/9781098135119/
2. BCC github
   https://github.com/iovisor/bcc/tree/master
3. eBPF docs:
   https://docs.ebpf.io/
4. bpftool tutorial
   https://qmonnet.github.io/whirl-offload/2021/09/23/bpftool-features-thread/
5. eBPF developer tutorial
   https://github.com/eunomia-bpf/bpf-developer-tutorial