From tracing to kernel programming

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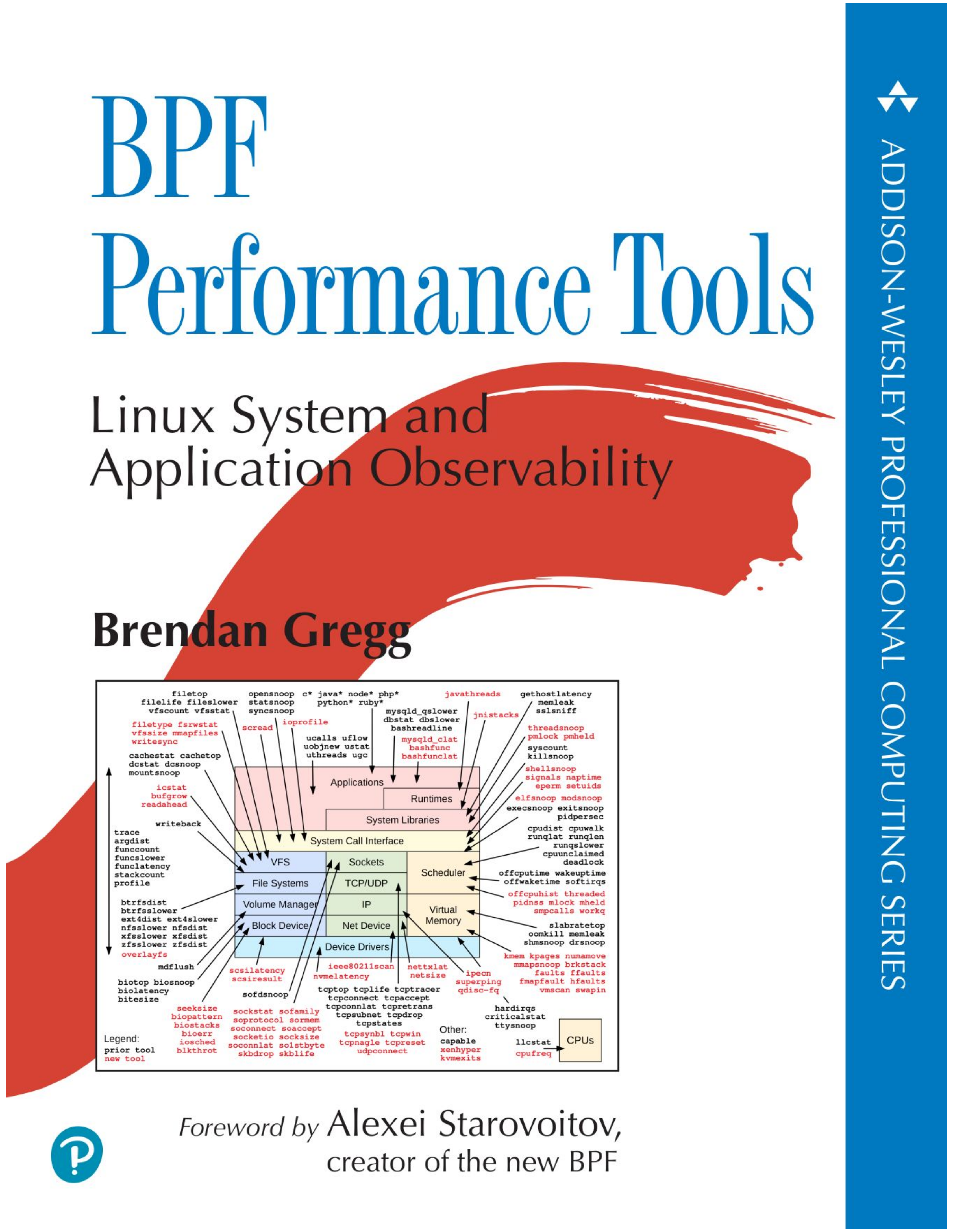
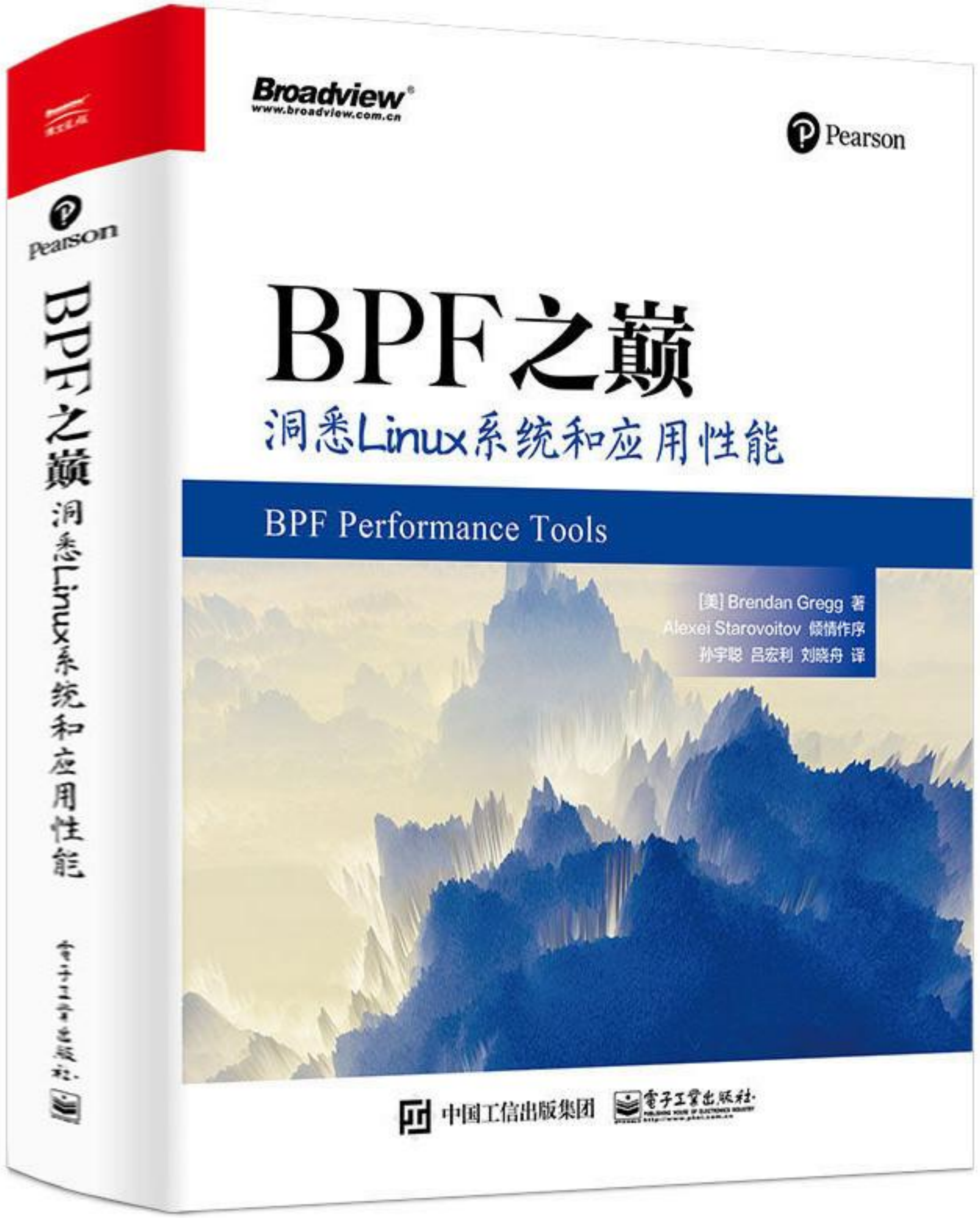
KERNEL
ENGINEERING
Meta

Agenda

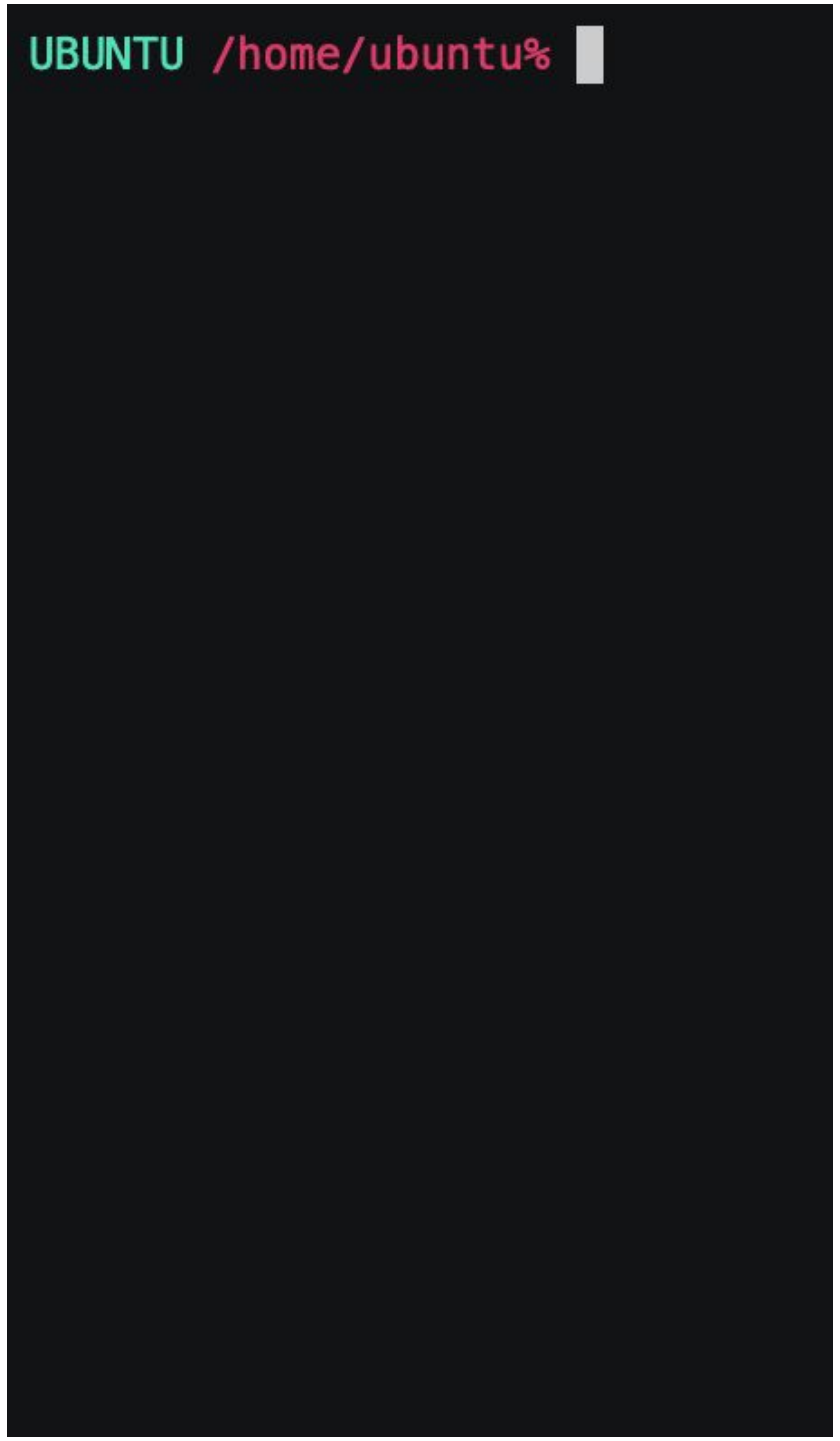
Tracing roots of BPF





tetris implemented as bpftrace script

https://github.com/mmisono/bpftrace-tetris



BPF is a sequence of commands that can be understood

BPF is an universal assembly language

- strictly typed assembly language
- safe for kernel and for HW
- stable instruction set
- extensions are backwards compatible

BPF use cases

- user space tells kernel what to do
- HW tells kernel what to do
- one computer tells another computer what to do

... the response could be: "yeah, I can do this" or "No, not right now".

... and since the intent is understood it's execution can be in a different form.
(CPU executes one instruction, BPF executes whole program)

BPF vs Sandboxing (wasm, ...)

- BPF program is understood before execution
- Sandbox restricts execution environment. It doesn't understand what's running in the sandbox.

BPF design

- verifiable ISA
- write programs in C and compile into BPF ISA with GCC/LLVM
- Just-In-Time convert to modern 64-bit CPU
- minimal performance overhead:
  - bpf vs native (C -> BPF ISA -> native ISA vs C -> native ISA)
  - transition from native to bpf (native code -> BPF code -> native code)
- BPF calling convention compatible with modern 64-bit ISAs
- extend BPF (eBPF) ISA proposed in 2013
  - first appeared in the kernel as internal BPF (iBPF)

- Quiz:
  - What's faster the kernel in C or compiled through BPF ?
  - How sandboxed code calls native ? Hint: https://en.wikipedia.org/wiki/Foreign_function_interface

extensions of extended BPF (2014 till now)

. ISA was extended 5 times

. <, <= instructions

. 32-bit compare

. atomics

. LLVM support -mcpu=v1, v2, v3

. -mcpu=v4 landed July 2023.

. sign extending loads

. bswap

. long jmp

. sdiv/smod

. GCC and LLVM support -mcpu=v4

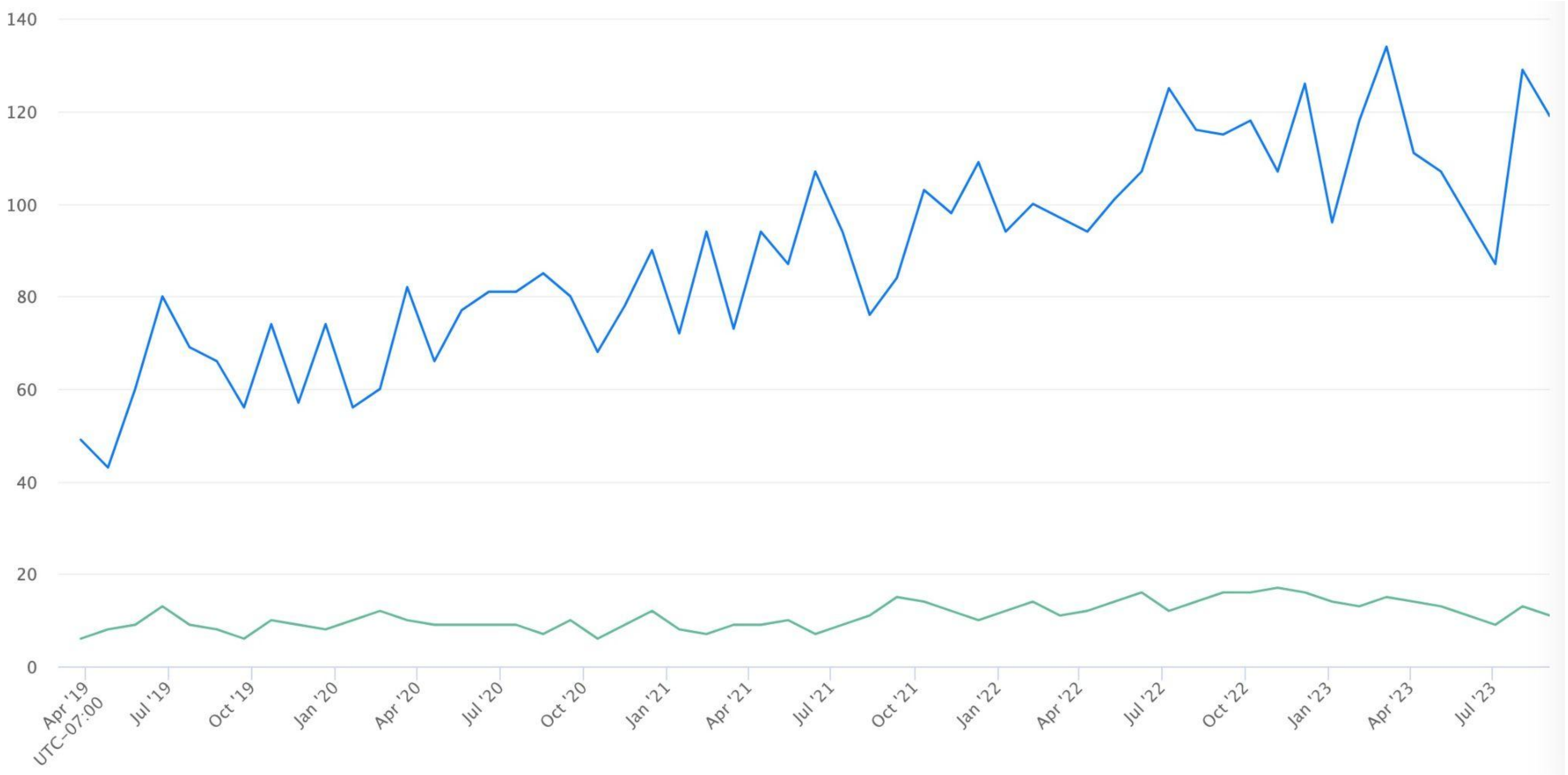
BPF enables innovation

- BPF satisfies my own thirst for innovation

- BPF enables others to innovate
  - within BPF infra
  - in other kernel subsystems

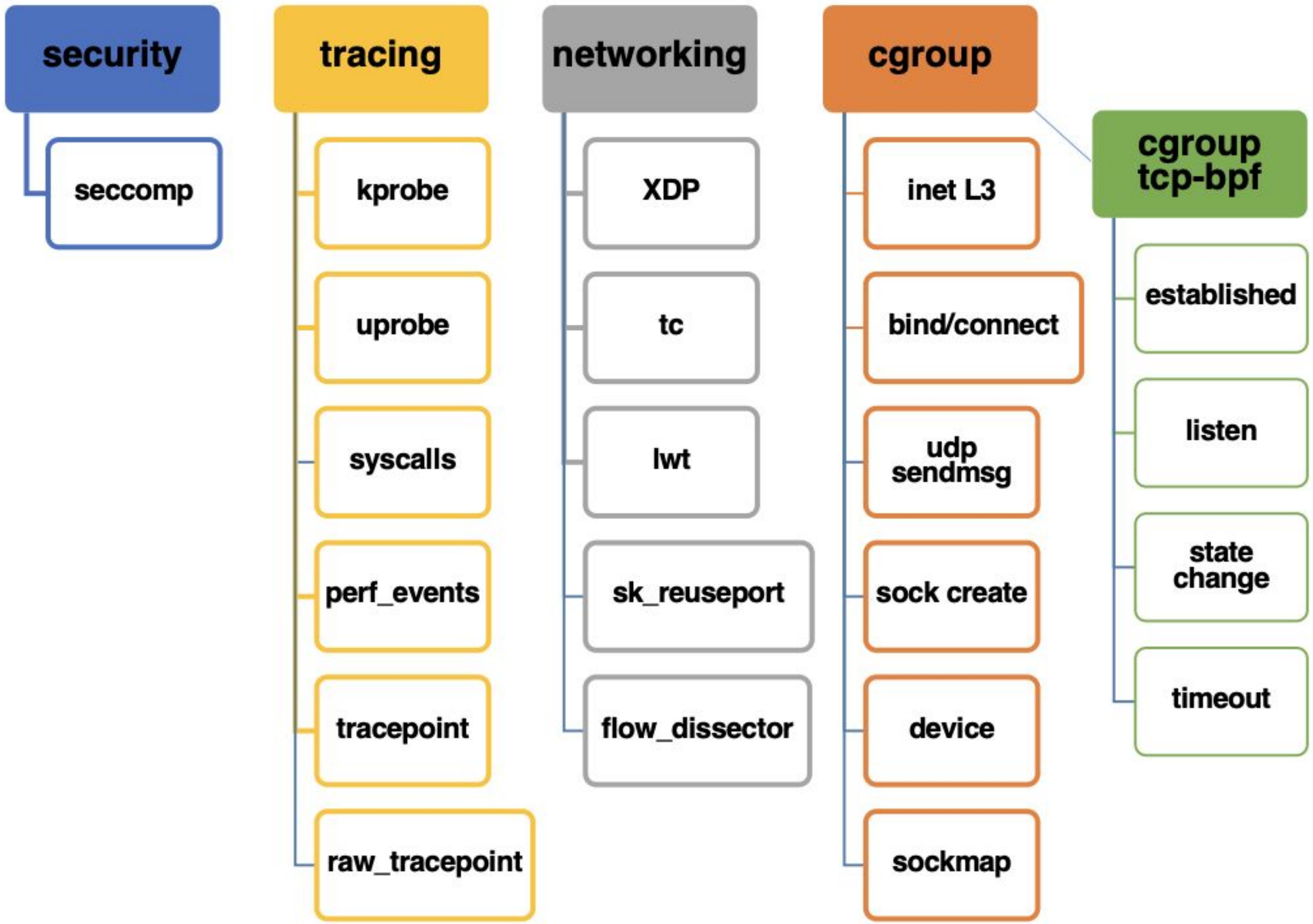
- That's why I still work on BPF !

Innovation in the kernel BPF subsystem (Sep 2023)



Number of BPF developers per month (green - Meta BPF team, blue - the rest of BPF community)

BPF hooks hierarchy



BPF tracing - BPF for kernel observability

- Tracing mechanisms:
  - [ku]probe + bpf
  - tracepoint + bpf
  - fentry + bpf

- Capabilities
  - read all kernel data
- Restrictions
  - cannot modify kernel state
  - cannot crash or warn

BPF for kernel and user observability

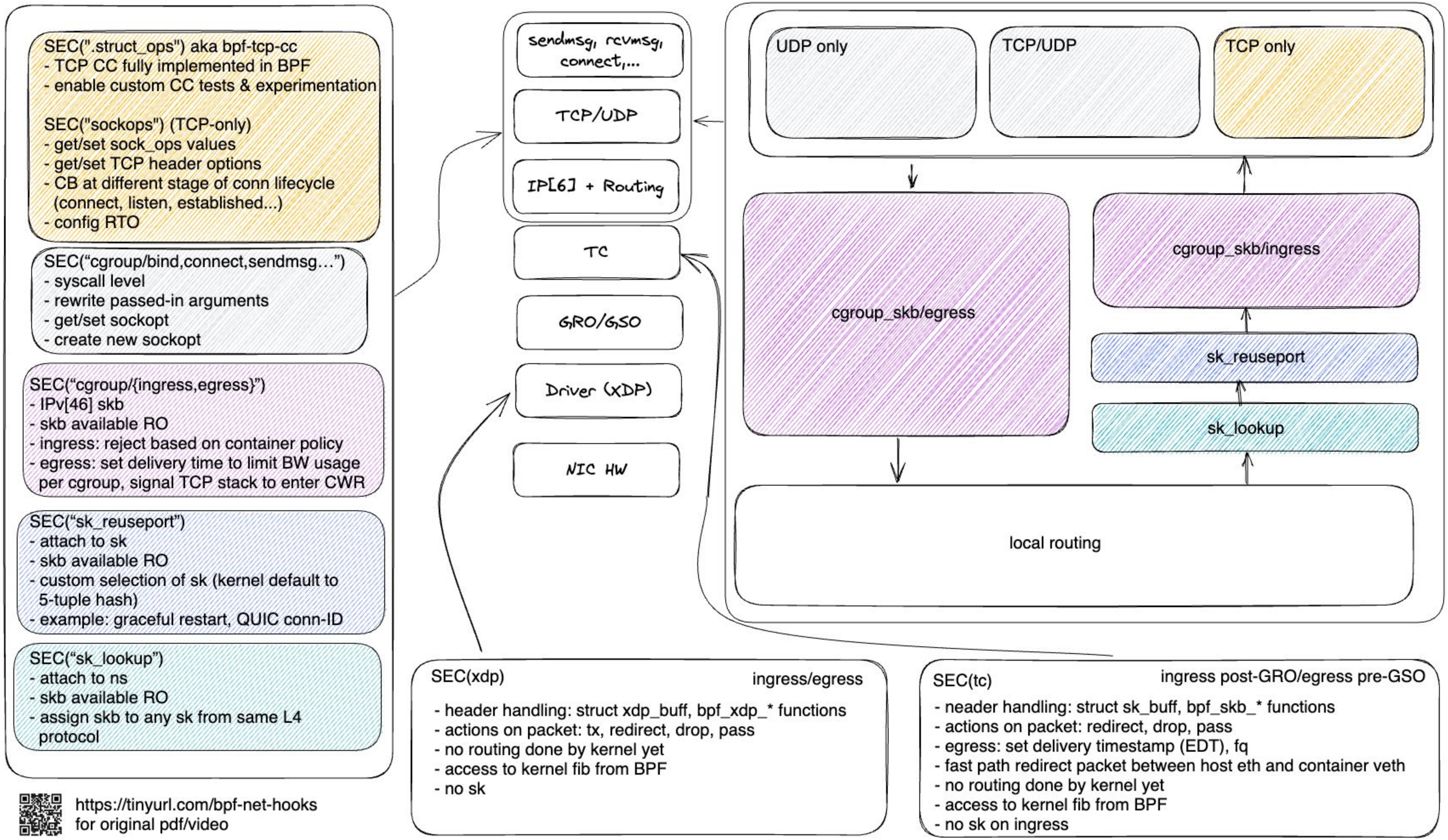
- Tools
  - bcc
  - bpftrace
  - retsnoop
  - pyperf

- Use cases implemented with "BPF tracing"
  - Explain why kernel returns -EINVAL
  - Measure the latency of this syscall
  - How much time GCC spends processing #include vs compiling the rest
  - Tell me where my python program spends time
  - How many Gbytes my android phone used on facebook and youtube

BPF networking - BPF in firewalls, routers

- Network stack:
  - XDP + bpf
  - TC + bpf
  - cgroup + bpf
  - netfilter + bpf
  - TCP + bpf

- Capabilities
  - read packet data
  - modify and drop packets
  - modify TCP state
- Restrictions
  - cannot read arbitrary kernel data
  - cannot modify kernel state



https://tinyurl.com/bpf-net-hooks
for original pdf/video

BPF networking

- Tools
  - cilium
  - katran

- Use cases
  - firewall
  - K8s network connectivity
  - L4 load balancer
  - L7 socket load balancing
  - live task upgrade without connectivity loss
  - TCP congestion control

BPF security

- Hooks:
  - LSM + bpf
  - syscall + bpf

- Capabilities and restrictions
  - can read arbitrary kernel data
  - can deny operations
  - can sleep

BPF security

- Tools
  - systemd
  - the rest is non public :(

- Use cases
  - Alternative to selinux and apparmor
  - Disallow use of file system X

BPF next

- Hooks:
  - scheduler + bpf
  - hid + bpf
  - oom + bpf
  - fuse + bpf

- Capabilities and restrictions
  - TBD
  - subsystem defines what is necessary

sched-ext

- New sched_class, at a lower priority than CFS
- Enables scheduling policies to be written in BPF programs
- No ABI stability restrictions – purely a kernel <-> kernel interface
- Run-time safety checks to make sure tasks are not starved

Implementing scheduling policy

- BPF program must implement a set of callbacks
  - Task wakeup (similar to select_task_rq())
  - Task enqueue/dequeue
  - Task state change (runnable, running, stopping, quiescent)
  - CPU needs task(s) (balance)
  - Cgroup integration

HID-BPF: changing how the device looks and talks

```
SEC("fmod_ret/hid_bpf_rdesc_fixup")
int BPF_PROG(rdesc_fixup, struct hid_bpf_ctx *hid_ctx)
{
	_u8 *data = hid_bpf_get_data(hid_ctx, 0, 4096 /* size */);

	/* invert X and Y definitions in the event stream interpretation */
	data[39] = 0x31;
	data[41] = 0x30;

	return 0;
}
```

`data` now contains the report descriptor of the device.

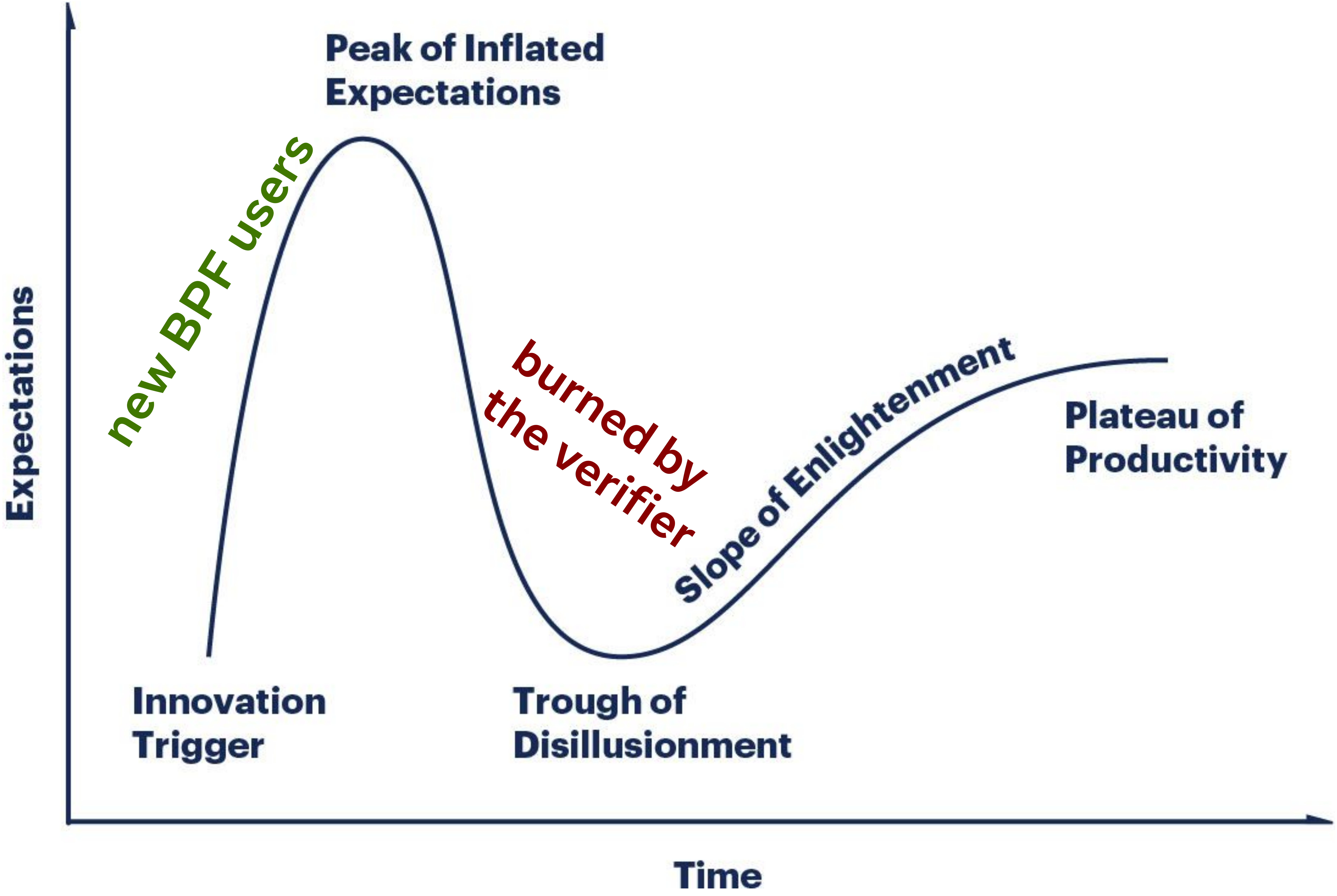
(Un)attaching this program triggers a disconnect/reconnect of the device.

Only 1 program of this type per HID device.

Ask AI: write eBPF program that parses IPv4

```c
#include <linux/bpf.h>
#include <linux/if_ether.h>
#include <linux/ip.h>

SEC("xdp")
int xdp_prog(struct xdp_md *ctx) {
    void *data = (void *)(long)ctx->data;
    void *data_end = (void *)(long)ctx->data_end;

    // Check packet length
    if (data + sizeof(struct ethhdr) + sizeof(struct iphdr) > data_end) {
        return XDP_DROP;
    }

    // Parse Ethernet header
    struct ethhdr *eth = data;
    if (eth->h_proto != htons(ETH_P_IP)) {
        return XDP_PASS;
    }

    // Parse IPv4 header
    struct iphdr *ip = data + sizeof(struct ethhdr);
    if (ip->version != 4) {
        return XDP_PASS;
    }

    // Extract source and destination IP addresses
    __u32 src_ip = ip->saddr;
    __u32 dst_ip = ip->daddr;

    // Do something with the IP addresses
    // ...

    return XDP_PASS;
}
```

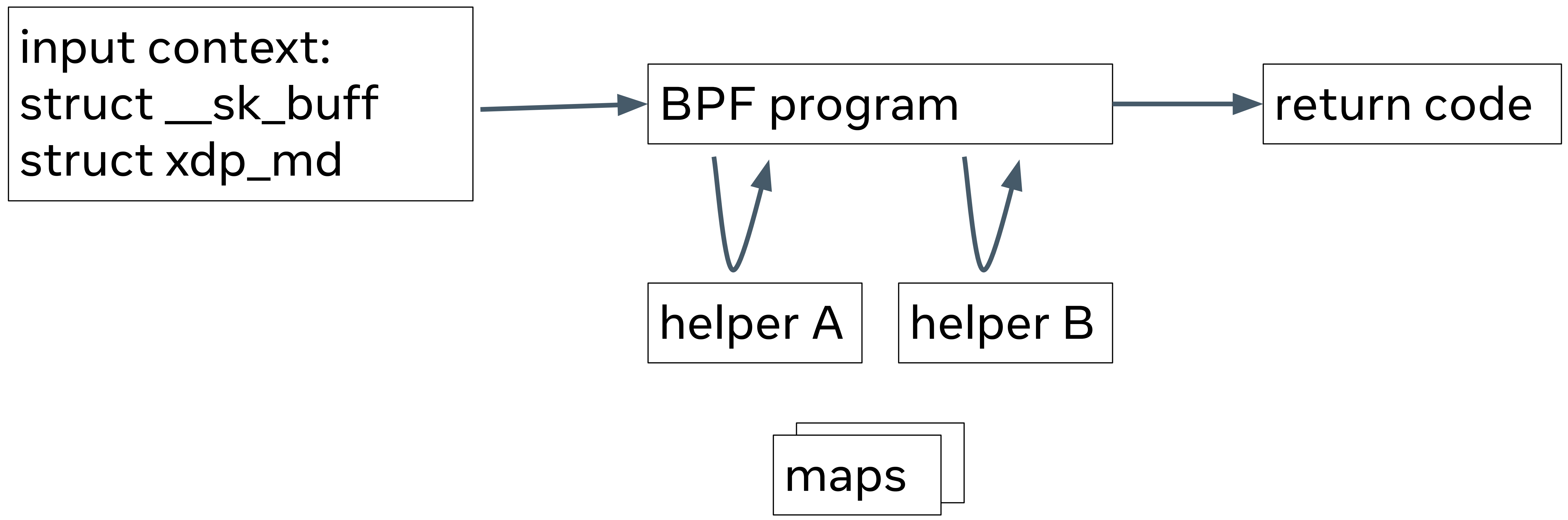
Everything on this slide is AI generated https://en.wikipedia.org/wiki/Gartner_hype_cycle



Major shift in BPF architecture happened in 2022

BPF and the kernel

- all BPF programs before 2022



stable hook:

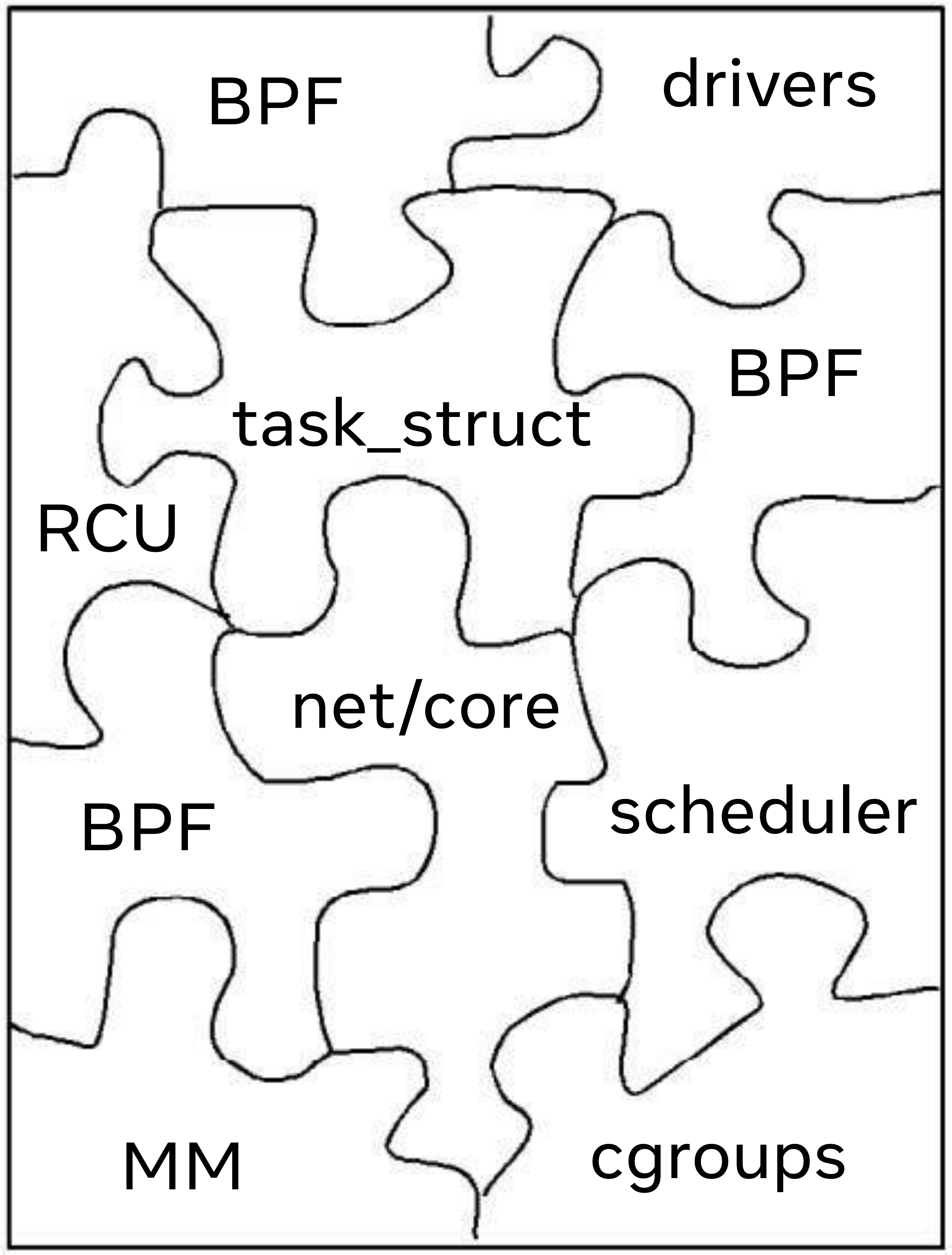
- kernel prepares data it wants BPF program to see
- kernel interprets return code

BPF in the kernel

- hid-bpf, sched-ext, netfilter, struct-ops
- "new tracing"

- Native calls: kernel↔BPF↔kernel
- BPF can refcnt ++, -- and stash kernel objects
- explicit bpf_rcu_read_lock/unlock

- NO stable API



Katran - production BPF prog written in "Restricted C"

uapi input context

```
SEC("xdp")
int balancer_ingress(struct xdp_md *ctx)
{
        void *data_end = (void *)(long)ctx->data_end;
        void *data = (void *)(long)ctx->data;
        struct eth_hdr *eth = data;
        __u32 eth_proto;
        __u32 nh_off;

        nh_off = sizeof(struct eth_hdr);
        if (data + nh_off > data_end)
                return XDP_DROP;
        eth_proto = eth->eth_proto;
        if (eth_proto == bpf_htons(ETH_P_IP))
                return process_packet(data, nh_off, data_end, false, ctx);
        else if (eth_proto == bpf_htons(ETH_P_IPV6))
                return process_packet(data, nh_off, data_end, true, ctx);
        else
                return XDP_PASS;
}
```

uapi return codes

Early days of BPF aka "Restricted C"

- All functions are __always_inline
- Single input argument
  - a pointer to context that is program type dependent. Ex: struct __sk_buff.
- No loops
- No memory allocation
- No type information

__attribute__((always_inline)) is no longer necessary.

BPF supports global and static functions.

```
static __always_inline __u32 get_packet_hash(struct packet_description *pckt,
                                             bool ipv6)
{
    // ..
}

static __always_inline bool get_packet_dst(struct real_definition **real,
                                           struct packet_description *pckt,
                                           struct vip_meta *vip_info,
                                           bool is_ipv6)
{
      __u32 hash = get_packet_hash(pckt, is_ipv6) % RING_SIZE;
      // ...
}

static __always_inline int parse_icmpv6(void *data, void *data_end, __u64 off,
                                        struct packet_description *pckt)
{
```

#pragma unroll is no longer necessary.

BPF supports iterators.

```
int i;

#if NEW_KERNEL
bpf_for(i, 0, STACK_MAX_LEN) {
#else
#pragma clang loop unroll(full)
for (i = 0; i < STACK_MAX_LEN; i++) {
#endif
 // ...
}
```

BPF extended C is a safer C

```c
int err_cast(struct task_struct *tsk)
{
   return((struct sk_buff *)tsk)->len;
}

int err_release_twice(struct __sk_buff *skb)
{
    struct bpf_sock_tuple tuple = {};

    struct bpf_sock *sk = bpf_sk_lookup_tcp(skb, &tuple, sizeof(tuple), 0, 0);
    bpf_sk_release(sk);
    bpf_sk_release(sk); // NOT OK in BPF C
    return 0;
}
```

OK in C.
NOT OK in BPF C.

Extended C with Symbolic Access

```
struct __sk_buff {
        __u32 len;
        __u32 pkt_type;
        __u32 mark;
        __u32 queue_mapping;
        ...
};
```

```
struct sk_buff {
        /* field names and sizes should match to those in the kernel */
        unsigned int len, data_len;
        __u16 mac_len, hdr_len, queue_mapping;
        struct net_device *dev;
        /* order of the fields doesn't matter */
        refcount_t users;
} __attribute__((preserve_access_index));
```

Instructs compiler to generate symbolic field access instead of constant integer offsets.
Dynamic structure layout.
BPF program adjusts itself depending on the target kernel.

Extended C with Type Information

```
SEC("tp_btf/netif_receive_skb")
int BPF_PROG(trace_netif_receive_skb, struct sk_buff *skb)
{
        p.type_id = bpf_core_type_id_kernel(struct sk_buff);
        p.ptr = skb;
        /* pretty print an skb */
        bpf_snprintf_btf(str, STRSIZE, &p, sizeof(p), 0);

        int .. = bpf_core_type_size(struct task_struct);

        bool .. = bpf_core_type_exists(struct io_uring);

}
```

BTF type id is determined at load time

Extended C with Kconfig

```
extern unsigned long CONFIG_HZ __kconfig;
extern int LINUX_KERNEL_VERSION __kconfig;

SEC("tc")
int nf_skb_ct_test(struct __sk_buff *ctx)
{
        struct nf_conn *ct_lk;

        test_delta_timeout = ct_lk->timeout - bpf_jiffies64();
        test_delta_timeout /= CONFIG_HZ;
}
```

Unlike kernel modules the kconfig values are not known at compile time. They become known at load time.

The verifier can optimize the code with dead-code-elimination.

Extended C with Exception Tables

```
#pragma clang attribute push (__attribute__((preserve_access_index)), apply_to = record)

struct net_device {
        int ifindex;
};

struct sk_buff {
        struct net_device *dev;
};

SEC("tp_btf/kfree_skb")
int BPF_PROG(trace_kfree_skb, struct sk_buff *skb, void *location)
{
  return skb->dev->ifindex;
}
```

Load instructions are replaced with inline version of copy_from_kernel_nofault() and exception tables generated.

Extended C with Type Tags

```
// include/linux/compiler_types.h

# if defined(CONFIG_DEBUG_INFO_BTF) && defined(CONFIG_PAHOLE_HAS_BTF_TAG) && \
        __has_attribute(btf_type_tag)
# define BTF_TYPE_TAG(value) __attribute__((btf_type_tag(#value)))

# define __user         BTF_TYPE_TAG(user)
# define __rcu          BTF_TYPE_TAG(rcu)
```

normal C: for debug kernel and for sparse tool to warn

extended C: access is enforced by the verifier.
Cannot do RCU dereference outside of RCU critical section.
rcu_read_unlock() invalidates the pointers.
Use-After-Free is prevented.

Extended C with Operator new

```
#define __kptr __attribute__((btf_type_tag("kptr")))
struct foo {
        int var;
};
struct map_value {
        // __kptr tag makes C pointer behave like std::unique_ptr<struct foo>
        struct foo __kptr *ptr;
};
struct {
        __uint(type, BPF_MAP_TYPE_LRU_HASH);
        __type(value, struct map_value);
} lru_map SEC(".maps");

SEC("fentry/do_nanosleep")
int nanosleep(void *ctx)
{
        // equivalent to C++ operator new that returns std::unique_ptr<struct foo>
        // std::make_unique<struct foo>();
        struct foo *p = bpf_obj_new(typeof(*p));

        struct map_value *v = bpf_map_lookup_elem(&lru_map, ...);

        // equivalent to C++ std::swap(v->ptr, p)
        old = bpf_kptr_xchg(&v->ptr, p);
}
```

Extended C with Safe Locks, Lists, RB-trees

```
struct foo {
    struct bpf_list_node node;
    int data;
};
struct bar {
    struct bpf_rb_node node;
    int var;
};
private(A) struct bpf_spin_lock lock;
private(A) struct bpf_list_head head __contains(foo, node);
private(A) struct bpf_rb_root root __contains(bar, node);

static bool cmp_less(struct bar *a, struct bar *b)
{
    return a->var < b->var;
}
void bpf_prog(struct foo *f, struct bar *b)
{
    bpf_spin_lock(&lock);
    f->data = 42;
    b->var = 0xeB9F;
    bpf_list_push_front(&head, &f->node);
    bpf_rbtree_add(&root, &b->node, cmp_less);
    bpf_spin_unlock(&lock);
}
```

__percpu pointers

```c
struct val_t {
        long b, c, d;
};
struct elem {
        long sum;
        struct val_t __percpu_kptr *pc;
};
struct {
        __uint(type, BPF_MAP_TYPE_CGRP_STORAGE);
        __uint(map_flags, BPF_F_NO_PREALLOC);
        __type(key, int);
        __type(value, struct elem);
} cgrp SEC(".maps");

const volatile int nr_cpus;
```

```c
SEC("fentry/foo")
int BPF_PROG(test_cgrp_local_storage)
{
        struct task_struct *task;
        struct val_t __percpu_kptr *p;
        struct val_t *v;
        struct elem *e;
        int i;

        task = bpf_get_current_task_btf();
        e = bpf_cgrp_storage_get(&cgrp,
                                 task->cgroups->dfl_cgrp, 0, 0);

        p = e->pc;

        bpf_for(i, 0, nr_cpus) {
                v = bpf_per_cpu_ptr(p, i);
                if (v)
                        sum_field_c += v->c;

        }
        return 0;
}
```

Extended C with Assertions

```
u8 cpu_to_dom_id(u32 cpu)
{
        u8 dom_id;

        bpf_assert(cpu < MAX_CPUS);
        dom_id = cpu_dom_id_map[cpu];
        bpf_assert(dom_id < MAX_DOMS);
        return dom_id;
}

void dom_add_cpu(u32 cpu, u8 dom_id)
{
        u64 *word = &dom_cpu[dom_id][cpu / 64];

        bpf_assert_within(word, dom_cpu, sizeof(dom_cpu));
        *word |= 1LLU << (cpu % 64);
}
```

assert() is a verifier aid. The verifier doesn't have to compute and enforce the bounds. The BPF program will automatically abort. The stack will be unwound, destructors called and program detached.

Early days BPF vs modern BPF

	Early BPF	Modern BPF
Execution context	rcu_read_lock + preempt_disable	rcu_read_lock_trace || rcu_read_lock + migrate_disable
API	stable uapi/bpf.h fixed input context (single argument) fixed set of helpers fixed output codes fixed set of hooks	Unstable and kernel dependent many arguments (type match) whitelisted set of kernel functions scalars and pointer return values (type match) whitelisted empty functions
New features appear as	new prog types new map types new hooks	one prog type kernel exposes new 'struct bpf_' types and kfuncs
Backward compatibility	guaranteed	relies on CO-RE. May fail to load depending on kconfig, version

Like user space

Like kernel modules

Pros and Cons of kernel modules vs BPF

- Pro
  - Arbitrary C code
  - Access to all EXPORT_SYMBOL

- Con
  - One wrong step and panic
  - Have to be compiled with the kernel sources
    - Dynamic Kernel Modules Support require compiler on the host
  - Once compiled becomes a binary blob with no visibility

BPF programs are safe and portable kernel modules

- Safety is builtin
- Portability is achieved with CO-RE, kconfigs, type info
  - It's not guaranteed. BPF program may need to be adjusted to remain portable.
- Debuggable
  - All types are embedded in BPF prog and maps
  - Source code is embedded in binary
  - The verifier understands the purpose. No way to hide what bpf prog is doing.
- EXPORT_SYMBOL_GPL == BPF kfuncs
  - there is no EXPORT_SYMBOL equivalent. All modern BPF progs are GPL.

BPF flavor of the C language is a better choice for kernel programming

Any kernel subsystem may choose to extend itself with BPF programs without touching BPF core and sending emails to bpf@vger