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The Challenges of XDP Hardware Offload

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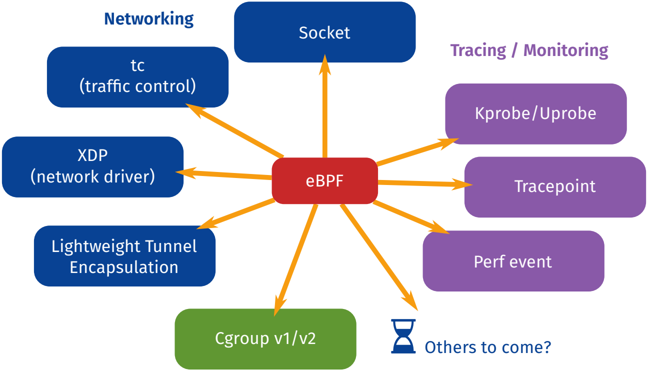
eBPF and XDP

Generic, efficient, secure in-kernel (Linux) virtual machine

Programs are injected and attached in the kernel, event-based

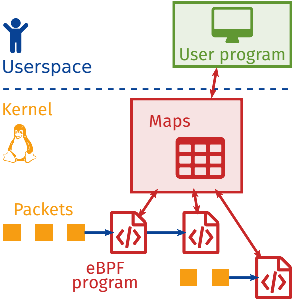


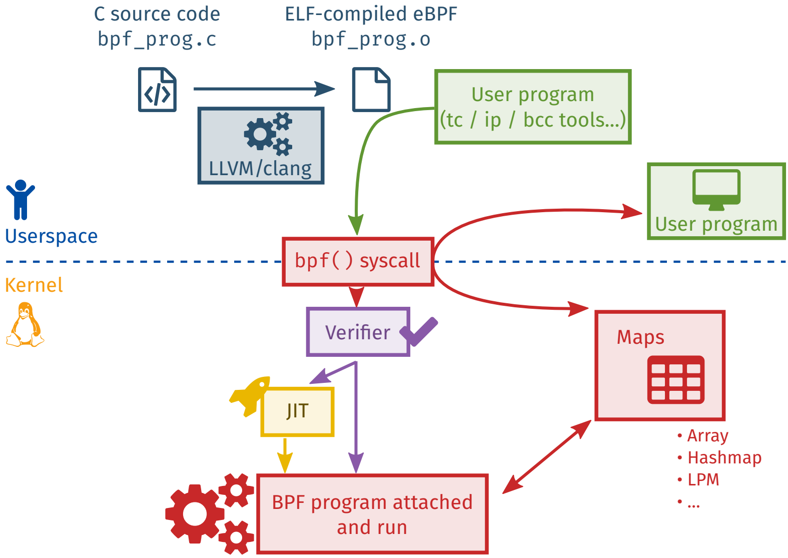
eBPF architecture

- Evolution from former BPF version (*cBPF*, used by `tcpdump`)
- Assembly-like instructions, 4096 maximum in a program
- 11 registers (64-bit), 512 bytes stack
- Read and write access to context (for networking: packets)
- LLVM backend to compile from C to eBPF (or from Lua, Go, P4, Rust, ...)
- In-kernel verifier to ensure safety, security
- JIT (Just-in-time) compiler available for main architectures
- Programs managed with `bpf()` system call, loaded with e.g. `tc`, `ip`

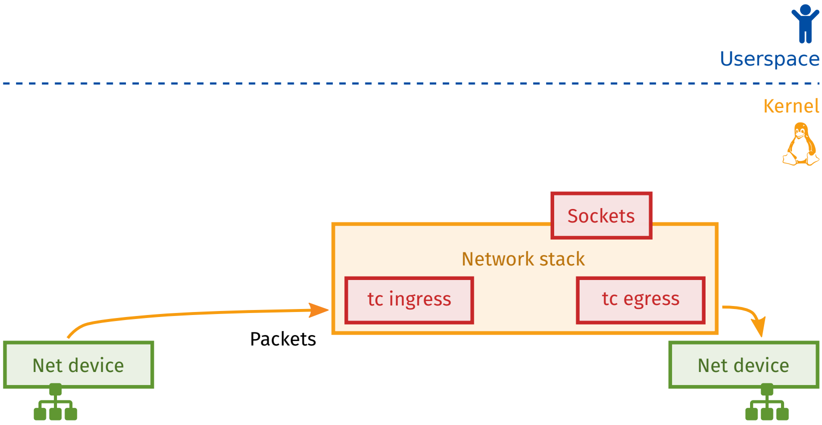
eBPF features

- **Maps**: key-value entries (hash, array, ...), shared between eBPF programs or with user space
- **Tail calls**: “long jump” from one program into an other, context is preserved
- **Helpers**: white-list of kernel functions to call from eBPF programs: get current time, print debug information, lookup or update maps, shrink or grow packets, ...




C source code
bpf_prog.c
ELF-compiled eBPF
bpf_prog.o
LLVM/clang
User program
(tc / ip / bcc tools...)
Userspace
User program
bpf( ) syscall
Kernel
Verifier
Maps
JIT
Array
Hashmap
LPM
...
BPF program attached
and run

- Introduced in Linux 4.8
- eBPF hook at the driver level (ingress)
  Intercept packet before it reaches the stack, before allocating `sk_buff`
- Rationale: implement a faster data path which is part of the kernel, maintained by the kernel community
- Rather for simple use cases. Complex processing: forward to stack
- Not a “kernel bypass”, works in cooperation with the networking stack


Userspace
Kernel
Sockets
Network stack
tc ingress
tc egress
Packets
Net device
Net device

XDP architecture

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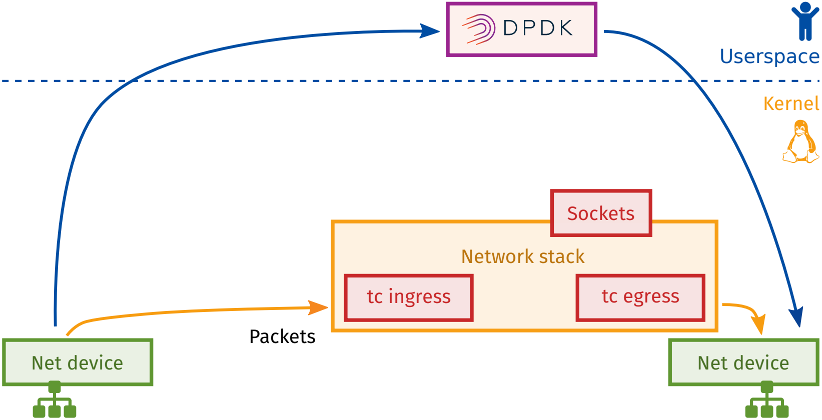
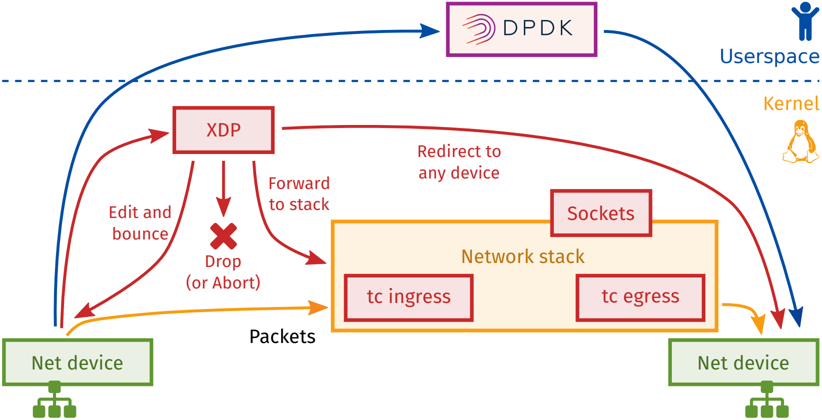



DPDK
Userspace
Kernel
XDP
Redirect to
any device
Forward
to stack
Edit and
bounce
Drop
(or Abort)
Sockets
Network stack
tc ingress
tc egress
Packets
Net device
Net device

Use cases for eBPF and XDP

- Load balancing
- Protection, mitigation against DDoS
- Distributed firewall
- And a lot more
  - Packet capture (Suricata)
  - Network fabric (OVN), Container ACLs (Cilium)
  - Virtual switching: Open vSwitch back-end
  - Stateful processing (BEBA research project)
  - ILA (Identifier-Locator Addressing) routing
  - QoS
  - ...

eBPF Hardware Offload

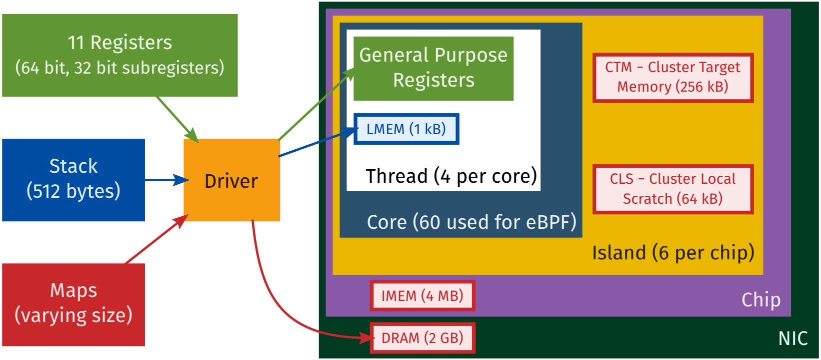
Lower, faster

Why offloading to hardware?

- eBPF is nearly “self-contained”, XDP is low-level: ideal for offload
- Get performances, and get programmability — without putting the charge on CPUs
- Work with the kernel: push hardware offload support upstream
  Still requires NIC and firmware, but make driver and eBPF core available to the community

1. Get the correct architecture

Mapping eBPF to the NFP-based NIC



JIT compiler, 32-bit eBPF, Optimisations

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How to get a program we can run?

- The driver has its own JIT, called by the kernel, and compiles to native instructions for the NIC.
- NIC has 32-bit registers: eBPF 32-bit support in the kernel
- Various optimisations in the JIT to reduce the number of instructions or speed up some tasks

The Challenges of eBPF Hardware Offload

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1. Get a compatible architecture
   - NIC architecture
   - Add 32-bit support for eBPF
   - Use own JIT-compiler
2. Add offload support to the kernel

Support for eBPF offload in kernel and driver

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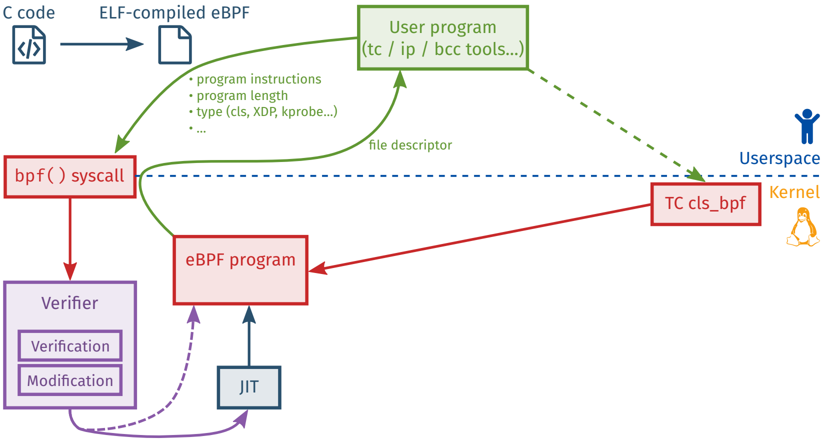
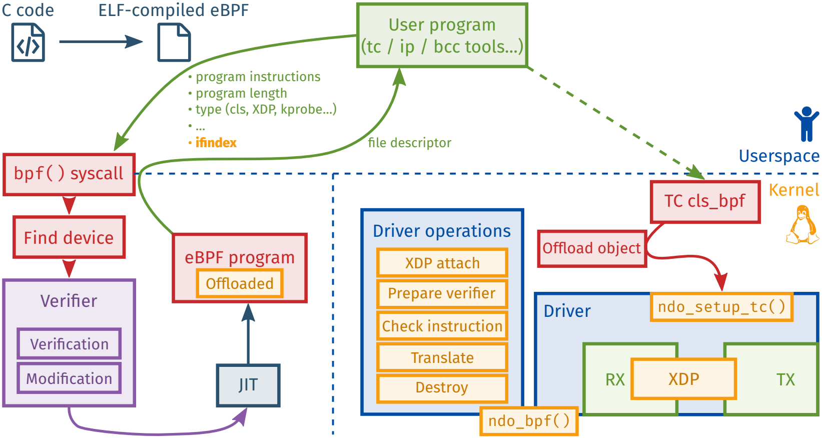
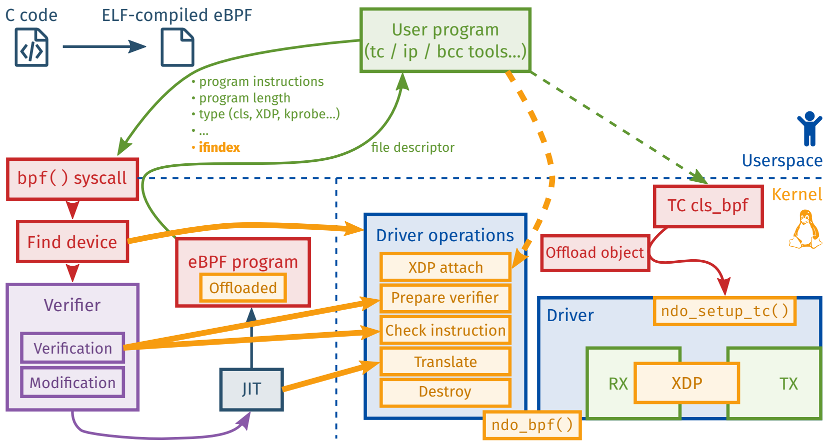


Support for eBPF offload in kernel and driver



Support for eBPF offload in kernel and driver



- The verifier uses a callback to check each instruction from the driver perspective
- The driver has its own errors that we must expose to users:
  - Verification time: reuse the log buffer from kernel verifier → STD_ERR
  - Program attachment time: use Netlink extended ack → STD_ERR

The Challenges of eBPF Hardware Offload

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1. Get a compatible architecture
   - NIC architecture
   - Add 32-bit support for eBPF
   - Use own JIT-compiler
2. Add offload support to the kernel
   - Update verifier
   - Make the core able to pass eBPF maps and programs
   - Keep it human-friendly
3. Update the tools

Tooling

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- Upgrade tools for handling offloaded programs (`tc`, `ip`)
  - Update command syntax
  - Pass the `ifindex` to the kernel
  - Also ask kernel to create maps on the NIC
- Create or update other tools to help working with eBPF
  - `bpftool`
    - List, load, pin, dump instructions (JIT-ed or not) for programs
    - List, pin, dump, lookup, update, delete for maps
    - List, attach, detach programs to cgroups
  - `llvm-mc`: Compile from “eBPF assembly” to object file

The Challenges of eBPF Hardware Offload

1. Get a compatible architecture
   - NIC architecture
   - Add 32-bit support for eBPF
   - Use own JIT-compiler
2. Add offload support to the kernel
   - Update the verifier
   - Make the core able to pass eBPF maps and programs
   - Keep it human-friendly
3. Update the tools
   - `tc`, `ip`, `llvm-mc`, `bpftool`
4. Gain better performances, everywhere you can!

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- `tc_cls` and XDP hardware offload (specific JIT)
- 32-bit sub-registers support
- Various JIT optimisations
- Nearly all instructions supported; Stack; Some helpers
- Direct packet access, packet modification (header or payload)
- XDP actions: Bounce, Pass to stack, Drop; Packet encapsulation
- Maps: hashes and arrays (RO from program, R/W from user space)
- Error messages through integration with kernel verifier, extack
- Tooling
  - `tc`, `ip` updated
  - `bpftool`
  - `llvm-mc`

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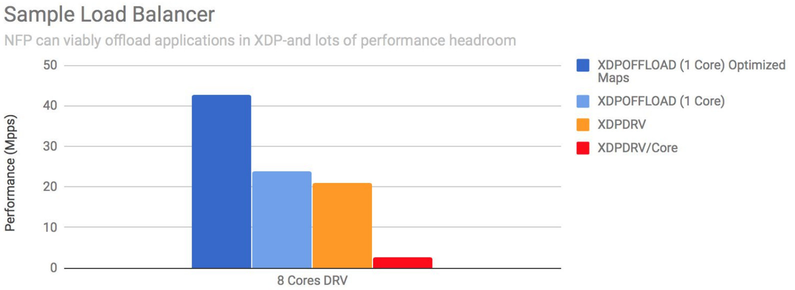
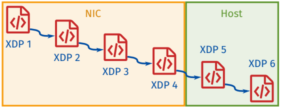
- Simple XDP load balancer (~ 800 eBPF insns, 4 map lookups)
  - Based on kernel test `tools/testing/selftests/bpf/test_l4lb.c`, combined with example `samples/bpf/xdp_tx_iptunnel_kern.c`
- Per CPU array changed to standard array to run offloaded
  - (No nice equivalent for per CPU at the moment on the NIC)



What we work on

- Redirect action
- Atomic add operation
- Map caching: map access from ~1000 to ~300 cycles
- Packet caching: packet accesses from ~50 to ~3 cycles
- 32-bit ALU from LLVM where possible: ALUs from ~4 to 1 machine code instruction
- Remove firmware locks for maps: double memory bandwidth
- Tail calls; Multi-stage processing, split between NIC and host



- Dump NFP instructions with `bpftool`: need patching binutils-dev
- More JIT optimisations
- ...

The Challenges of eBPF Hardware Offload

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- eBPF and XDP introduce fast and efficient networking inside Linux kernel
- Host CPU is a resource and must be used efficiently
  Getting faster networking without increasing CPU usage requires an efficient and transparent general offload infrastructure in cooperation with the kernel
- eBPF, XDP offload provides programmability and performances, but also a dynamically reloadable sandbox
- Kernel, driver: everything is upstream!

Thank you!

Questions?

Additional resources:

Open-NFP.org platform, with resources about eBPF offload
https://open-nfp.org/dataplanes-ebpf/

Resources on BPF — *Dive into BPF: a list of reading material*
https://qmonnet.github.io/whirl-offload/2016/09/01/dive-into-bpf/

Upstream driver, eBPF bits
Linux kernel tree, under `drivers/net/ethernet/netronome/nfp/bpf`

Netronome website
https://www.netronome.com/

We're hiring!