On getting tc classifier fully programmable with cls_bpf.

Daniel Borkmann
<daniel@iogearbox.net>
Noiro Networks / Cisco

netdev 1.1, Sevilla, February 12, 2016
Background, history.

- BPF origins as a generic, fast and 'safe' solution to packet parsing
- tcpdump → libpcap → compiler → bytecode → kernel interpreter
- Intended as early drop point in AF_PACKET kernel receive path
- JIT’able for x86_64 since 2011, ppc, sparc, arm, arm64, s390, mips
- BPF used today: networking, tracing, sandboxing

```
# tcpdump -i any -d ip
(000) ldh [14]
(001) jeq #0x800 jt 2 jf 3
(002) ret #65535
(003) ret #0
```
Classic BPF (cBPF) in a nutshell.

- 32 bit, available register: A, X, M[0-15], (pc)
- A used for almost everything, X temporary register, M[] stack
- Insn: 64 bit (u16:code, u8:jt, u8:jf, u32:k)
- Insn classes: ld, ldx, st, stx, alu, jmp, ret, misc
- Forward jumps, max 4096 instructions, statically verified in kernel
- Linux-specific extensions overload ldb/ldh/ldw with k← off+x
- bpf_asm: 33 instructions, 11 addressing modes, 16 extensions
- Input data/”context” (ctx), e.g. skb, seccomp_data
- Semantics of exit code defined by application
Extended BPF (eBPF) as next step.

- 64 bit, 32 bit sub-registers, available register: R0-R10, stack, (pc)
- Insn: 64 bit (u8:code, u8:dst_reg, u8:src_reg, s16:off, s32:imm)
- New insns: dw ld/st, mov, alu64 + signed shift, endian, calls, xadd
- Forward & backward* jumps, max 4096 instructions
- Generic helper function concept, several kernel-provided helpers
- Maps with arbitrary sharing (user space apps, between eBPF progs)
- Tail call concept for eBPF programs, eBPF object pinning
- LLVM eBPF backend: clang -O2 -target bpf -o foo.o foo.c
  - C → LLVM → ELF → tc → kernel (verification/JIT) → cls_bpf (exec)
eBPF, General remarks.

- Stable ABI for user space, like the case with cBPF
- Management via `bpf(2)` syscall through file descriptors
- Points to kernel resource → eBPF map / program
- No cBPF interpreter in kernel anymore, all eBPF!
- Kernel performs internal cBPF to eBPF migration for cBPF users
- JITs for eBPF: x86_64, s390, arm64 (remaining ones are still cBPF)
- Various stages for in-kernel cBPF loader
- Security (verifier, non-root restrictions, JIT hardening)
eBPF and cls_bpf.

- cls_bpf as cBPF-based classifier in 2013, eBPF support since 2015
- Minimal fast-path, just calls into `BPF_PROG_Run()`
- Instance holds one or more BPF programs, 2 operation modes:
  - Calls into full tc action engine `tcf_exts_exec()` for e.g. `act_bpf`
  - Direct-action (DA) fast-path for immediate return after BPF run
- In DA, eBPF prog sets `skb->tc_classid`, returns action code
  - Possible codes: ok, shot, stolen, redirect, unspec
- tc frontend does all the setup work, just sends fd via netlink
eBPF and cls_bpf.

- skb metadata:
  - Read/write: mark, priority, tc_index, cb[5], tc_classid
  - Read: len, pkt_type, queue_mapping, protocol, vlan_*, ifindex, hash

- Tunnel metadata:
  - Read/write: tunnel key for IPv4/IPv6 (dst-meta by vxlan, geneve, gre)

- Helpers:
  - eBPF map access (lookup/update/delete)
  - Tail call support
  - Store/load payload (multi-)bytes
  - L3/L4 csum fixups
  - skb redirection (ingress/egress)
  - Vlan push/pop and tunnel key
  - trace_printk debugging
  - net_cls cgroup classid
  - Routing realms (dst->tclassid)
  - Get random number/cpu/ktime
cls_bpf, Invocation points.

- **Ingress qdisc**
- **clsact qdisc**
- **RX path**
- **TX path**

- \_netif\_receive\_skb\_core()
- \_dev\_queue\_xmit()
- **Qdisc**
- \_dev\_handle\_ingress()
- \_dev\_handle\_egress()
- fq\_codel, sfq, drr, ...

Daniel Borkmann
cls_bpf, Example setup in 1 slide.

$ clang -O2 -target bpf -o foo.o foo.c

# tc qdisc add dev em1 clsact
# tc qdisc show dev em1
[...]
qdisc clsact ffff: parent ffff:fff1

# tc filter add dev em1 ingress bpf da obj foo.o sec p1
# tc filter add dev em1 egress bpf da obj foo.o sec p2

# tc filter show dev em1 ingress
filter protocol all pref 49152 bpf
filter protocol all pref 49152 bpf handle 0x1 foo.o:[p1] direct-action

# tc filter show dev em1 egress
filter protocol all pref 49152 bpf
filter protocol all pref 49152 bpf handle 0x1 foo.o:[p2] direct-action

# tc filter del dev em1 ingress pref 49152
# tc filter del dev em1 egress pref 49152
tc frontend.

- Common loader backend for f_bpf, m_bpf, e_bpf
- Walks ELF file to generate program fd, or fetches fd from pinned
- Setup via ELF object file in multiple steps:
  - Mounts bpf fs, fetches all ancillary sections
  - Sets up maps (fd from pinned or new with pinning)
  - Relocations for injecting map fds into program
  - Loading of actual eBPF program code into kernel
  - Setup and injection of tail called sections
- Grafting of existing prog arrays
- Dumping trace pipe
tc eBPF examples, minimal module.

```
$ cat >foo.c <<EOF
#include "bpf_api.h"

__section_cls_entry
int cls_entry(struct __sk_buff *skb)
{
    /* char fmt[] = "hello prio%u world!\n"; */
    skb->priority = get_cgroup_classid(skb);
    /* trace_printk(fmt, sizeof(fmt), skb->priority); */
    return TC_ACT_OK;
}

BPF_LICENSE("GPL");
EOF

$ clang -O2 -target bpf -o foo.o foo.c
# tc filter add dev em1 egress bpf da obj foo.o
# tc exec bpf dbg # -> dumps trace_printk()

# cgcreate -g net_cls:/foo
# echo 6 > foo/net_cls.classid
# cgexec -g net_cls:foo ./bar # -> app ./bar xmits with priority of 6
```
tc eBPF examples, map sharing.

#include "bpf_api.h"

BPF_ARRAY4(map_sh, 0, PIN_OBJECT_NS, 1);
BPF_LICENSE("GPL");

__section("egress") int egr_main(struct __sk_buff *skb)
{
    int key = 0, *val;
    val = map_lookup_elem(&map_sh, &key);
    if (val)
        lock_xadd(val, 1);
    return BPF_H_DEFAULT;
}

__section("ingress") int ing_main(struct __sk_buff *skb)
{
    char fmt[] = "map val: %d\n";
    int key = 0, *val;
    val = map_lookup_elem(&map_sh, &key);
    if (val)
        trace_printk(fmt, sizeof(fmt), *val);
    return BPF_H_DEFAULT;
}
tc eBPF examples, tail calls.

#include "bpf_api.h"

BPF_PROG_ARRAY(jmp_tc, JMP_MAP, PIN_GLOBAL_NS, 1);
BPF_LICENSE("GPL");

__section_tail(JMP_MAP, 0) int cls_foo(struct __sk_buff *skb)
{
    char fmt[] = "in cls_foo\n";
    trace_printk(fmt, sizeof(fmt));
    return TC_H_MAKE(1, 42);
}

__section_cls_entry int cls_entry(struct __sk_buff *skb)
{
    char fmt[] = "fallthrough\n";
    tail_call(skb, &jmp_tc, 0);
    trace_printk(fmt, sizeof(fmt));
    return BPF_H_DEFAULT;
}

$ clang -O2 -DJMP_MAP=0 -target bpf -o graft.o graft.c
# tc filter add dev em1 ingress bpf obj graft.o
Code and further information.

- **Take-aways:**
  - Writing eBPF programs for `tc` is really easy
  - Stable ABI, fully programmable for specific use-cases
  - Native performance when JITed!

- **Code:**
  - Everything upstream in kernel, `iproute2` and `llvm`!
  - Available from usual places, e.g. `https://git.kernel.org/`

- **Some further information:**
  - Examples in `iproute2`'s `examples/bpf/`
  - Documentation/networking/filter.txt
  - Man pages `bpf(2), tc-bpf(8)`
Appendix / Backup.
eBPF, Helper functions.

- Signature: `u64 foo(u64 r1, u64 r2, u64 r3, u64 r4, u64 r5)`

- Calling convention:
  - R0 \(\rightarrow\) return value
  - R1-R5 \(\rightarrow\) function arguments
  - R6-R9 \(\rightarrow\) callee saved
  - R10 \(\rightarrow\) read-only frame pointer

- Specification for verifier, example:

  ```c
  static const struct bpf_func_proto foo_proto = {
    .func = foo,
    .gpl_only = false,
    .ret_type = RET_INTEGER,
    .arg1_type = ARG_CONST_MAP_PTR,
    .arg2_type = ARG_PTR_TO_MAP_KEY,
    .arg3_type = ARG_PTR_TO_MAP_VALUE,
    .arg4_type = ARG_ANYTHING,
  };
  ```
eBPF, Helper functions.

- **eBPF program**
  - Populates R1 – R5 depending on specification
  - BPF_RAW_INSN(BPF_JMP | BPF_CALL, 0, 0, 0, BPF_FUNC_foo)
  - Reads out R0 if needed
  - Can only use core kernel provided BPF_FUNC_* helpers

- **Kernel space**
  - eBPF verification step
  - Mapping of BPF_FUNC_* (insn->imm) to struct bpf_func_proto
  - Call fixup: insn->imm = fn->func - __bpf_call_base;
  - Invocation: R0 = (__bpf_call_base + insn->imm)(R1, ..., R5);
  - JITing rather straightforward, x86_64 → 1:1 mapping to HW registers
eBPF, Maps.

- Lightweight key/value store for keeping state
  - Generic, efficient data structures
    - Array, hash table, (per CPU variants soon)
  - Application-specific data structures
    - Program array, perf event array
- Map creation only from user space \( \rightarrow \) bpf(2)
- Map access for lookup, update, delete:
  - User space application \( \rightarrow \) bpf(2) with fd
  - eBPF program \( \rightarrow \) helper functions
eBPF, Maps.

- eBPF loader/program
  - Map mostly used in R1 as type ARG_CONST_MAP_PTR
  - Loader fetches map fd via bpf(2)
  - Rewrites instruction BPF_LD_MAP_FD(BPF_REG_1, fd)
  - Expands to double bpf_insn BPF_LD | BPF_IMM | BPF_DW
  - First part holds .src_reg = BPF_PSEUDO_MAP_FD, .imm = fd

- Kernel space
  - eBPF verification step
  - Recognizes BPF_PSEUDO_MAP_FD keyword
  - Fetches real map from process fd table
  - Stores actual map pointer in BPF_LD | BPF_IMM | BPF_DW
eBPF, Tail calls.

- Idea: allow eBPF programs to call other eBPF programs
- No return to old program, same stack frame used (think of long jump)
- Consists of 2 components:
  - Program array map, populated by user space with eBPF fds
  - eBPF helper: `bpf_tail_call(ctx, &jmp_table, index)`
- Kernel caches actual pointers to map, updates `xchg()`'ed
- Kernel translates BPF_FUNC_tail_call into instructions
- Fall-through when lookup failed, otherwise `insn = prog->insn`
- Powerful concept for live eBPF program updates, dispatching protocol parsers, etc
eBPF, Object pinning.

- Everything being tied to fds → thus, tied to program livetime
- Makes f.e. eBPF map sharing cumbersome
- Option 1: UDS
  - File descriptor passing, works in general with eBPF fds
  - Requires deploying extra daemon for each application
- Option 2: small special purpose fs (utilized by tc)
  - Maps/programs can be pinned via `bpf(2)` as fs node
  - Picked up via `bpf(2)` again, point to same map/program
  - No difference to "normal" created `bpf(2)` fds
  - fs per mountns, supports bind-mounts, hard links, etc
eBPF, Security.

- Aim for BPF is to be "safe" as in "cannot crash the kernel" ;)
- Primary job of the verifier, eBPF one more complex
  - Checks for cyclic prog flow, uninitialized mem, dead code, types, etc
- CONFIG_DEBUG_SET_MODULE_RONX on x86_64, arm, arm64, s390
  - Locks down an entire eBPF program as RO for its lifetime
  - When JITed, locks module memory as RO and randomizes start address
  - Near future: constant blinding to mitigate JIT spraying
  - JIT switch: sysctl net.core.bpf_jit_enable
- eBPF restricted for unprivileged programs (socket filters)
  - Very few helpers allowed (map access, tail calls, and few others)
  - Restrictions on pointers (no arithmetic, passing to helpers, etc)
  - Once switch: sysctl kernel.unprivileged_bpf_disabled
eBPF, LLVM.

- And most importantly: `clang -O2 -target bpf -o foo.o foo.c`
- eBPF progs written in "restricted C", other frontends possible (P4)
- Compiled to eBPF insns by LLVM (since 3.7), outputs ELF file
  - `clang -O2 -target bpf -c foo.c -S -o -`
  - `readelf -a foo.o, readelf -x ... foo.o`
- ELF file → container for map specs, program code, license, etc
- Holds everything for "loaders" like `tc` to get it into kernel
- Typical workflow, example:
  - C → LLVM → ELF → tc → kernel (verification/JIT) → cls_bpf (exec)