Building socket-aware BPF programs

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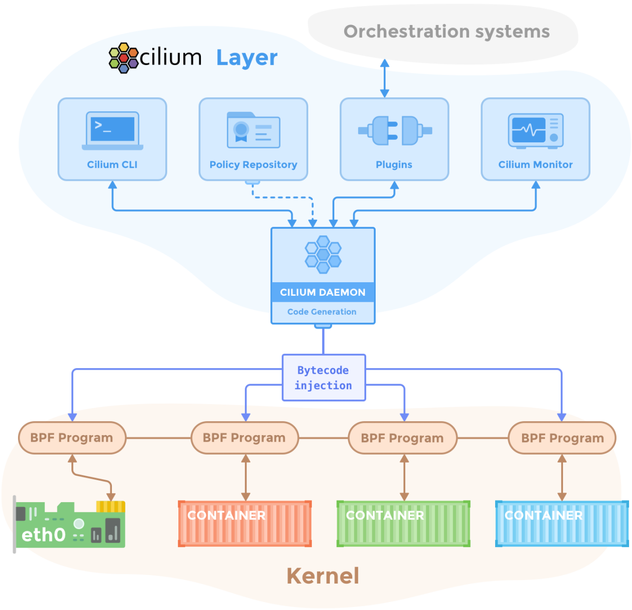

Orchestration systems
cilium Layer
Cilium CLI
Policy Repository
Plugins
Cilium Monitor
CILIUM DAEMON
Code Generation
Bytecode injection
BPF Program
BPF Program
BPF Program
BPF Program
eth0
CONTAINER
CONTAINER
CONTAINER
Kernel

Network Policy

"Endpoint A can talk to endpoint B"

$$\Longrightarrow$$

"Endpoint B can reply to endpoint A"

How have we built these before?

```
      +-+    +--------------+    +--------------+
+-----+      |  Connection  |    |    Policy    |
| NIC +------>   Tracker    +---->              +---->
+-----+      +--------------+    +--------------+
```

Why model it like this?

- Firewalls might not be co-located with the workload
- Firewalls should drop packets as quickly as possible
- Solution? Build up state on-demand while processing packets

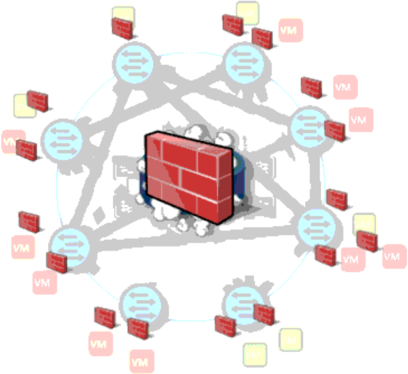
Let's do this with BPF

- Attach BPF to packet hook ✓
- "Connection Tracking" BPF map ✓
  - Key by 5-tuple
  - Associate counters, NAT state, etc.
  - Handle tuple flipping
- "Policy" map ✓
- Deploy! ✓

Let's do this with BPF

- Attach BPF to packet hook ✓
- "Connection Tracking" BPF map ✓
  - Key by 5-tuple
  - Associate counters, NAT state, etc.
- "Policy" map ✓
- Deploy! ✗
  - `nf_conntrack: table full, dropping packet`
  - Hmm, how big should this map be again?
  - How do we clean this up...

Recent trends: Distributed filtering



If we're co-located with the sockets . . .

. . . why build our own connection table?

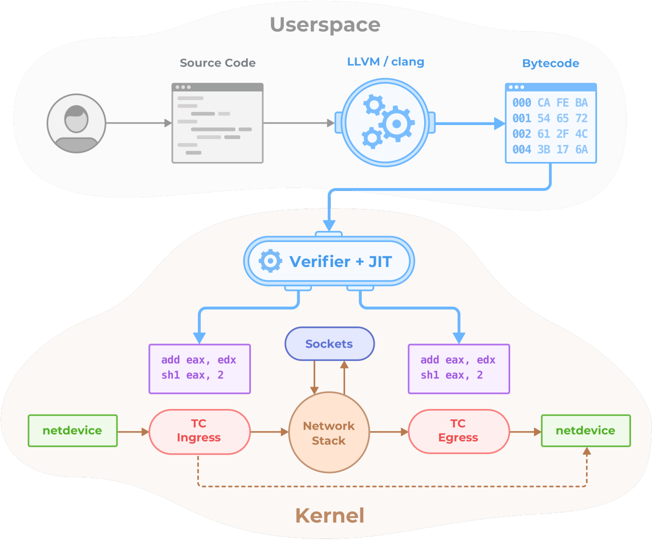
Socket table as a connection tracker

```
     +-+    +---------------+    +---------------+
+-----+     |    Socket     |    |    Policy     |
| NIC +------->   Table      +---->               +---->
+-----+     +---------------+    +---------------+
```

Revisiting the model

- Workloads operate on a separate kernel
- Network stacks are delicate flowers
- This approach doesn't work in all scenarios

Extending the BPF verifier


Userspace
Source Code
LLVM / clang
Bytecode
000 CA FE BA
001 54 65 72
002 61 2F 4C
004 3B 17 6A
Verifier + JIT
add eax, edx
shl eax, 2
Sockets
add eax, edx
shl eax, 2
netdevice
TC
Ingress
Network
Stack
TC
Egress
netdevice
Kernel

BPF verifier: Recap

- At load time, loop over all instructions
  - Validate pointer access
  - Ensure no loops
  - ...
- Access memory out of bounds? ✗
- Returns pointers it shouldn't? ✗
- Everything safe? ✓

Socket safety

- Sockets are reference-counted internally
  - Some memory-management under RCU rules
- `BPF_PROG_TYPE_CGROUP_SOCK`
  - Access safety via reference held across BPF execution
  - Bounds safety provided via bounds access checker
- Packet hooks may execute before associated socket is known

Socket reference counting

Implicit

```
struct bpf_sock *sk;

sk = bpf_sk_lookup(...);
if (sk) {
   ...
}
/* Kernel will free ‘sk’ */
```

Explicit (mainline)

```
struct bpf_sock *sk;

sk = bpf_sk_lookup(...);
if (sk) {
   ...
}
bpf_sk_release(sk);
```

Reference counting in the BPF verifier

- Resource acquisition
- Execution paths while resource is held
- Resource release

Reference Acquisition

- Generate an identifier
- Store the identifier in the verifier state
- Associate the register with the identifier

Reference misuse

- Mangle and release
- `bpf_tail_call()`
- `BPF_LD_ABS`, `BPF_LD_IND`

Reference release

- Validation of pointers
- Remove identifier reference from state
- Unassociate register identifier associations

Extending the BPF API

Simplest form

- `struct bpf_sock *bpf_sk_lookup(struct sk_buff *);`
- `void bpf_sk_release(struct bpf_sock *);`

Considerations for the API

- Network Namespaces
- Arbitrary socket lookup
- Extensibility
- Performance

Namespaces

```
+----------------------------------------+
|                 +--------------------+ |
|                 | +------+  +------+ | |
|                 | |      |  |      | | |
|                 | |  c1  |  |  c2  | | |
|                 | |      |  |      | | |
|                 | +------+  +------+ | |
|    +--------+   |  +--+  Pod         | |
|    | netdev |   |  |  |              | |
|    +----+---+   +--+-++--------------+ |
|         |            |                 |
|     +---+------------++                |
|     |     Bridge      |         Host   |
|     +---+-------------+                |
|         |                              |
+---------+------------------------------+
```

Arbitrary socket lookup

- Use any tuple for lookup
- Ease API across clsact, XDP
- Simplify packet mangle and lookup

Extensibility

- Allow influencing lookup behaviour
- Determine socket type support at load time

Optimizations

- Avoid reference counting
- Allow lookup using direct packet pointers

Socket lookup API

```
struct bpf_sock *
bpf_sk_lookup_tcp(void *ctx, struct bpf_sock_tuple *tuple,
                  u32 tuple_size, u32 netns, u64 flags);
struct bpf_sock *
bpf_sk_lookup_udp(void *ctx, struct bpf_sock_tuple *tuple,
                  u32 tuple_size, u32 netns, u64 flags);

void bpf_sk_release(struct bpf_sock *sk);
```

Socket lookup structures

```
struct bpf_sock_tuple {
        union {
                struct {
                        __be32 saddr;
                        __be32 daddr;
                        __be16 sport;
                        __be16 dport;
                } ipv4;
                struct {
                        __be32 saddr[4];
                        __be32 daddr[4];
                        __be16 sport;
                        __be16 dport;
                } ipv6;
        };
};
```

Socket structure

```
struct bpf_sock {
        __u32 bound_dev_if;
        __u32 family;
        __u32 type;
        __u32 protocol;
        __u32 mark;
        __u32 priority;
        __u32 src_ip4;              /* NBO */
        __u32 src_ip6[4];           /* NBO */
        __u32 src_port;             /* NBO */
};
```

Epilogue

Use case: Network devices

- Socket lookup from XDP
- Management traffic? Send up the stack
- Other traffic? Forward, route, load-balance

Future work

- Stronger firewall guarantees
- More socket attribute access
- Associate metadata with sockets
- More uses for reference tracking

Thank you

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