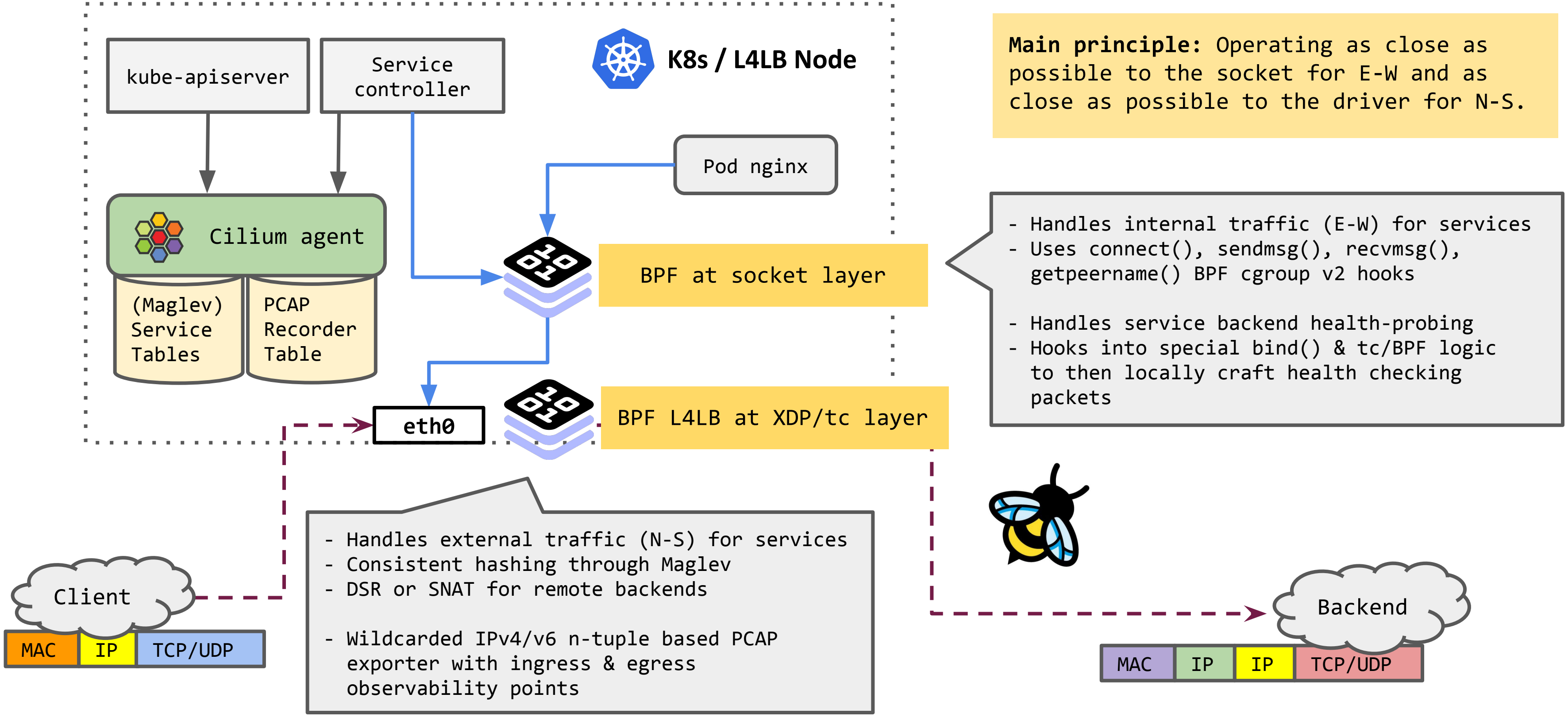
LINUX PLUMBERS CONFERENCE September 20-24, 2021

BPF datapath extensions for K8s workloads

Daniel Borkmann & Martynas Pumputis, Cilium.io

Cilium’s Load Balancer in one picture

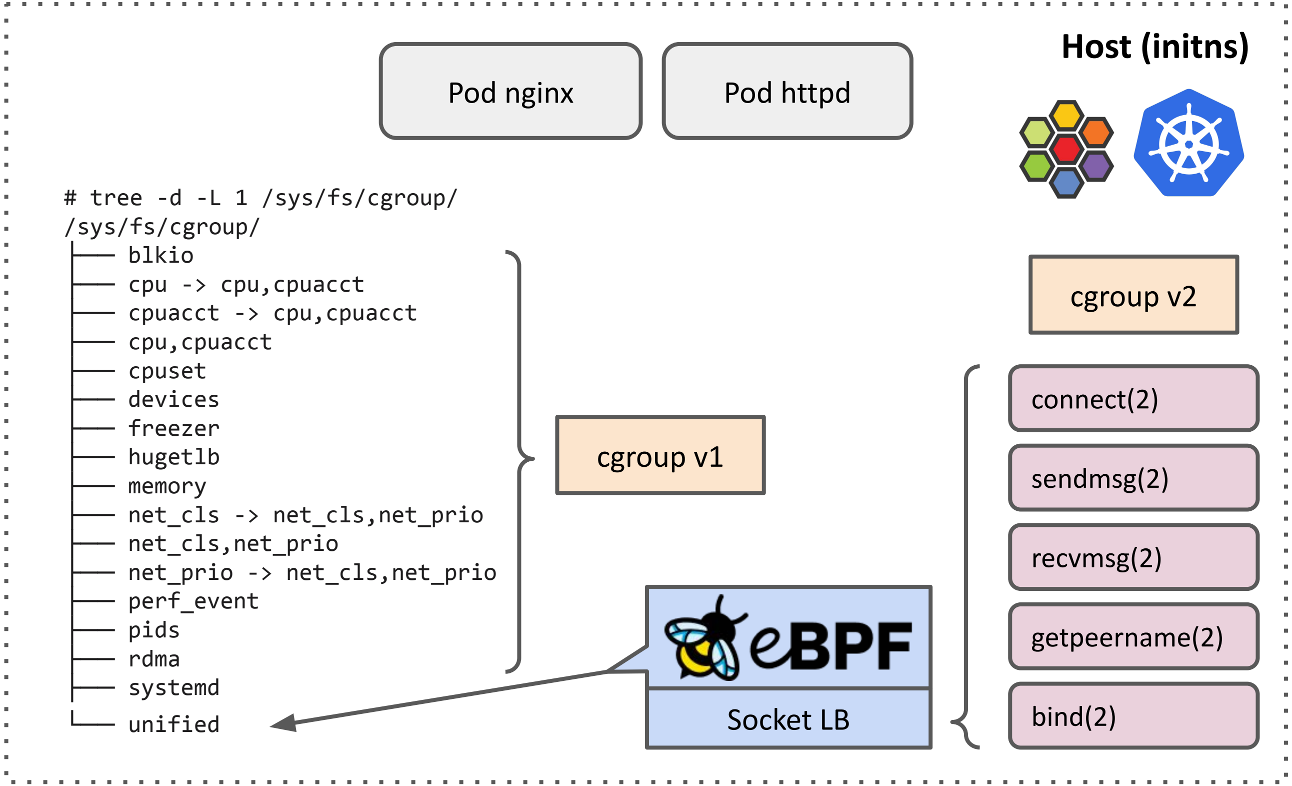


Agenda: Ongoing development items

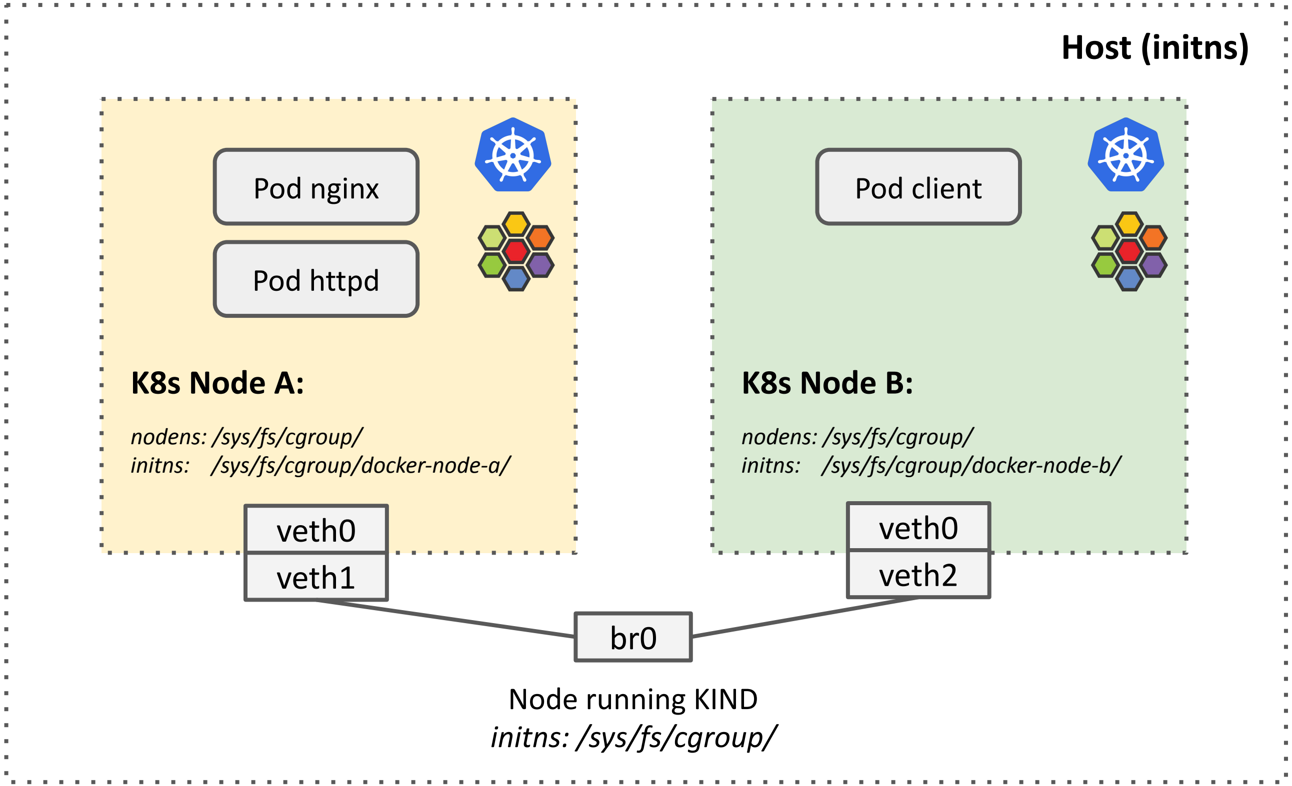
- ➔ Part 1: The cgroup v1/v2 interference problem
- ➔ Part 2: TCP pacing for Pods from initns
- ➔ Part 3: Managed neighbor entries and fib extensions
- ➔ Part 4: Wildcarded BPF map lookups

Part 1: The cgroup v1/v2 interference

Cgroup v2 layout on (bare metal) K8s node



Cgroup v2 layout on KIND (K8s in Docker)



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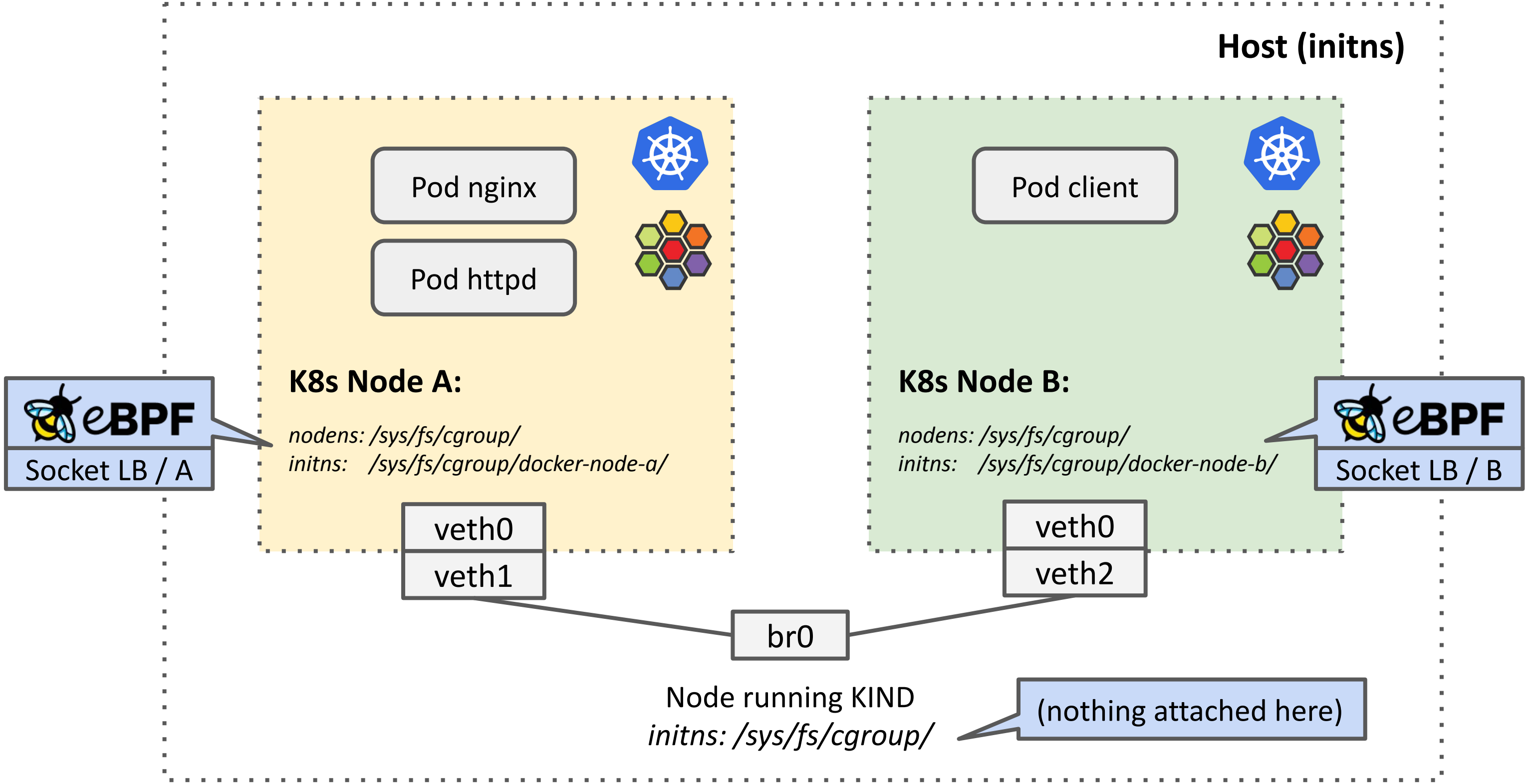
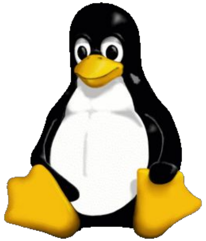


Cgroup v1/v2 interference: Context



The case for saving 8 byte in the socket structure

- ➔ Assumption back in 2015: "no reason to mix cgroup v1/v2"
  - struct sock_cgroup_data is a union with v1/v2 data
  - cgroup v1 net_cls/net_prio tags vs cgroup v2 pointer
- ➔ Reality check: Environments today have both flavors mounted

Cgroup v1/v2 interference: Context

Retrieving socket's cgroup v2 pointer in fast-path:

```
static inline struct cgroup *sock_cgroup_ptr(struct sock_cgroup_data *skcd)
{
#if defined(CONFIG_CGROUP_NET_PRIO) || defined(CONFIG_CGROUP_NET_CLASSID)
        unsigned long v;

        /*
         * @skcd->val is 64bit but the following is safe on 32bit too as we
         * just need the lower ulong to be written and read atomically.
         */
        v = READ_ONCE(skcd->val);

        if (v & 3)
                return &cgrp_dfl_root.cgrp;

        return (struct cgroup *)(unsigned long)v ?: &cgrp_dfl_root.cgrp;
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If cgroup v1 tagging is used on the socket, fallback to cgroup v2 root.

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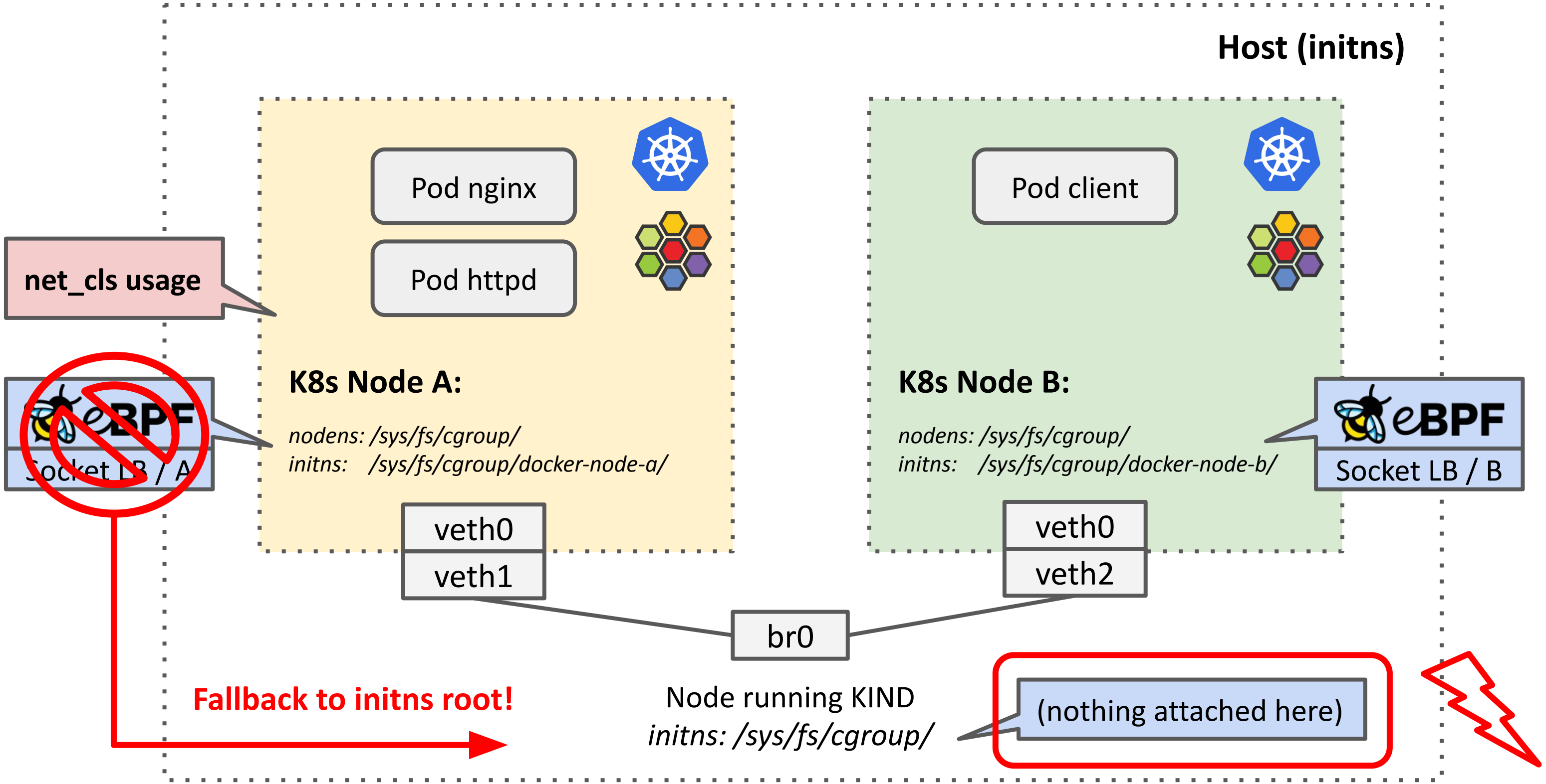
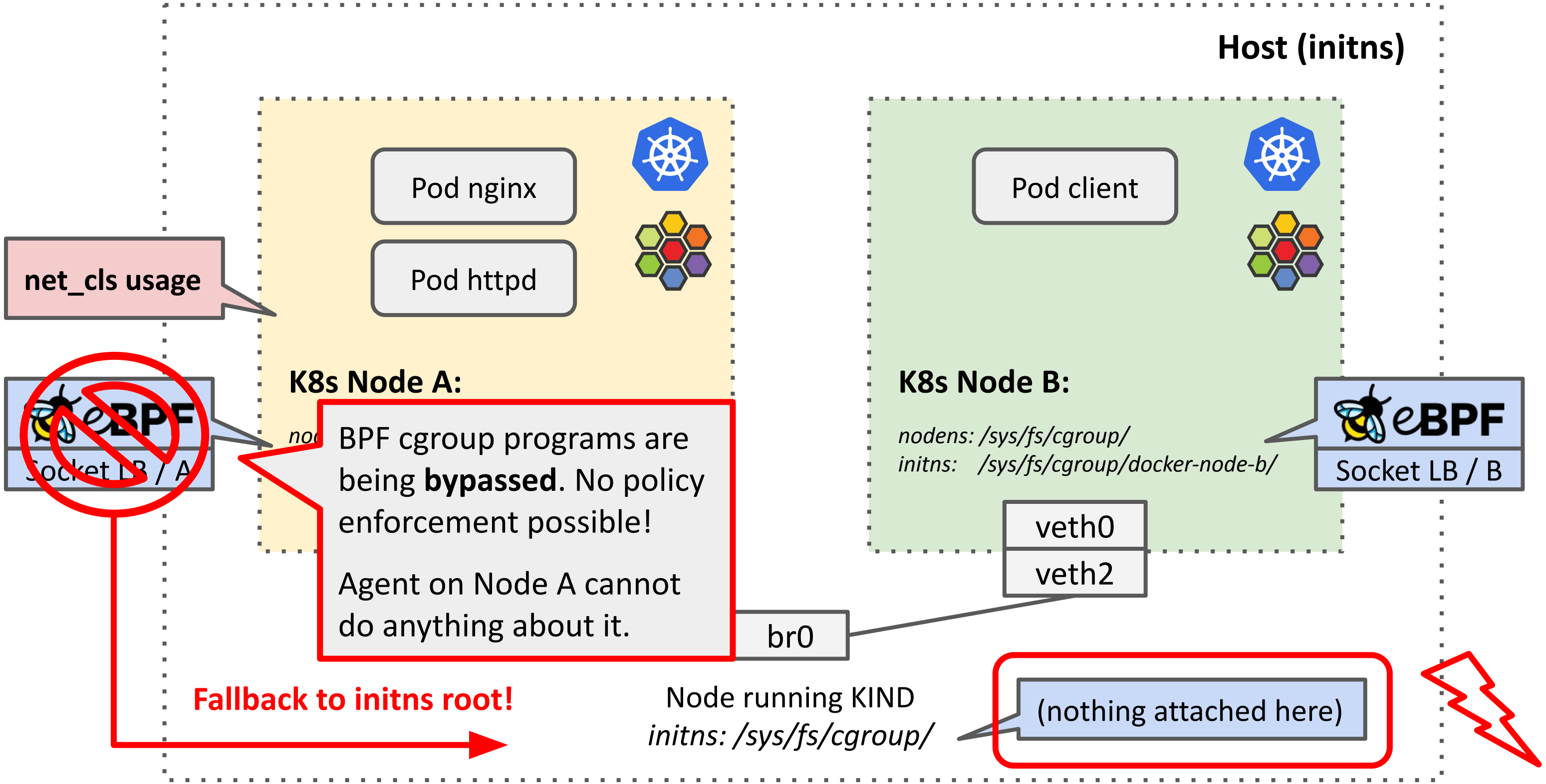
Problematic for today's environments!

Cgroup v2 layout on KIND (K8s in Docker)



Cgroup v2 layout on KIND (K8s in Docker)



Cgroup v1/v2 interference: Recap

v2 cgroup management complex and cumbersome

- ➔ Incompatible to cgroup namespaces or non-root cgroup paths
- ➔ v2-to-v1 switch on the socket leaks v2 object references
- ➔ Unreliable v2 invocation hinders adoption of BPF cgroup programs
  - Independent 3rd party agents inevitably step on each other
  - Distros usually enable everything for max compatibility

Approach to fixing the cgroup v1/v2 interference

Fix: biting the bullet and detangle the two ...

```
static inline struct cgroup *sock_cgroup_ptr(struct sock_cgroup_data *skcd)
{
        return skcd->cgroup;
}
```

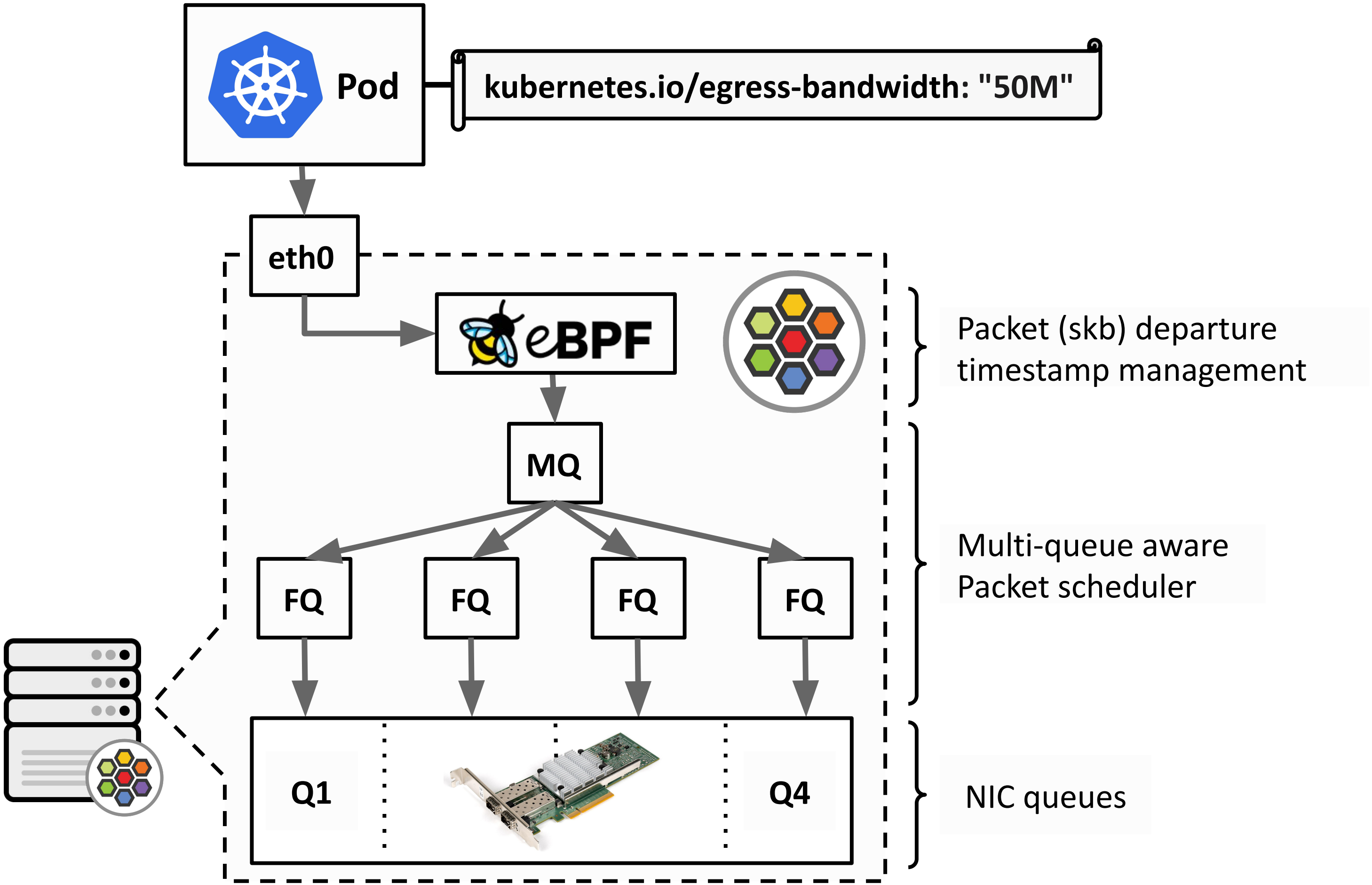
- ➔ struct sock_cgroup_data always holds reliable cgroup pointer
- ➔ Implicitly also addresses the v2 reference count leaks
- ➔ Fix along with test cases has been upstreamed recently

Part 2: TCP pacing for Pods from initns

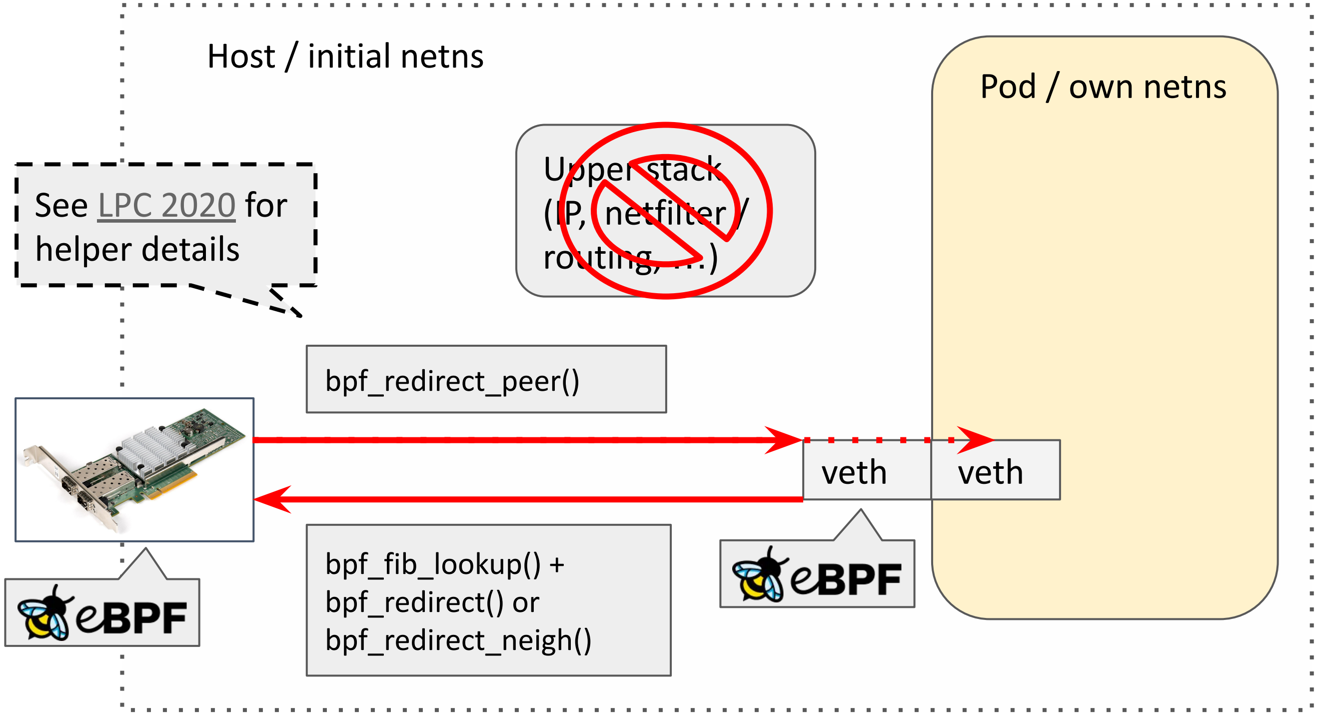
Current state: Cilium & K8s

K8s Pod-specific ingress/egress bandwidth annotation:

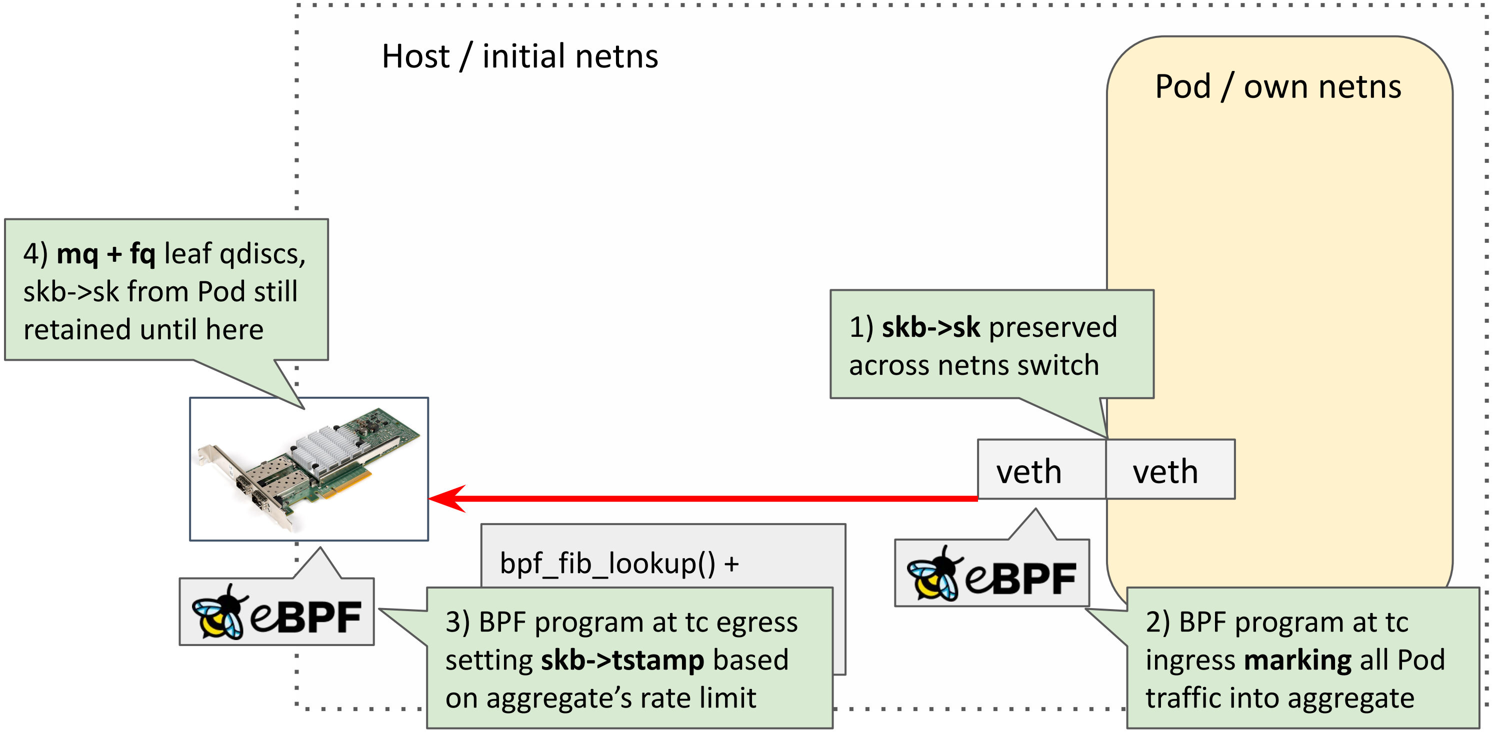
- ➔ Handled by K8s CNI plugins (e.g. Cilium or bandwidth plugin)
- ➔ Semantics for rate enforcement points defined by plugin:
  - K8s bandwidth plugin uses combination of ifb & tbf qdisc
  - Cilium natively implements EDT via BPF & fq qdisc for egress


Pod
kubernetes.io/egress-bandwidth: "50M"
eth0
eBPF
MQ
FQ
FQ
FQ
FQ
Q1
Q4
Packet (skb) departure
timestamp management
Multi-queue aware
Packet scheduler
NIC queues

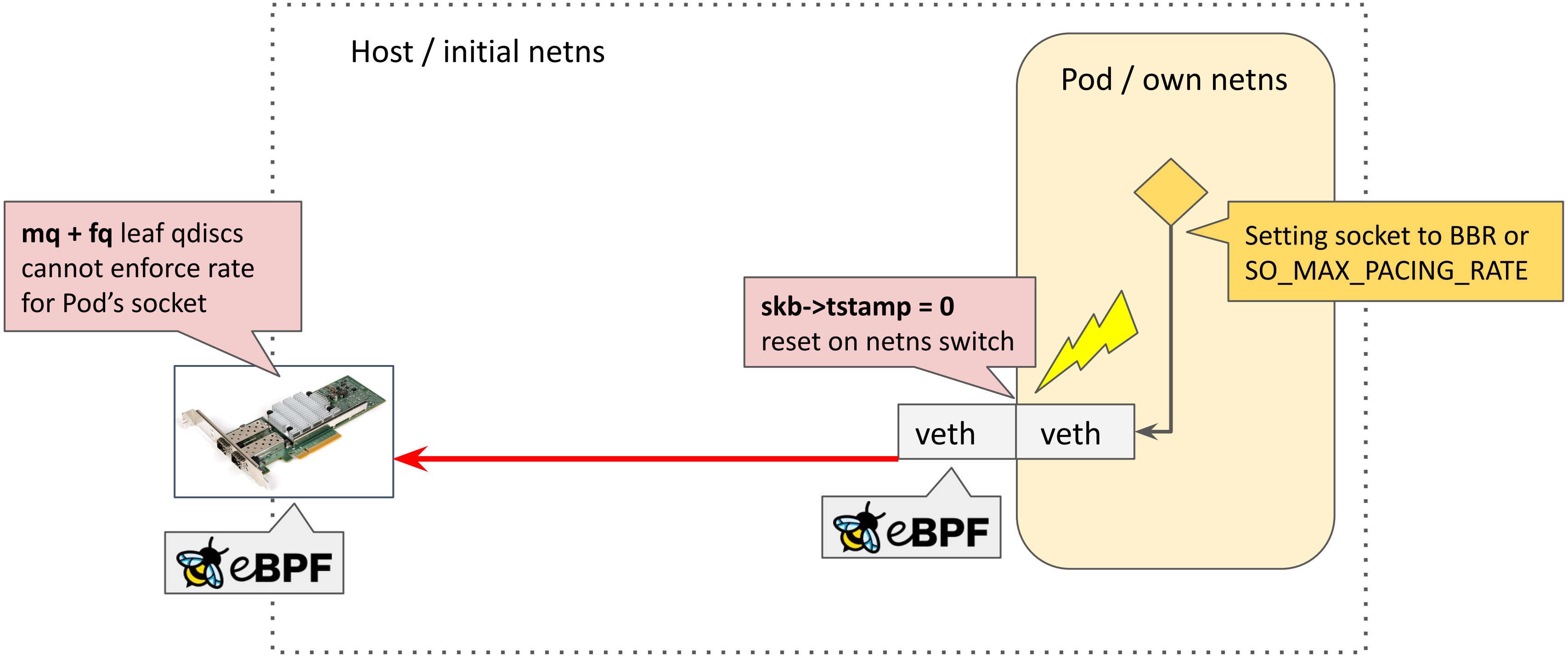
BPF datapath walk-through: Overview forwarding



BPF datapath walk-through: Works today



BPF datapath walk-through: Next steps



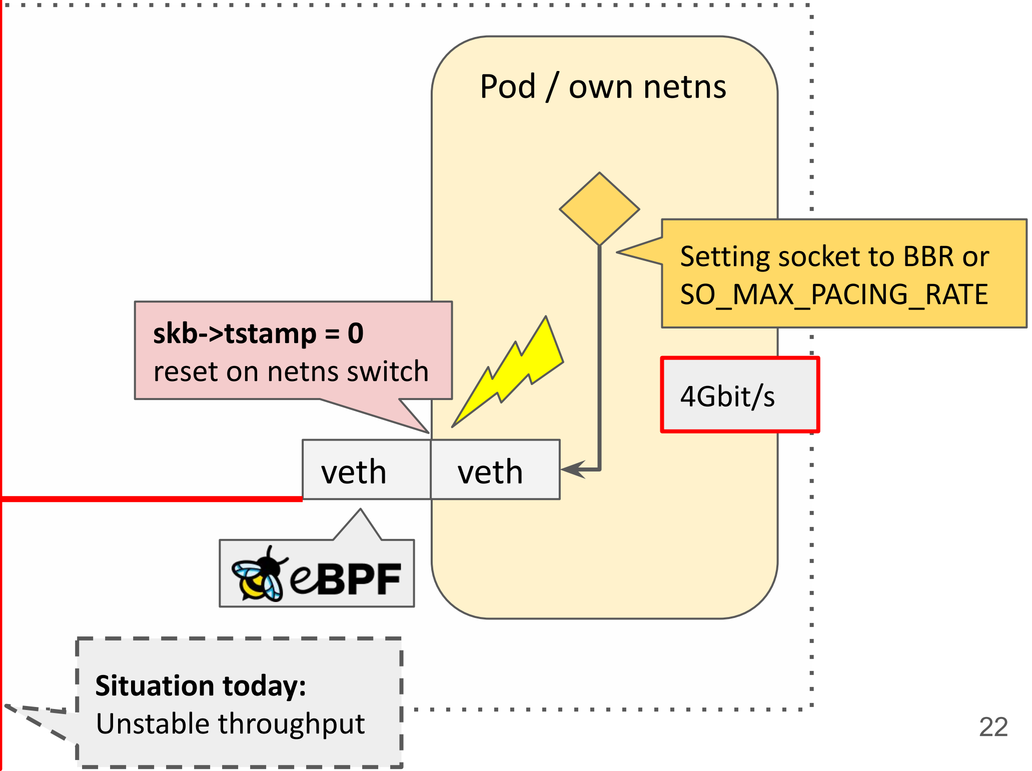
BPF datapath walk-through: Next steps

```
root@apoc:~/go/src/github.com/cilium/cilium# netperf
MIGRATED TCP STREAM TEST from 0.0.0.0 (0.0.0.0) port
Recv   Send    Send
Socket Socket  Message  Elapsed
Size   Size    Size     Time     Throughput
bytes  bytes   bytes    secs.    10^6bits/sec
 87380  16384  16384    40.04     655.52

root@apoc:~/go/src/github.com/cilium/cilium# netperf
MIGRATED TCP STREAM TEST from 0.0.0.0 (0.0.0.0) port
Recv   Send    Send
Socket Socket  Message  Elapsed
Size   Size    Size     Time     Throughput
bytes  bytes   bytes    secs.    10^6bits/sec
 87380  16384  16384    40.07    1274.70

root@apoc:~/go/src/github.com/cilium/cilium# netperf
MIGRATED TCP STREAM TEST from 0.0.0.0 (0.0.0.0) port
Recv   Send    Send
Socket Socket  Message  Elapsed
Size   Size    Size     Time     Throughput
bytes  bytes   bytes    secs.    10^6bits/sec
 87380  16384  16384    40.07    1519.32

root@apoc:~/go/src/github.com/cilium/cilium# netperf
MIGRATED TCP STREAM TEST from 0.0.0.0 (0.0.0.0) port
Recv   Send    Send
Socket Socket  Message  Elapsed
Size   Size    Size     Time     Throughput
bytes  bytes   bytes    secs.    10^6bits/sec
 87380  16384  16384    40.06     849.96
```



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Recv   Send    Send
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Size   Size    Size     Time     Throughput
bytes  bytes   bytes    secs.    10^6bits/sec
 87380  16384  16384    40.01    3976.04

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MIGRATED TCP STREAM TEST from 0.0.0.0 (0.0.0.0) port
Recv   Send    Send
Socket Socket  Message  Elapsed
Size   Size    Size     Time     Throughput
bytes  bytes   bytes    secs.    10^6bits/sec
 87380  16384  16384    40.01    3961.40

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Recv   Send    Send
Socket Socket  Message  Elapsed
Size   Size    Size     Time     Throughput
bytes  bytes   bytes    secs.    10^6bits/sec
 87380  16384  16384    40.01    3957.66

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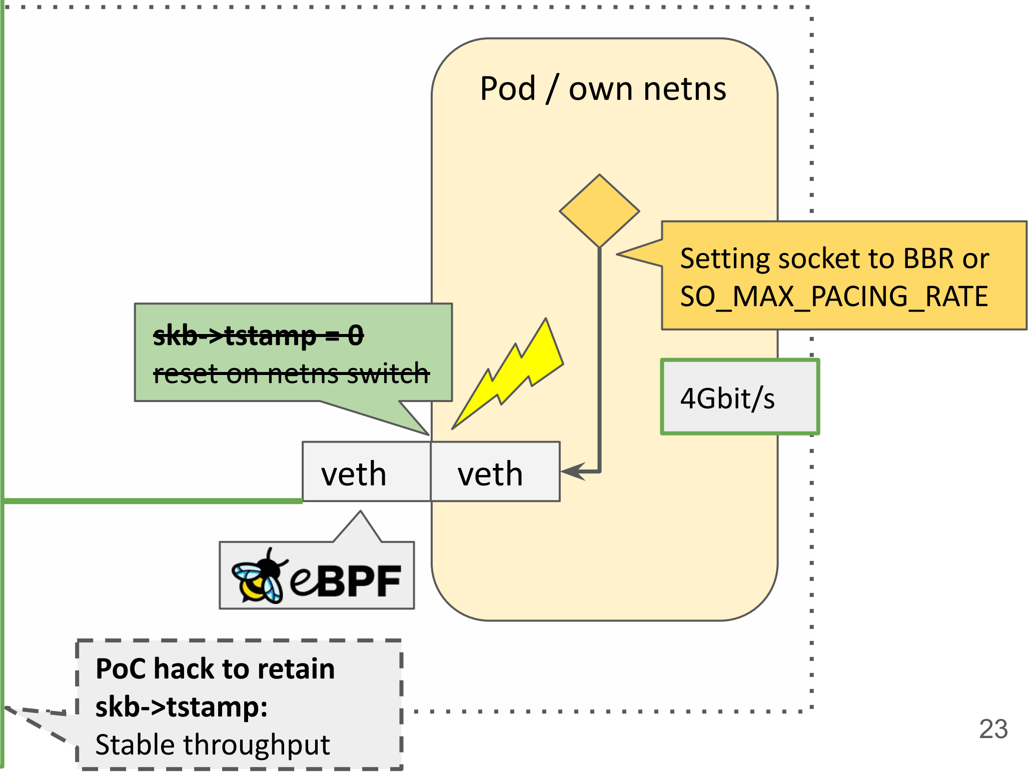
MIGRATED TCP STREAM TEST from 0.0.0.0 (0.0.0.0) port
Recv   Send    Send
Socket Socket  Message  Elapsed
Size   Size    Size     Time     Throughput
bytes  bytes   bytes    secs.    10^6bits/sec
 87380  16384  16384    40.01    3977.37
```



Rationale on today’s timestamp reset

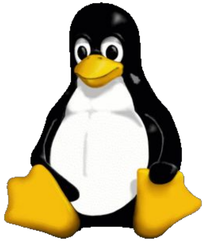
Kernel uses different clock bases for skb->tstamp:

➔ Ingress is CLOCK_TAI, egress is CLOCK_MONOTONIC (as is fq)

➔ Forwarding from RX to TX would cause drop in fq due to overreaching fq’s drop horizon (given clock’s offsets)

➔ No means to figure out clock base from skb->tstamp, hence reset

Rationale on today's timestamp reset



Can skb->tstamp be normalized to a single base?

- ➔ Initially TCP EDT was based on CLOCK_TAI as well
- ➔ Nodes were seen where improper RTC setup caused clock discontinuities of +50yrs during boot
- ➔ Confused fq which lead to drops, thus broke TCP
  - Hence CLOCK_MONOTONIC & reset on direction switch

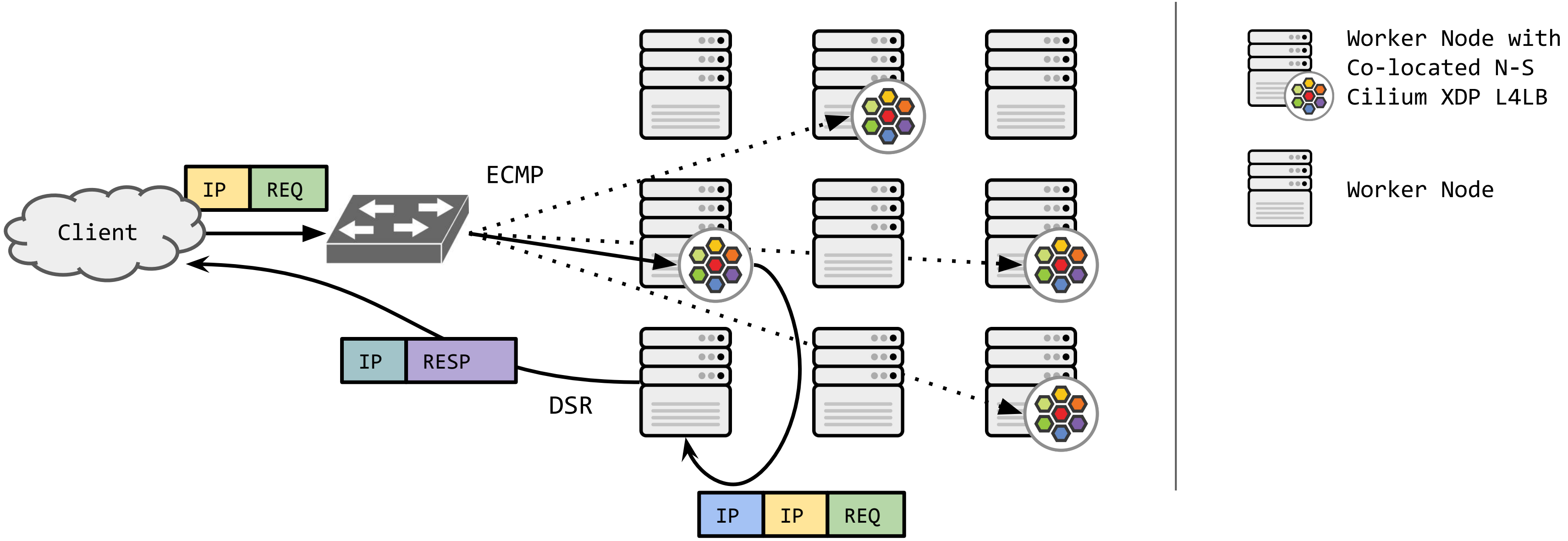
Approach to fixing the timestamp reset

Adding new skb->tstamp_base bit (defines: 0 ➔ TAI, 1 ➔ MONO)

- ➔ skb_set_tstamp_{mono,tai}(skb, ktime) helper used by RX and TX
- ➔ fq_enqueue() detects TAI clock and resets skb->tstamp
- ➔ All skb->tstamp = 0 due to forwarding are then removed
  - skb_mstamp_ns union could be removed as well
- ➔ net_timestamp_check() must be deferred in RX after tc ingress

Part 3: Managed neighbor/fib extensions

Use case: Cilium's XDP L4LB



Current state: Cilium's XDP L4LB

XDP LB receives packet to svcIP/port, forwards to backendIP/port:

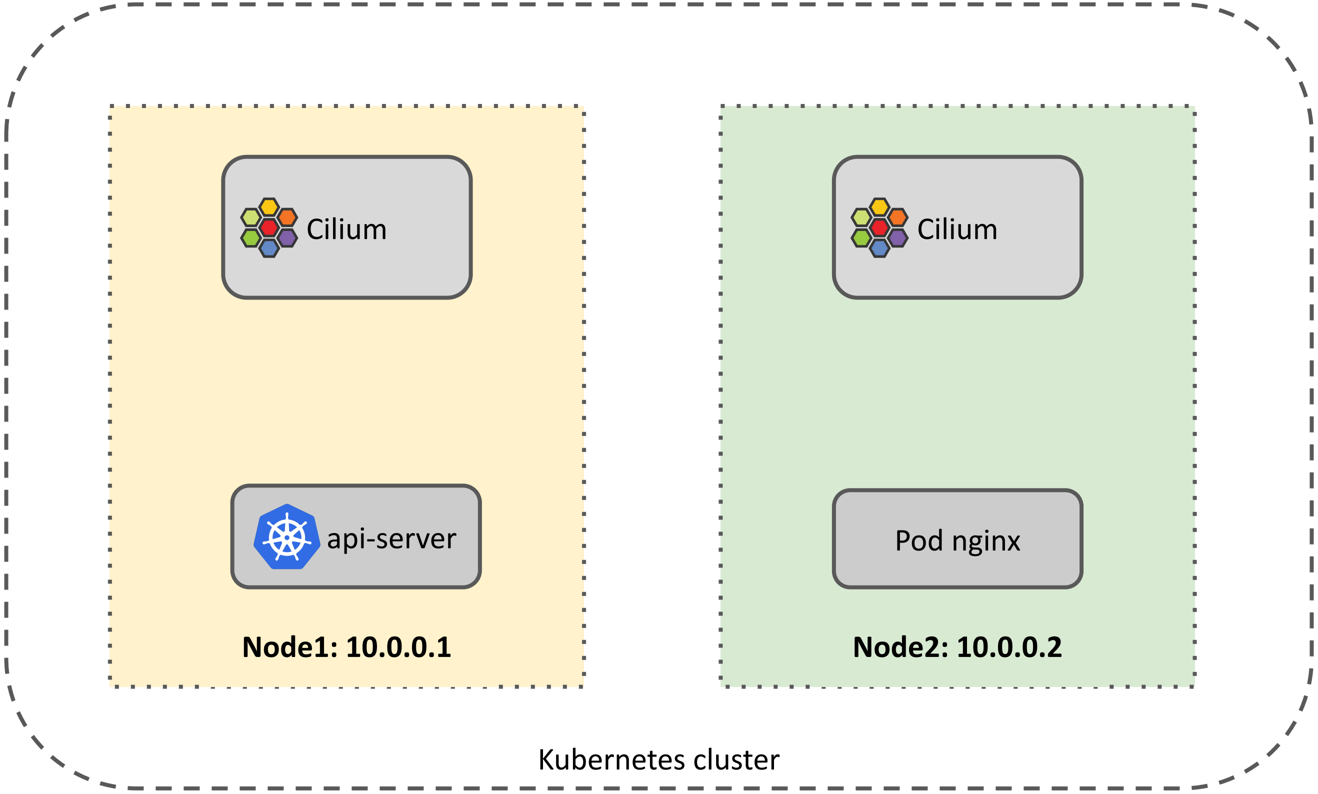
- ➔ BPF: Either DNAT & SNAT or DSR with IPIP/IP6IP6 encapsulation
- ➔ In both cases outer header has backendIP as destination
- ➔ bpf_fib_lookup() used to piggyback on neighbor resolution
- ➔ Pushed back out via XDP_TX (transparent of phys/bond device)

Current state: Cilium’s XDP L4LB

Neighbor resolution under XDP:

- ➔ Neighbor entry must be present in table, cannot resolve from XDP
- ➔ Agent currently resolves entries manually which is a pain point
- ➔ Pushes resolution as NUD_PERMANENT into neighbor table

Current state: Neighbor entry management



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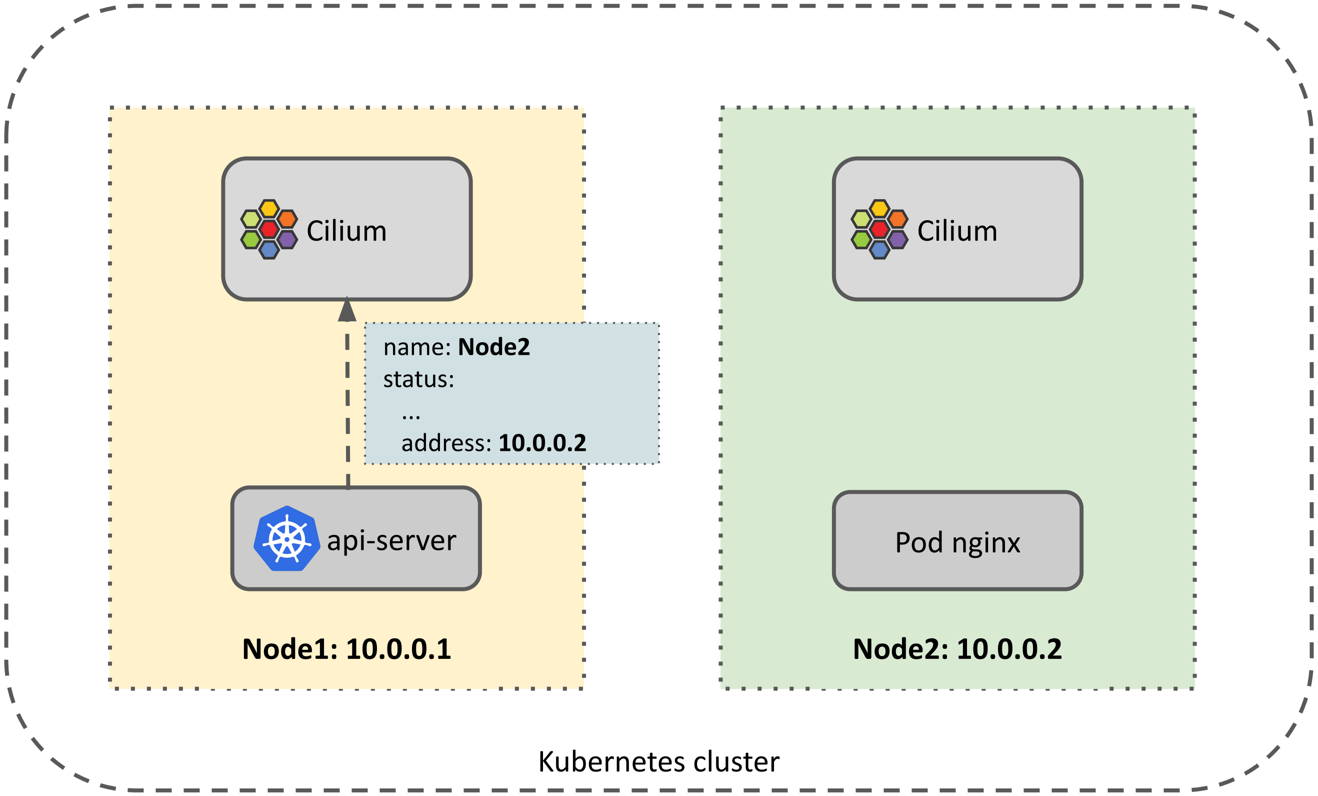

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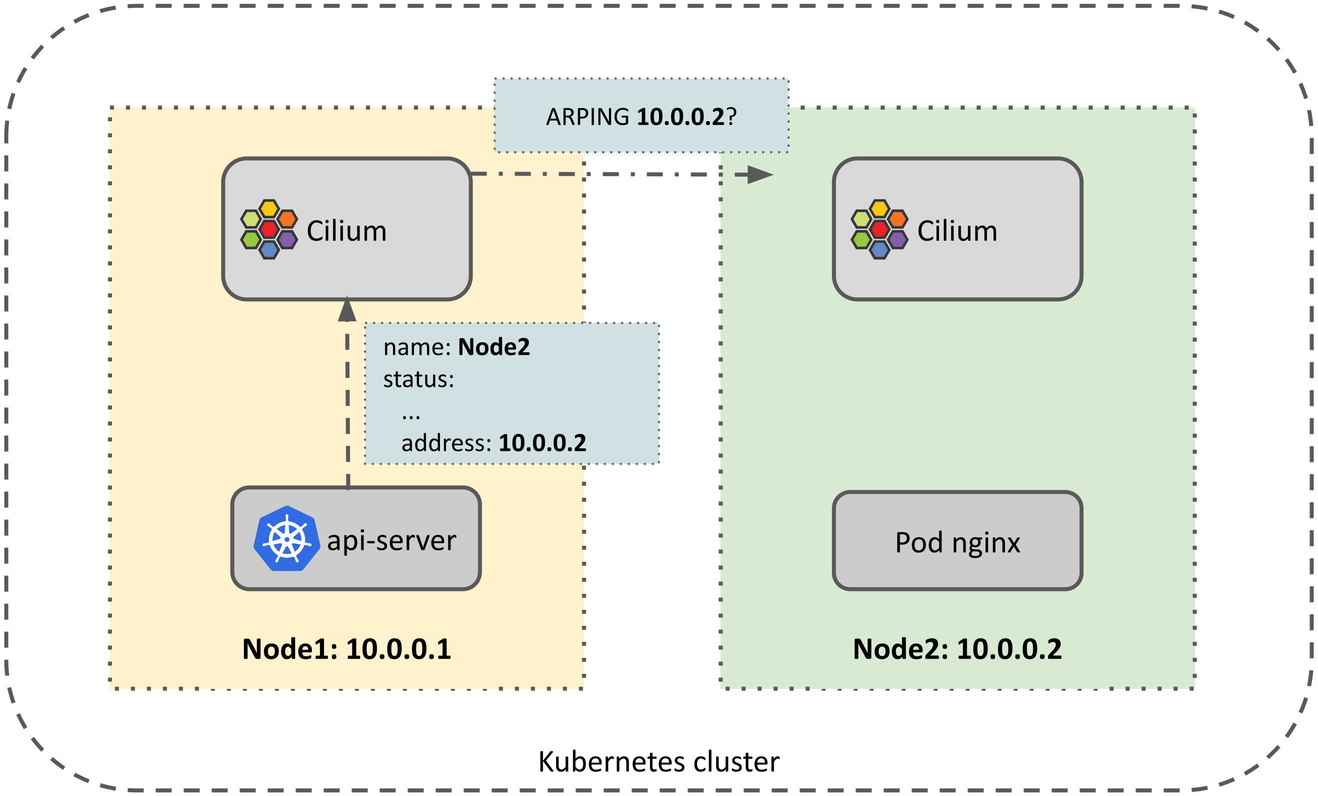

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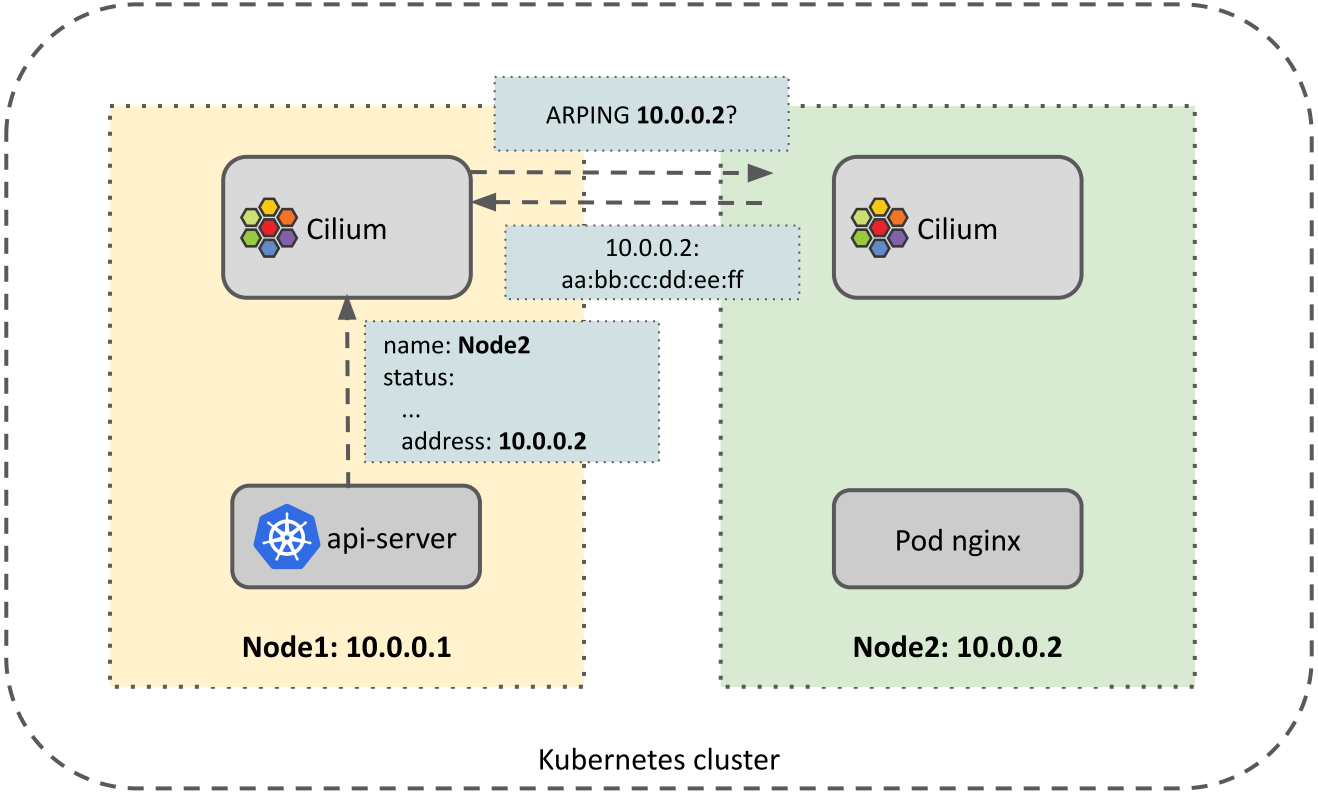

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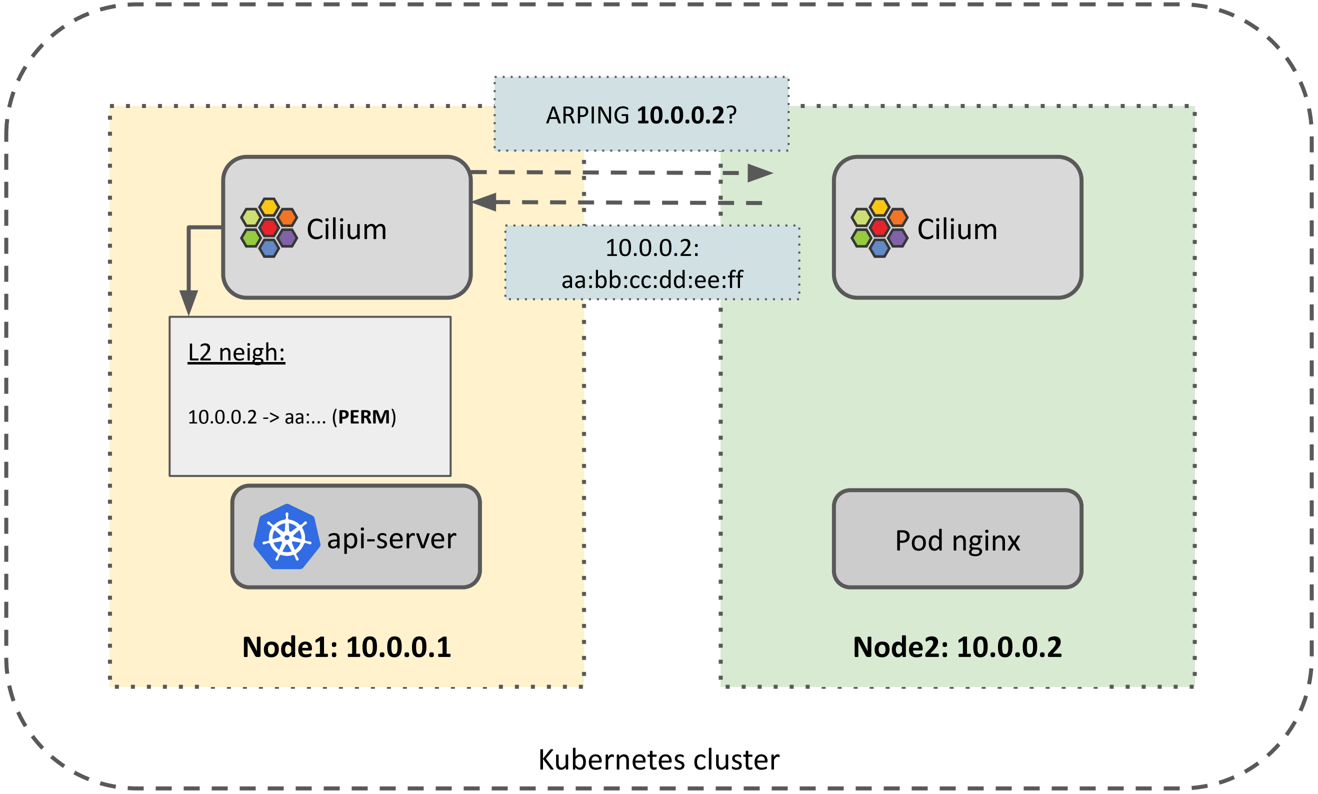

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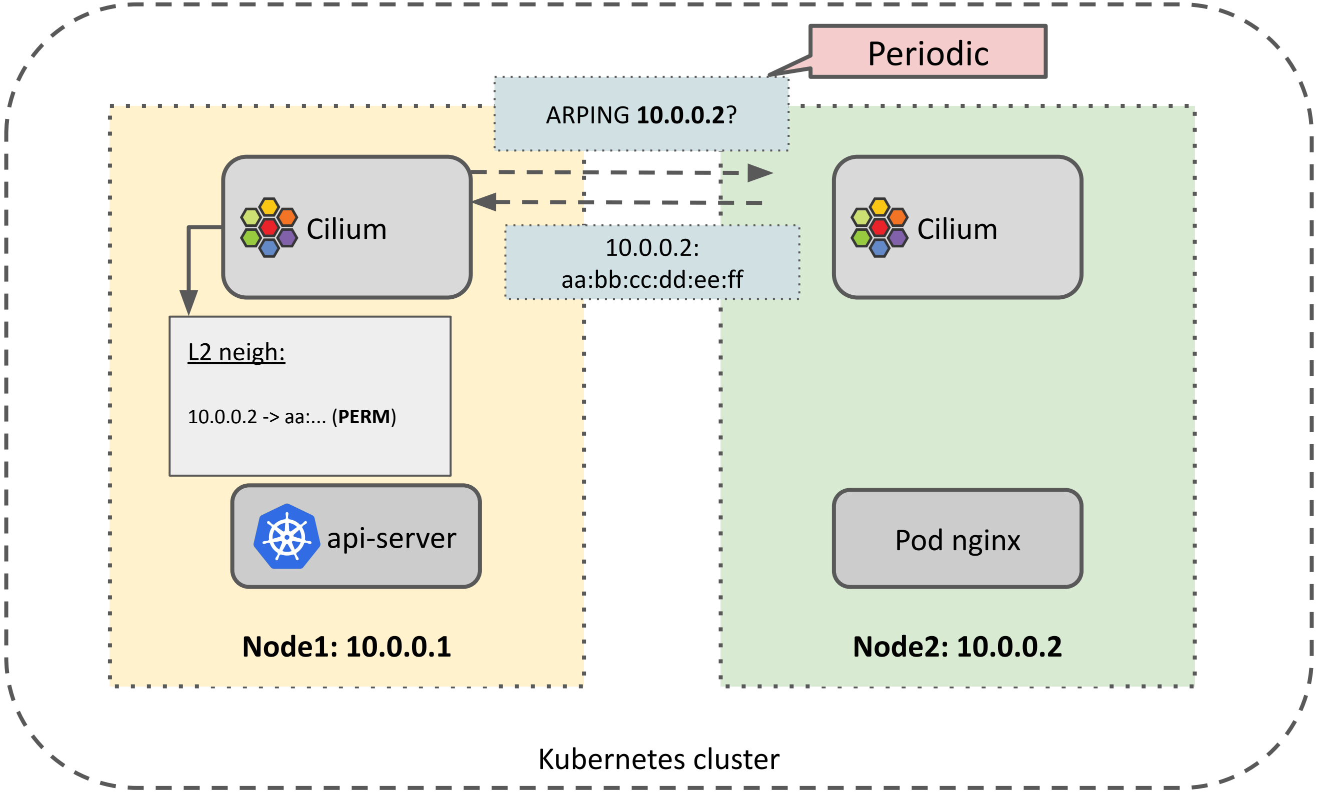
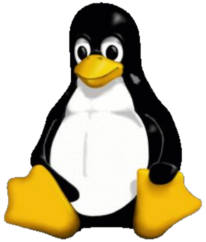


Problems with current approach

- ➔ How often to arping? (Currently once every 5 min)
- ➔ Buggy, for example:
  - ○ An obsolete NUD_PERMANENT entry for the api-server node is fatal after agent restart if the former’s L2 address changed
  - ○ No auto-updates from active traffic processed by the local stack
- ➔ Duplicating logic of net/ipv4/arp.c
- ➔ Need an equivalent for IPv6’s ND

Managed neighbor entry: Rationale



- ➔ Control plane (here: Cilium agent) requirements
  - ○ Netlink route lookup: backendIP in same L2 or via GW IP?
  - ○ Pushes L3 (without L2) addresses into neighbor table
- ➔ Neighboring subsystem auto-resolves them
- ➔ Periodically keeps them in REACHABLE state
- ➔ Option to avoid GC eviction
- ➔ Visibility for agent restart to resync/clean obsolete L3 entries

Managed neighbor entry: Design

➔ We can piggyback on NTF_USE | NTF_EXT_LEARNED neigh flag
  - Gets us quite close already:
    - Triggers one-time resolution via neigh_event_send()
    - Updates STALE state upon external/internal traffic events
    - Ensures that neigh entries are not added to GC list

Managed neighbor entry: Design

- ➔ We can piggyback on NTF_USE | NTF_EXT_LEARNED neigh flag
  - ○ What it does not do:
    - No self-managed auto-refresh to get back to REACHABLE from STALE state due to inactivity
    - Creation flags not propagated back to user space
    - Not retained upon carrier-down events (like NUD_PERMANENT)

Managed neighbor entry: Design

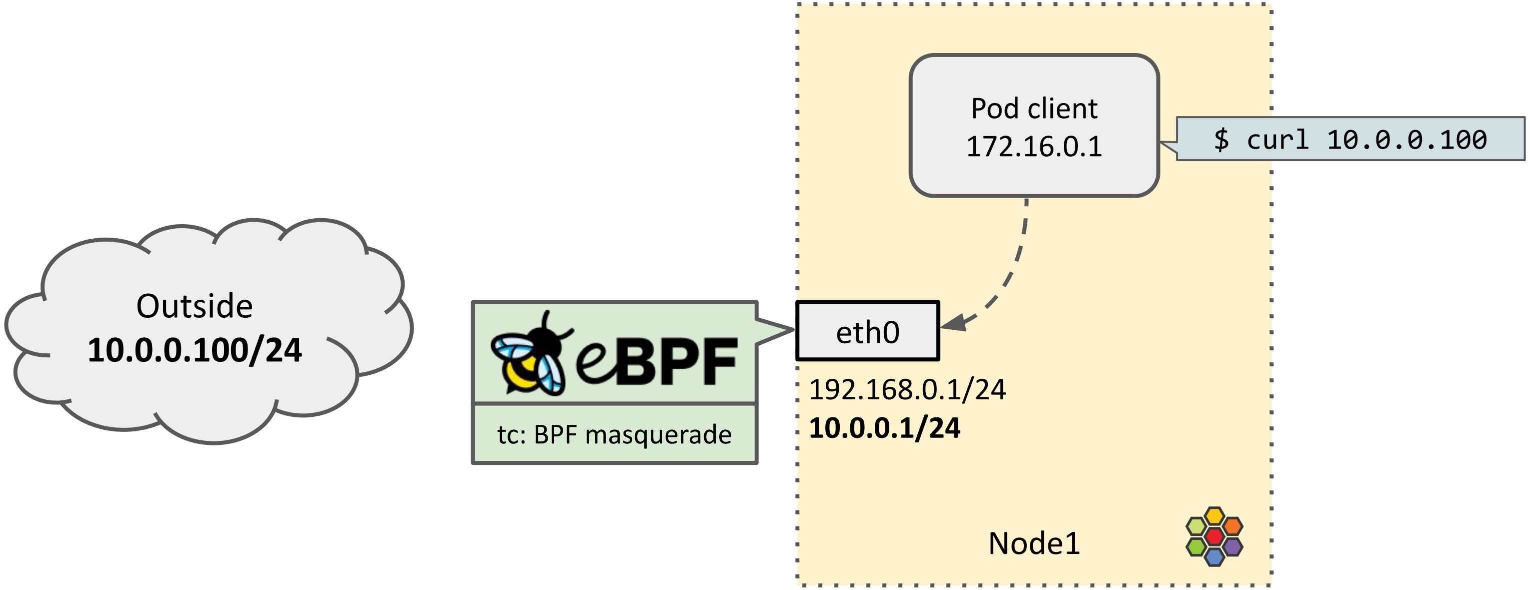
- ➔ Proposal: New NUD_MANAGED state for neigh entry creation
  - ○ Volatile pseudo-state (not fixed as in NUD_PERMANENT):
    - Implies NTF_USE and adds entry to a per-neigh table list
  - ○ Uses delayed system-wq to trigger neigh_event_send() for entries
  - ○ Triggered on BASE_REACHABLE_TIME/2 with slack
  - ○ NUD_MANAGED can be combined with NTF_EXT_LEARNED
  - ○ Retained upon carrier-down & refreshed once up again

Managed neighbor entry: iproute2 example

- Entry creation via ‘nud managed’:
  - `ip neigh replace 192.168.1.99 dev enp5s0 extern_learn nud managed`

- Entry dump (including flag propagation fix):
  - `192.168.1.99 dev enp5s0 lladdr 98:9b:cb:05:2e:ae use extern_learn REACHABLE`

FIB extensions 1/2: Source IP address selection for SNAT



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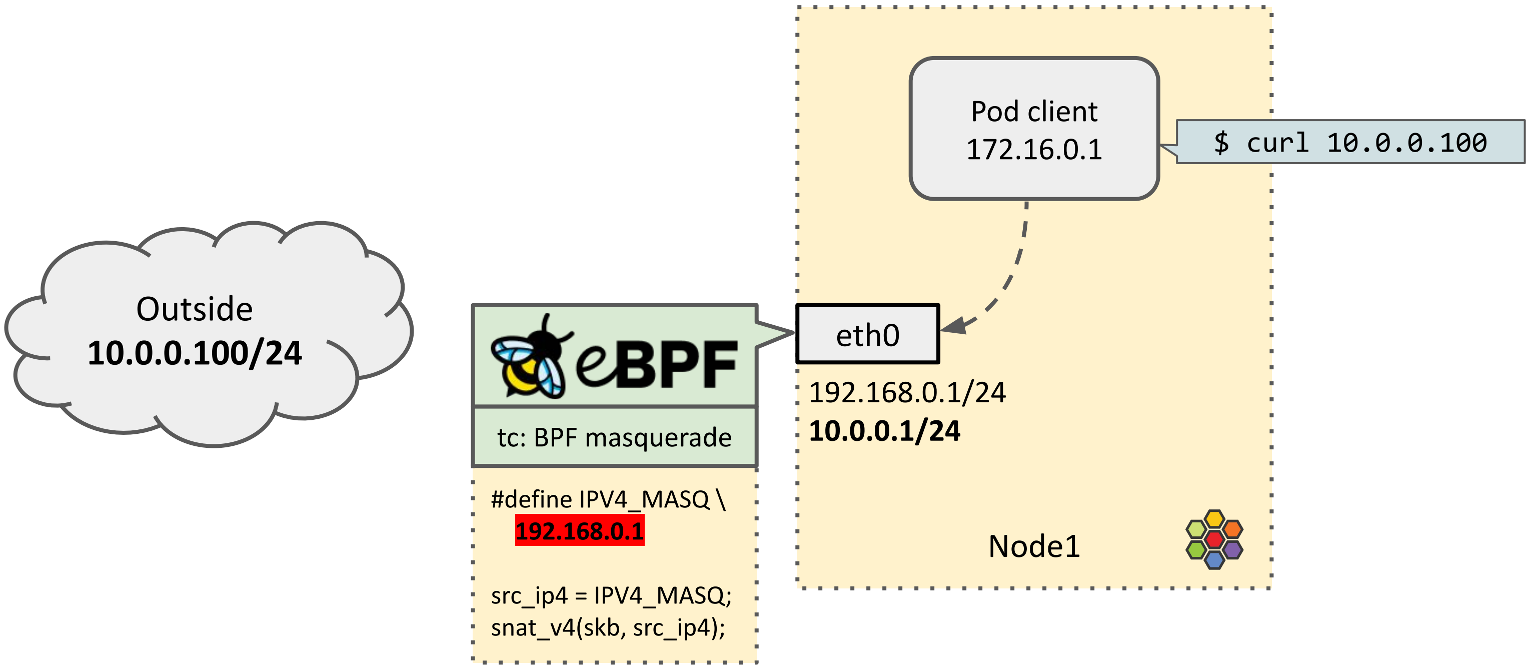

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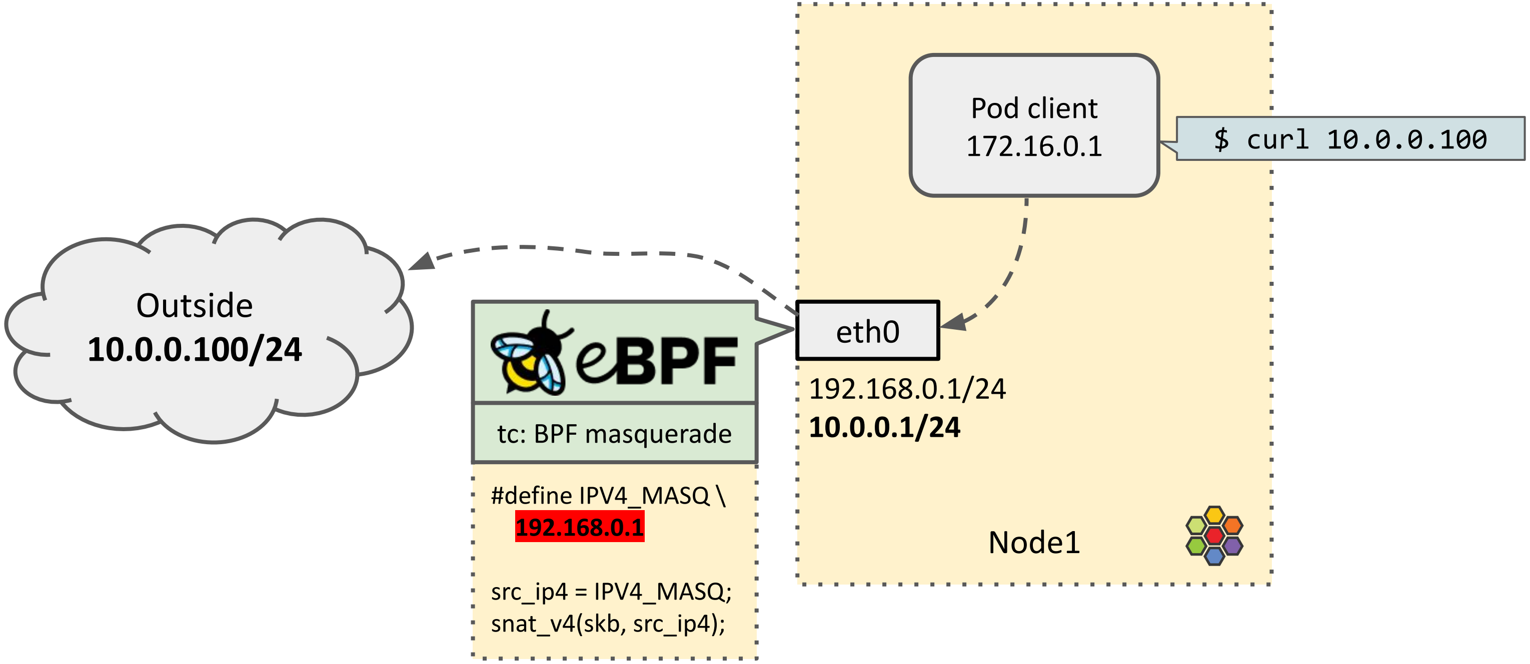

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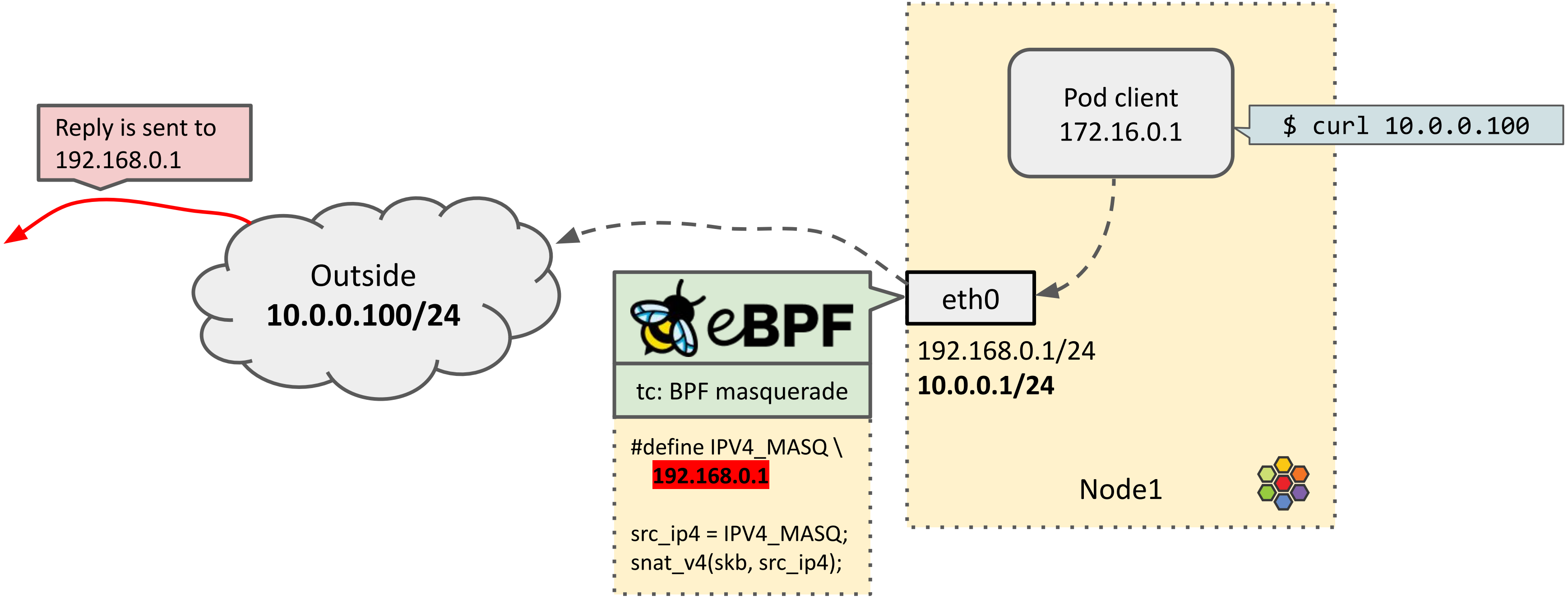

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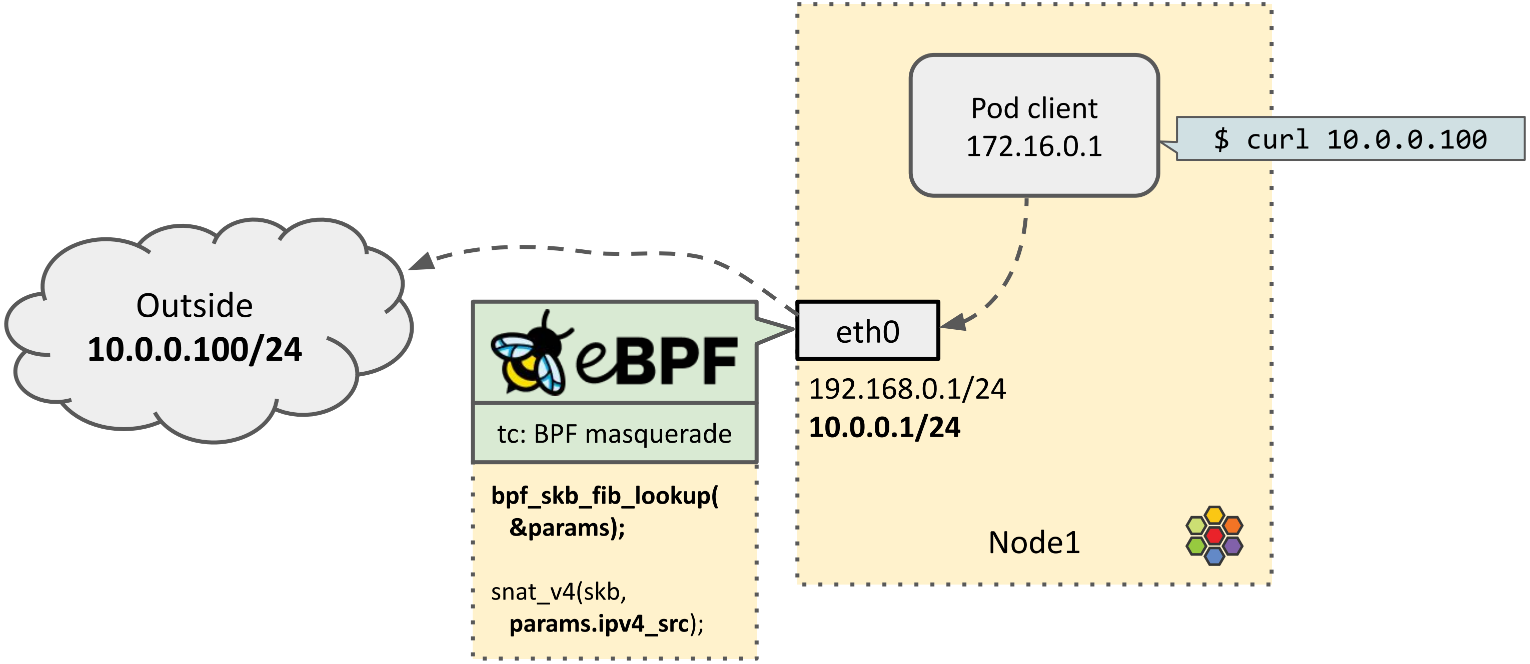
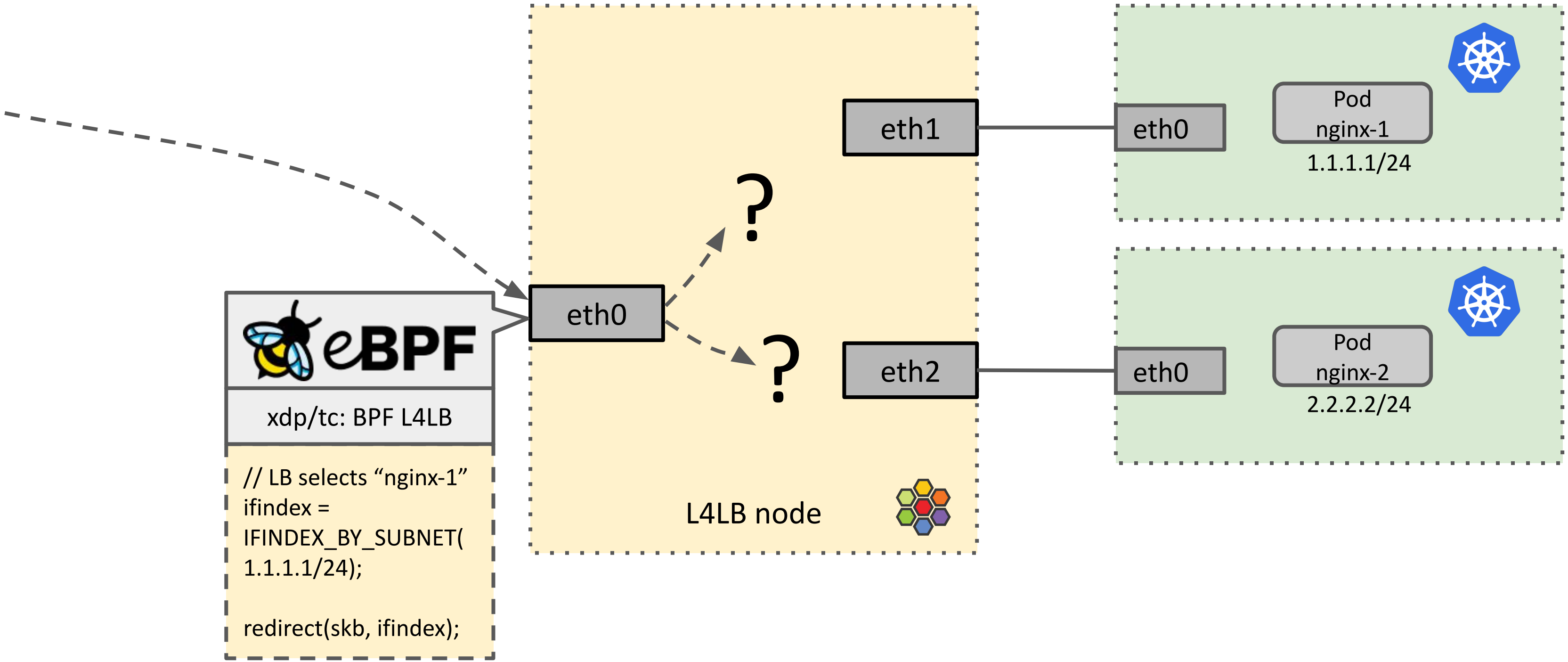


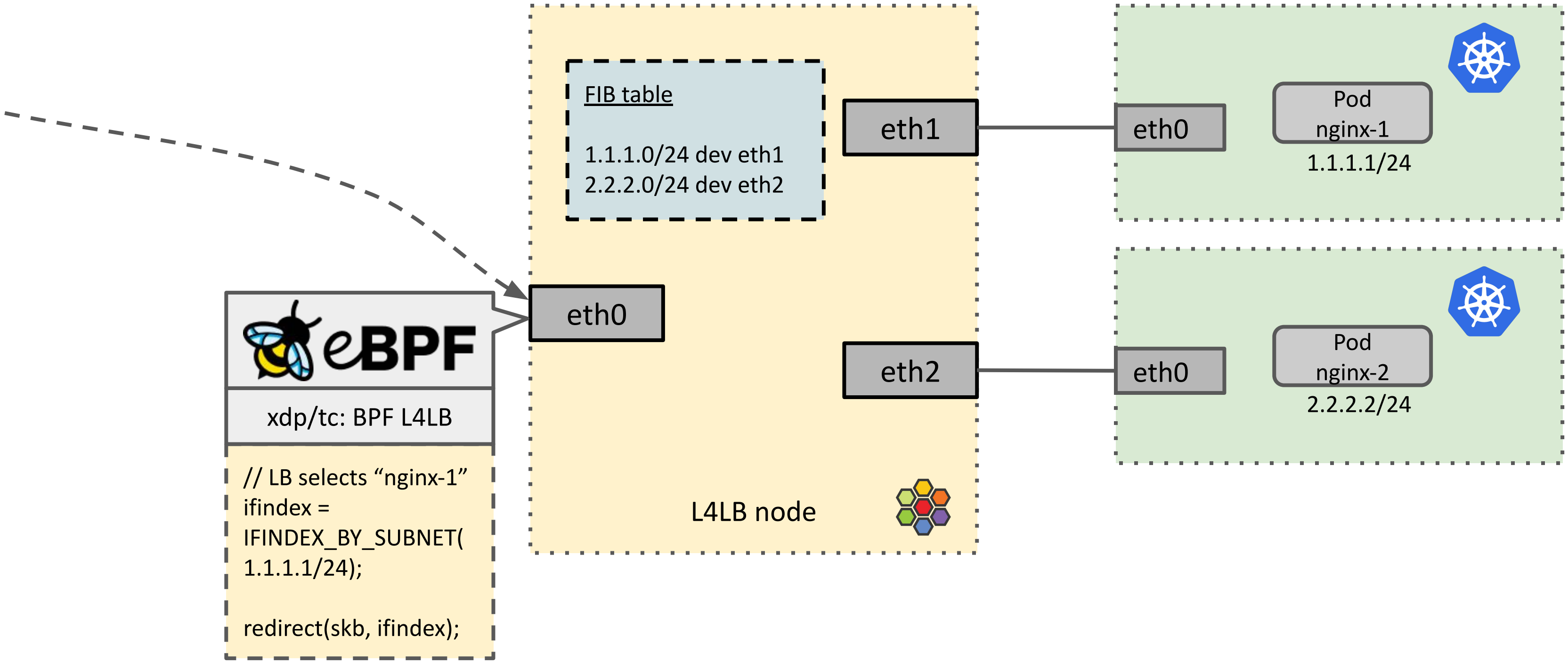
Proposed solution for source address selection

- ➔ Use bpf_{xdp,skb}_fib_lookup() for source IP address selection
  - ○ Requires changes to the BPF helper implementation
- ➔ Introduction of a new BPF_FIB_LOOKUP_SET_SRC flag
  - ○ Sets the fib_params.ipv{4,6}_src address to: fib_result_prefsrc() / fib6_info.fib6_src
- ➔ Another benefit: No need to hardcode IP addresses into the datapath

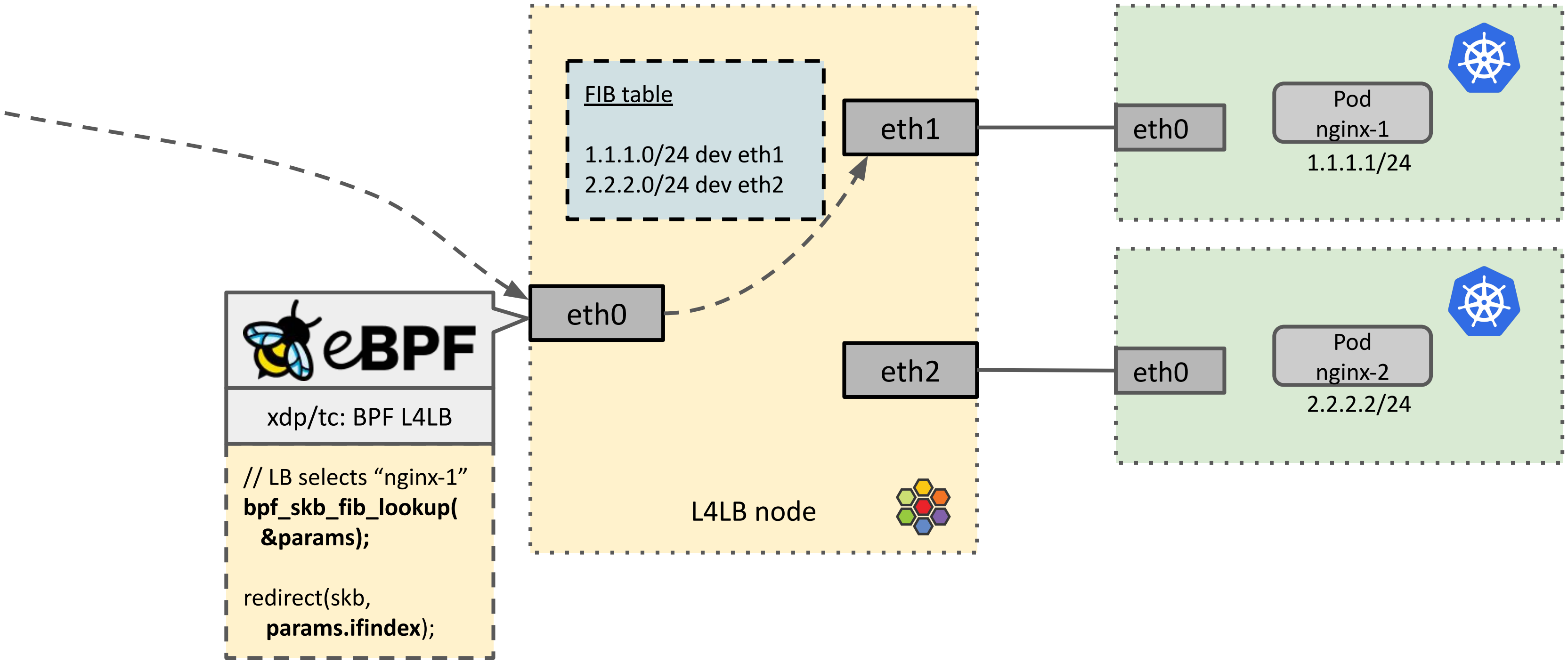
FIB extensions 2/2: Redirect in multi-homed network



FIB extensions 2/2: Redirect in multi-homed network



FIB extensions 2/2: Redirect in multi-homed network



Proposed solution for target ifindex selection

- ➔ Use bpf_{xdp,skb}_fib_lookup() to determine ifindex
  - Requires fixing the BPF helper implementation, too
- ➔ Do not require ifindex when !BPF_FIB_LOOKUP_DIRECT
  - “params->ifindex = dev->ifindex;” already exists
  - Is current behavior a bug?
- ➔ Commit for making params->ifindex optional (to be upstreamed)

Part 4: Wildcarded BPF map lookups

Current state: Cilium XDP L4LB use case

Flexible LB traffic recorder to correlate inbound/outbound pkts:

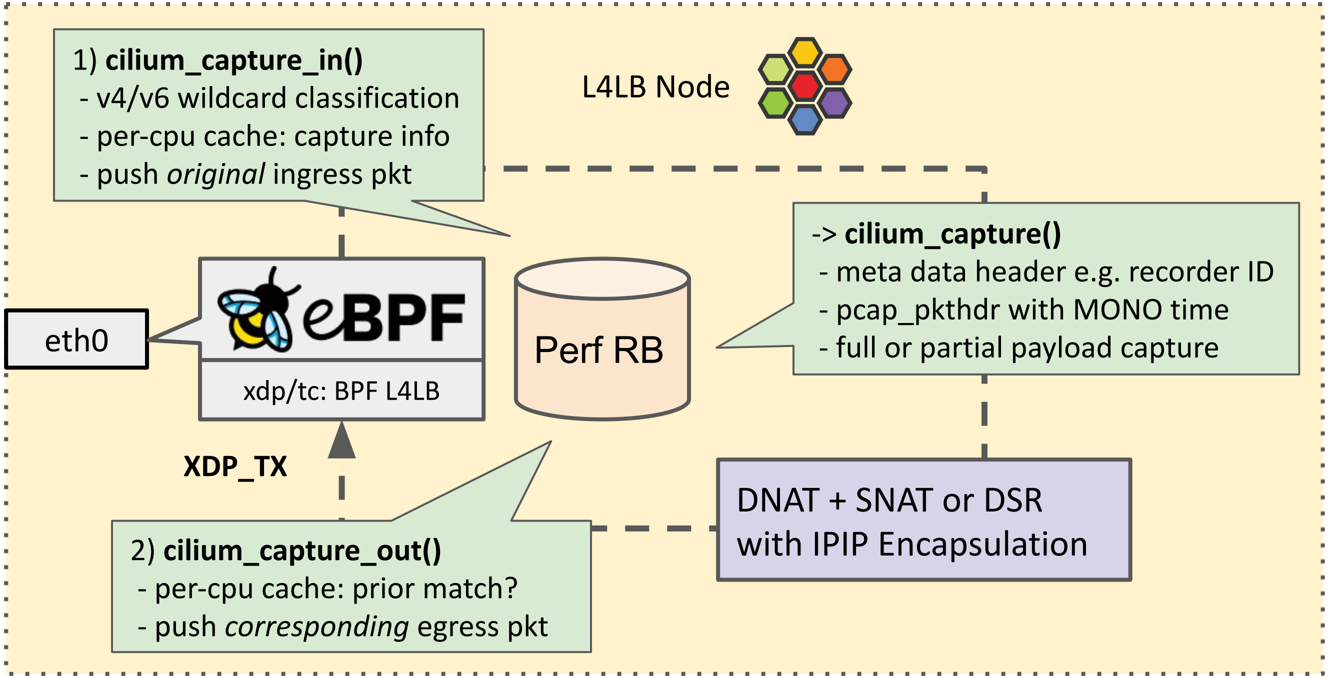
- ➔ Introspection on path taken from fabric to L4LBs to L7 proxies/backends
- ➔ Higher-level API for out-of-band programming of L4LB agents
- ➔ Hubble then constructing PCAP for offline troubleshooting

```
$ hubble record "0.0.0.0/0 0 192.168.33.11/32 80 TCP"
Started recording. Press CTRL+C to stop.
2021-05-19T10:54:07Z Status: 345 packets (27445 bytes) written
```

```
$ cilium recorder list
ID     Capture Length   Wildcard Filters
4241   full             0.0.0.0/0:0        ->   192.168.33.11/32:80   TCP

Users   Priority      Wildcard Masks
1       56            00000000:0      ->   ffffffff:ffff   ff
$
```

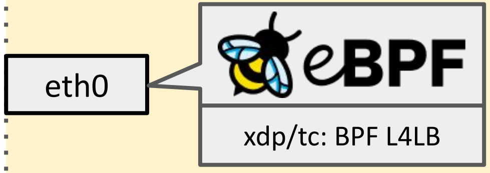
Cilium XDP L4LB: PCAP recorder overview



PCAP recorder: Classifier rules

1) **cilium_capture_in()**
- v4/v6 wildcard classification

L4LB Node

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Users   Priority     Wildcard Masks
1       56           00000000:0        ->    ffffffff:ffff    ff
$ 
```

One 'Recorder' consists of:

- Source CIDR, destination CIDR
- Source Port, destination Port (0: any, n: direct match)
  - Currently unsupported: n-m range
- Protocol (0: any, n: direct match)

PCAP recorder: Classifier rules

1) **cilium_capture_in()**
- v4/v6 wildcard classification

L4LB Node

eth0

eBPF

xdp/tc: BPF L4LB

```
$ cilium recorder list
ID      Capture Length    Wildcard Filters
4241    full              0.0.0.0/0:0         ->    192.168.33.11/32:80    TCP

Users   Priority    Wildcard Masks
1       56          00000000:0        ->    ffffffff:ffff    ff
$ 
```

One 'Recorder' consists of:

- Source CIDR, destination CIDR
- Source Port, destination Port (0/n)
  - Currently unsupported: n-m range
- Protocol (0/n)

Agent:

- User API for programming recorders
- Tracking different masks from rules
- Regens datapath on mask set change
- v4/v6 hashtable each for rule lookup

PCAP recorder: Classifier rules

```
static __always_inline struct capture_rule *
cilium_capture4_classify_wcard(struct __ctx_buff *ctx)
{
	struct capture4_wcard prefix_masks[] = { PREFIX_MASKS4 };

	[...]

_Pragma("unroll")
	for (i = 0; i < size; i++) {
		cilium_capture4_masked_key(&okey, &prefix_masks[i], &lkey);
		match = map_lookup_elem(&CAPTURE4_RULES, &lkey);
		if (match)
			return match;
	}

	return NULL;
}
```

PCAP recorder: Classifier rules

```
static __always_inline struct capture_rule *
cilium_capture4_classify_wcard(struct __ctx_buff *ctx)
{
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        [...]

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                match = map_lookup_elem(&CAPTURE4_RULES, &lkey);
                if (match)
                        return match;
        }

        return NULL;
}
```

Dynamic, ordered mask set, regenerated by agent on the fly.

PCAP recorder: Classifier rules

```
static __always_inline struct capture_rule *
cilium_capture4_classify_wcard(struct __ctx_buff *ctx)
{
        struct capture4_wcard prefix_masks[] = { PREFIX_MASKS4 };

        [ ... ]

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                cilium_capture4_masked_key(&okey, &prefix_masks[i], &lkey);
                match = map_lookup_elem(&CAPTURE4_RULES, &lkey);
                if (match)
                        return match;
        }

        return NULL;
}
```

Generating masked key (lkey) from original tuple (okey) and current mask.

PCAP recorder: Classifier rules

```
static __always_inline struct capture_rule *
cilium_capture4_classify_wcard(struct __ctx_buff *ctx)
{
        struct capture4_wcard prefix_masks[] = { PREFIX_MASKS4 };

        [...]

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                if (match)
                        return match;
        }

        return NULL;
}
```

Using masked key (lkey) for the hashtable lookup.

PCAP recorder: Classifier rules

```
static __always_inline struct capture_rule *
cilium_capture4_classify_wcard(struct __ctx_buff *ctx)
{
        struct capture4_wcard prefix_masks[] = { PREFIX_MASKS4 };

        [...]

_Pragma("unroll")
        for (i = 0; i < size; i++) {
                cilium_capture4_masked_key(&okey, &prefix_masks[i], &lkey);
                match = map_lookup_elem(&CAPTURE4_RULES, &lkey);
                if (match)
                        return match;
        }

        return NULL;
}
```

Holds Recorder ID and capture length.

PCAP recorder: Classifier rules

```c
static __always_inline void
cilium_capture4_masked_key(const struct capture4_wcard *orig,
                           const struct capture4_wcard *mask,
                           struct capture4_wcard *out)
{
        out->daddr = orig->daddr & mask->daddr;
        out->saddr = orig->saddr & mask->saddr;
        out->dport = orig->dport & mask->dport;
        out->sport = orig->sport & mask->sport;
        out->nexthdr = orig->nexthdr & mask->nexthdr;
        out->dmask = mask->dmask;
        out->smask = mask->smask;
}
```

Masked key (lkey) generation for the map lookup.

Problems with current approach

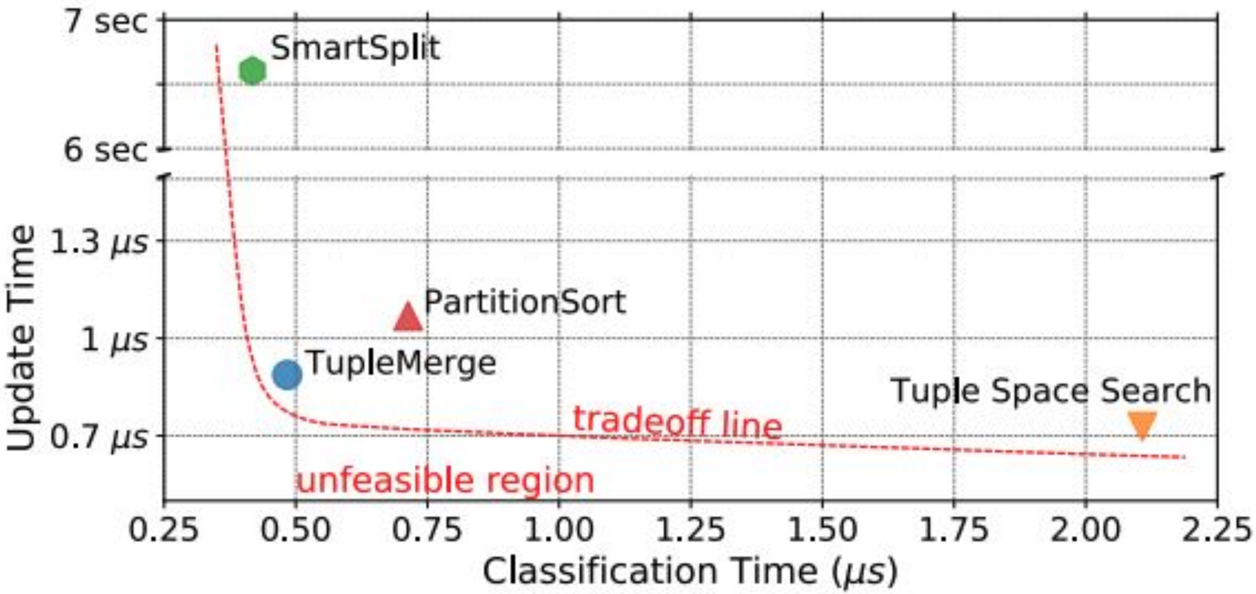
- ➔ “Poor man’s version” of wildcard match:
  - Assumes small number of masks, *but* allows for large number of matches within the mask set: acceptable for our use-case
  - Requires expensive on-the-fly recompilation on mask set change
  - Linearity for probing different masks
- ➔ Works on old kernels, but loop unrolling risks verifier complexity issues

Native wildcard-supported BPF map

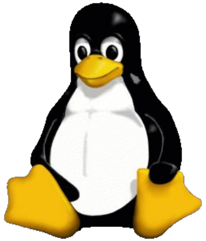
- ➔ Ideally native BPF map to avoid costly code regeneration:
  - ‘Very fast’ lookup time (Millions/sec)
  - ‘Reasonably fast’ update time (Thousands/sec)
- ➔ First use-case dates back to 2018 in context of BPF + OVS to implement Megaflows in BPF, effort stalled however

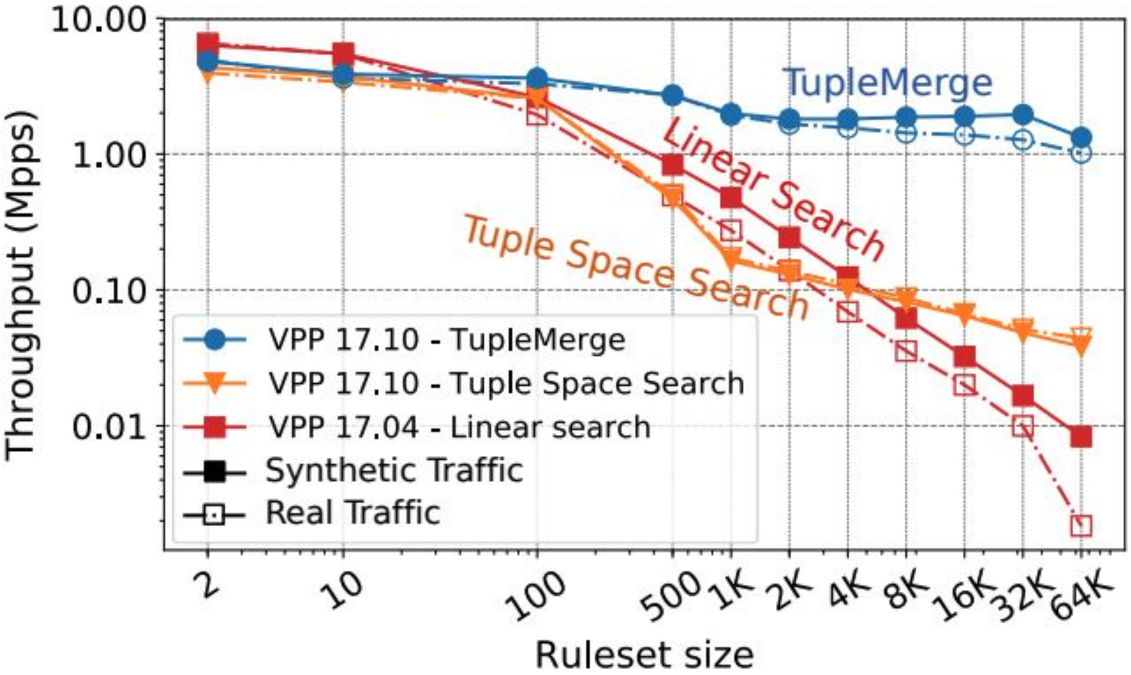
Native wildcard-supported BPF map

➔ Potential map candidate: TupleMerge (Eric Torng et al.)
  ○ Current state-of-the-art in classification algorithms



Native wildcard-supported BPF map





➔ Next step on our agenda: PoC implementation for BPF runtime

Thanks! Questions, feedback, comments?

- ➔ Try it out: https://cilium.link/kubeproxy-free
- ➔ Cilium: https://github.com/cilium/cilium
- ➔ PoC code: https://git.kernel.org/[...]/dborkman/bpf.git
  https://github.com/brb/linux