Application-layer traffic processing with eBPF

extended Barkeley packet filter

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BPF vs eBPF - *classical BPF*

- BPF - Berkeley Packet Filter
- Initially used as socket filter by packet capture tool tcpdump (via libpcap)
- Introduced in Linux in 1997 in kernel version 2.1.75

- Use cases:
- Mainly socket filters (drop or trim packet and pass to user space)
- used by tcpdump/libpcap, wireshark, nmap, dhcp ..

BPF vs eBPF - *extended BPF*

- New set of patches introduced in the Linux kernel since 3.15 (June 8th, 2014) and into 4.0 (April 12th, 2015) and into 4.1 and 4.3
- Current Linux kernel version 4.3.99 (November 2015)
- More registers (64 bit)
- In-kernel JIT compiler (safe) : x86, ARM64, s390 …
- “Universal in-kernel virtual machine”
- Portable – any platform that LLVM compiles into will work

- Use Cases:
- Networking (packet filtrering , network traffic control, etc ...)
- Tracing (analytics, monitoring, debugging)

Extended BPF

- Idea: improve and extend existing BPF infrastructure
- Programs can be written in C and translated into eBPF
- instructions using Clang/LLVM, loaded in kernel and executed
- LLVM backend available to compile eBPF programs (llvm 3.7)
- Safety checks performed by kernel
- Added arm64, arm, mips, powerpc, s390, sparc JITs
- ISA is close to x86-64 and arm64

eBPF - *low level VM architecture*

classic BPF	extended BPF
2 registers + stack 32-bit registers 4-byte load/store to stack 1-4 byte load from packet Conditional jump forward +, -, *, … instructions	10 registers + stack 64-bit registers with 32-bit sub-registers 1-8 byte load/store to stack, maps, context Same + store to packet Conditional jump forward and backward Same + signed_shift + endian Call instruction tail_call map lookup/update/delete helpers packet rewrite, csum, clone_redirect sk_buff read/write tunnel metadata read/write vlan push/pop hash/array/prog/perf_event map types

eBPF new features - *maps*

- BPF maps are key/value storage of different types.
- Example
  value = bpf_table_lookup(table_id, key) – lookup key in a table

- Userspace can read/modify the tables
- Generic memory allocated
- Transfer data from userspace to kernel and vice versa
- Share data among many eBPF programs (see next)
- A map is identified by a file descriptor returned by a bpf() system call that creates the map
- Attributes: max elements, size of key, size of value
- Types of maps: BPF_MAP_TYPE_ARRAY, BPF_MAP_TYPE_HASH

eBPF – *maps example*

- Restrictive C program to:
- obtain the protocol type (UDP, TCP, ICMP, …) from each packet
- keep a count for each protocol in a “map”:

```
int bpf_prog1(struct __sk_buff *skb)
 {
      int index = load_byte(skb, ETH_HLEN +
 offsetof(struct iphdr, protocol));
      long *value;

      value = bpf_map_lookup_elem(&my_map, &index);
      if (value)
          __sync_fetch_and_add(value, 1);
      return 0;
 }
```

eBPF – *maps sharing*

eBPF programs can be attached to different events. These events can be the arrival of network packets, tracing events, classification events by network queueing disciplines (for eBPF programs attached to a tc(8) classifier), and other types that may be added in the future. A new event triggers execution of the eBPF program, which may store information about the event in eBPF maps. Beyond storing data, eBPF programs may call a fixed set of in-kernel helper functions.

The same eBPF program can be attached to multiple events and different eBPF programs can access the same map:

```
tracing     tracing    tracing    packet      packet     packet
event A     event B    event C    on eth0     on eth1    on eth2
 |             |         |          |           |          ^
 |             |         |          |           v          |
 --> tracing <--     tracing      socket    tc ingress   tc egress
      prog_1          prog_2      prog_3    classifier    action
      |  |              |           |         prog_4      prog_5
   |---  -----|  |------|          map_3        |           |
 map_1       map_2                              --| map_4 |--
```

http://man7.org/linux/man-pages/man2/bpf.2.html

eBPF – maps functions

- BPF_MAP_CREATE: creates a new map
- BPF_MAP_LOOKUP_ELEM: find element by key, return value
- BPF_MAP_UPDATE_ELEM: find element by key, change value
- BPF_MAP_DELETE_ELEM: find element by key, delete it
- BPF_MAP_GET_NEXT_KEY: find element by key, return key of next element

eBPF – function calls using maps

- It's possible to use map index as function pointer and use it to jump to other ebpf functions.

https://github.com/iovisor/bcc/tree/master/examples/networking/tunnel_monitor

```
/*from tunnel_monitor/monitor.c*/
BPF_TABLE("prog", int, int, parser, 10);
...
parser.call(skb, 1);  // jump to generic packet parser
parser.call(skb, 2);

# from tunnel_monitor/monitor.py

outer_fn = b.load_func("handle_outer", BPF.SCHED_CLS)
inner_fn = b.load_func("handle_inner", BPF.SCHED_CLS)

# using jump table for inner and outer packet split
parser = b.get_table("parser")
parser[c_int(1)] = c_int(outer_fn.fd)
parser[c_int(2)] = c_int(inner_fn.fd)
```

BCC – BPF Compiler Collection

https://github.com/iovisor/bcc

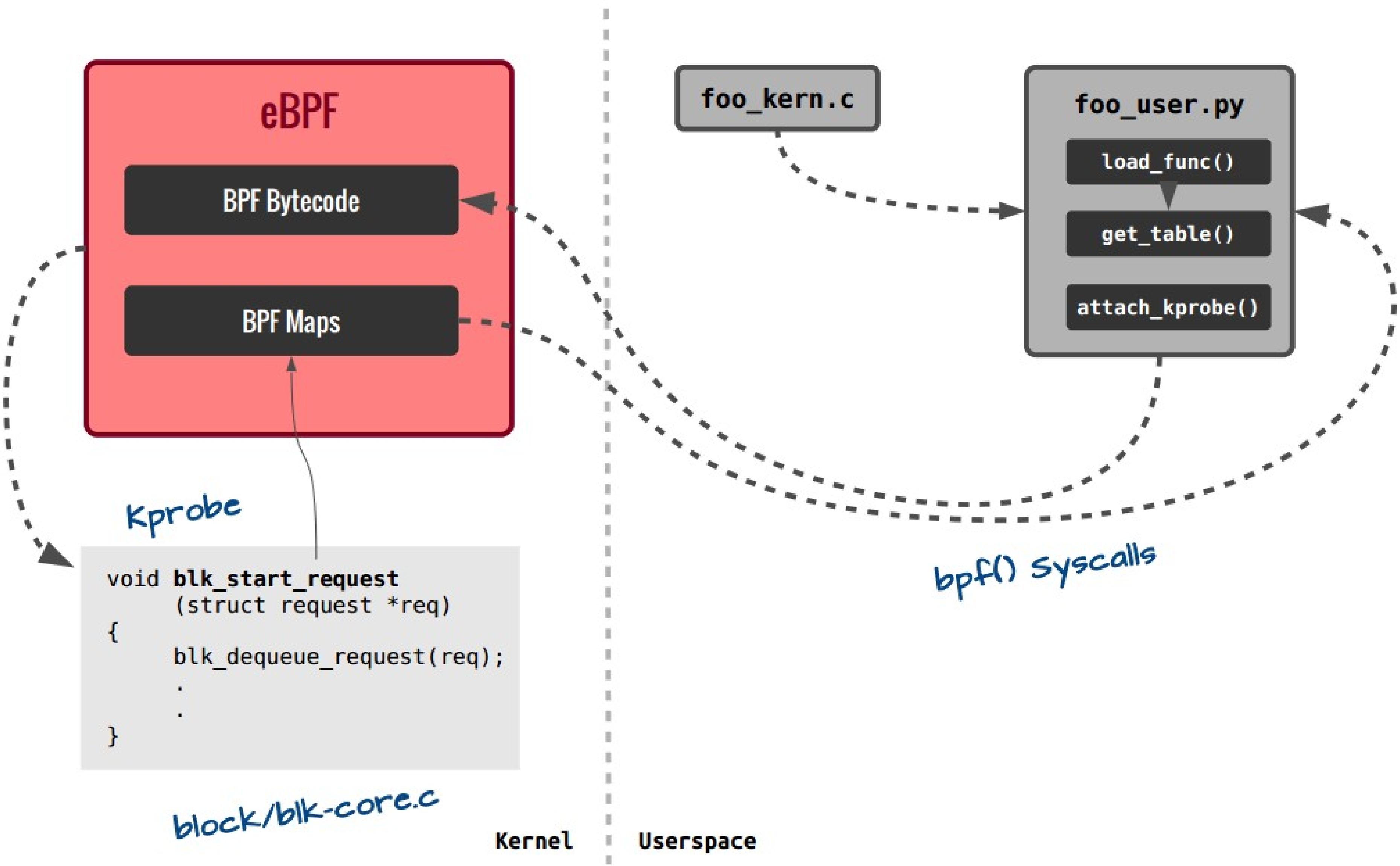
BCC – BPF Compiler Collection

BCC is a toolkit for creating efficient kernel tracing and manipulation programs. It makes use of eBPF (Extended Berkeley Packet Filters)

eBPF was described by Ingo Molnár as: “*One of the more interesting features in this cycle is the ability to attach eBPF programs (user-defined, sandboxed bytecode executed by the kernel) to kprobes. This allows user-defined instrumentation on a live kernel image that can never crash, hang or interfere with the kernel negatively.”*

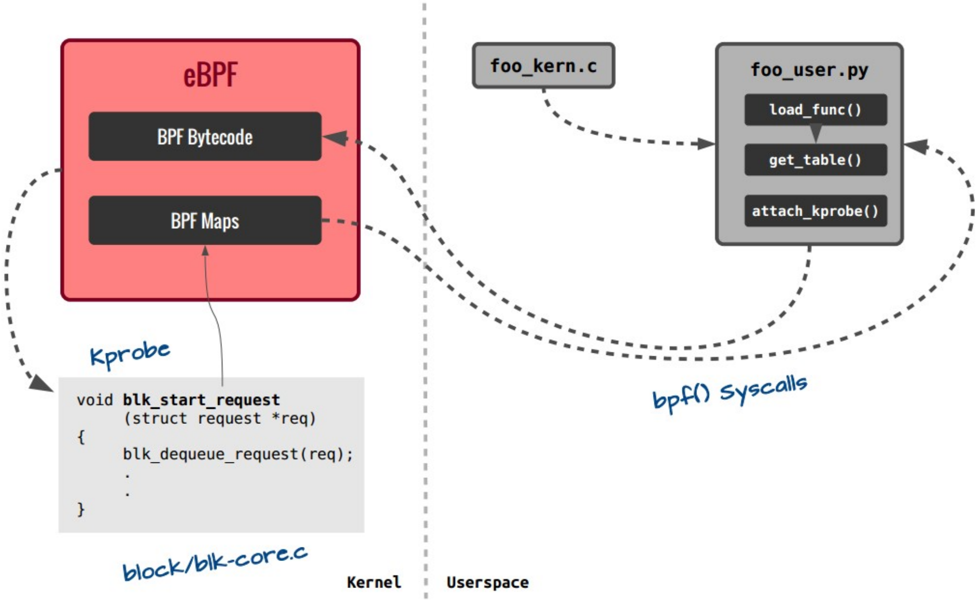
BCC makes eBPF programs easier to write, with kernel instrumentation in C and a front-end in Python. It is suited for many tasks, including performance analysis and network traffic control.

EBPF – Session workflow (.py + BCC)

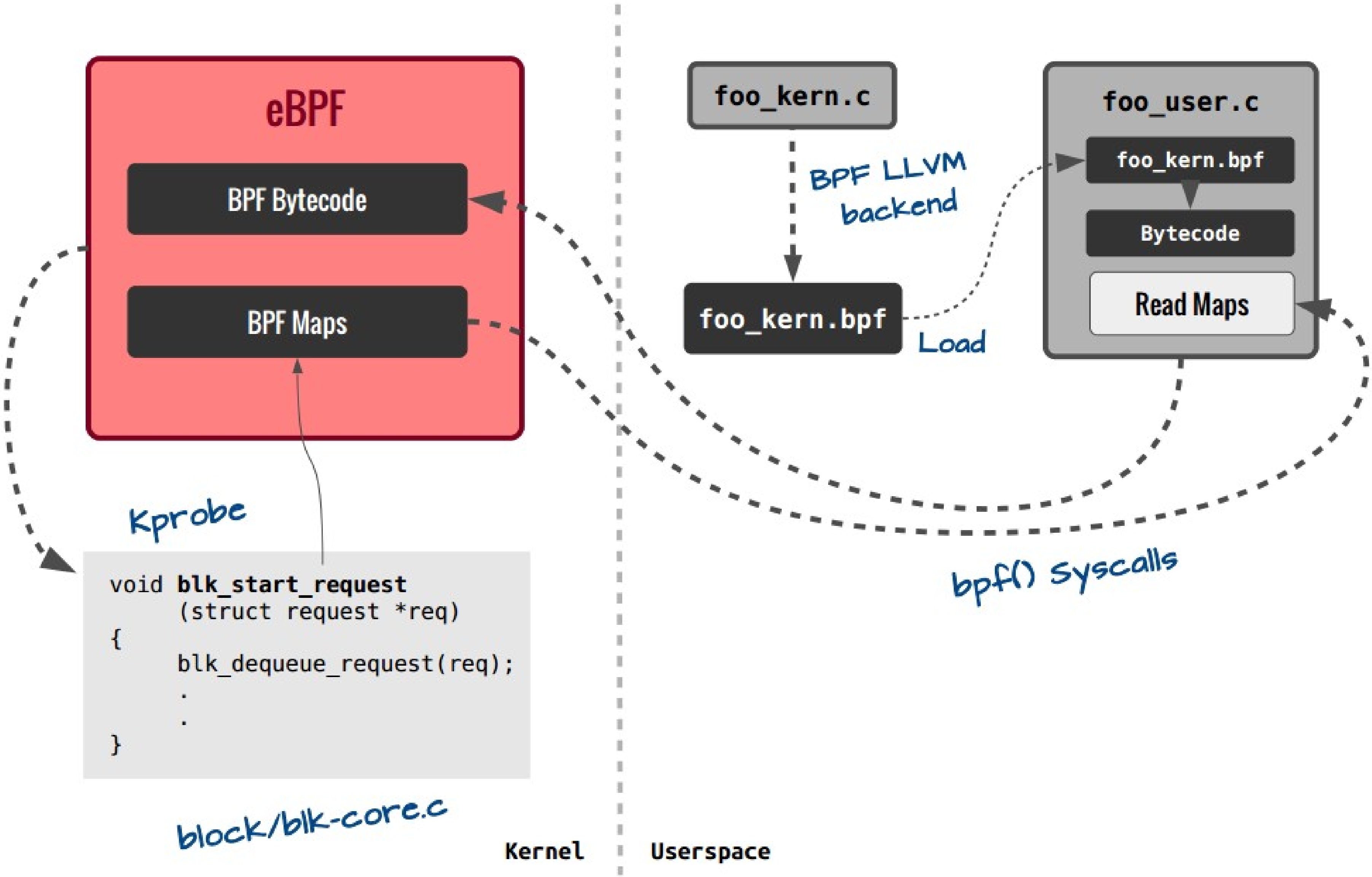


EBPF – Session workflow (.py + BCC)

- Write your BPF program in C, inline or in a separate file
- Write a python script that loads and interacts with your BPF program
- Attach the program to kprobes, socket, tc filter/action
- Read/update maps
- https://github.com/iovisor/bcc

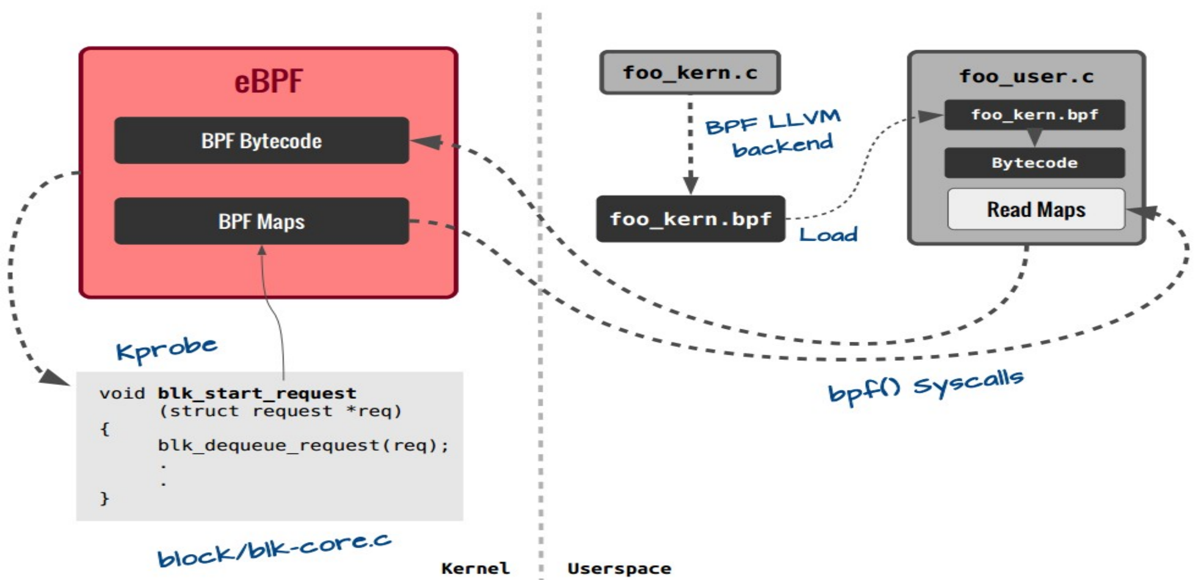


EBPF – Session workflow (c program)



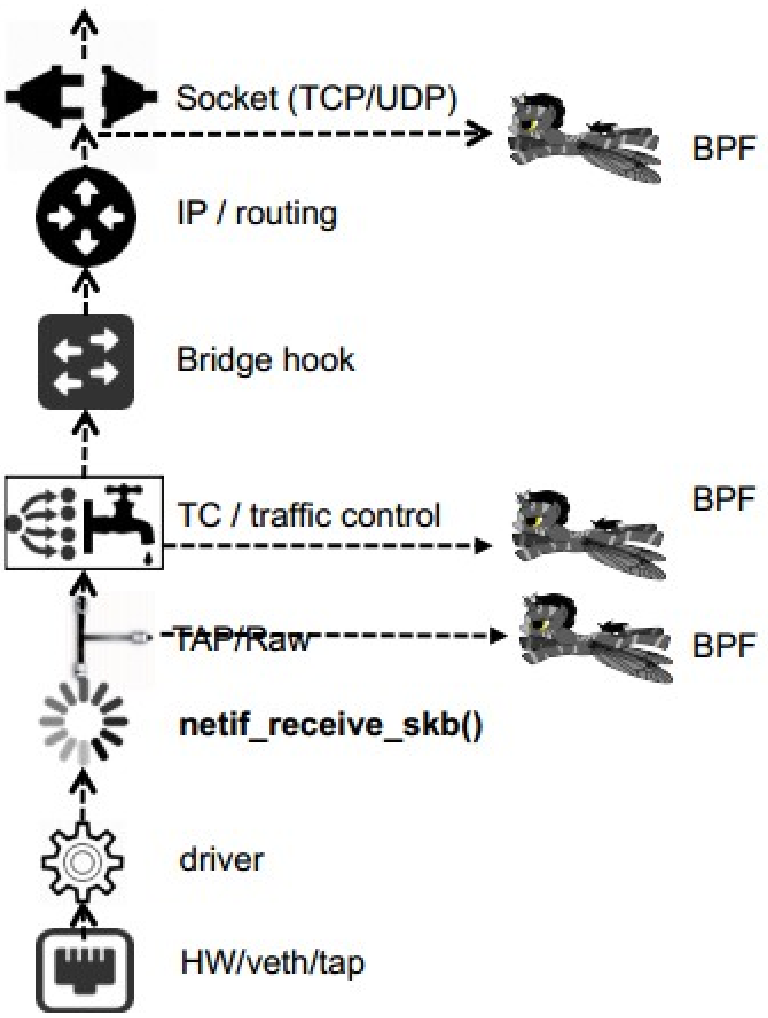
EBPF – Session workflow (c program)

- C API for working with BPF programs - libbpfprog.so
- JIT compile a C source file to BPF bytecode (using clang+llvm)
- Load bytecode and maps to kernel with bpf() syscall
- Attach 1 or more BPF programs to 1 or more hook points
- kprobe, socket, tc classifier, tc action



eBPF & Networking
Hooking into Linux networking stack (RX)

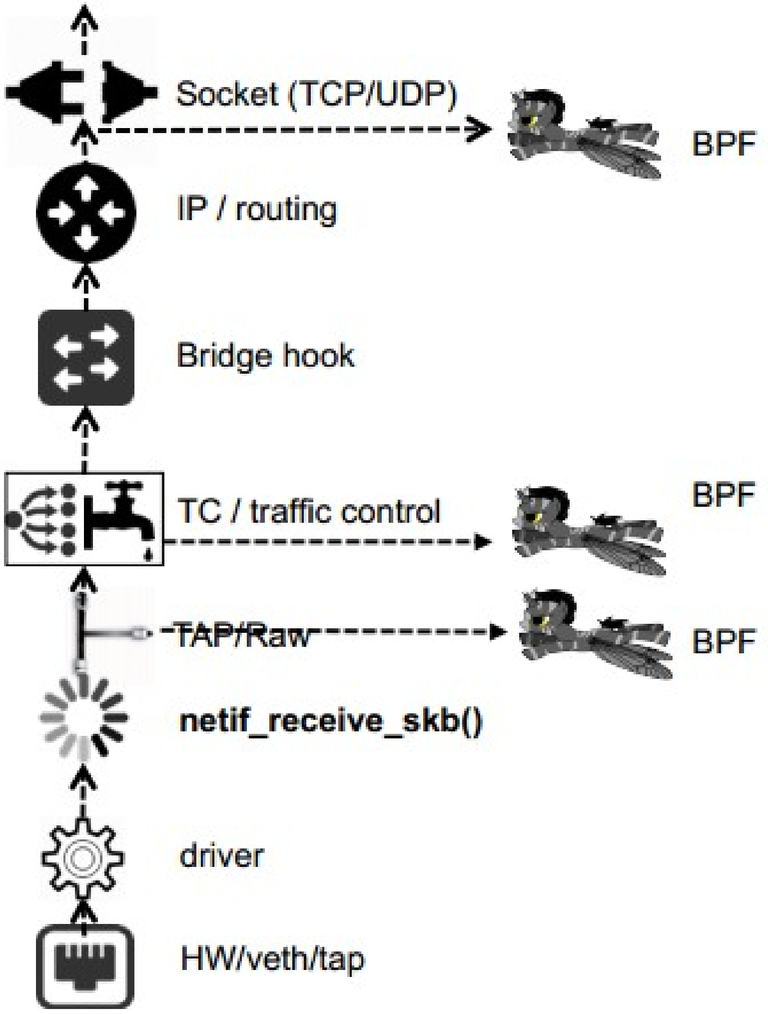
- BPF programs can attach to sockets or the traffic control (TC) subsystem, kprobes, syscalls, tracepoints ...
- sockets: STREAM (L4/UDP), DATAGRAM (L4/TCP) or RAW (TC)
- This allows to hook at different levels of the Linux networking stack, providing the ability to act on traffic that has or hasn't been processed already by other pieces of the stack
- Opens up the possibility to implement network functions at different layers of the stack



eBPF & Networking

Hooking into Linux networking stack (TX)

- Opens up the possibility to implement network functions at different layers of the stack



eBPF Retrieving Data

How userspace program can retrieve data from eBPF program running in in-kernel vm ?

- Can read the <debugfs>/trace_pipe file from userspace (BCC wrap it to bpf_trace_printk())
- Can retrieve registers values (they are the ctx)
- Can read/write from maps
- Filtered packets, read from socket

eBPF Limitation & Safety

- Max 4096 instructions per program
- Stage 1 reject program if:
  - Loops and cyclic flow structure
  - Unreachable instructions
  - Bad jumps
- Stage 2 Static code analyzer:
  - Evaluate each path/instruction while keeping track of regs and stack states
  - Arguments validity in calls

eBPF Usecases & Examples

- **Some eBPF example using BCC (from https://github.com/iovisor/bcc)**
- tools/tcpaccept: Trace TCP passive connections (accept()).
- tools/tcpconnect:Trace TCP active connections (connect()).
- examples/distributed_bridge/: Distributed bridge example.
- examples/simple_tc.py: Simple traffic control example.
- examples/tc_neighbor_sharing.py: Per-IP classification and rate limiting.
- examples/tunnel_monitor/: Efficiently monitor traffic flows.
- examples/vlan_learning.py: Demux Ethernet traffic into worker veth+namespaces.

Links

- https://github.com/iovisor/bcc
- https://github.com/iovisor/bpf-docs
- http://lwn.net/Articles/603984/
- http://lwn.net/Articles/603983/
- https://lwn.net/Articles/625224/
- https://www.kernel.org/doc/Documentation/networking/filter.txt
- http://man7.org/linux/man-pages/man2/bpf.2.html
- https://linuxplumbersconf.org/2015/ocw//system/presentations/3249/original/bpf_llvm_2015aug19.pdf
- https://videos.cdn.redhat.com/summit2015/presentations/13737_an-overview-of-linux-networking-subsystem-extended-bpf.pdf
- https://github.com/torvalds/linux/tree/master/samples/bpf
- https://suchakra.wordpress.com/2015/05/18/bpf-internals-i/
- https://suchakra.wordpress.com/2015/08/12/bpf-internals-ii/
- http://events.linuxfoundation.org/sites/events/files/slides/tracing-linux-ezannoni-linuxcon-ja-2015_0.pdf