2021-09-23

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BPF User Experience Rough Edges

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Agenda

What can go wrong when:

1. humans write BPF code (Jakub)
2. machines write BPF code (Arthur)

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BPF is great!

Our goals:

- ❏ share know-how
- ❏ trigger discussion
- ❏ show where help is needed

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Here is the story...

Meet our dev **buzz**

```
$ nstat
#kernel
IpInReceives                    238653             0.0
IpForwDatagrams                 54032              0.0
IpInDelivers                    182008             0.0
IpOutRequests                   280068             0.0
IpOutDiscards                   1454               0.0
IpOutNoRoutes                   2489               0.0
IcmpInMsgs                      198                0.0
IcmpInErrors                    5                  0.0
IcmpInDestUnreachs              197                0.0
IcmpInEchos                     1                  0.0
IcmpOutMsgs                     45                 0.0
...
```

... but per cgroup!

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Our benchmark for UX

1. create BPF map
2. load BPF program
3. create BPF link
4. pin BPF link
5. inspect attached program
6. read BPF map from user-space

Sad Panda if we run into problems

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Our test environments

```
vagrant@bullseye:~$ hostnamectl
…
  Operating System: Debian GNU/Linux 11 (bullseye)
            Kernel: Linux 5.10.0-8-amd64
      Architecture: x86-64
```

stable kernel

```
[vagrant@f34 ~]$ hostnamectl
Operating System: Fedora 34 (Cloud Edition)
     CPE OS Name: cpe:/o:fedoraproject:fedora:34
          Kernel: Linux 5.13.13-200.fc34.x86_64
    Architecture: x86-64
```

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Little helper to change UID and raise caps

```
#!/bin/bash
# -*- mode: shell-script -*-
#
# runas: Run command as given user with given capabilities.
#

readonly user="$1"
readonly caps="-all,$2"
shift 2

exec setpriv \
     --reuid=$user --regid=$user --clear-groups \
     --inh-caps=$caps --ambient-caps=$caps --bounding-set=$caps \
     --reset-env -- env PATH=/usr/sbin:/usr/bin "$@"
```

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It is similar to systemd service unit like

```
[Service]
…
User=buzz
Group=buzz
AmbientCapabilities=CAP_BPF CAP_NET_ADMIN CAP_SYS_RESOURCE
CapabilityBoundingSet=CAP_BPF CAP_NET_ADMIN CAP_SYS_RESOURCE
…
```

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(1) Creating a BPF map

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buzz needs a BPF map to count things!

```
int main(void)
{
    int fd = bpf_create_map_name(BPF_MAP_TYPE_ARRAY, "pkt_stats",
                                 /*key_size=*/ 4, /*value_size=*/ 8,
                                 /*max_entries=*/ 1, /*map_flags=*/ 0);
    if (fd < 0)
        error(EXIT_FAILURE, errno, "map create");

    close(fd);
    return EXIT_SUCCESS;
}
```

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Let's create a BPF map!

```
vagrant@bullseye:/lpc-2021$ make
cc -Wall -Wextra -ggdb -o 01/map-create 01/map_create.c -lbpf


vagrant@bullseye:/lpc-2021$ 01/map-create
./map-create: map create: Operation not permitted


vagrant@bullseye:/lpc-2021$ strace -e bpf 01/map-create
bpf(BPF_MAP_CREATE, {map_type=BPF_MAP_TYPE_ARRAY, key_size=4, value_size=8,
 max_entries=1, map_flags=0, inner_map_fd=0, map_name="pkt_stats", ...}, 120)
 = -1 EPERM (Operation not permitted)
01/map-create: map create: Operation not permitted
+++ exited with 1 +++
```

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Nowadays we should expect

```
$ /usr/sbin/sysctl kernel.unprivileged_bpf_disabled
kernel.unprivileged_bpf_disabled = 2

$ grep BPF_UNPRIV_DEFAULT_OFF /boot/config-5.10.0-8-amd64
CONFIG_BPF_UNPRIV_DEFAULT_OFF=y
```

unprivileged BPF disabled by default

need at least CAP_BPF

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Give me superpowers!

```
$ sudo 01/map-create
01/map-create: map create: Operation not permitted
```

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Where are my superpowers?

```
$ sudo perf ftrace -G '*sys_bpf' -g '*irq*' 01/map-create
...
# CPU  DURATION                  FUNCTION CALLS
# |     |   |                     |   |   |   |
 0)               |  __x64_sys_bpf() {
...
 0)               |    array_map_alloc() {
 0)               |      capable() {
 0)               |        security_capable() {
 0)   0.097 us    |          cap_capable();
 0)   0.102 us    |          apparmor_capable();
 0)   0.519 us    |        }
 0)   0.721 us    |      }
 0)               |      bpf_map_charge_init() {
 0)   0.142 us    |        free_uid();
 0)   0.417 us    |      }
 0)   1.590 us    |    }
 0) + 16.631 us   |  }
```

We only get this far

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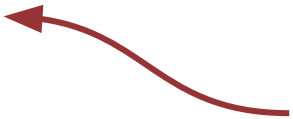
In Linux v5.10.46 LTS we have

```
int bpf_map_charge_init(struct bpf_map_memory *mem, u64 size)
{
    …
    user = get_current_user();
    ret = bpf_charge_memlock(user, pages);
    if (ret) {
        free_uid(user);
        return ret;
    }
    …
}
```



We saw this in ftrace output

`bpf_charge_memlock()` used to be `bpf_map_precharge_memlock()` in v4.19.

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Locked memory limit, of course 🤦

Debian Bullseye - 64 MiB

```
vagrant@bullseye:~$ sudo prlimit --memlock
RESOURCE DESCRIPTION                             SOFT     HARD UNITS
MEMLOCK  max locked-in-memory address space 67108864 67108864 bytes
```

Fedora 34 - 64 KiB

```
[vagrant@fedora ~]$ sudo prlimit --memlock
RESOURCE DESCRIPTION                           SOFT  HARD UNITS
MEMLOCK  max locked-in-memory address space 65536 65536 bytes
```

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How to check current memlock usage?

```
$ sudo bpftrace --btf -e '
> BEGIN {
>   printf("%ld bytes", curtask->cred->user->locked_vm.counter << 12);
>   exit();
> }'
Attaching 1 probe...
67158016 bytes
```

PAGE_SHIFT

we're slightly over 64 MiB

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Why are we over the limit?

Usage tracked per **user**, not per **task**.
But checked against a limit set per **task**.

Quota is shared between:

- BPF maps
- AF_XDP UMEM areas
- io_uring objects
- MSG_ZEROCOPY buffers
- perf event buffers

... created under the same **UID** (from task creds).

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Solution? No limit, no problem

```
$ sudo strace -e prlimit64 \
> bpftool map create /sys/fs/bpf/pkt_stats \
>   type array name pkt_stats \
>   key 4 value 8 entries 1
prlimit64(0, RLIMIT_MEMLOCK, {rlim_cur=RLIM64_INFINITY, rlim_max=RLIM64_INFINITY}, NULL) = 0
+++ exited with 0 +++
```

```
$ sudo strace -e bpf prlimit --memlock=unlimited ./map-create
bpf(BPF_MAP_CREATE, {map_type=BPF_MAP_TYPE_ARRAY, key_size=4, ...}, 120) = 3
+++ exited with 0 +++
```

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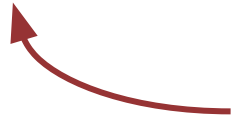
Perhaps a better solution? Dedicated UID

```
$ sudo bpftrace --btf -e '
> tracepoint:syscalls:sys_enter_geteuid {
>   printf("%ld bytes", curtask->cred->user->locked_vm.counter << 12);
> }' \
> -c '/usr/bin/setpriv --reuid=buzz id'
Attaching 1 probe...
uid=1001(buzz) gid=0(root) groups=0(root)
0 bytes
```



No allocations yet

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BPF map created 👌

```
$ sudo ./runas buzz +cap_39 strace -e bpf 01/map-create
bpf(BPF_MAP_CREATE, {map_type=BPF_MAP_TYPE_ARRAY, ...}, 120) = 3
+++ exited with 0 +++
```

UID != 0 and CAP_BPF (cap_39)

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Things changed in v5.11

BPF map allocations are now charged against **memory cgroup limit**

```
# mkdir /sys/fs/cgroup/test.slice
# echo $[32*1024*1024] > /sys/fs/cgroup/test.slice/memory.max
# echo $$ > /sys/fs/cgroup/test.slice/cgroup.procs

# bpftool map create /sys/fs/bpf/array_64M type array \
>         key 4 value $[64*1024] entries 1024 name array_64M
Error: map create failed: Cannot allocate memory
#

# echo $[128*1024*1024] > /sys/fs/cgroup/test.slice/memory.max
# bpftool map create /sys/fs/bpf/array_64M type array \
>         key 4 value $[64*1024] entries 1024 name array_64M
#
```

32 MiB limit

64 MiB map

128 MiB limit

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(2) Loading the BPF program

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Our little BPF program

```
SEC("cgroup_skb/ingress")
int count_pkts(struct __sk_buff *skb)
{
    __u32 key = STAT_IN_RECEIVES;
    __u64 *count = bpf_map_lookup_elem(&stats, &key);

    if (count)
        __sync_fetch_and_add(count, 1);

    return 1;
}
```

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Build it, load it

```
$ clang -O2 -g -fno-asynchronous-unwind-tables -Wall \
>       -target bpf -c 02/pkt_counter.c -o 02/pkt_counter.o
```

```
$ sudo ./runas buzz +bpf bpftool prog load 02/pkt_counter.o /sys/fs/bpf/pkt_counter
libbpf: Error in bpf_object__probe_loading():ERROR: strerror_r(524)=22(524). Couldn't
load trivial BPF program. Make sure your kernel supports BPF (CONFIG_BPF_SYSCALL=y)
and/or that RLIMIT_MEMLOCK is set to big enough value.
libbpf: failed to load object '02/pkt_counter.o'
Error: failed to load object file
```

it's not memlock, we're on v5.13

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Trace it, load it

```
$ sudo ./runas buzz +bpf \
> strace -o /tmp/prog_load.strace -e bpf \
> bpftool prog load 02/pkt_counter.o /sys/fs/bpf/pkt_counter
```

```
$ cat /tmp/prog_load.strace
bpf(BPF_PROG_LOAD, {prog_type=BPF_PROG_TYPE_SOCKET_FILTER, ...}, 120)
  = -1 ENOTSUPP (Unknown error 524)
+++ exited with 255 +++
```

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Trace it harder, load it

```
$ sudo perf ftrace -G '*sys_bpf' -g '*irq*' --graph-opts depth=6 \
> ./runas buzz +bpf \
> bpftool prog load 02/pkt_counter.o /sys/fs/bpf/pkt_counter \
> > /tmp/prog_load.ftrace
```

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Trace it harder - ftrace output

```
0)               |  __x64_sys_bpf() {
0)               |    bpf_prog_load() {
                          ...
0)               |      bpf_prog_select_runtime() {
0)   0.137 us    |        bpf_prog_alloc_jited_linfo();
0)               |        bpf_int_jit_compile() {
                            ...
0)               |          bpf_jit_binary_alloc() {
0)   0.350 us    |            bpf_jit_charge_modmem();
0)   0.673 us    |          }
                            ...
0)   0.492 us    |          kfree();
0)   6.658 us    |        }
0)               |        bpf_prog_jit_attempt_done() {
0)   0.333 us    |        }
0)   7.736 us    |      }
                       ...
```

failed?

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`bpf_jit_limit` - limit check for BPF JIT memory

```
int bpf_jit_charge_modmem(u32 pages)
{
    if (atomic_long_add_return(pages, &bpf_jit_current) >
        (bpf_jit_limit >> PAGE_SHIFT)) {
        if (!capable(CAP_SYS_ADMIN)) {
            atomic_long_sub(pages, &bpf_jit_current);
            return -EPERM;
        }
    }

    return 0;
}
```

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Are we over `bpf_jit_limit`?

```
$ sudo sysctl net.core.bpf_jit_limit
net.core.bpf_jit_limit = 1048576
```

1 MiB, set just for test (default 252 MiB)

```
$ sudo bpftrace -e '
> BEGIN {
>   printf("%ld", *kaddr("bpf_jit_current") << 12);
>   exit();
> }'
Attaching 1 probe...
1294336
```

> 1 MiB

Why are we over the limit?

```
$ for ((i = 0; i < 100; i++)); do
>   sudo iptables -A OUTPUT -m bpf --bytecode '4,48 0 0 9,21 0 1 6,6 0 0 1,6 0 0 0' -j ACCEPT
> done
```

```
$ sudo iptables -vnL OUTPUT | head -10
Chain OUTPUT (policy ACCEPT 6 packets, 456 bytes)
 pkts bytes target     prot opt in     out     source               destination
  260 23280 ACCEPT     all  --  *      *       0.0.0.0/0            0.0.0.0/0            match bpf 48 0 0 9,21 0 1 6,6 0 0 1,6 0 0 0
    0     0 ACCEPT     all  --  *      *       0.0.0.0/0            0.0.0.0/0            match bpf 48 0 0 9,21 0 1 6,6 0 0 1,6 0 0 0
    0     0 ACCEPT     all  --  *      *       0.0.0.0/0            0.0.0.0/0            match bpf 48 0 0 9,21 0 1 6,6 0 0 1,6 0 0 0
    0     0 ACCEPT     all  --  *      *       0.0.0.0/0            0.0.0.0/0            match bpf 48 0 0 9,21 0 1 6,6 0 0 1,6 0 0 0
    0     0 ACCEPT     all  --  *      *       0.0.0.0/0            0.0.0.0/0            match bpf 48 0 0 9,21 0 1 6,6 0 0 1,6 0 0 0
    0     0 ACCEPT     all  --  *      *       0.0.0.0/0            0.0.0.0/0            match bpf 48 0 0 9,21 0 1 6,6 0 0 1,6 0 0 0
    0     0 ACCEPT     all  --  *      *       0.0.0.0/0            0.0.0.0/0            match bpf 48 0 0 9,21 0 1 6,6 0 0 1,6 0 0 0
    0     0 ACCEPT     all  --  *      *       0.0.0.0/0            0.0.0.0/0            match bpf 48 0 0 9,21 0 1 6,6 0 0 1,6 0 0 0
```

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Why are we hitting the limit?

All BPF programs are charged:

- progs loaded with `bpf(BPF_PROG_LOAD)`
- `seccomp` programs (auto cBPF to BPF translation)
- iptables `xt_bpf` programs (auto cBPF to BPF translation)

Limit is **not** per-netns! **`bpf_jit_limit`** is global.

[bpf] bpf_jit_limit close shave

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(3) Creating a BPF link

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Attach it, but not the “old” way

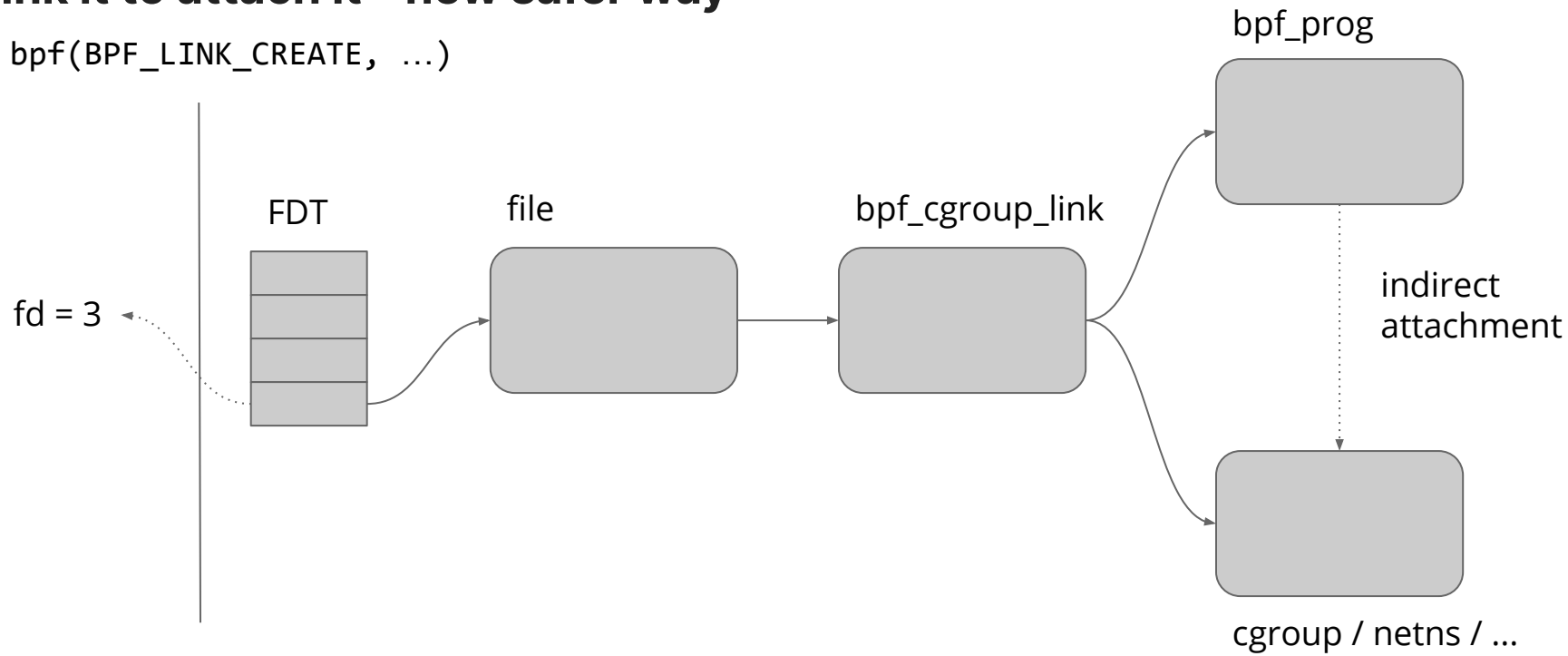
```
$ sudo bpftool prog load ./pkt_counter.o /sys/fs/bpf/pkt_counter
```

```
$ sudo strace -e bpf \
> bpftool cgroup attach /sys/fs/cgroup/test.slice/ ingress pinned /sys/fs/bpf/pkt_counter
bpf(BPF_OBJ_GET, {pathname="/sys/fs/bpf/pkt_counter", bpf_fd=0, file_flags=0}, 120) = 4
bpf(BPF_PROG_ATTACH, {target_fd=3, attach_bpf_fd=4, attach_type=BPF_CGROUP_INET_INGRESS,
attach_flags=0, replace_bpf_fd=0}, 120) = 0
```

discouraged and unsupported by newer prog types

Link it to attach it - new safer way

```
bpf(BPF_LINK_CREATE, ...)
```



link FD closed ⇒ (1) program detached, (2) program destroyed

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buzz needs a tool to create a BPF link

```
/* (1) Open a cgroup FD */
cg_fd = open("/sys/fs/cgroup/…", O_DIRECTORY | O_RDONLY);

/* (2) Create BPF map, load BPF program using BPF skeleton */
obj = pkt_counter__open_and_load();

/* (3) Attach BPF program to cgroup */
link = bpf_program__attach_cgroup(obj->progs.prog, cg_fd);

/* (4) Pin BPF link */
err = bpf_link__pin(link, "/sys/fs/bpf/…");
```

bpftool *can't do this yet*

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(4) Pinning BPF link

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buzz wants to pin a link. But where?

```
buzz@bullseye:~$ ls -ld /sys/fs/bpf
drwx-----T 2 root root 0 Sep 12 10:02 /sys/fs/bpf
```

only root has access

systemd/src/core/mount-setup.c:

```
static const MountPoint mount_table[] = {
    …
    { "bpf", "/sys/fs/bpf", "bpf", "mode=700", MS_NOSUID|MS_NOEXEC|MS_NODEV, …
    …
};
```

[systemd] bpf: mount bpffs by default on boot
[systemd] mount-setup: change bpf mount mode to 0700

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Best practice - dedicated BPF fs instance

```
$ sudo mkdir -p /run/mount/bpf/pkt_counter
$ sudo mount -t bpf -o uid=buzz,gid=buzz,mode=0700 none /run/mount/bpf/pkt_counter
$ ls -ld /run/mount/bpf/pkt_counter
drwx-----T. 2 root root 0 Sep 13 09:12 /run/mount/bpf/pkt_counter
```

bpf file system doesn't understand **uid=** *and* **gid=** *options*

```
$ sudo chown buzz.buzz /run/mount/bpf/pkt_counter
```

..., but systemd **.mount** *units don't support* **User=** *or* **Group=** *options*

[bpf] Can we share /sys/fs/bpf like /tmp?

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(5) Inspecting the attached program

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buzz wants to examine the attached prog

Why would want to do that?

- ❏ find which maps prog is using
- ❏ read prog tag

```
$ sudo ./runas buzz +bpf bpftool link show pinned /run/mount/bpf/pkt_counter/link
23: cgroup  prog 256
        cgroup_id 4966  attach_type ingress
```

```
$ sudo ./runas buzz +bpf bpftool prog show id 256
Error: get by id (256): Operation not permitted
```

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What is stopping us?

```
$ strace -e bpf bpftool prog show id 256
…
bpf(BPF_PROG_GET_FD_BY_ID, {prog_id=256, next_id=0, open_flags=0}, 120) = -1 EPERM
(Operation not permitted)
Error: get by id (256): Operation not permitted
+++ exited with 255 +++
```

```
static int bpf_prog_get_fd_by_id(const union bpf_attr *attr)
{
    …
    if (!capable(CAP_SYS_ADMIN)) // 👈
        return -EPERM;
    …
}
```

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Can’t get from link FD to prog

```
$ sudo bpftool prog show id 256
256: cgroup_skb  name count_pkts  tag 42341c82f6736baa  gpl
        loaded_at 2021-09-09T10:12:59+0000  uid 1001 ⇦ this is us 🐝
        xlated 160B  jited 95B  memlock 4096B  map_ids 103
        btf_id 271
```

kernel knows buzz *created the program!*

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Workaround? Pin links, progs, and maps

```
$ ls -l /run/mount/bpf/pkt_counter
total 0
-rw-------. 1 buzz buzz 0 Sep 22 16:28 link
-r--------. 1 root root 0 Sep 22 10:59 maps.debug
-rw-------. 1 buzz buzz 0 Sep 22 16:28 prog
-r--------. 1 root root 0 Sep 22 10:59 progs.debug
-rw-------. 1 buzz buzz 0 Sep 22 16:28 stats
```

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(6) Reading from a BPF map in user-space

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buzz wants a metrics scraper read BPF map

```
$ chmod o+r /run/mount/bpf/pkt_counter/stats
$ ls -l /run/mount/bpf/pkt_counter/stats
-rw----r--. 1 buzz buzz 0 Sep 15 16:51 /run/mount/bpf/pkt_counter/stats
```

give read access to anyone

```
$ chmod o+x /run/mount/bpf/pkt_counter
$ ls -ld /run/mount/bpf/pkt_counter
drwx-----t. 2 buzz buzz 0 Sep 15 16:51 /run/mount/bpf/pkt_counter
```

make bpf fs instance accessible by anyone

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Can the scraper read it?

```
$ sudo ./runas scraper +bpf bpftool map dump pinned /run/mount/bpf/pkt_counter/stats
Error: bpf obj get (/run/mount/bpf/pkt_counter): Permission denied
```

what is failing?

```
$ sudo ./runas scraper +bpf strace -e bpf \
> bpftool map dump pinned /run/mount/bpf/pkt_counter/stats
bpf(BPF_OBJ_GET, {pathname="/run/mount/bpf/pkt_counter/stats", bpf_fd=0,
file_flags=0}, 120) = -1 EACCES (Permission denied)
Error: bpf obj get (/run/mount/bpf/pkt_counter): Permission denied
```

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Where are we failing?

```
$ sudo perf ftrace -G '*sys_bpf' -g '*irq*' --graph-opts depth=3 \
> ./runas scraper +bpf bpftool map dump pinned …
 0)               |  __x64_sys_bpf() {
…
 0)               |    bpf_obj_get_user() {
 0)   0.505 us    |      bpf_get_file_flag();
 0)               |      user_path_at_empty() {
 0) ! 259.191 us  |      }
 0)   4.750 us    |      inode_permission();
 0)               |      path_put() {
 0) ! 102.123 us  |      }
 0) ! 429.527 us  |    }
 0) ! 493.568 us  |  }
```

suspect?

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Where are we failing?

```
static void *bpf_obj_do_get(const struct filename *pathname,
                            enum bpf_type *type, int flags)
{
    …
    inode = d_backing_inode(path.dentry);
    ret = inode_permission(inode, ACC_MODE(flags));
    if (ret)
        goto out;
    …
}
```

flags come from `attr->file_flags`

passed to `BPF_OBJ_GET`

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What is flags set to?

```
int bpf_get_file_flag(int flags)
{
    if ((flags & BPF_F_RDONLY) && (flags & BPF_F_WRONLY))
        return -EINVAL;
    if (flags & BPF_F_RDONLY)
        return O_RDONLY;
    if (flags & BPF_F_WRONLY)
        return O_WRONLY;
    return O_RDWR;
}
```

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`bpftool map dump` requests RW access

```
$ strace -e bpf bpftool map dump pinned /run/mount/bpf/pkt_counter/stats
bpf(BPF_OBJ_GET, {pathname="/run/mount/bpf/pkt_counter/stats", bpf_fd=0,
file_flags=0}, 120) = -1 EACCES (Permission denied)
Error: bpf obj get (/run/mount/bpf/pkt_counter): Permission denied
+++ exited with 255 +++
```

Need to write a custom dumper.

Easy?

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Dumping a read-only BPF map

libbpf doesn't support setting `file_flags`

must call `bpf()` *syscall directly*

```
union bpf_attr attr = {};

attr.pathname = (uintptr_t)map_path;
attr.file_flags = BPF_F_RDONLY;
map_fd = syscall(SYS_bpf, BPF_OBJ_GET, &attr, sizeof(attr));
if (map_fd < 0)
    error(EXIT_FAILURE, errno, "BPF_OBJ_GET");
```

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After making panda sad 9 times...

```
$ sudo systemd-run --unit pinger --uid=buzz --gid=buzz ping 1.1.1.1
Running as unit: pinger.service


$ sudo ./runas buzz +bpf,+net_admin 05/attach-pkt-counter \
> /sys/fs/cgroup/system.slice/pinger.service /run/mount/bpf/pkt_counter
Pinned map at /run/mount/bpf/pkt_counter/stats
Pinned prog at /run/mount/bpf/pkt_counter/prog
Pinned link at /run/mount/bpf/pkt_counter/link
Attached to cgroup /sys/fs/cgroup/system.slice/pinger.service


$ sudo ./runas scraper +bpf 06/map-dump /run/mount/bpf/pkt_counter/stats
111
$ sudo ./runas scraper +bpf 06/map-dump /run/mount/bpf/pkt_counter/stats
112
```

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Why is panda sad today?

- distros disable unprivileged BPF by default
- per-user locked memory limit can make `BPF_MAP_CREATE` fail (LTS kernel only)
- kernel global JIT memory limit can make `BPF_PROG_LOAD` fail
- `bpftool` can't create BPF links
- systemd limits `/sys/fs/bpf` access to root only
- can't set default owner when mounting `bpf` file system
- can't query programs loaded by the user by prog ID
- `bpftool map dump` requests read+write access by default
- libbpf `BPF_OBJ_GET` wrapper doesn't support `file_flags`

Links

Code:
https://github.com/jsitnicki/lpc-2021-bpf-ux-bench

Email: jakub@cloudflare.com
Twitter: @jkbs0

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Sad Panda image from Hana Emojis Panda Edition Collection licensed under CC BY 3.0

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Autogenerated BPF

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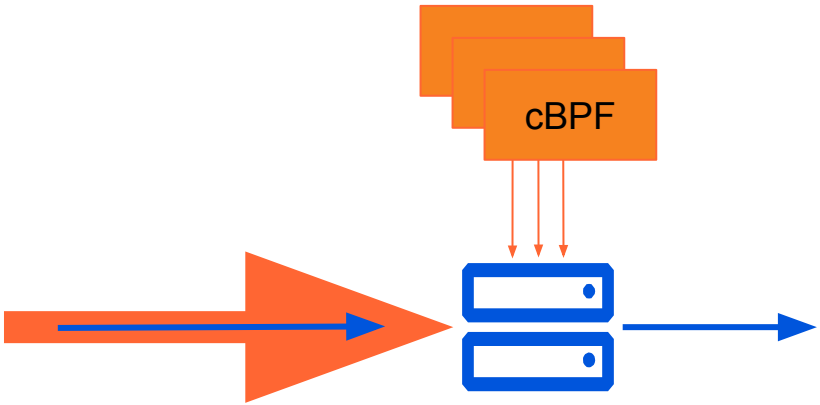
DDOS

- Drop DDOS packets
- Mitigation system generates classic BPF
  - What libpcap / tcpdump uses
  - Matching packets should be dropped



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cBPF

- Very flexible
- Sources:
  - libpcap
  - Custom generators
  - Handwritten
- Run as:
  - iptables with xt_bpf
  - XDP with cbpfc
    - Compile cBPF to C
    - C to eBPF with clang

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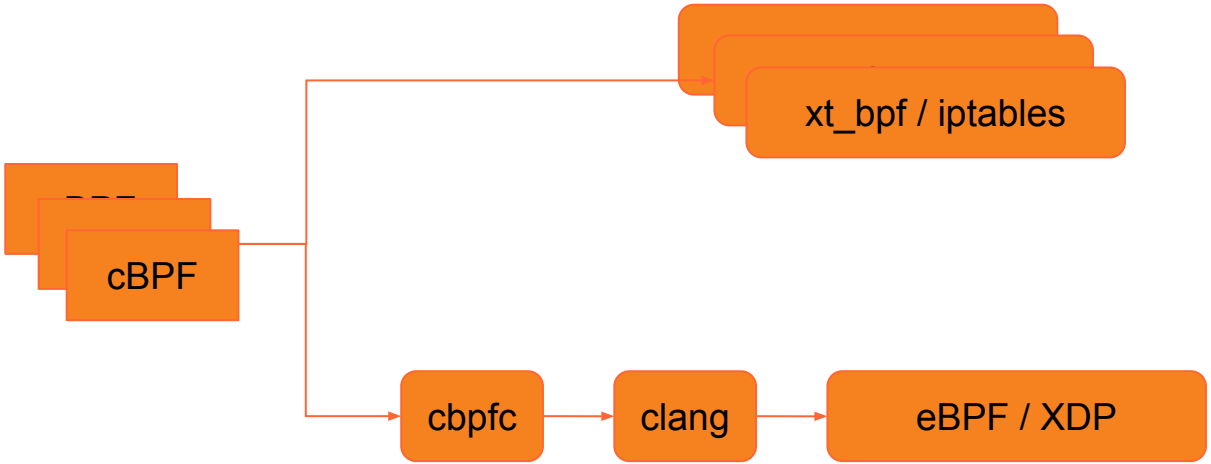
cBPF



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Failures

- Rejected by verifier
  - Guard packet accesses:

```
if (data + x > data_end) return 0;
```

  - Check division by 0:

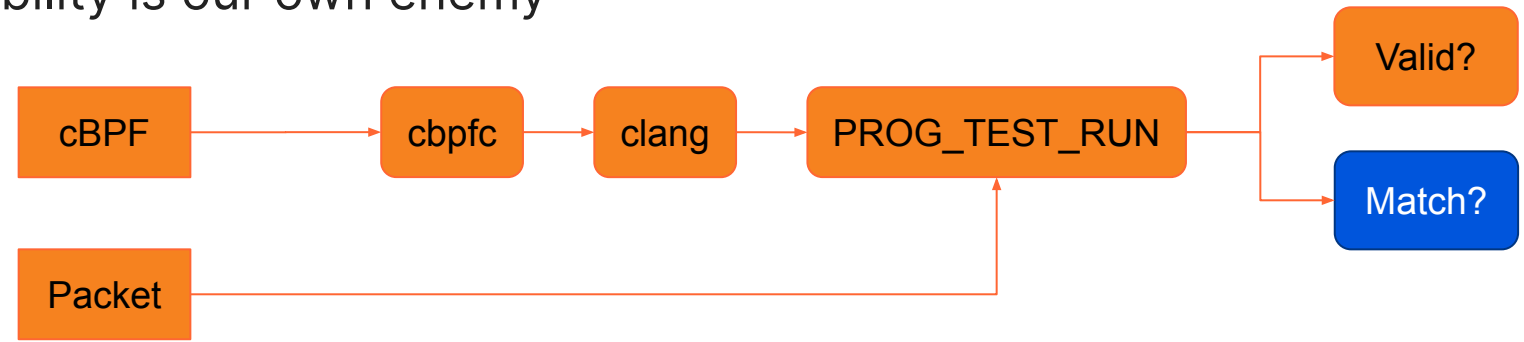
```
if (x == 0) return 0;
```

  - Hardest part
  - Blocks DDOS mitigations
- Incorrect behavior
  - Drop wrong packets
  - Hard to notice

CLOUDFLARE

Testing

- Unit tests to cover known rules
- Verifier: `BPF_PROG_LOAD`
- Correctness: `BPF_PROG_TEST_RUN`
  - Specially crafted packets as input
- Can only cover so much
  - Flexibility is our own enemy



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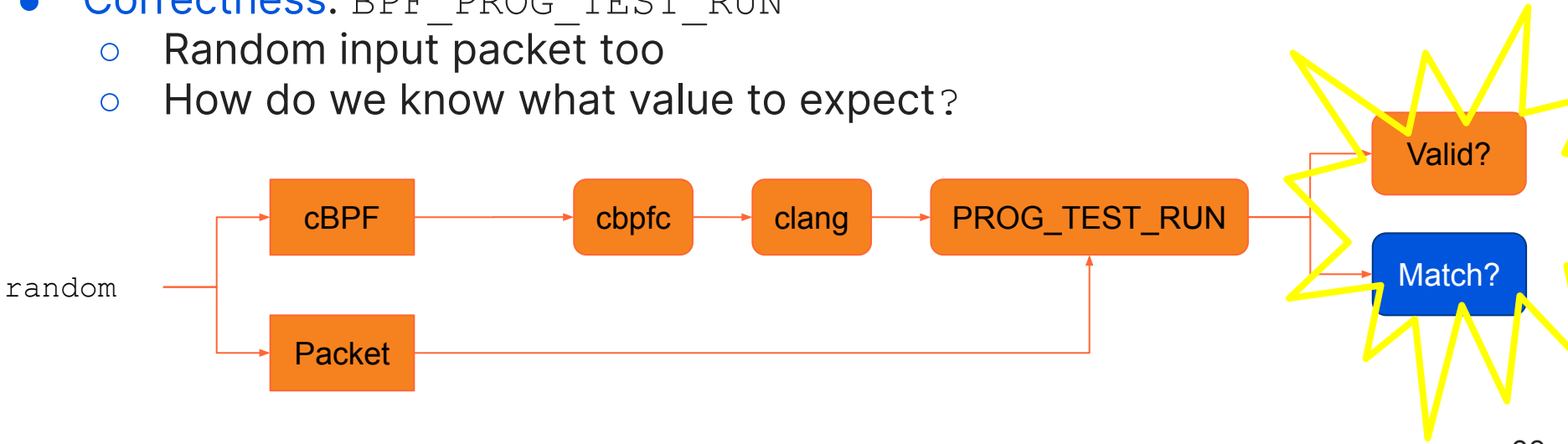
Testing Unknowns

- Random cBPF instructions
- Verifier: `BPF_PROG_LOAD`
  - How do we know if cBPF is valid?
- Correctness: `BPF_PROG_TEST_RUN`
  - Random input packet too
  - How do we know what value to expect?



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Testing Unknowns

- Compare to reference implementation!
  - Attach cBPF to unix socket as socket filter
- Verifier: `BPF_PROG_LOAD`
  - Same result as attaching socket filter
- Correctness: `BPF_PROG_TEST_RUN`
  - Run packet through unix socket:
    - Packet dropped: no match
    - Packet passed: match

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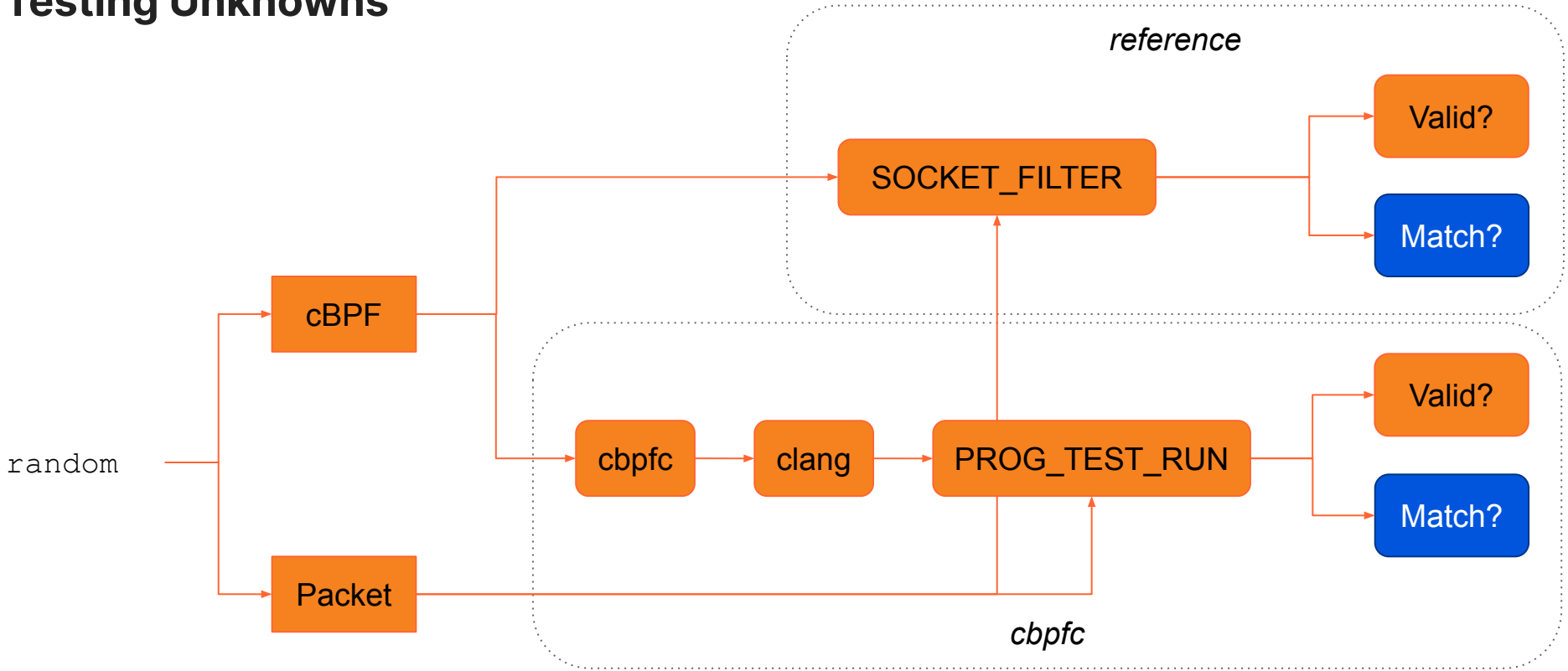
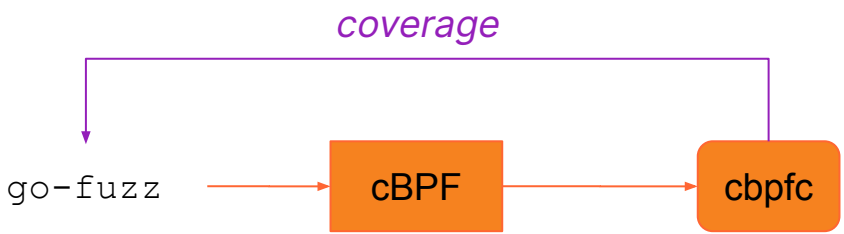
Testing Unknowns



CLOUDFLARE

Fuzzing

- One step away from fuzzing!
- go-fuzz



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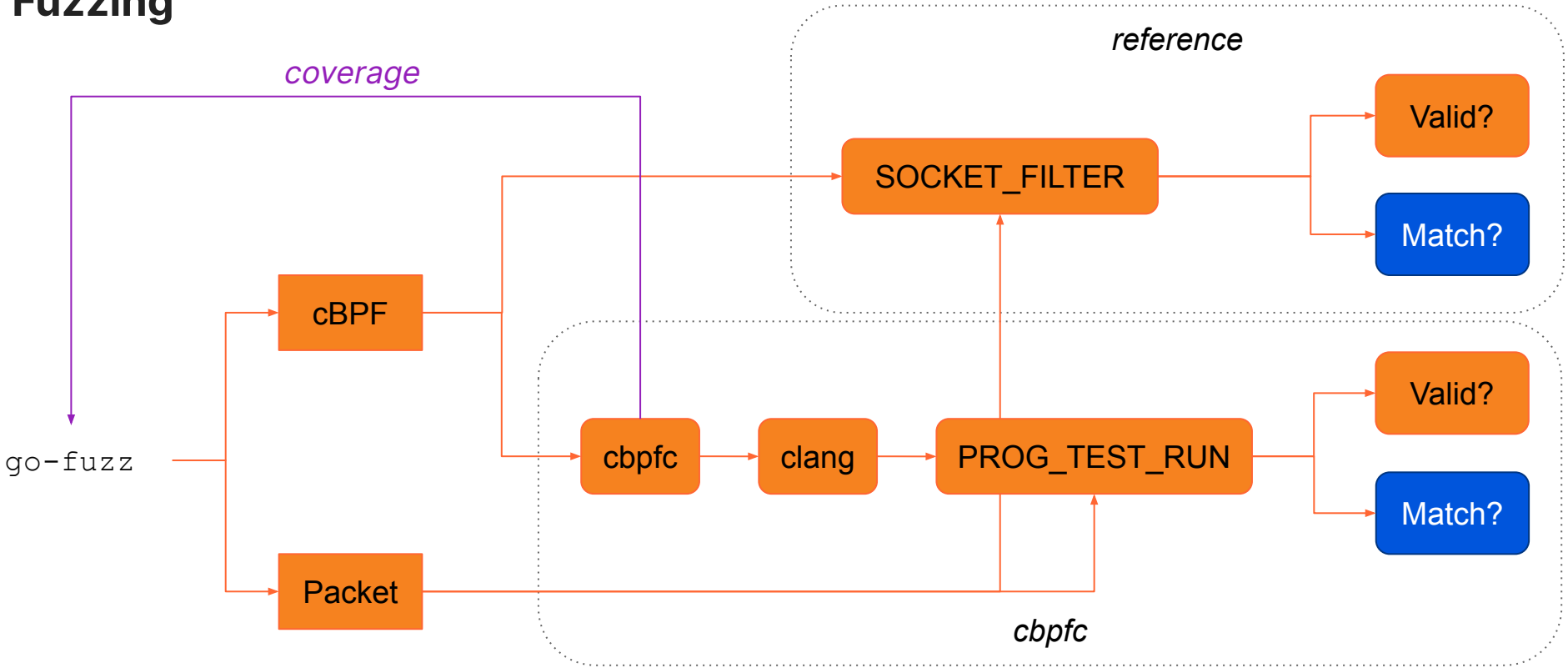
Fuzzing



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Fuzzing

- Slow
- Time to first bug: ~ days

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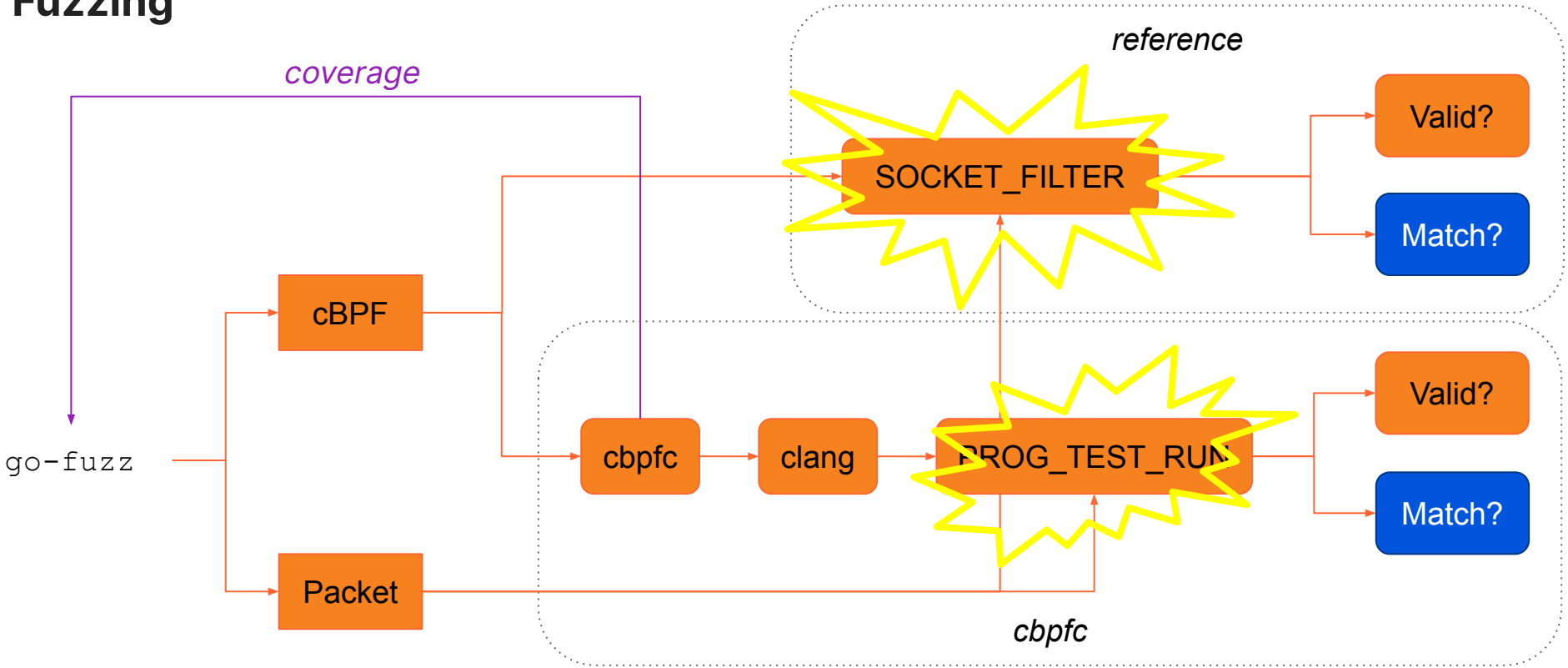
Fuzzing



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KCOV

- Collect kernel code coverage
  - https://www.kernel.org/doc/html/v5.0/dev-tools/kcov.html
- Can read covered PCs from userspace
  - `/sys/kernel/debug/kcov`
- Powers syzkaller
- Replace go-fuzz with libFuzzer

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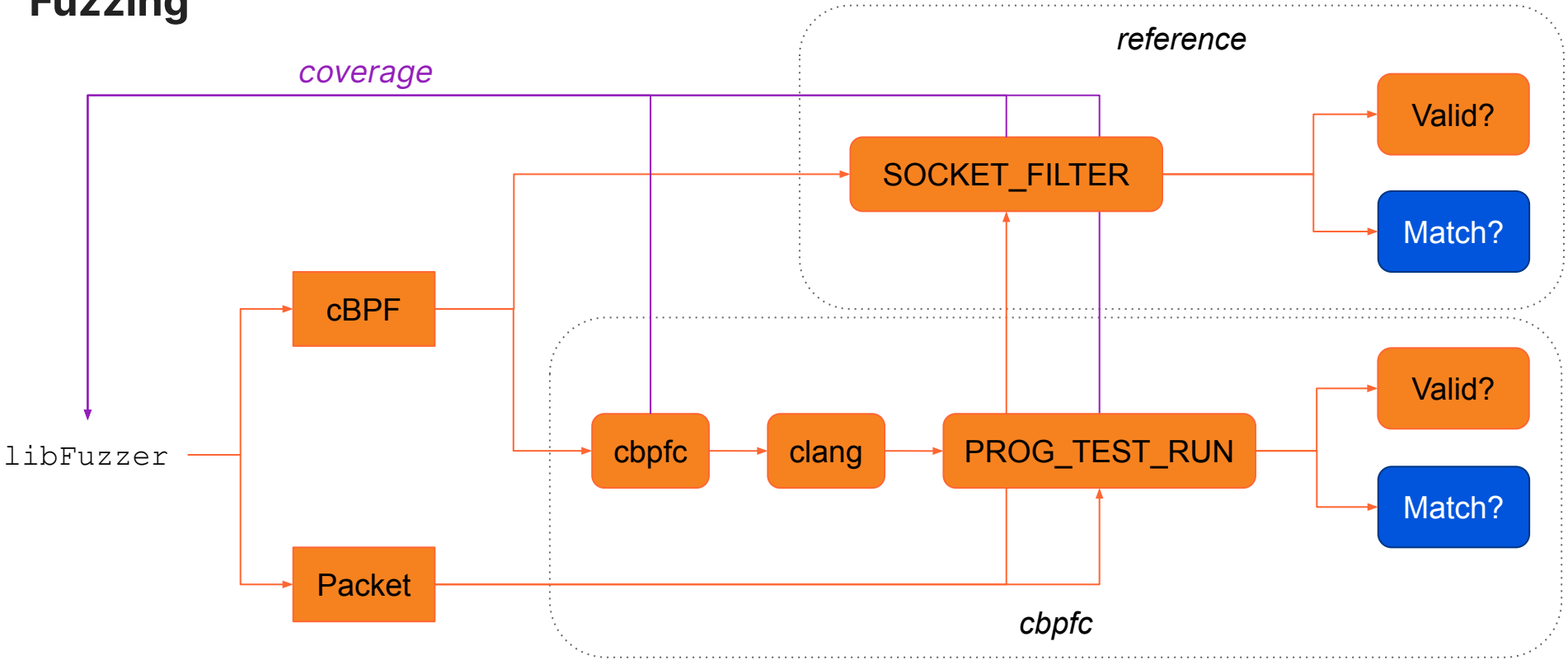
Fuzzing



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Fuzzing

- libFuzzer with userspace and kernel coverage
- Time to first bug: ~ minutes

- Trophies:
  - Missing packet bounds check
  - Missing overflow check
    - Packet offsets need to be `< 2^16`

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Clang Optimizations: Packet Bounds

- Challenge: read last byte of packet!

```
uint8_t *data = (uint8_t *)(long)ctx->data;
uint8_t *data_end = (uint8_t *)(long)ctx->data_end;

size_t size = data_end - data;

if (data + size > data_end) {
    return 0;
}

uint8_t last = *(data + size - 1);
return last;
```

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Clang Optimizations: Packet Bounds

- Challenge: read last byte of packet!

```
0: (b4) w0 = 0
; uint8_t *data_end = (uint8_t *)(long)ctx->data_end;
1: (61) r1 = *(u32 *)(r1 +4)
; if (data + size > data_end) {
2: (2d) if r1 > r1 goto pc+1
R0_w=inv0 R1_w=pkt_end(id=0,off=0,imm=0) R10=fp0
; uint8_t last = *(data + size - 1);
3: (71) r0 = *(u8 *)(r1 -1)
R1 invalid mem access 'pkt_end'
```

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Clang Optimizations: Packet Bounds

- Not clear how to fix this
- Magic annotation so clang doesn’t optimize bounds checks?
  - But optimizations are useful sometimes

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Register Mirroring

```
25: (bf) r4 = r3
R2=pkt(...) R3=inv(id=3) R4_w=inv(id=3)
26: (67) r4 <<= 32
27: (77) r4 >>= 32
R2=pkt(...) R3=inv(id=3) R4_w=inv(id=0,umax_value=4294967295)
; if (x >= 65467 || data + x + 68 > data_end) return 0;
29: (25) if r4 > 0xffba goto pc+15
R2=pkt(...) R3=inv(id=3) R4_w=inv(id=0,umax_value=65466)
; if (x >= 65467 || data + x + 68 > data_end) return 0;
30: (67) r3 <<= 32
31: (77) r3 >>= 32
R2=pkt(...) R3_w=inv(id=0,umax_value=4294967295)
R4_w=inv(id=0,umax_value=65466)
```

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Register Mirroring

- Clang is “correct”
- Should verifier figure out regs are the same?
  - Seems hard
- Explicit casts / using uint64 directly doesn’t help

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Direct eBPF

- Is a world without clang better?
- Generate eBPF directly
  - More predictable
  - Can still link to handwritten C

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Invalid Values

```
R2=pkt(...)
5:   (71) r5 = *(u8 *)(r2 +14)
7:   (b4) r4 = 512
R2=pkt(...) R4=inv512 R5=inv(umax_value=255)
8:   (2d) if r4 > r5 goto pc+8
R2=pkt(...) R4=inv512 R5=inv(umin_value=512,umax_value=255)
11: (0f) r2 += r5
R2=inv(id=0) R5=invP(umin_value=512,umax_value=255)
15: (61) r4 = *(u32 *)(r2 +14)
R7 invalid mem access 'inv'
```

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Invalid Values

- Code is nonsensical
  - Doesn’t happen with clang, only direct to eBPF
- But legal?
  - Other languages would allow this
- Fix verifier to allow this?
- Or deal with it in userspace?

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Fuzzing Challenges

- Hard to suppress errors
  - Verifier output is always different
  - Too many errors to keep fuzzing C
    - Suppress based on PCs?
- How well does KCOV work for JIT vs interpreter?

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Info

- clang-13
- Kernel 5.10.64
- Test cases: https://github.com/arthurfabre/lpc-2021
- https://github.com/cloudflare/cbpfc
  - Fuzzing PR

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Thank you