Two bugs with one PoC: Rooting Pixel 6 from Android 12 to Android 13

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Whoami

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- Focus on Android/Chrome vulnerability
- BlackHat{ASIA/EU/USA}/HITBAMS/Zer0Con/POC/CanSecWest
- Nominated at Pwnie Award 2019(Best Privilege Escalation)

Agenda

- Introduction
- Bug #1
- Bug #2
- Conclusion

Android kernel mitigations 101

- Android 12/13 – kernel 5.10(5.15)
  - PXN - Privileged eXecute Never
  - PAN - Privileged Access Never
  - UAO - User Access Override
  - PAC - Pointer Authentication Code
  - MTE - Memory Tagging Extension
  - KASLR - Kernel Address Space Layout Randomization
  - CONFIG_DEBUG_LIST
  - CONFIG_SLAB_FREELIST_RANDOM/HARDENED
  - # CONFIG_SLAB_MERGE_DEFAULT is not set
  - CONFIG_BPF_JIT_ALWAYS_ON

User Access Override

- Without UAO, corrupting addr_limit of thread_info is the only step to gain AARW
  - AAR: write(pipefd[1], kbuf, count);/read(pipefd[0], ubuf, count);
  - AAW: write(pipefd[1], ubuf, count);/read(pipefd[0], kbuf, count);

User Access Override

- Without UAO, corrupting addr_limit of thread_info is the only step to gain AARW
  - AAR: write(pipefd[1], kbuf, count);/read(pipefd[0], ubuf, count);
  - AAW: write(pipefd[1], ubuf, count);/read(pipefd[0], kbuf, count);
- UAO state
  - KERNEL_DS(-1), enabled
  - Other, disabled

```
/* Restore the UAO state depending on next's addr_limit */
void uao_thread_switch(struct task_struct *next)
{
        if (IS_ENABLED(CONFIG_ARM64_UAO)) {
                if (task_thread_info(next)->addr_limit == KERNEL_DS)
                        asm(ALTERNATIVE("nop", SET_PSTATE_UAO(1), ARM64_HAS_UAO));
                else
                        asm(ALTERNATIVE("nop", SET_PSTATE_UAO(0), ARM64_HAS_UAO));
        }
}
```

CONFIG_DEBUG_LIST

```c
static inline void __list_add(struct list_head *new,
                              struct list_head *prev,
                              struct list_head *next)
{
    if (!__list_add_valid(new, prev, next))
        return;

    next->prev = new;
    new->next = next;
    new->prev = prev;
    WRITE_ONCE(prev->next, new);
}
```

```c
static inline void __list_del_entry(struct list_head *entry)
{
    if (!__list_del_entry_valid(entry))
        return;

    __list_del(entry->prev, entry->next);
}
```

```c
bool __list_add_valid(struct list_head *new, struct list_head *prev,
                      struct list_head *next)
{
    if (CHECK_DATA_CORRUPTION(next->prev != prev,
            "list_add corruption. next->prev should be prev (%px), but was %px. (next=%px).\n",
            prev, next->prev, next) ||
        CHECK_DATA_CORRUPTION(prev->next != next,
            "list_add corruption. prev->next should be next (%px), but was %px. (prev=%px).\n",
            next, prev->next, prev) ||
        CHECK_DATA_CORRUPTION(new == prev || new == next,
            "list_add double add: new=%px, prev=%px, next=%px.\n",
            new, prev, next))
        return false;

    return true;
}
EXPORT_SYMBOL(__list_add_valid);

bool __list_del_entry_valid(struct list_head *entry)
{
    struct list_head *prev, *next;

    prev = entry->prev;
    next = entry->next;

    if (CHECK_DATA_CORRUPTION(next == LIST_POISON1,
            "list_del corruption, %px->next is LIST_POISON1 (%px)\n",
            entry, LIST_POISON1) ||
        CHECK_DATA_CORRUPTION(prev == LIST_POISON2,
            "list_del corruption, %px->prev is LIST_POISON2 (%px)\n",
            entry, LIST_POISON2) ||
        CHECK_DATA_CORRUPTION(prev->next != entry,
            "list_del corruption. prev->next should be %px, but was %px\n",
            entry, prev->next) ||
        CHECK_DATA_CORRUPTION(next->prev != entry,
            "list_del corruption. next->prev should be %px, but was %px\n",
            entry, next->prev))
        return false;

    return true;

}
EXPORT_SYMBOL(__list_del_entry_valid);
```

CONFIG_SLAB_FREELIST_RANDOM

Without randomization

With randomization

CONFIG_SLAB_FREELIST_HARDENED

```
static inline void *freelist_ptr(const struct kmem_cache *s, void *ptr,
                 unsigned long ptr_addr)
{
#ifdef CONFIG_SLAB_FREELIST_HARDENED
    /*
     * When CONFIG_KASAN_SW/HW_TAGS is enabled, ptr_addr might be tagged.
     * Normally, this doesn't cause any issues, as both set_freepointer()
     * and get_freepointer() are called with a pointer with the same tag.
     * However, there are some issues with CONFIG_SLUB_DEBUG code. For
     * example, when __free_slub() iterates over objects in a cache, it
     * passes untagged pointers to check_object(). check_object() in turns
     * calls get_freepointer() with an untagged pointer, which causes the
     * freepointer to be restored incorrectly.
     */
    return (void *)((unsigned long)ptr ^ s->random ^
            swab((unsigned long)kasan_reset_tag((void *)ptr_addr)));
#else
    return ptr;
#endif
}
```

CONFIG_SLAB_MERGE_DEFAULT is not set

Heap isolation

```
FFFFFFC010508BC0                    EXPORT __kmem_cache_alias
FFFFFFC010508BC0 __kmem_cache_alias
FFFFFFC010508BC0                    PACIASP
FFFFFFC010508BC4                    MOV             X0, XZR
FFFFFFC010508BC8                    AUTIASP
FFFFFFC010508BCC                    RET
FFFFFFC010508BCC ; End of function __kmem_cache_alias
```

Pixel 6 kernel image

- No dedicated cache will be merged into a general cache.
- Different types of objects explicitly allocated from kmalloc-N still share the same cache.
- Cross-cache attack techniques have to be applied to make different types of objects share the same memory.

https://i.blackhat.com/USA-22/Thursday/US-22-WANG-Ret2page-The-Art-of-Exploiting-Use-After-Free-Vulnerabilities-in-the-Dedicated-Cache.pdf

CONFIG_BPF_JIT_ALWAYS_ON

The ultimate ROP

Finally, it's time to consider our ROP payload. Because we can write at most 15 distinct 64-bit values into the stack via our overflow (2 of which we've already used), we'll need to be careful about keeping the ROP payload small.

When I mentioned this progress to Jann, he suggested that I check the function `___bpf_prog_run()`, which he described as the ultimate ROP gadget. And indeed, if your kernel has it compiled in, it does appear to be the ultimate ROP gadget!

`___bpf_prog_run()` is responsible for interpreting eBPF bytecode that has already been deemed safe by the eBPF verifier. As such, it provides a number very powerful primitives, including:

1. arbitrary control flow in the eBPF program;
2. arbitrary memory load;
3. arbitrary memory store;
4. arbitrary kernel function calls with up to 5 arguments and a 64-bit return value.

https://googleprojectzero.blogspot.com/2020/12/an-ios-hacker-tries-android.html

Google Tensor

		First-generation (2021)	Second-generation (2022)
SoC	Model number	GS101 (S5P9845)[15][23]	GS201 (S5P9855)[24][25]
	Codename	Whitechapel[15]	Cloudripper[24]
	Manufacturer	Samsung Electronics[15]	?
	Fabrication	5 nm LPE[6][26]	5 nm[27][28]
CPU	ISA	ARMv8.2-A[29]	?
	Bit width	64-bit[29]	64-bit[30]
	μarch	Octa-core:[21][6] 2.8 GHz Cortex-X1 (2×) 2.25 GHz Cortex-A76 (2×) 1.8 GHz Cortex-A55 (4×)	Octa-core:[31] 2.85 GHz Cortex-X1 (2×) 2.35 GHz Cortex-A78 (2×) 1.8 GHz Cortex-A55 (4×)
	Security	TrustZone (Trusty OS)[32]	TrustZone (Trusty OS)[33]
GPU	μarch	Mali-G78 MP20[6][21]	Mali-G710 MP7[31]
	Frequency	848 MHz[26]	?
RAM	Type	LPDDR5[26]	LPDDR5[31]
	Bus width	4×16-bit quad-channel[26]	?
	Bandwidth	51.2 GB/s[26]	?
ISP	NPU	edgeTPU[26]	edgeTPU[33]
	Storage type	UFS 3.1[34][35]	UFS 3.1[36][37]
Connectivity	Modem	Exynos 5123[26]	Exynos 5300[38]
	Wireless	Wi-Fi 6 and Wi-Fi 6E[34][35]	Wi-Fi 6[36][37]
		Bluetooth 5.2[34][35]	Bluetooth 5.2[36][37]
	Navigation	Dual-band GNSS[34][35]	Dual-band GNSS[36][37]

https://en.wikipedia.org/wiki/Google_Tensor

Android LPE attack surfaces

- DAC
  - ptmx (root root 0o666) ptmx_device
  - tty (root root 0o666) owntty_device
  - system (system system 0o664) dmabuf_system_heap_device
  - ashmem (root root 0o666) ashmem_device
  - binder(root root 0o777) binder_device
  - kgsl-3d0 (system system 0o666) gpu_device / mali0 (system system 0o664) gpu_device

- SELinux policy
  - ALLOW domain-->ptmx_device (chr_file) [map append write ioctl watch_reads getattr read watch lock open]
  - ALLOW domain-->owntty_device (chr_file) [map append write ioctl watch_reads getattr read watch lock open]
  - ALLOW domain-->ashmem_device (chr_file) [map append write ioctl getattr read lock]
  - ALLOW untrusted_app-->dmabuf_system_heap_device (chr_file) [map ioctl watch_reads getattr read watch lock open]
  - ALLOW untrusted_app-->binder_device (chr_file) [map ioctl watch_reads getattr read watch lock open]
  - ALLOW untrusted_app-->gpu_device (chr_file) [map ioctl watch_reads getattr read watch lock open]

Motivation

- Why gpu_device?
  - Not ubiquitous
  - Complicated
  - Bugs reported

Motivation

- Why gpu_device?
  - Not ubiquitous
  - Complicated
  - Bugs reported
  - Exploitable bugs in the wild

Android has updated the May security with notes that 4 vulns were exploited in-the-wild.

Qualcomm GPU: CVE-2021-1905, CVE-2021-1906
ARM Mali GPU: CVE-2021-28663, CVE-2021-28664

source.android.com/security/bulle...
翻译推文

下午9:12 · 2021年5月19日

Agenda

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CVE-2021-28664 analysis

Title	**Mali GPU Kernel Driver elevates CPU RO pages to writable**
CVE	CVE-2021-28664
Date of issue	18th March 2021
Affects	• Midgard GPU Kernel Driver: All versions from r8p0 – r30p0 • Bifrost GPU Kernel Driver: All versions from r0p0 – r29p0 • Valhall GPU Kernel Driver: All versions from r19p0 - r29p0
Impact	A non-privileged user can get a write access to read-only memory, and may be able to gain root privilege, corrupt memory and modify the memory of other processes.
Resolution	This issue is fixed in Bifrost and Valhall GPU Kernel Driver r30p0 and in Midgard GPU Kernel Driver r31p0 release. Users are recommended to upgrade if they are impacted by this issue.
Credit	n/a

https://developer.arm.com/Arm%20Security%20Center/Mali%20GPU%20Driver%20Vulnerabilities

CVE-2021-28664 analysis

- kbase_mem_from_user_buffer diff(Bifrost r28 vs r29)

```
#if LINUX_VERSION_CODE < KERNEL_VERSION(4, 6, 0)
    faulted_pages = get_user_pages(current, current->mm, address, *va_pages,
#if KERNEL_VERSION(4, 4, 168) <= LINUX_VERSION_CODE && \
KERNEL_VERSION(4, 5, 0) > LINUX_VERSION_CODE
            reg->flags & KBASE_REG_GPU_WR ? FOLL_WRITE : 0,
            pages, NULL);
#else
            reg->flags & KBASE_REG_GPU_WR, 0, pages, NULL);
#endif
#elif LINUX_VERSION_CODE < KERNEL_VERSION(4, 9, 0)
    faulted_pages = get_user_pages(address, *va_pages,
            reg->flags & KBASE_REG_GPU_WR, 0, pages, NULL);
#else
    faulted_pages = get_user_pages(address, *va_pages,
            reg->flags & KBASE_REG_GPU_WR ? FOLL_WRITE : 0,
            pages, NULL);
#endif
```

```
#if KERNEL_VERSION(4, 6, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(current, current->mm, address, *va_pages,
#if KERNEL_VERSION(4, 4, 168) <= LINUX_VERSION_CODE && \
KERNEL_VERSION(4, 5, 0) > LINUX_VERSION_CODE
            reg->flags & KBASE_REG_CPU_WR ? FOLL_WRITE : 0,
            pages, NULL);
#else
            reg->flags & KBASE_REG_CPU_WR, 0, pages, NULL);
#endif
#elif KERNEL_VERSION(4, 9, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(address, *va_pages,
            reg->flags & KBASE_REG_CPU_WR, 0, pages, NULL);
#else
    faulted_pages = get_user_pages(address, *va_pages,
            reg->flags & KBASE_REG_CPU_WR ? FOLL_WRITE : 0,
            pages, NULL);
#endif
```

- Only GPU_WR permission check
  - CPU_WR instead of GPU_WR

CVE-2021-28664 analysis

- kbase_mem_from_user_buffer diff(Bifrost r29 vs r30)

```
#if KERNEL_VERSION(4, 6, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(current, current->mm, address, *va_pages,
#if KERNEL_VERSION(4, 4, 168) <= LINUX_VERSION_CODE && \
KERNEL_VERSION(4, 5, 0) > LINUX_VERSION_CODE
            reg->flags & KBASE_REG_CPU_WR ? FOLL_WRITE : 0,
            pages, NULL);
#else
            reg->flags & KBASE_REG_CPU_WR, 0, pages, NULL);
#endif
#elif KERNEL_VERSION(4, 9, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(address, *va_pages,
            reg->flags & KBASE_REG_CPU_WR, 0, pages, NULL);
#else
    faulted_pages = get_user_pages(address, *va_pages,
            reg->flags & KBASE_REG_CPU_WR ? FOLL_WRITE : 0,
            pages, NULL);
#endif
```

```
    write = reg->flags & (KBASE_REG_CPU_WR | KBASE_REG_GPU_WR);

#if KERNEL_VERSION(4, 6, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(current, current->mm, address, *va_pages,
#if KERNEL_VERSION(4, 4, 168) <= LINUX_VERSION_CODE && \
KERNEL_VERSION(4, 5, 0) > LINUX_VERSION_CODE

            write ? FOLL_WRITE : 0, pages, NULL);
#else
            write, 0, pages, NULL);
#endif
#elif KERNEL_VERSION(4, 9, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(address, *va_pages,
            write, 0, pages, NULL);
#else
    faulted_pages = get_user_pages(address, *va_pages,

            write ? FOLL_WRITE : 0, pages, NULL);
#endif
```

- Check both CPU_WR and GPU_WR

CVE-2021-28664 PoC

- KBASE_IOCTL_MEM_IMPORT

```
imported_ubuf.ptr = (u64)ro_page; // Read-only memory
imported_ubuf.length = ro_len;
mem_import.in.flags = BASE_MEM_PROT_CPU_RD |
BASE_MEM_PROT_CPU_WR | BASE_MEM_PROT_GPU_RD;
mem_import.in.phandle = (__u64)&imported_ubuf;
mem_import.in.type = BASE_MEM_IMPORT_TYPE_USER_BUFFER;
mem_import.in.padding = 0;
mem_import.in.header_page_number = 0;
```

- mmap the buffer

```
mmap(0, ro_len, PROT_READ | PROT_WRITE, MAP_SHARED, fd,
mem_import.out.gpu_va);
```

CVE-2021-28664 PoC

- Always SIGBUS

```
static vm_fault_t kbase_cpu_vm_fault(struct vm_fault *vmf)
{
    struct vm_area_struct *vma = vmf->vma;
    struct kbase_cpu_mapping *map = vma->vm_private_data;
    pgoff_t map_start_pgoff;
    pgoff_t fault_pgoff;
    size_t i;
    pgoff_t addr;
    size_t nents;
    struct tagged_addr *pages;
    vm_fault_t ret = VM_FAULT_SIGBUS;
    struct memory_group_manager_device *mgm_dev;

    KBASE_DEBUG_ASSERT(map);
    KBASE_DEBUG_ASSERT(map->count > 0);
    KBASE_DEBUG_ASSERT(map->kctx);
    KBASE_DEBUG_ASSERT(map->alloc);

    map_start_pgoff = vma->vm_pgoff - map->region->start_pfn;

    kbase_gpu_vm_lock(map->kctx);
    if (unlikely(map->region->cpu_alloc->type == KBASE_MEM_TYPE_ALIAS)) {
        struct kbase_aliased *aliased =
                get_aliased_alloc(vma, map->region, &map_start_pgoff, 1);

        if (!aliased)
            goto exit;

        nents = aliased->length;
        pages = aliased->alloc->pages + aliased->offset;
    } else  {
        nents = map->alloc->nents;
        pages = map->alloc->pages;
    }

    fault_pgoff = map_start_pgoff + (vmf->pgoff - vma->vm_pgoff);

    if (fault_pgoff >= nents)
        goto exit;
```

CVE-2021-28664 PoC

- Always SIGBUS
- No physical pages 🤔

```
switch (query) {
case KBASE_MEM_QUERY_COMMIT_SIZE:
    if (reg->cpu_alloc->type != KBASE_MEM_TYPE_ALIAS) {
        *out = kbase_reg_current_backed_size(reg);
    } else {
        size_t i;
        struct kbase_aliased *aliased;
        *out = 0;
        aliased = reg->cpu_alloc->imported.alias.aliased;
        for (i = 0; i < reg->cpu_alloc->imported.alias.nents; i++)
            *out += aliased[i].length;
    }
    break;
```

```
static vm_fault_t kbase_cpu_vm_fault(struct vm_fault *vmf)
{
    struct vm_area_struct *vma = vmf->vma;
    struct kbase_cpu_mapping *map = vma->vm_private_data;
    pgoff_t map_start_pgoff;
    pgoff_t fault_pgoff;
    size_t i;
    pgoff_t addr;
    size_t nents;
    struct tagged_addr *pages;
    vm_fault_t ret = VM_FAULT_SIGBUS;
    struct memory_group_manager_device *mgm_dev;

    KBASE_DEBUG_ASSERT(map);
    KBASE_DEBUG_ASSERT(map->count > 0);
    KBASE_DEBUG_ASSERT(map->kctx);
    KBASE_DEBUG_ASSERT(map->alloc);

    map_start_pgoff = vma->vm_pgoff - map->region->start_pfn;

    kbase_gpu_vm_lock(map->kctx);
    if (unlikely(map->region->cpu_alloc->type == KBASE_MEM_TYPE_ALIAS)) {
        struct kbase_aliased *aliased =
                get_aliased_alloc(vma, map->region, &map_start_pgoff, 1);

        if (!aliased)
            goto exit;

        nents = aliased->length;
        pages = aliased->alloc->pages + aliased->offset;
    } else  {
        nents = map->alloc->nents;
        pages = map->alloc->pages;
    }

    fault_pgoff = map_start_pgoff + (vmf->pgoff - vma->vm_pgoff);

    if (fault_pgoff >= nents)
        goto exit;
```

CVE-2021-28664 PoC

```
if (pages) {
    struct device *dev = kctx->kbdev->dev;
    unsigned long local_size = user_buf->size;
    unsigned long offset = user_buf->address & ~PAGE_MASK;
    struct tagged_addr *pa = kbase_get_gpu_phy_pages(reg);

    /* Top bit signifies that this was pinned on import */
    user_buf->current_mapping_usage_count |= PINNED_ON_IMPORT;

    for (i = 0; i < faulted_pages; i++) {
        dma_addr_t dma_addr;
        unsigned long min;

        min = MIN(PAGE_SIZE - offset, local_size);
        dma_addr = dma_map_page(dev, pages[i],
                offset, min,
                DMA_BIDIRECTIONAL);
        if (dma_mapping_error(dev, dma_addr))
            goto unwind_dma_map;

        user_buf->dma_addrs[i] = dma_addr;
        pa[i] = as_tagged(page_to_phys(pages[i]));

        local_size -= min;
        offset = 0;
    }

    reg->gpu_alloc->nents = faulted_pages;
}
```

```
    if (reg->gpu_alloc->properties & KBASE_MEM_PHY_ALLOC_LARGE)
        user_buf->pages = vmalloc(*va_pages * sizeof(struct page *));
    else
        user_buf->pages = kmalloc_array(*va_pages,
                sizeof(struct page *), GFP_KERNEL);

    if (!user_buf->pages)
        goto no_page_array;

    /* If the region is coherent with the CPU then the memory is imported
     * and mapped onto the GPU immediately.
     * Otherwise get_user_pages is called as a sanity check, but with
     * NULL as the pages argument which will fault the pages, but not
     * pin them. The memory will then be pinned only around the jobs that
     * specify the region as an external resource.
     */
    if (reg->flags & KBASE_REG_SHARE_BOTH) {
        pages = user_buf->pages;
        *flags |= KBASE_MEM_IMPORT_HAVE_PAGES;
    }
```

```
if (!kbase_device_is_cpu_coherent(kctx->kbdev)) {
    if (flags & BASE_MEM_COHERENT_SYSTEM_REQUIRED &&
            !(flags & BASE_MEM_UNCACHED_GPU))
        return -EINVAL;
} else if (flags & (BASE_MEM_COHERENT_SYSTEM |
        BASE_MEM_COHERENT_SYSTEM_REQUIRED)) {
    reg->flags |= KBASE_REG_SHARE_BOTH;
}
```

CVE-2021-28664 PoC

```
if (pages) {
    struct device *dev = kctx->kbdev->dev;
    unsigned long local_size = user_buf->size;
    unsigned long offset = user_buf->address & ~PAGE_MASK;
    struct tagged_addr *pa = kbase_get_gpu_phy_pages(reg);

    /* Top bit signifies that this was pinned on import */
    user_buf->current_mapping_usage_count |= PINNED_ON_IMPORT;

    for (i = 0; i < faulted_pages; i++) {
        dma_addr_t dma_addr;
        unsigned long min;

        min = MIN(PAGE_SIZE - offset, local_size);
        dma_addr = dma_map_page(dev, pages[i],
                offset, min,
                DMA_BIDIRECTIONAL);
        if (dma_mapping_error(dev, dma_addr))
            goto unwind_dma_map;

        user_buf->dma_addrs[i] = dma_addr;
        pa[i] = as_tagged(page_to_phys(pages[i]));

        local_size -= min;
        offset = 0;
    }

    reg->gpu_alloc->nents = faulted_pages;
}
```

```
    if (reg->gpu_alloc->properties & KBASE_MEM_PHY_ALLOC_LARGE)
        user_buf->pages = vmalloc(*va_pages * sizeof(struct page *));
    else
        user_buf->pages = kmalloc_array(*va_pages,
                sizeof(struct page *), GFP_KERNEL);

    if (!user_buf->pages)
        goto no_page_array;

    /* If the region is coherent with the CPU then the memory is imported
     * and mapped onto the GPU immediately.
     * Otherwise get_user_pages is called as a sanity check, but with
     * NULL as the pages argument which will fault the pages, but not
     * pin them. The memory will then be pinned only around the jobs that
     * specify the region as an external resource.
     */
    if (reg->flags & KBASE_REG_SHARE_BOTH) {
        pages = user_buf->pages;
        *flags |= KBASE_MEM_IMPORT_HAVE_PAGES;
    }
```

```
if (!kbase_device_is_cpu_coherent(kctx->kbdev)) {
    if (flags & BASE_MEM_COHERENT_SYSTEM_REQUIRED &&
            !(flags & BASE_MEM_UNCACHED_GPU))
        return -EINVAL;
} else if (flags & (BASE_MEM_COHERENT_SYSTEM |
        BASE_MEM_COHERENT_SYSTEM_REQUIRED)) {
    reg->flags |= KBASE_REG_SHARE_BOTH;
}
```

- Cannot set KBASE_REG_SHARE_BOTH on my MTK phone 😢

CVE-2021-28664 PoC

```c
if (katom->core_req & BASE_JD_REQ_EXTERNAL_RESOURCES) {
    /* handle what we need to do to access the external resources */
    if (kbase_jd_pre_external_resources(katom, user_atom) != 0) {
        /* setup failed (no access, bad resource, unknown resource types, etc.) */
        katom->event_code = BASE_JD_EVENT_JOB_INVALID;
        return jd_done_nolock(katom, NULL);
    }
}
```

```c
struct kbase_mem_phy_alloc *kbase_map_external_resource(
        struct kbase_context *kctx, struct kbase_va_region *reg,
        struct mm_struct *locked_mm)
{
    int err;

    lockdep_assert_held(&kctx->reg_lock);

    /* decide what needs to happen for this resource */
    switch (reg->gpu_alloc->type) {
    case KBASE_MEM_TYPE_IMPORTED_USER_BUF: {
        if ((reg->gpu_alloc->imported.user_buf.mm != locked_mm) &&
            (!reg->gpu_alloc->nents))
            goto exit;

        reg->gpu_alloc->imported.user_buf.current_mapping_usage_count++;
        if (1 == reg->gpu_alloc->imported.user_buf.current_mapping_usage_count) {
            err = kbase_jd_user_buf_map(kctx, reg);
            if (err) {
                reg->gpu_alloc->imported.user_buf.current_mapping_usage_count--;
                goto exit;
            }
        }
    }
    break;
```

```c
    for (res_no = 0; res_no < katom->nr_extres; res_no++) {
        struct base_external_resource *res = &input_extres[res_no];
        struct kbase_va_region *reg;
        struct kbase_mem_phy_alloc *alloc;
#ifdef CONFIG_MALI_DMA_FENCE
        bool exclusive;
        exclusive = (res->ext_resource & BASE_EXT_RES_ACCESS_EXCLUSIVE)
                ? true : false;
#endif
        reg = kbase_region_tracker_find_region_enclosing_address(
                katom->kctx,
                res->ext_resource & ~BASE_EXT_RES_ACCESS_EXCLUSIVE);
        /* did we find a matching region object? */
        if (kbase_is_region_invalid_or_free(reg)) {
            /* roll back */
            goto failed_loop;
        }

        if (!(katom->core_req & BASE_JD_REQ_SOFT_JOB) &&
                (reg->flags & KBASE_REG_PROTECTED)) {
            katom->atom_flags |= KBASE_KATOM_FLAG_PROTECTED;
        }

        alloc = kbase_map_external_resource(katom->kctx, reg,
                current->mm);
        if (!alloc) {
            err_ret_val = -EINVAL;
            goto failed_loop;
        }
```

CVE-2021-28664 PoC

```c
static int kbase_jd_user_buf_map(struct kbase_context *kctx,
        struct kbase_va_region *reg)
{
    long pinned_pages;
    struct kbase_mem_phy_alloc *alloc;
    struct page **pages;
    struct tagged_addr *pa;
    long i;
    unsigned long address;
    struct device *dev;
    unsigned long offset;
    unsigned long local_size;
    unsigned long gwt_mask = ~0;
    int err = kbase_jd_user_buf_pin_pages(kctx, reg);

    if (err)
        return err;

    alloc = reg->gpu_alloc;
    pa = kbase_get_gpu_phy_pages(reg);
    address = alloc->imported.user_buf.address;
    pinned_pages = alloc->nents;
    pages = alloc->imported.user_buf.pages;
    dev = kctx->kbdev->dev;
    offset = address & ~PAGE_MASK;
    local_size = alloc->imported.user_buf.size;
```

```c
int kbase_jd_user_buf_pin_pages(struct kbase_context *kctx,
        struct kbase_va_region *reg)
{
    struct kbase_mem_phy_alloc *alloc = reg->gpu_alloc;
    struct page **pages = alloc->imported.user_buf.pages;
    unsigned long address = alloc->imported.user_buf.address;
    struct mm_struct *mm = alloc->imported.user_buf.mm;
    long pinned_pages;
    long i;

    if (WARN_ON(alloc->type != KBASE_MEM_TYPE_IMPORTED_USER_BUF))
        return -EINVAL;

    if (alloc->nents) {
        if (WARN_ON(alloc->nents != alloc->imported.user_buf.nr_pages))
            return -EINVAL;
        else
            return 0;
    }

    if (WARN_ON(reg->gpu_alloc->imported.user_buf.mm != current->mm))
        return -EINVAL;

#if LINUX_VERSION_CODE < KERNEL_VERSION(4, 6, 0)
    pinned_pages = get_user_pages(NULL, mm,
            address,
            alloc->imported.user_buf.nr_pages,
#if KERNEL_VERSION(4, 4, 168) <= LINUX_VERSION_CODE && \
KERNEL_VERSION(4, 5, 0) > LINUX_VERSION_CODE
            reg->flags & KBASE_REG_GPU_WR ? FOLL_WRITE : 0,
            pages, NULL);
#else
            reg->flags & KBASE_REG_GPU_WR,
            0, pages, NULL);
#endif
#elif LINUX_VERSION_CODE < KERNEL_VERSION(4, 9, 0)
    pinned_pages = get_user_pages_remote(NULL, mm,
            address,
            alloc->imported.user_buf.nr_pages,
            reg->flags & KBASE_REG_GPU_WR,
            0, pages, NULL);
#elif LINUX_VERSION_CODE < KERNEL_VERSION(4, 10, 0)
    pinned_pages = get_user_pages_remote(NULL, mm,
            address,
            alloc->imported.user_buf.nr_pages,
            reg->flags & KBASE_REG_GPU_WR ? FOLL_WRITE : 0,
```

CVE-2021-28664 PoC

- 1. Mmap the Read-Only anonymous memory (CPU_VA1)
- 2. Import the CPU memory with BASE_MEM_PROT_CPU_WR
- 3. Mmap the GPU memory (CPU_VA2)
- 4. Submit a JOB with BASE_JD_REQ_EXTERNAL_RESOURCES (CPU_VA2, same VA)
- 5. Write the CPU_VA1 via CPU_VA2

Insufficient fix

```
int kbase_jd_user_buf_pin_pages(struct kbase_context *kctx,
        struct kbase_va_region *reg)
{
    struct kbase_mem_phy_alloc *alloc = reg->gpu_alloc;
    struct page **pages = alloc->imported.user_buf.pages;
    unsigned long address = alloc->imported.user_buf.address;
    struct mm_struct *mm = alloc->imported.user_buf.mm;
    long pinned_pages;
    long i;

    if (WARN_ON(alloc->type != KBASE_MEM_TYPE_IMPORTED_USER_BUF))
        return -EINVAL;

    if (alloc->nents) {
        if (WARN_ON(alloc->nents != alloc->imported.user_buf.nr_pages))
            return -EINVAL;
        else
            return 0;
    }

    if (WARN_ON(reg->gpu_alloc->imported.user_buf.mm != current->mm))
        return -EINVAL;

#if LINUX_VERSION_CODE < KERNEL_VERSION(4, 6, 0)
    pinned_pages = get_user_pages(NULL, mm,
            address,
            alloc->imported.user_buf.nr_pages,
#if KERNEL_VERSION(4, 4, 168) <= LINUX_VERSION_CODE && \
KERNEL_VERSION(4, 5, 0) > LINUX_VERSION_CODE
            reg->flags & KBASE_REG_GPU_WR ? FOLL_WRITE : 0,
            pages, NULL);
#else
            reg->flags & KBASE_REG_GPU_WR,
            0, pages, NULL);
#endif
#elif LINUX_VERSION_CODE < KERNEL_VERSION(4, 9, 0)
    pinned_pages = get_user_pages_remote(NULL, mm,
            address,
            alloc->imported.user_buf.nr_pages,
            reg->flags & KBASE_REG_GPU_WR,
            0, pages, NULL);
#elif LINUX_VERSION_CODE < KERNEL_VERSION(4, 10, 0)
    pinned_pages = get_user_pages_remote(NULL, mm,
            address,
            alloc->imported.user_buf.nr_pages,
            reg->flags & KBASE_REG_GPU_WR ? FOLL_WRITE : 0,
```

```
#if KERNEL_VERSION(4, 6, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(current, current->mm, address, *va_pages,
#if KERNEL_VERSION(4, 4, 168) <= LINUX_VERSION_CODE && \
KERNEL_VERSION(4, 5, 0) > LINUX_VERSION_CODE
            reg->flags & KBASE_REG_CPU_WR ? FOLL_WRITE : 0,
            pages, NULL);
#else
            reg->flags & KBASE_REG_CPU_WR, 0, pages, NULL);
#endif
#elif KERNEL_VERSION(4, 9, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(address, *va_pages,
            reg->flags & KBASE_REG_CPU_WR, 0, pages, NULL);
#else
    faulted_pages = get_user_pages(address, *va_pages,
            reg->flags & KBASE_REG_CPU_WR ? FOLL_WRITE : 0,
            pages, NULL);
#endif
```

```
    write = reg->flags & (KBASE_REG_CPU_WR | KBASE_REG_GPU_WR);

#if KERNEL_VERSION(4, 6, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(current, current->mm, address, *va_pages,
#if KERNEL_VERSION(4, 4, 168) <= LINUX_VERSION_CODE && \
KERNEL_VERSION(4, 5, 0) > LINUX_VERSION_CODE
            write ? FOLL_WRITE : 0, pages, NULL);
#else
            write, 0, pages, NULL);
#endif
#elif KERNEL_VERSION(4, 9, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(address, *va_pages,
            write, 0, pages, NULL);
#else
    faulted_pages = get_user_pages(address, *va_pages,
            write ? FOLL_WRITE : 0, pages, NULL);
#endif
```

- It sounds like double fetch

Import again

Insufficient fix

```
int kbase_jd_user_buf_pin_pages(struct kbase_context *kctx,
        struct kbase_va_region *reg)
{
    struct kbase_mem_phy_alloc *alloc = reg->gpu_alloc;
    struct page **pages = alloc->imported.user_buf.pages;
    unsigned long address = alloc->imported.user_buf.address;
    struct mm_struct *mm = alloc->imported.user_buf.mm;
    long pinned_pages;
    long i;

    if (WARN_ON(alloc->type != KBASE_MEM_TYPE_IMPORTED_USER_BUF))
        return -EINVAL;

    if (alloc->nents) {
        if (WARN_ON(alloc->nents != alloc->imported.user_buf.nr_pages))
            return -EINVAL;
        else
            return 0;
    }

    if (WARN_ON(reg->gpu_alloc->imported.user_buf.mm != current->mm))
        return -EINVAL;

#if LINUX_VERSION_CODE < KERNEL_VERSION(4, 6, 0)
    pinned_pages = get_user_pages(NULL, mm,
            address,
            alloc->imported.user_buf.nr_pages,
#if KERNEL_VERSION(4, 4, 168) <= LINUX_VERSION_CODE && \
KERNEL_VERSION(4, 5, 0) > LINUX_VERSION_CODE
            reg->flags & KBASE_REG_GPU_WR ? FOLL_WRITE : 0,
            pages, NULL);
#else
            reg->flags & KBASE_REG_GPU_WR,
            0, pages, NULL);
#endif
#elif LINUX_VERSION_CODE < KERNEL_VERSION(4, 9, 0)
    pinned_pages = get_user_pages_remote(NULL, mm,
            address,
            alloc->imported.user_buf.nr_pages,
            reg->flags & KBASE_REG_GPU_WR,
            0, pages, NULL);
#elif LINUX_VERSION_CODE < KERNEL_VERSION(4, 10, 0)
    pinned_pages = get_user_pages_remote(NULL, mm,
            address,
            alloc->imported.user_buf.nr_pages,
            reg->flags & KBASE_REG_GPU_WR ? FOLL_WRITE : 0,
```

Import again

```
#if KERNEL_VERSION(4, 6, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(current, current->mm, address, *va_pages,
#if KERNEL_VERSION(4, 4, 168) <= LINUX_VERSION_CODE && \
KERNEL_VERSION(4, 5, 0) > LINUX_VERSION_CODE
            reg->flags & KBASE_REG_CPU_WR ? FOLL_WRITE : 0,
            pages, NULL);
#else
            reg->flags & KBASE_REG_CPU_WR, 0, pages, NULL);
#endif
#elif KERNEL_VERSION(4, 9, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(address, *va_pages,
            reg->flags & KBASE_REG_CPU_WR, 0, pages, NULL);
#else
    faulted_pages = get_user_pages(address, *va_pages,
            reg->flags & KBASE_REG_CPU_WR ? FOLL_WRITE : 0,
            pages, NULL);
#endif
```

```
    write = reg->flags & (KBASE_REG_CPU_WR | KBASE_REG_GPU_WR);

#if KERNEL_VERSION(4, 6, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(current, current->mm, address, *va_pages,
#if KERNEL_VERSION(4, 4, 168) <= LINUX_VERSION_CODE && \
KERNEL_VERSION(4, 5, 0) > LINUX_VERSION_CODE
            write ? FOLL_WRITE : 0, pages, NULL);
#else
            write, 0, pages, NULL);
#endif
#elif KERNEL_VERSION(4, 9, 0) > LINUX_VERSION_CODE
    faulted_pages = get_user_pages(address, *va_pages,
            write, 0, pages, NULL);
#else
    faulted_pages = get_user_pages(address, *va_pages,
            write ? FOLL_WRITE : 0, pages, NULL);
#endif
```

- It sounds like double fetch
  - KBASE_IOCTL_MEM_IMPORT: just touch the user memory
  - KBASE_IOCTL_JOB_SUBMIT: import the physical pages

PoC

- 1. Mmap the Read/Write anonymous memory (CPU_VA1)
- 2. Import the CPU memory with BASE_MEM_PROT_CPU_WR
- 3. Mmap the GPU memory (CPU_VA2)
- 4. Munmap the CPU_VA1
- 5. Fixedly mmap the Read-Only memory (CPU_VA1)
- 6. Submit a JOB with BASE_JD_REQ_EXTERNAL_RESOURCES (CPU_VA2, same VA)
- 7. Write the CPU_VA1 via CPU_VA2

Fix

CVE-2022-22706 / CVE-2021-39793: Mali GPU driver makes read-only imported pages host-writable

Jann Horn

The Basics

Disclosure or Patch Date: March 7, 2022

Product: Arm Mali GPU driver for Linux/Android

Advisory:

- from Arm (upstream): https://developer.arm.com/Arm%20Security%20Center/Mali%20GPU%20Driver%20Vulnerabilities
- from Google Pixel: https://source.android.com/security/bulletin/pixel/2022-03-01#pixel

Affected Versions: see Arm advisory (note that the affected version range for the Bifrost version of the related CVE-2021-28664 seems to be off-by-one)

First Patched Version:

- for Arm: see Arm advisory
- for Pixel: patch level 2022-03-05

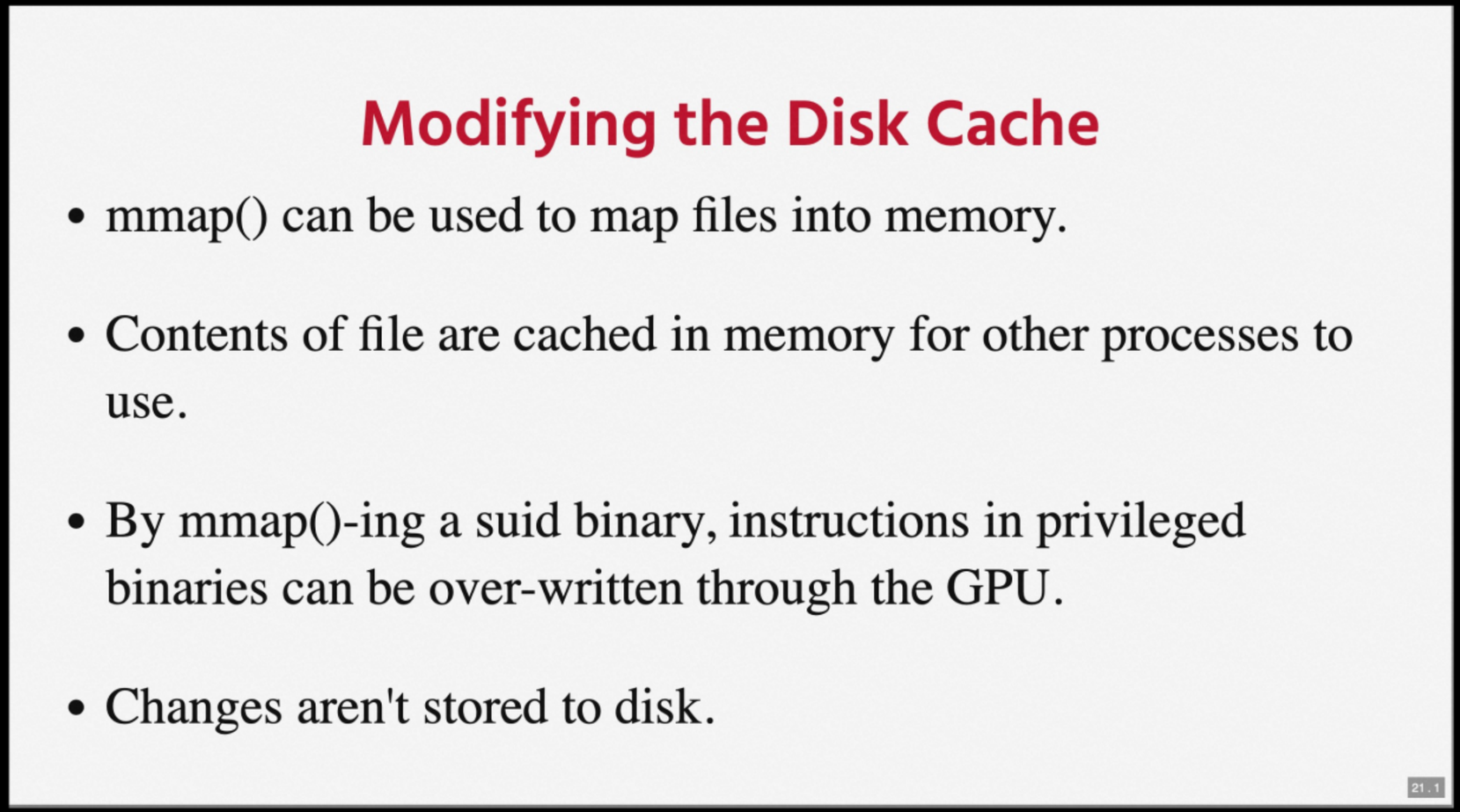
Issue/Bug Report: N/A

Patch CL: https://android.googlesource.com/kernel/google-modules/gpu/+/5381ff7b4106b277ff207396e293ede2bf959f0c%5E%21/

https://googleprojectzero.github.io/0days-in-the-wild//0day-RCAs/2021/CVE-2021-39793.html

Exploit – Modifying the disk cache

- Old way



https://www.blackhat.com/docs/eu-16/materials/eu-16-Taft-GPU-Security-Exposed.pdf

Exploit – Modifying the disk cache

- New way

Loadable Kernel Modules

As part of the module kernel requirements introduced in Android 8.0, all system-on-chip (SoC) kernels must support loadable kernel modules.

Kernel configuration options

To support loadable kernel modules, android-base.cfg in all common kernels includes the following ker options (or their kernel-version equivalent):

```
CONFIG_MODULES=y
CONFIG_MODULE_UNLOAD=y
CONFIG_MODVERSIONS=y
```

All device kernels must enable these options. Kernel modules should also support unloading and reloading whenever possible.

Module signing

Module-signing is not supported for GKI vendor modules. On devices required to support verified boot, Android requires kernel modules to be in the partitions that have dm-verity enabled. This removes the need for signing individual modules for their authenticity. Android 13 introduced the concept of GKI modules. GKI modules use the kernel's build time signing infrastructure to differentiate between GKI and other modules at run time. Unsigned modules are allowed to load as long as they only use symbols appearing on the allowlist or provided by other unsigned modules. To facilitate GKI modules signing during GKI build using kernel's build time key pair, GKI kernel config has enabled `CONFIG_MODULE_SIG_ALL=y`. To avoid signing non-GKI modules during device kernel builds, you must add `# CONFIG_MODULE_SIG_ALL is not set` as part of your kernel config fragments.

https://source.android.com/docs/core/architecture/kernel/loadable-kernel-modules

Exploit – Modifying the disk cache

- It’s similar to Dirty pipe exploit for Android

- Exploit steps:
  - 1. Modify a shared library and hijack a privileged process
  - 2. Patch the modprobe and a shared library as the kernel module, transit the SELinux context, and execute the patched modprobe
  - 3. Insert the kernel module and gain the kernel arbitrary code execution ability

Exploit – Memory corruption

- Not GKI (<kernel 5.10)
- Module signing enabled

```
CONFIG_RT_MUTEXES=y
CONFIG_BASE_SMALL=0
CONFIG_MODULE_SIG_FORMAT=y
CONFIG_MODULES=y
# CONFIG_MODULE_FORCE_LOAD is not set
CONFIG_MODULE_UNLOAD=y
# CONFIG_MODULE_FORCE_UNLOAD is not set
CONFIG_MODVERSIONS=y
CONFIG_ASM_MODVERSIONS=y
# CONFIG_MODULE_SRCVERSION_ALL is not set
CONFIG_MODULE_SCMVERSION=y
CONFIG_MODULE_SIG=y
CONFIG_MODULE_SIG_FORCE=y
CONFIG_MODULE_SIG_ALL=y
# CONFIG_MODULE_SIG_SHA1 is not set
# CONFIG_MODULE_SIG_SHA224 is not set
# CONFIG_MODULE_SIG_SHA256 is not set
# CONFIG_MODULE_SIG_SHA384 is not set
CONFIG_MODULE_SIG_SHA512=y
CONFIG_MODULE_SIG_HASH="sha512"
# CONFIG_MODULE_COMPRESS is not set
# CONFIG_MODULE_ALLOW_MISSING_NAMESPACE_IMPORTS is not set
# CONFIG_UNUSED_SYMBOLS is not set
CONFIG_TRIM_UNUSED_KSYMS=y
```

Exploit – Memory corruption

- Read only memory
- vm_insert_page
  - User buffer can be imported

```
static int binder_mmap(struct file *filp, struct vm_area_struct *vma)
{
    struct binder_proc *proc = filp->private_data;

    if (proc->tsk != current->group_leader)
        return -EINVAL;

    if (vma->vm_flags & FORBIDDEN_MMAP_FLAGS) { // VM_WRITE
        pr_err("%s: %d %lx-%lx %s failed %d\n", __func__,
               proc->pid, vma->vm_start, vma->vm_end, "bad vm_flags", -EPERM);
        return -EPERM;
    }
    vma->vm_flags |= VM_DONTCOPY | VM_MIXEDMAP;
    vma->vm_flags &= ~VM_MAYWRITE;

    vma->vm_ops = &binder_vm_ops;
    vma->vm_private_data = proc;

    return binder_alloc_mmap_handler(&proc->alloc, vma);
}
```

```
page->page_ptr = alloc_page(GFP_KERNEL |
                            __GFP_HIGHMEM |
                            __GFP_ZERO);
if (!page->page_ptr) {
    pr_err("%d: binder_alloc_buf failed for p
           alloc->pid, page_addr);
    goto err_alloc_page_failed;
}
page->alloc = alloc;
INIT_LIST_HEAD(&page->lru);

user_page_addr = (uintptr_t)page_addr;
ret = vm_insert_page(vma, user_page_addr, page[0].page_ptr);
```

Exploit – Memory corruption

- Craft the flat_binder_object by modifying the binder's user buffer

```
struct flat_binder_object {
    struct binder_object_header hdr;
    __u32                  flags;

    /* 8 bytes of data. */
    union {
        binder_uintptr_t    binder; /* local object */
        __u32               handle; /* remote object */
    };

    /* extra data associated with local object */
    binder_uintptr_t    cookie;
};
```

```
hdr = &object.hdr;
switch (hdr->type) {
case BINDER_TYPE_BINDER:
case BINDER_TYPE_WEAK_BINDER: {
    struct flat_binder_object *fp;
    struct binder_node *node;

    fp = to_flat_binder_object(hdr);
    node = binder_get_node(proc, fp->binder);
    if (node == NULL) {
        pr_err("transaction release %d bad node %016llx\n",
                debug_id, (u64)fp->binder);
        break;
    }
    binder_debug(BINDER_DEBUG_TRANSACTION,
                 "        node %d u%016llx\n",
                 node->debug_id, (u64)node->ptr);
    binder_dec_node(node, hdr->type == BINDER_TYPE_BINDER,
                    0);
    binder_put_node(node);
} break;
```

Exploit – Memory corruption

- Exploit the UAF bug like CVE-2020-0041
  - https://labs.bluefrostsecurity.de/blog/2020/04/08/cve-2020-0041-part-2-escalating-to-root/

```
if (t->buffer->target_node) {
    struct binder_node *target_node = t->buffer->target_node;
    struct binder_priority node_prio;

    trd->target.ptr = target_node->ptr;
    trd->cookie =  target_node->cookie;
    node_prio.sched_policy = target_node->sched_policy;
    node_prio.prio = target_node->min_priority;
    binder_transaction_priority(current, t, node_prio,
                                target_node->inherit_rt);
    cmd = BR_TRANSACTION;
} else {
    trd->target.ptr = 0;
    trd->cookie = 0;
    cmd = BR_REPLY;
}
trd->code = t->code;
trd->flags = t->flags;
trd->sender_euid = from_kuid(current_user_ns(), t->sender_euid);
```

Exploit – Memory corruption

- Exploit the UAF bug like CVE-2020-0041
  - https://labs.bluefrostsecurity.de/blog/2020/04/08/cve-2020-0041-part-2-escalating-to-root/

```
} else {
    BUG_ON(!list_empty(&node->work.entry));
    spin_lock(&binder_dead_nodes_lock);
    /*
     * tmp_refs could have changed so
     * check it again
     */
    if (node->tmp_refs) {
        spin_unlock(&binder_dead_nodes_lock);
        return false;
    }
    hlist_del(&node->dead_node);
    spin_unlock(&binder_dead_nodes_lock);
    binder_debug(BINDER_DEBUG_INTERNAL_REFS,
```

Agenda

- Introduction
- Bug #1
- *Bug #2*
- Conclusion

Bug #1 PoC more details

- 1. Mmap the Read/Write anonymous memory (CPU_VA1)
- 2. Import the CPU memory with BASE_MEM_PROT_CPU_WR
- 3. Mmap the GPU memory (CPU_VA2)
- 4. Munmap the CPU_VA1
- 5. Fixedly mmap the Read-Only memory (CPU_VA1)
- 6. Submit a JOB with BASE_JD_REQ_EXTERNAL_RESOURCES (CPU_VA2, same VA)
- 7. Write the CPU_VA1 via CPU_VA2
  - Wait a moment for kbase_jd_user_buf_pin_pages to be called

Bug #1 PoC more details

- 1. Mmap the Read/Write anonymous memory (CPU_VA1)
- 2. Import the CPU memory with BASE_MEM_PROT_CPU_WR
- 3. Mmap the GPU memory (CPU_VA2)
- 4. Munmap the CPU_VA1
- 5. Fixedly mmap the Read-Only memory (CPU_VA1)
- 6. Submit a JOB with BASE_JD_REQ_EXTERNAL_RESOURCES (CPU_VA2, same VA)
- 7. Write the CPU_VA1 via CPU_VA2
  - Sleep(5) == Always SIGBUS

Bug #1 PoC more details

- No physical pages, why? 🤔

```
switch (query) {
case KBASE_MEM_QUERY_COMMIT_SIZE:
    if (reg->cpu_alloc->type != KBASE_MEM_TYPE_ALIAS) {
        *out = kbase_reg_current_backed_size(reg);
    } else {
        size_t i;
        struct kbase_aliased *aliased;
        *out = 0;
        aliased = reg->cpu_alloc->imported.alias.aliased;
        for (i = 0; i < reg->cpu_alloc->imported.alias.nents; i++)
            *out += aliased[i].length;
    }
    break;
```

```
static vm_fault_t kbase_cpu_vm_fault(struct vm_fault *vmf)
{
    struct vm_area_struct *vma = vmf->vma;
    struct kbase_cpu_mapping *map = vma->vm_private_data;
    pgoff_t map_start_pgoff;
    pgoff_t fault_pgoff;
    size_t i;
    pgoff_t addr;
    size_t nents;
    struct tagged_addr *pages;
    vm_fault_t ret = VM_FAULT_SIGBUS;
    struct memory_group_manager_device *mgm_dev;

    KBASE_DEBUG_ASSERT(map);
    KBASE_DEBUG_ASSERT(map->count > 0);
    KBASE_DEBUG_ASSERT(map->kctx);
    KBASE_DEBUG_ASSERT(map->alloc);

    map_start_pgoff = vma->vm_pgoff - map->region->start_pfn;

    kbase_gpu_vm_lock(map->kctx);
    if (unlikely(map->region->cpu_alloc->type == KBASE_MEM_TYPE_ALIAS)) {
        struct kbase_aliased *aliased =
                get_aliased_alloc(vma, map->region, &map_start_pgoff, 1);

        if (!aliased)
            goto exit;

        nents = aliased->length;
        pages = aliased->alloc->pages + aliased->offset;
    } else  {
        nents = map->alloc->nents;
        pages = map->alloc->pages;
    }

    fault_pgoff = map_start_pgoff + (vmf->pgoff - vma->vm_pgoff);

    if (fault_pgoff >= nents)
        goto exit;
```

Bug #1 PoC more details

```c
static void kbase_jd_post_external_resources(struct kbase_jd_atom *katom)
{
    KBASE_DEBUG_ASSERT(katom);
    KBASE_DEBUG_ASSERT(katom->core_req & BASE_JD_REQ_EXTERNAL_RESOURCES);

#ifdef CONFIG_MALI_DMA_FENCE
    kbase_dma_fence_signal(katom);
#endif /* CONFIG_MALI_DMA_FENCE */

    kbase_gpu_vm_lock(katom->kctx);
    /* only roll back if extres is non-NULL */
    if (katom->extres) {
        u32 res_no;

        res_no = katom->nr_extres;
        while (res_no-- > 0) {
            struct kbase_mem_phy_alloc *alloc = katom->extres[res_no].alloc;
            struct kbase_va_region *reg;

            reg = kbase_region_tracker_find_region_base_address(
                    katom->kctx,
                    katom->extres[res_no].gpu_address);
            kbase_unmap_external_resource(katom->kctx, reg, alloc);
        }
        kfree(katom->extres);
        katom->extres = NULL;
    }
    kbase_gpu_vm_unlock(katom->kctx);
}
```

```c
case KBASE_MEM_TYPE_IMPORTED_USER_BUF: {
    alloc->imported.user_buf.current_mapping_usage_count--;

    if (0 == alloc->imported.user_buf.current_mapping_usage_count) {
        bool writeable = true;

        if (!kbase_is_region_invalid_or_free(reg) &&
                reg->gpu_alloc == alloc)
            kbase_mmu_teardown_pages(
                    kctx->kbdev,
                    &kctx->mmu,
                    reg->start_pfn,
                    kbase_reg_current_backed_size(reg),
                    kctx->as_nr);

        if (reg && ((reg->flags & KBASE_REG_GPU_WR) == 0))
            writeable = false;

        kbase_jd_user_buf_unmap(kctx, alloc, writeable);
    }
}
```

```c
static void kbase_jd_user_buf_unmap(struct kbase_context *kctx,
        struct kbase_mem_phy_alloc *alloc, bool writeable)
{
    long i;
    struct page **pages;
    unsigned long size = alloc->imported.user_buf.size;

    KBASE_DEBUG_ASSERT(alloc->type == KBASE_MEM_TYPE_IMPORTED_USER_BUF);
    pages = alloc->imported.user_buf.pages;
    for (i = 0; i < alloc->imported.user_buf.nr_pages; i++) {
        unsigned long local_size;
        dma_addr_t dma_addr = alloc->imported.user_buf.dma_addrs[i];

        local_size = MIN(size, PAGE_SIZE - (dma_addr & ~PAGE_MASK));
        dma_unmap_page(kctx->kbdev->dev, dma_addr, local_size,
                DMA_BIDIRECTIONAL);
        if (writeable)
            set_page_dirty_lock(pages[i]);
#if !MALI_USE_CSF
        put_page(pages[i]);
        pages[i] = NULL;
#endif

        size -= local_size;
    }
#if !MALI_USE_CSF
    alloc->nents = 0;
#endif
}
```

- Physical pages will be released when the JOB is finished
- Trigger the VM_FAULT before the pages are released

Bug #1 PoC more details

- 1. Mmap the Read/Write anonymous memory (CPU_VA1)
- 2. Import the CPU memory with BASE_MEM_PROT_CPU_WR
- 3. Mmap the GPU memory (CPU_VA2)
- 4. Munmap the CPU_VA1
- 5. Fixedly mmap the Read-Only memory (CPU_VA1)
- 6. Submit a JOB with BASE_JD_REQ_EXTERNAL_RESOURCES (CPU_VA2, same VA)
- 7. Write the CPU_VA1 via CPU_VA2
  - Query the GPU VA whether the pages are imported or not

Bug #1 PoC more details

```
case KBASE_MEM_TYPE_IMPORTED_USER_BUF: {
    alloc->imported.user_buf.current_mapping_usage_count--;

    if (0 == alloc->imported.user_buf.current_mapping_usage_count) {
        bool writeable = true;

        if (!kbase_is_region_invalid_or_free(reg) &&
                reg->gpu_alloc == alloc)
            kbase_mmu_teardown_pages(
                    kctx->kbdev,
                    &kctx->mmu,
                    reg->start_pfn,
                    kbase_reg_current_backed_size(reg),
                    kctx->as_nr);

        if (reg && ((reg->flags & KBASE_REG_GPU_WR) == 0))
            writeable = false;

        kbase_jd_user_buf_unmap(kctx, alloc, writeable);
    }
}
```

```
static void kbase_jd_user_buf_unmap(struct kbase_context *kctx,
        struct kbase_mem_phy_alloc *alloc, bool writeable)
{
    long i;
    struct page **pages;
    unsigned long size = alloc->imported.user_buf.size;

    KBASE_DEBUG_ASSERT(alloc->type == KBASE_MEM_TYPE_IMPORTED_USER_BUF);
    pages = alloc->imported.user_buf.pages;
    for (i = 0; i < alloc->imported.user_buf.nr_pages; i++) {
        unsigned long local_size;
        dma_addr_t dma_addr = alloc->imported.user_buf.dma_addrs[i];

        local_size = MIN(size, PAGE_SIZE - (dma_addr & ~PAGE_MASK));
        dma_unmap_page(kctx->kbdev->dev, dma_addr, local_size,
                DMA_BIDIRECTIONAL);
        if (writeable)
            set_page_dirty_lock(pages[i]);
#if !MALI_USE_CSF
        put_page(pages[i]);
        pages[i] = NULL;
#endif

        size -= local_size;
    }
#if !MALI_USE_CSF
    alloc->nents = 0;
#endif
}
```

Bug #1 PoC more details

```
static void kbase_jd_user_buf_unmap(struct kbase_context *kctx,
        struct kbase_mem_phy_alloc *alloc, bool writeable)
{
    long i;
    struct page **pages;
    unsigned long size = alloc->imported.user_buf.size;

    KBASE_DEBUG_ASSERT(alloc->type == KBASE_MEM_TYPE_IMPORTED_USER_BUF);
    pages = alloc->imported.user_buf.pages;
    for (i = 0; i < alloc->imported.user_buf.nr_pages; i++) {
        unsigned long local_size;
        dma_addr_t dma_addr = alloc->imported.user_buf.dma_addrs[i];

        local_size = MIN(size, PAGE_SIZE - (dma_addr & ~PAGE_MASK));
        dma_unmap_page(kctx->kbdev->dev, dma_addr, local_size,
                DMA_BIDIRECTIONAL);
        if (writeable)
            set_page_dirty_lock(pages[i]);
#if !MALI_USE_CSF
        put_page(pages[i]);
        pages[i] = NULL;
#endif

        size -= local_size;
    }
#if !MALI_USE_CSF
    alloc->nents = 0;
#endif
}
```

```
int kbase_mem_shrink(struct kbase_context *const kctx,
        struct kbase_va_region *const reg, u64 const new_pages)
{
    u64 delta, old_pages;
    int err;

    lockdep_assert_held(&kctx->reg_lock);

    if (WARN_ON(!kctx))
        return -EINVAL;

    if (WARN_ON(!reg))
        return -EINVAL;

    old_pages = kbase_reg_current_backed_size(reg);
    if (WARN_ON(old_pages < new_pages))
        return -EINVAL;

    delta = old_pages - new_pages;

    /* Update the GPU mapping */
    err = kbase_mem_shrink_gpu_mapping(kctx, reg,
            new_pages, old_pages);
    if (err >= 0) {
        /* Update all CPU mapping(s) */
        kbase_mem_shrink_cpu_mapping(kctx, reg,
                new_pages, old_pages);

        kbase_free_phy_pages_helper(reg->cpu_alloc, delta);
        if (reg->cpu_alloc != reg->gpu_alloc)
            kbase_free_phy_pages_helper(reg->gpu_alloc, delta);
    }

    return err;
}
```

- The CPU mapping has not been handled 😊
- The imported pages can be freed and reclaimed

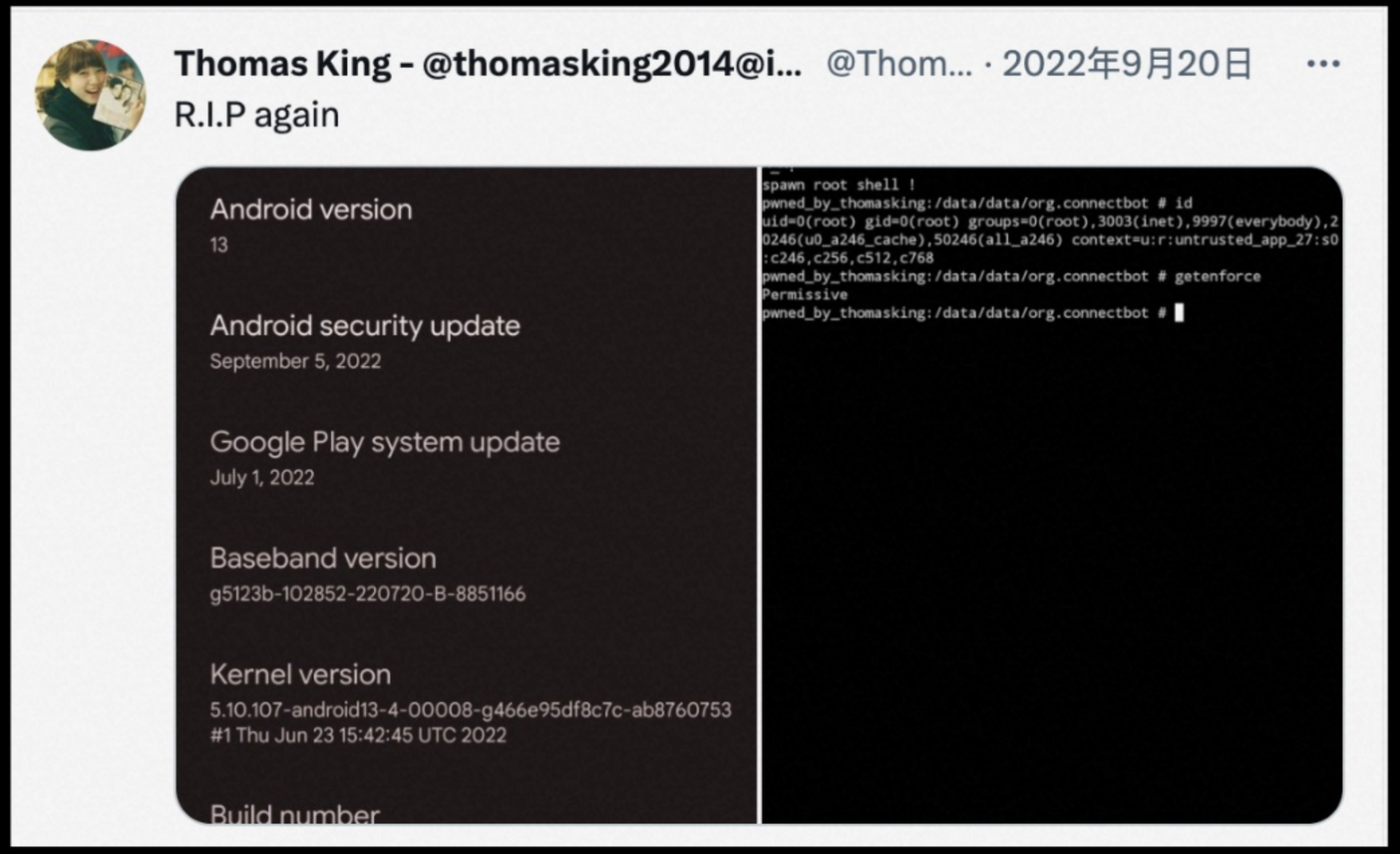
Two bugs One PoC

- 1. Mmap the Read/Write anonymous memory (CPU_VA1)
- 2. Import the CPU memory with BASE_MEM_PROT_CPU_WR
- 3. Mmap the GPU memory (CPU_VA2)
- 4. Munmap the CPU_VA1
- 5. Fixedly mmap the Read-Only memory (CPU_VA1)
- 6. Submit a JOB with BASE_JD_REQ_EXTERNAL_RESOURCES (CPU_VA2, same VA)
- 7. Read/Write the CPU_VA2 and trigger the VM_FAULT on the CPU side
- 8. Munmap and release the CPU_VA1
- 9. Read/Write the freed pages via CPU_VA2

Bug #2 PoC

- 1. Mmap the Read/Write anonymous memory (CPU_VA1)
- 2. Import the CPU memory with BASE_MEM_PROT_CPU_WR
- 3. Submit a JOB with BASE_JD_REQ_EXTERNAL_RESOURCES (CPU_VA2, same VA)
- 4. Read the CPU_VA2 and trigger the VM_FAULT on the CPU side
- 5. Munmap and release the CPU_VA1
- 6. Read/Write the freed pages via CPU_VA2

Fix



Tuesday, November 22, 2022

Mind the Gap

By Ian Beer, Project Zero

Note: The vulnerabilities discussed in this blog post (CVE-2022-33917) are fixed by the upstream vendor, but at the time of publication, these fixes have not yet made it downstream to affected Android devices (including Pixel, Samsung, Xiaomi, Oppo and others). Devices with a Mali GPU are currently vulnerable.

Introduction

In June 2022, Project Zero researcher Maddie Stone gave a talk at FirstCon22 titled 0-day In-the-Wild Exploitation in 2022...so far. A key takeaway was that approximately 50% of the observed 0-days in the first half of 2022 were variants of previously patched vulnerabilities. This finding is consistent with our understanding of attacker behavior: attackers will take the path of least resistance, and as long as vendors don't consistently perform thorough root-cause analysis when fixing security vulnerabilities, it will continue to be worth investing time in trying to revive known vulnerabilities before looking for novel ones.

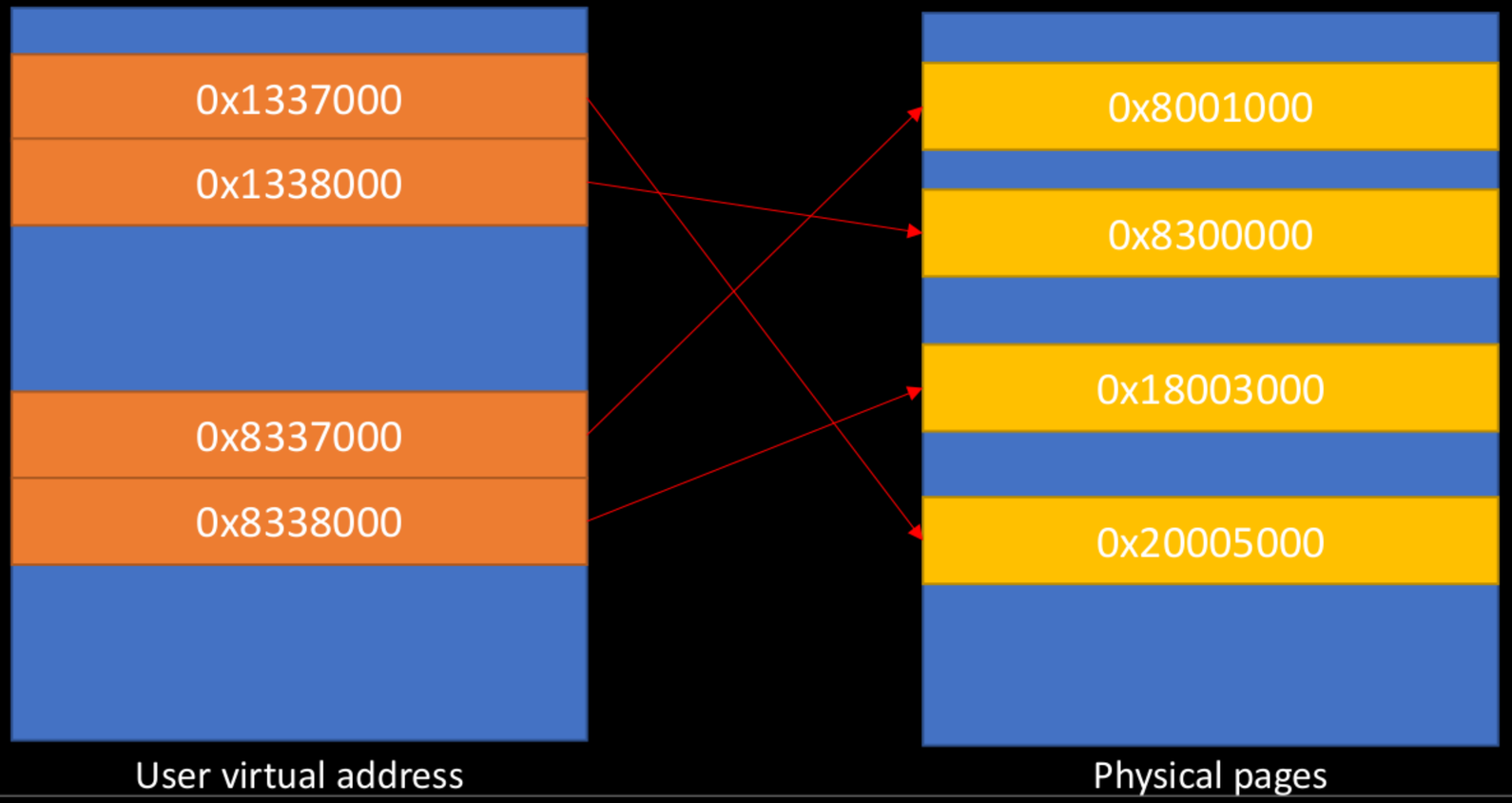
The presentation discussed an in the wild exploit targeting the Pixel 6 and leveraging CVE-2021-39793, a vulnerability in the ARM Mali GPU driver used by a large number of other Android devices. ARM's advisory described the vulnerability as:

Title	Mali GPU Kernel Driver may elevate CPU RO pages to writable
CVE	CVE-2022-22706 (also reported in CVE-2021-39793)
Date of issue	6th January 2022
Impact	A non-privileged user can get a write access to read-only memory pages [*sic*].

The week before FirstCon22, Maddie gave an internal preview of her talk. Inspired by the description of an in-the-wild vulnerability in low-level memory management code, fellow Project Zero researcher Jann Horn started auditing the ARM Mali GPU driver. Over the next three weeks, Jann found five more exploitable vulnerabilities (2325, 2327, 2331, 2333, 2334).

Exploit

- Physical pages Use-After-Free
  - In theory, all the pages within the free state can be imported and reused

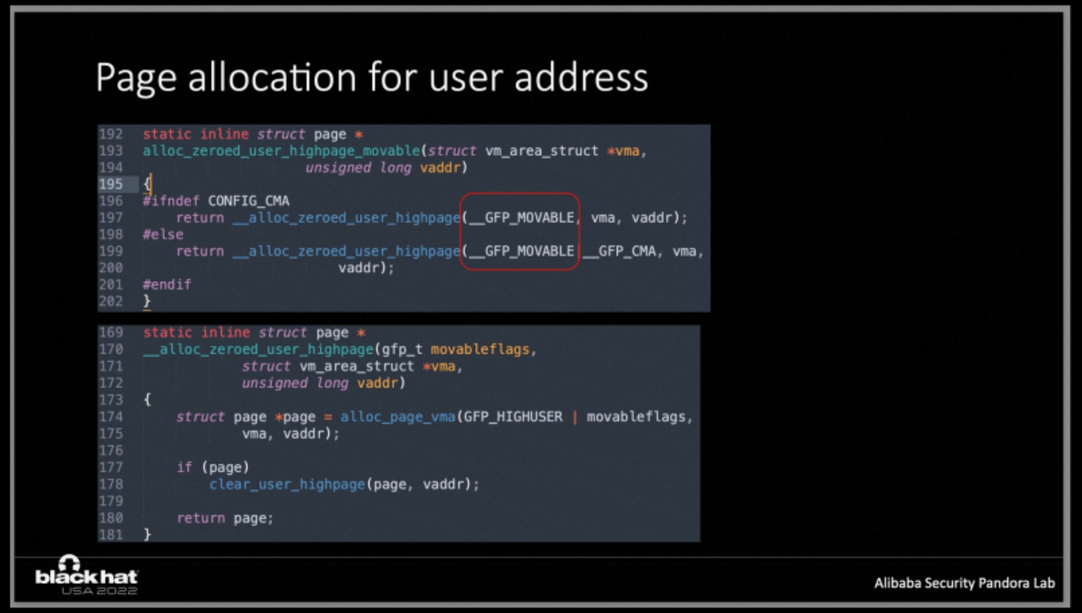


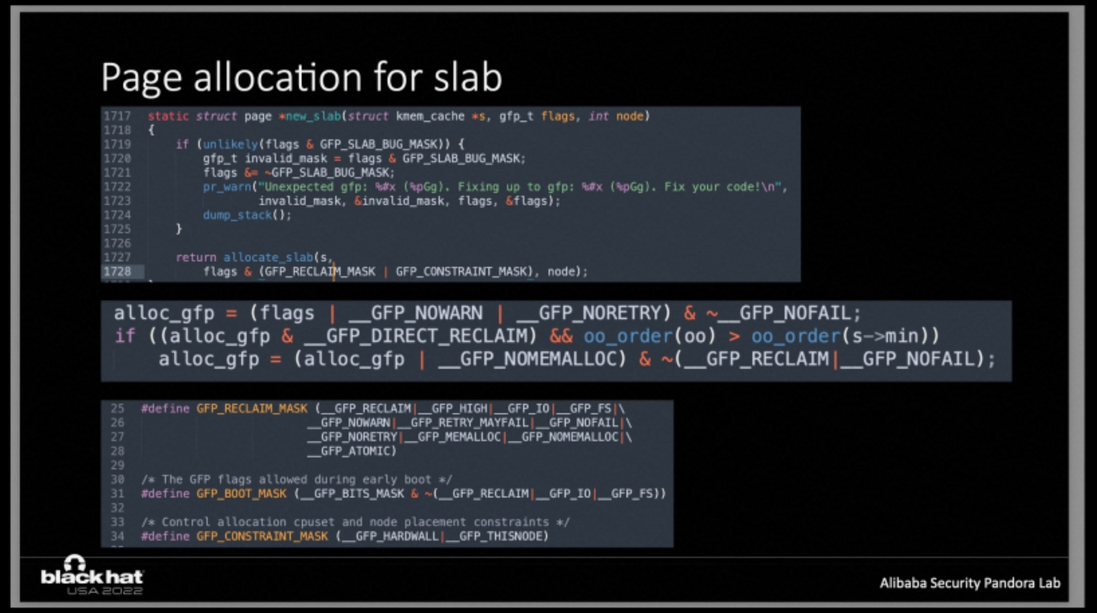
Exploit

- Physical pages Use-After-Free
  - In theory, all the pages within the free state can be imported and reused
- Hijack a kernel object

Exploit

- Physical pages Use-After-Free
  - In theory, all the pages within the free state can be imported and reused
- Hijack a kernel object
  - MIGRATE_UNMOVABLE VS MIGRATE_MOVABLE





http://i.blackhat.com/USA-22/Thursday/US-22-WANG-Ret2page-The-Art-of-Exploiting-Use-After-Free-Vulnerabilities-in-the-Dedicated-Cache.pdf

Exploit

- task_struct as the target object
  - Leak kernel pointer to bypass KASLR
  - Leak cred pointer to gain ROOT privilege later

```
struct task_struct {
#ifdef CONFIG_THREAD_INFO_IN_TASK
    /*
     * For reasons of header soup (see current_thread_info()), this
     * must be the first element of task_struct.
     */
    struct thread_info      thread_info;
#endif
    /* -1 unrunnable, 0 runnable, >0 stopped: */
    volatile long           state;

    /*
     * This begins the randomizable portion of task_struct. Only
     * scheduling-critical items should be added above here.
     */
    randomized_struct_fields_start

    void                    *stack;
    refcount_t              usage;
    /* Per task flags (PF_*), defined further below: */
    unsigned int            flags;
    unsigned int            ptrace;

#ifdef CONFIG_SMP
    int             on_cpu;
    struct __call_single_node   wake_entry;
#ifdef CONFIG_THREAD_INFO_IN_TASK
    /* Current CPU: */
    unsigned int            cpu;
#endif
    unsigned int            wakee_flips;
    unsigned long           wakee_flip_decay_ts;
    struct task_struct      *last_wakee;
```

Exploit

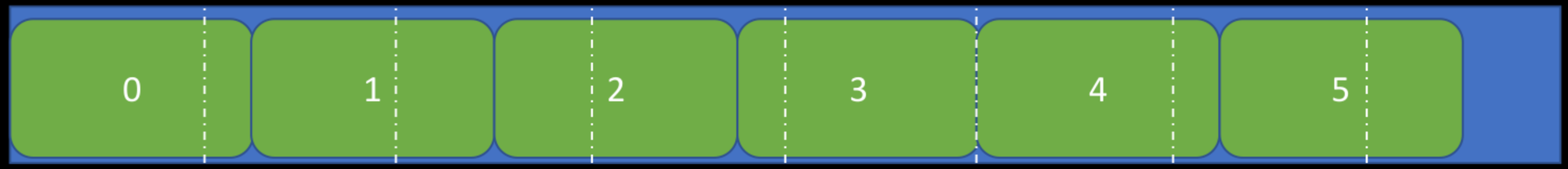
- task_struct as the target object
  - Leak kernel pointer to bypass KASLR
  - Leak cred pointer to gain ROOT privilege later
  - Can be easily found

```
 pid_t                pid;
 pid_t                tgid;

def CONFIG_STACKPROTECTOR
 /* Canary value for the -fstack-protector GCC feature: */
 unsigned long           stack_canary;
dif
 /*
  * Pointers to the (original) parent process, youngest child, younger sibling,
  * older sibling, respectively.  (p->father can be replaced with
  * p->real_parent->pid)
  */

 /* Real parent process: */
 struct task_struct __rcu    *real_parent;

 /* Recipient of SIGCHLD, wait4() reports: */
 struct task_struct __rcu    *parent;
```

Exploit

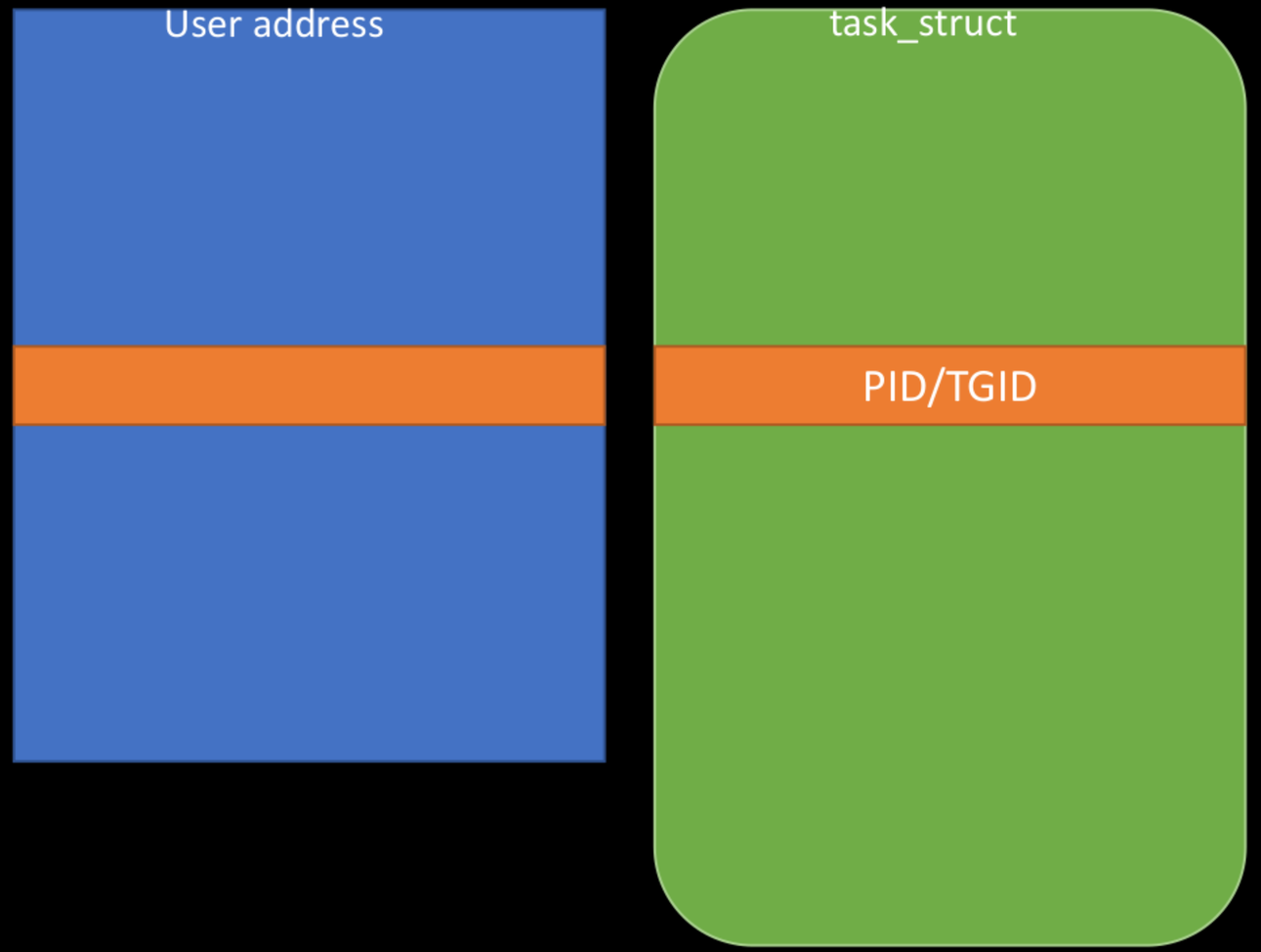
- cat /proc/slabinfo |grep task_struct
  - task_struct 3536 3804 4736 6 8 : tunables 0 0 0 : slabdata 634 634 0

- Some objects can occupy two pages
  - The physical pages corresponding to user addresses are unlikely to be contiguous



Exploit

- Search the task_struct objects
  - PID/TID
  - Comm
  - …
- The target object only occupies one page
- Leak kernel pointers
  - Cred - *(u64*)(A + OFF_CRED – OFF_PID)



Share the same physical page(start address aligned)

Exploit

- The victim thread can be identified
  - The addr_limit of thread_info is completely under the control

Exploit

- The victim thread can be identified
  - The addr_limit of thread_info is completely under the control
- AARW – (Write primitive step)
  - Main process write the data to pipe
    - Any value
    - USER_DS
  - Main process write KERNEL_DS to the addr_limit of victim thread
  - Victim thread wake up and use the kernel pointer as read buffer
    - Target kernel address
    - addr_limit kernel address
  - Victim read the data from pipe

Exploit

- Exploit steps
  - 1. Mmap a large chunk of anonymous memory(RW permission)
  - 2. Import the CPU memory with BASE_MEM_PROT_CPU_WR
  - 3. Submit a JOB with BASE_JD_REQ_EXTERNAL_RESOURCES
  - 4. Read the mapped GPU VA and trigger the VM_FAULT on the CPU side
  - 5. Munmap and release the anonymous memory
  - 6. Spawn a large number of threads
  - 7. Search the mapped GPU VA and find the target thread
  - 8. Leak the kernel pointers and bypass KASLR
  - 9. Patch the cred and SELinux state
  - 10. Spawn a ROOT shell

```
oriole:/ $
```

Agenda

- Introduction
- Bug #1
- Bug #2
- *Conclusion*

Black Hat Sound Bytes

- Analyzing the old bug is always an efficient way to find a new one.
- Memory corruption is good, logic bug is better.
- Even with more and more both hardware and software mitigations, Android rooting is still possible.

References

[1] https://googleprojectzero.blogspot.com/2022/11/a-very-powerful-clipboard-samsung-in-the-wild-exploit-chain.html

[2] https://i.blackhat.com/USA-22/Thursday/US-22-WANG-Ret2page-The-Art-of-Exploiting-Use-After-Free-Vulnerabilities-in-the-Dedicated-Cache.pdf

[3] https://googleprojectzero.blogspot.com/2020/12/an-ios-hacker-tries-android.html

[4] https://www.blackhat.com/docs/eu-16/materials/eu-16-Taft-GPU-Security-Exposed.pdf

[5] https://googleprojectzero.github.io/0days-in-the-wild//0day-RCAs/2021/CVE-2021-39793.html

[6] https://source.android.com/docs/core/architecture/kernel/loadable-kernel-modules

[7] https://labs.bluefrostsecurity.de/blog/2020/04/08/cve-2020-0041-part-2-escalating-to-root/


Thank you!
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