PhantomMap: GPU-Assisted Kernel Exploitation

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Outline

1. **Motivation**
2. **New Findings**
3. **PhantomMap Technique**
    a) **Exploit Chains Identification**
    b) **Exploitability Evaluation**
4. **Lightweight Mitigation**
5. **Takeaways**

Motivation: CPU vs GPU

Robust CPU have raised the bar for direct kernel exploitation, forcing attackers to seek other targets.

Hardened CPU

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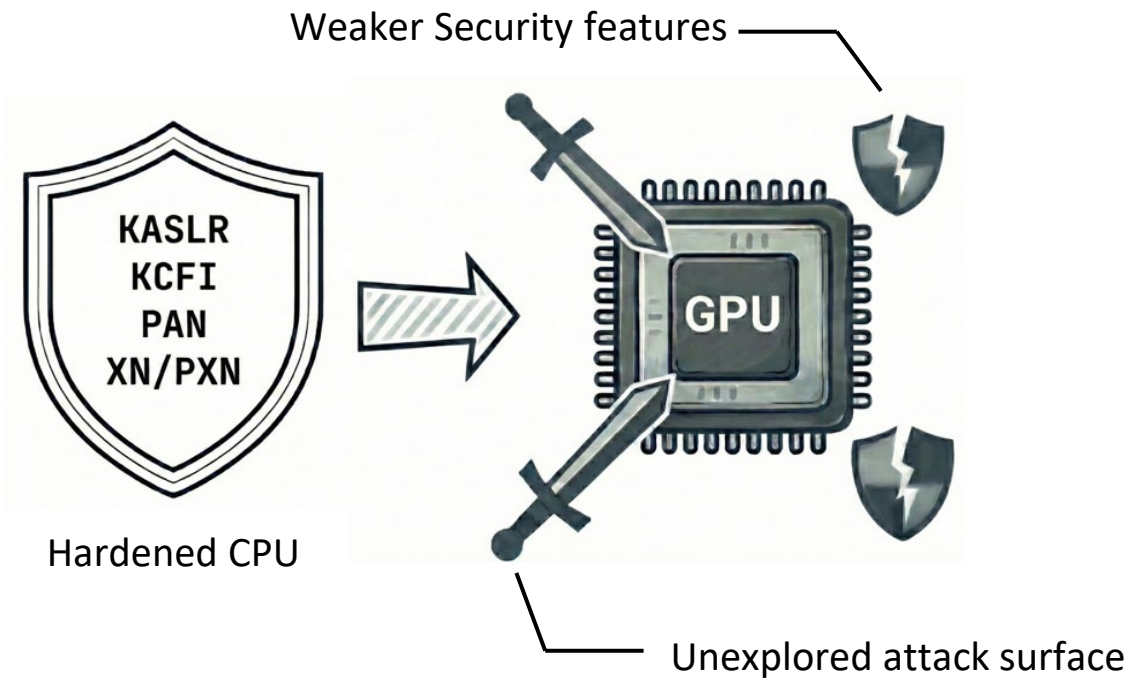

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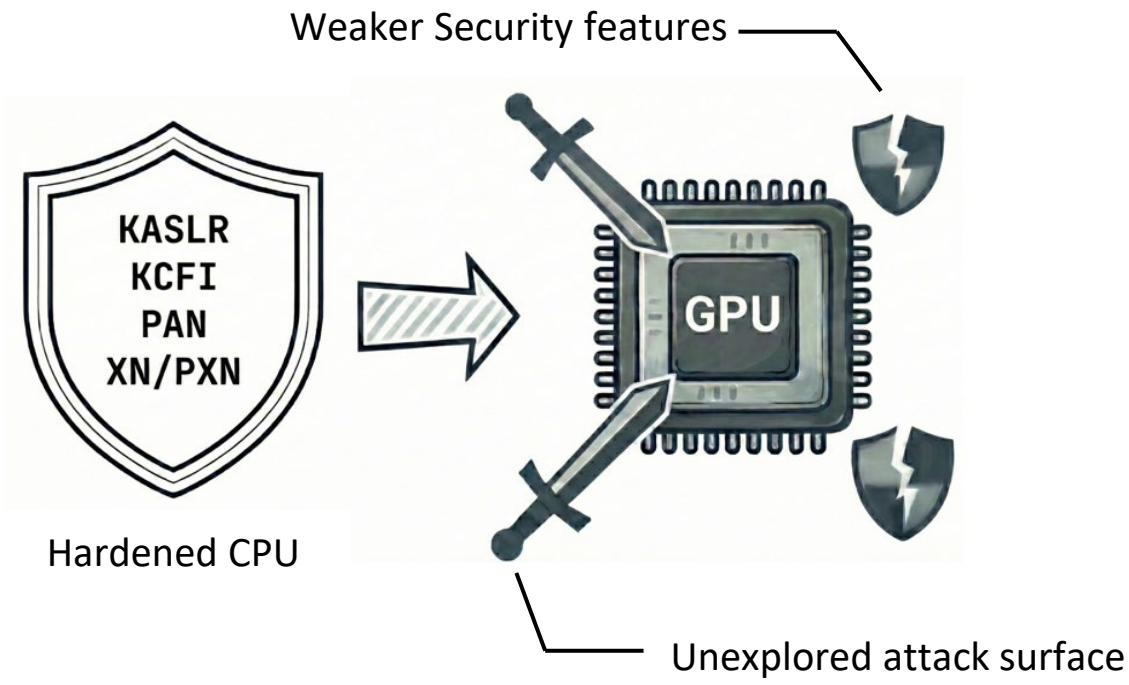

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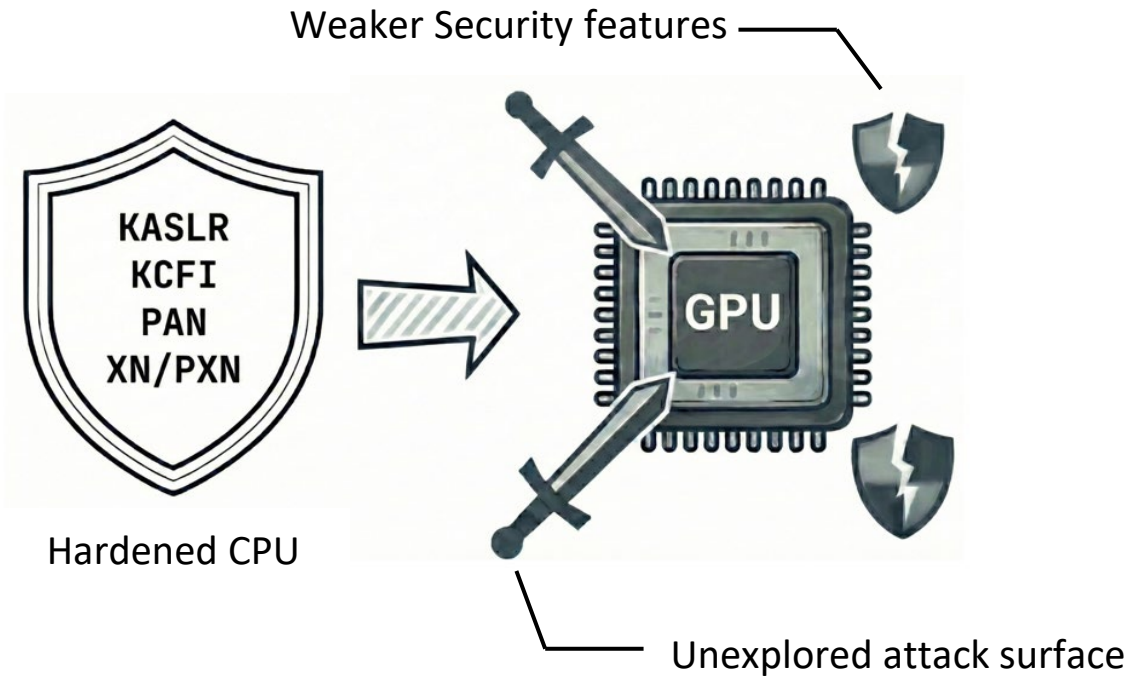

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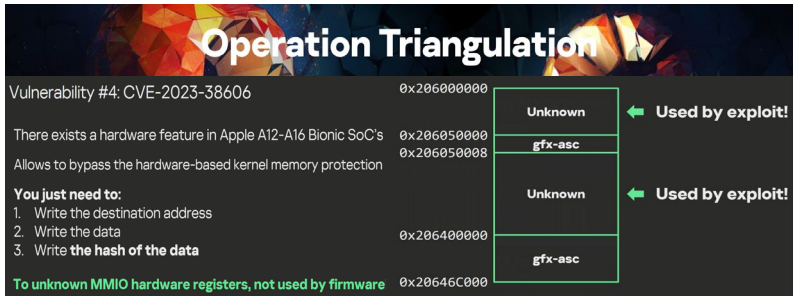
- **Unexplored/Potential Attack Surface**

  e.g., Operation Triangulation leveraged undocumented MMIO registers within the GPU coprocessor to bypass kernel protections and escalate privileges in iOS.



Motivation: Mali GPU popularity

Dominant SoC Adoption: integrated into MediaTek and Unisoc platforms.

Massive Device Reach: Deployed in Google Pixels, Samsung, Xiaomi, OPPO, and Vivo, etc.

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Qualcomm	24%	25%	27%	26%	24%
Apple	17%	21%	15%	15%	18%
UNISOC	13%	14%	10%	13%	14%
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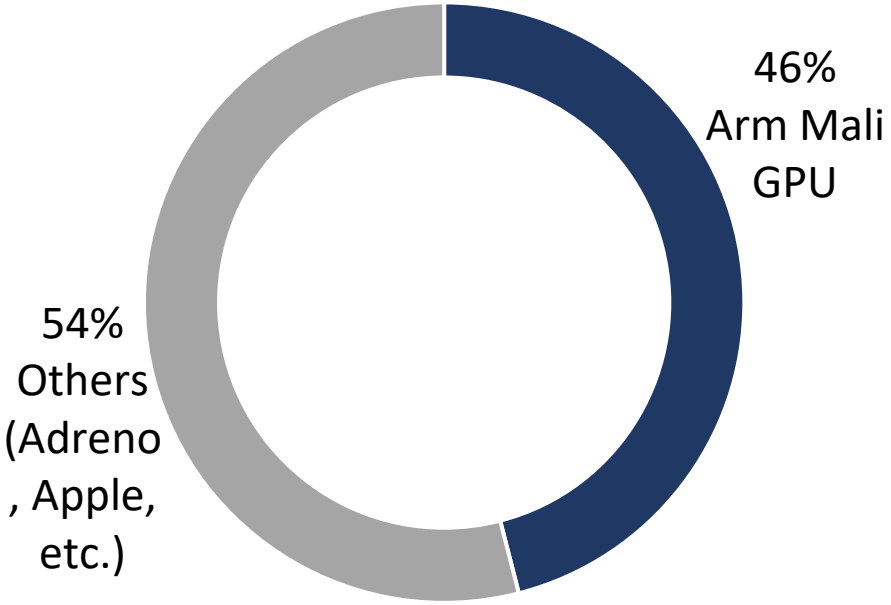
Global Smartphone GPU Market Share → **Arm Mali: 46% Global Market Share**



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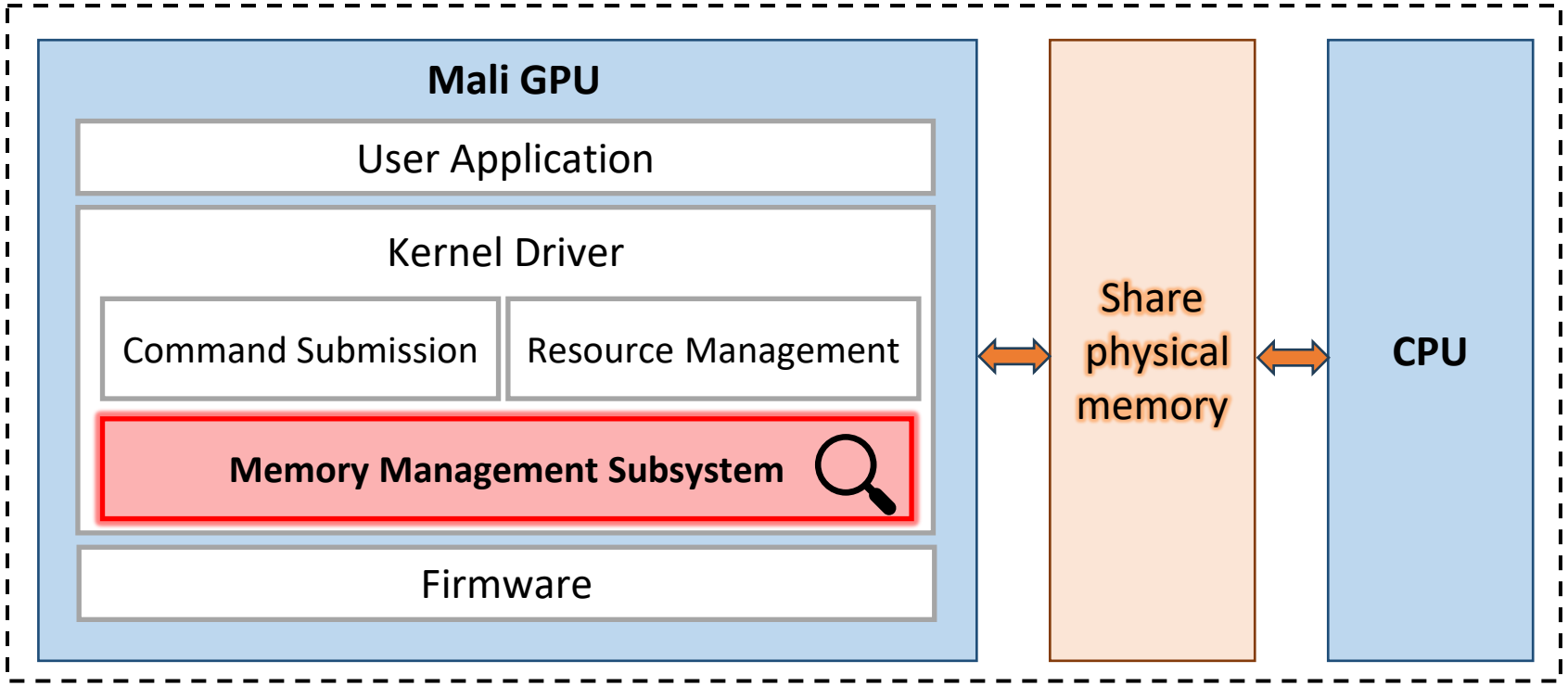

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- **Insight2:** The memory management subsystem of Mali GPU are critical. But security analysis has been ad-hoc and manual

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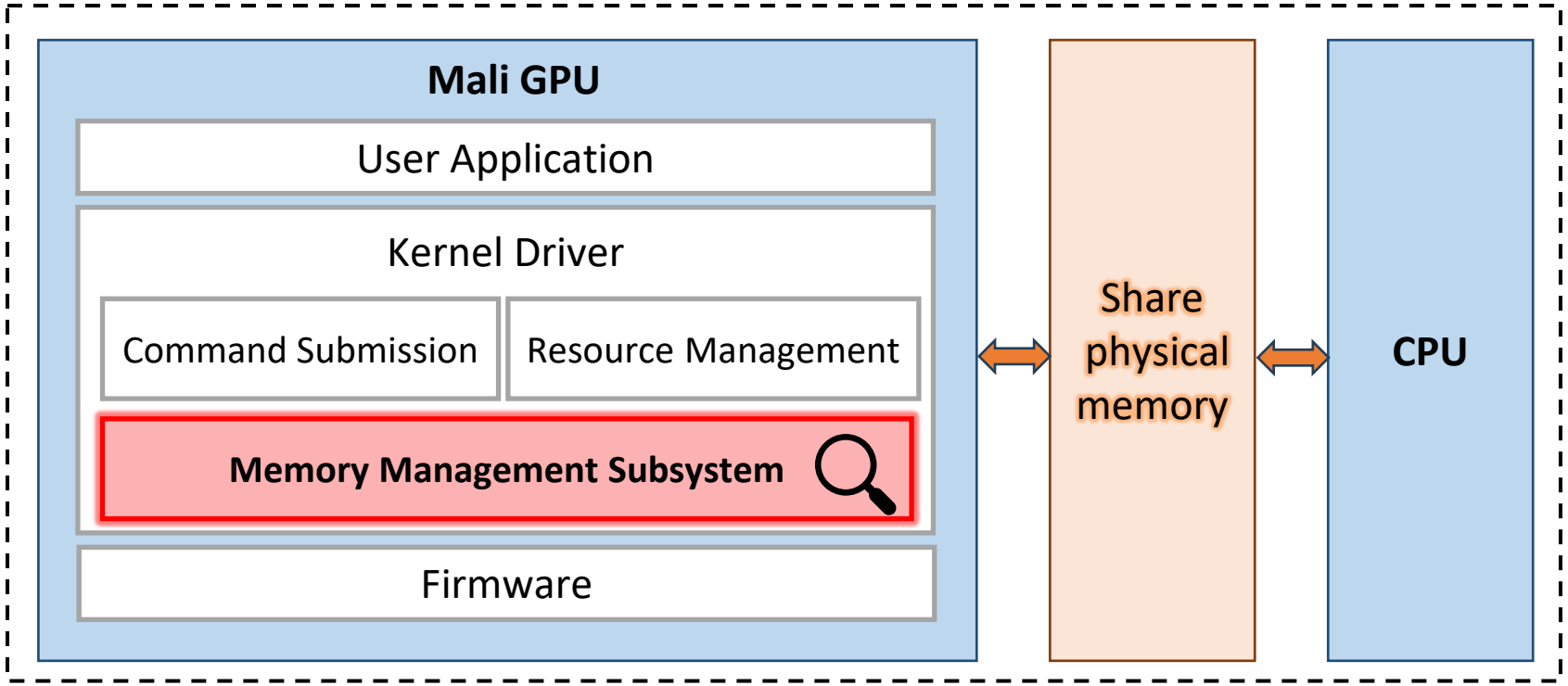

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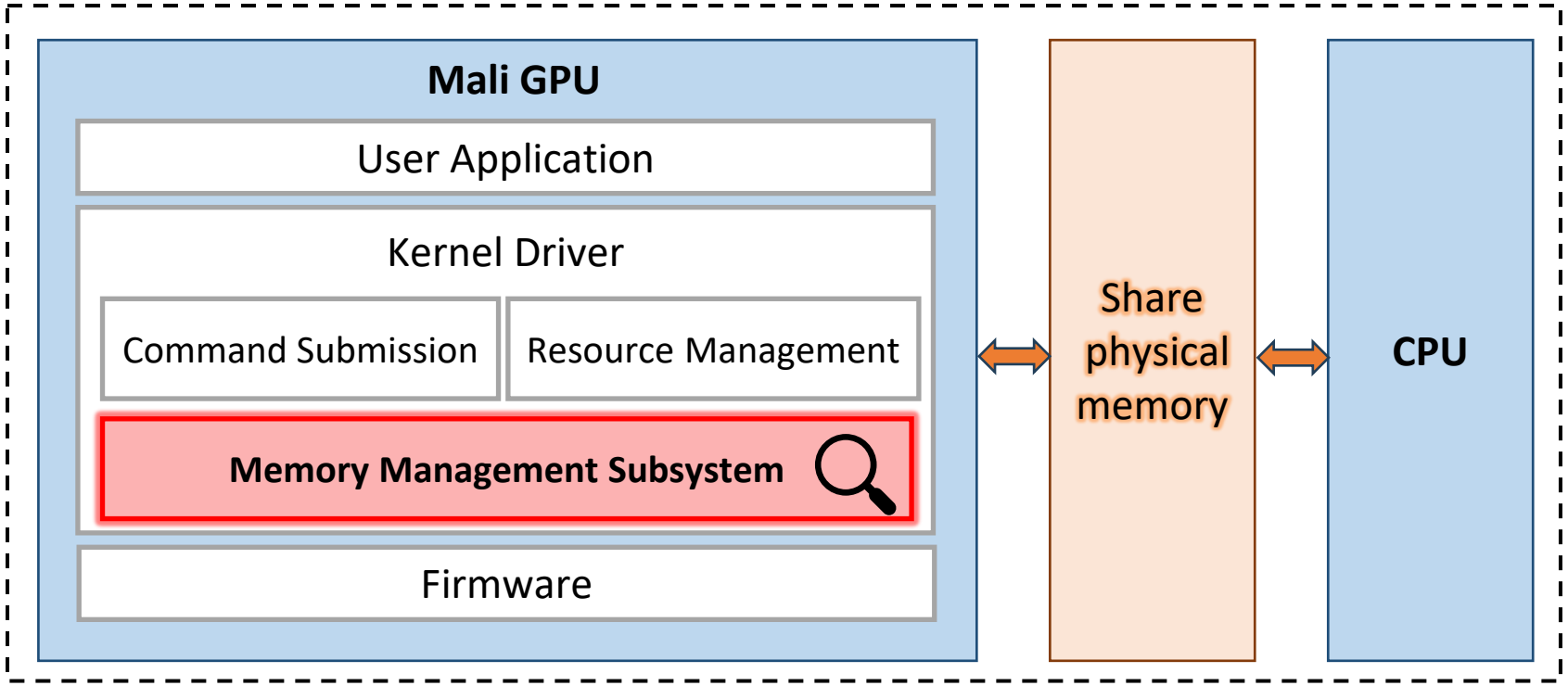

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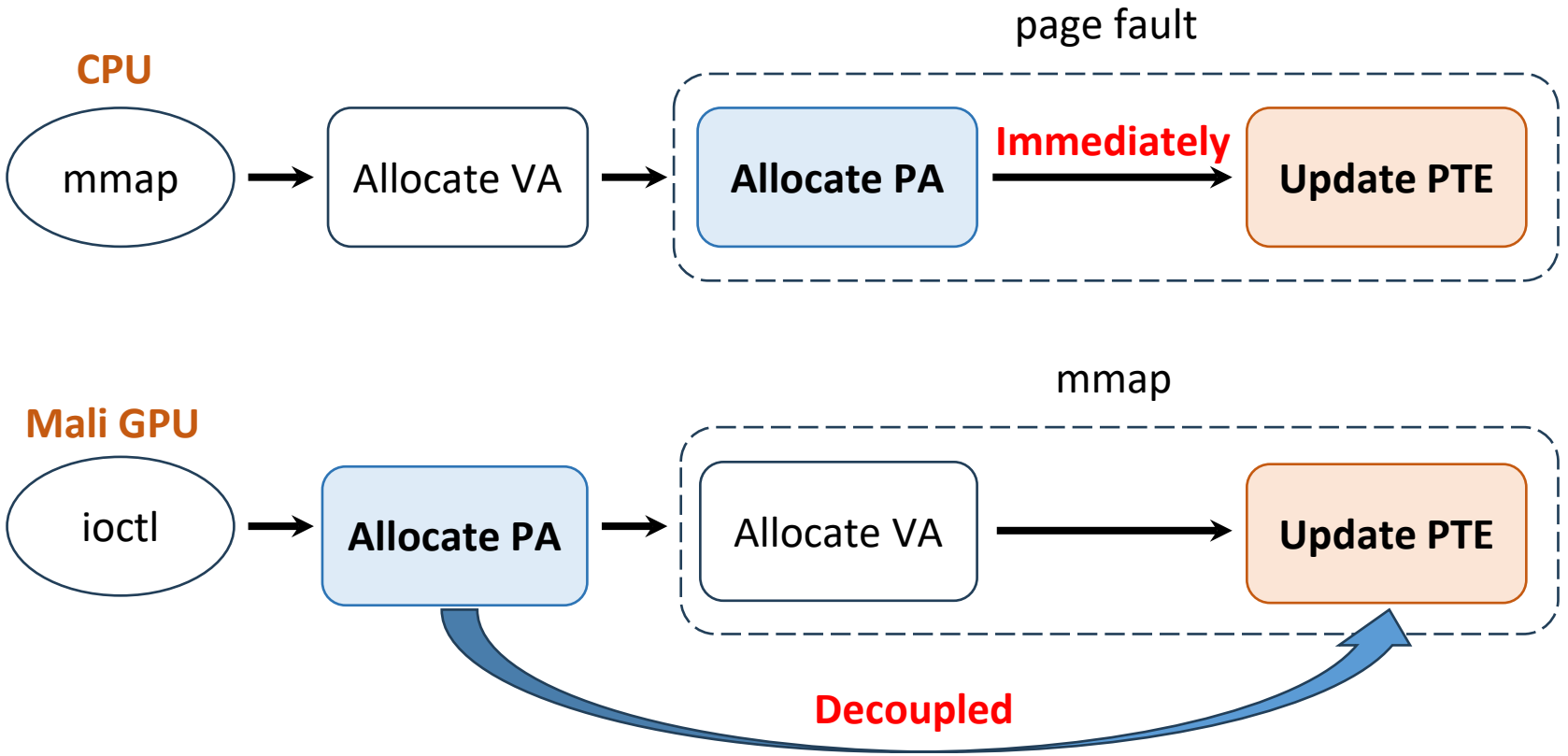
✅ We conduct the first systematic analysis of memory mapping mechanism of Mali GPU.

New Findings: decoupled memory operations



No time window 😩

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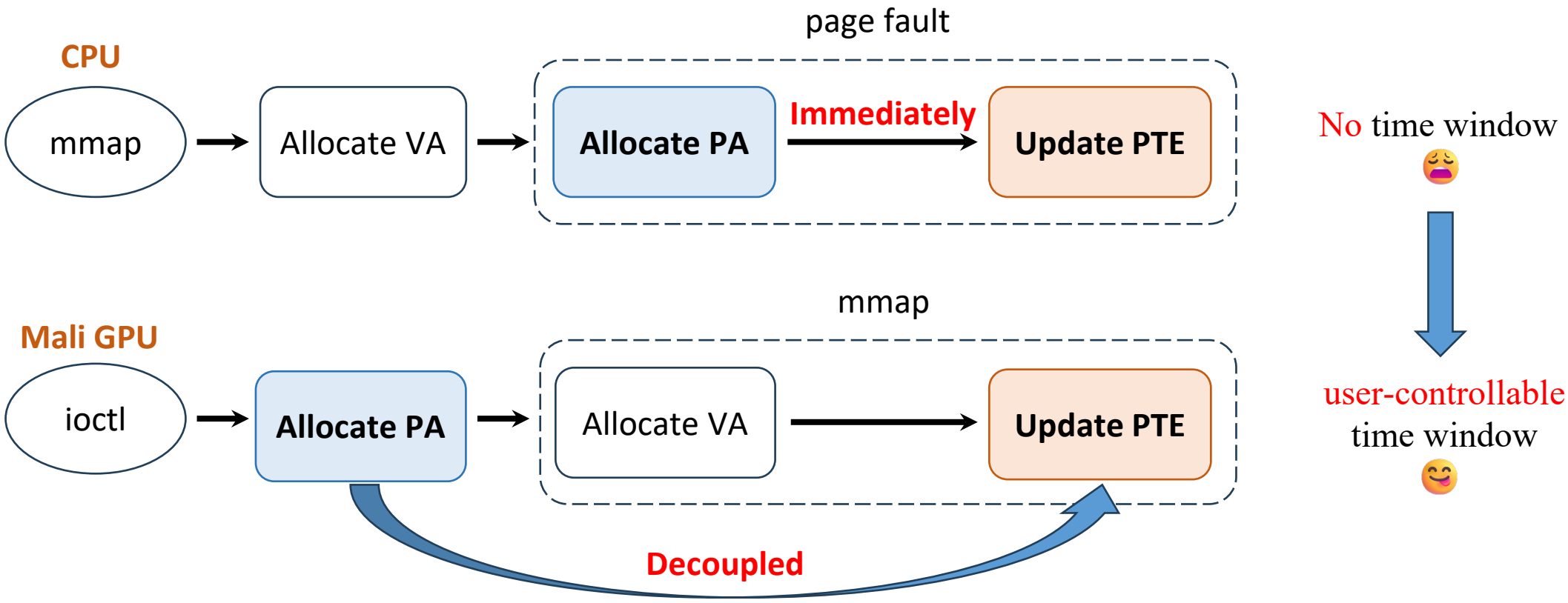
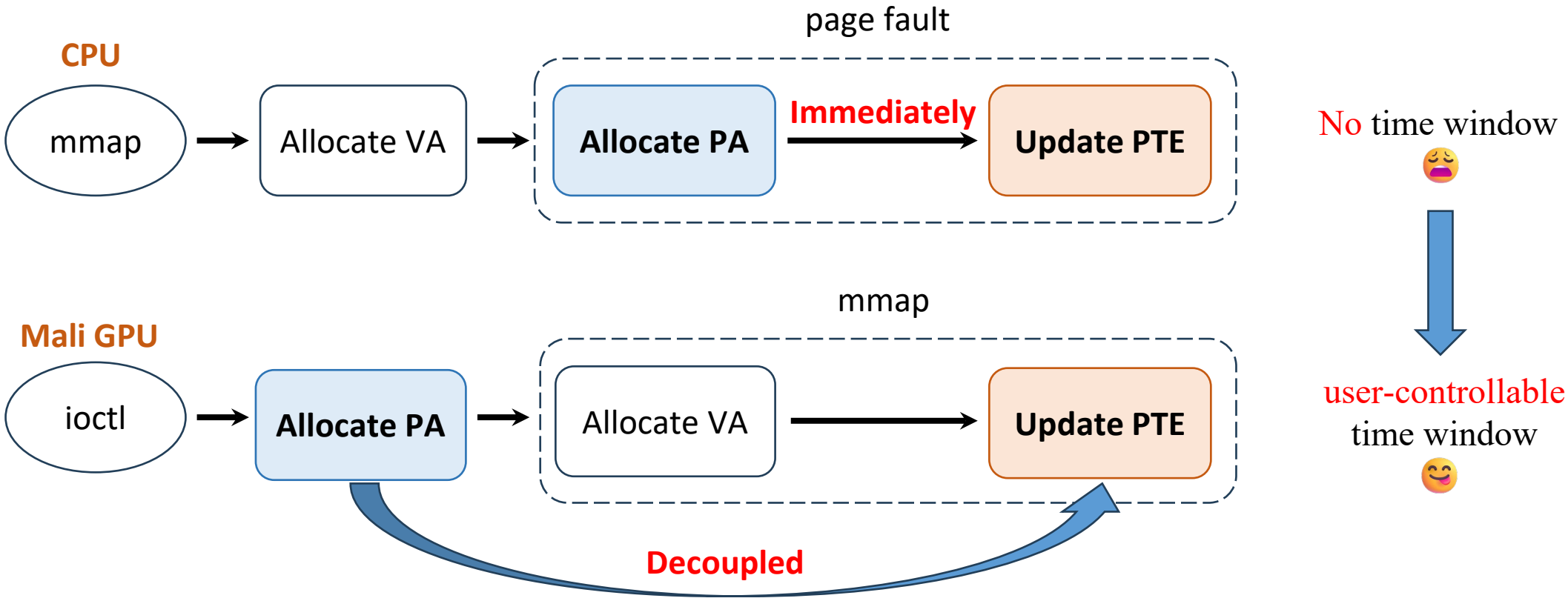


New Findings: decoupled memory operations

Finding-1: The Mali GPU driver decouples physical memory allocation from page table updation, creating a user-controllable time window that can be exploited to remap physical memory.



New Findings: missing GPU physical address validation

In CPU-mapping process, essential checks ensure page validity before inserting physical addresses into and updating the CPU page-table.

```
int insert_page(struct vm_area_struct *vma,...struct
↪  page *page,...) {
    ...
    retval = validate_page_before_insert(vma, page);
    if (retval)
        goto out;
    ...
    retval = insert_page_into_pte_locked(page, ...);
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```
int validate_page_before_insert(...,struct page*page){
    struct folio *folio = page_folio(page);
    if (!folio_ref_count(folio))
        return -EINVAL;
    ...
    if (folio_test_anon(folio) ||
    ↪  folio_test_slab(folio) || page_has_type(page))
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- Check if the reference count for the page's folio is zero. ≫ Prevent mapping UAF page.
- Ensure the page is not of an anonymous or slab type. ≫ Avoid mapping critical regions to user-space.

New Findings: missing GPU physical address validation

Arm Mali GPU driver implements custom memory mapping and pagefault handling interfaces for GPU-specific Virtual MemoryAreas (VMAs).

```
int kbase_mmu_insert_pages(struct tagged_addr *phys,
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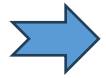

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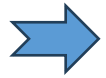

Without any validation of provided physical address

😨 Driver blindly inserts whatever physical address into GPU page-table !

New Findings: missing GPU physical address validation

Finding-2: The Mali GPU driver doesn't validate physical pages before mapping, allowing arbitrary or sensitive kernel memory to be remapped into user space without any security checks.

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Based on the two findings, we proposed a novel GPU-assisted exploitation technique: **PhantomMap** 

The key idea of PhantomMap: exploit Mali's decoupled allocation-and-mapping workflow by corrupting GPU key structures, then the driver remaps arbitrary physical memory into GPU user-space without validation.

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① **GPU memory allocation**

ioctl(fd, KBASE_IOCTL_MEM_ALLOC)

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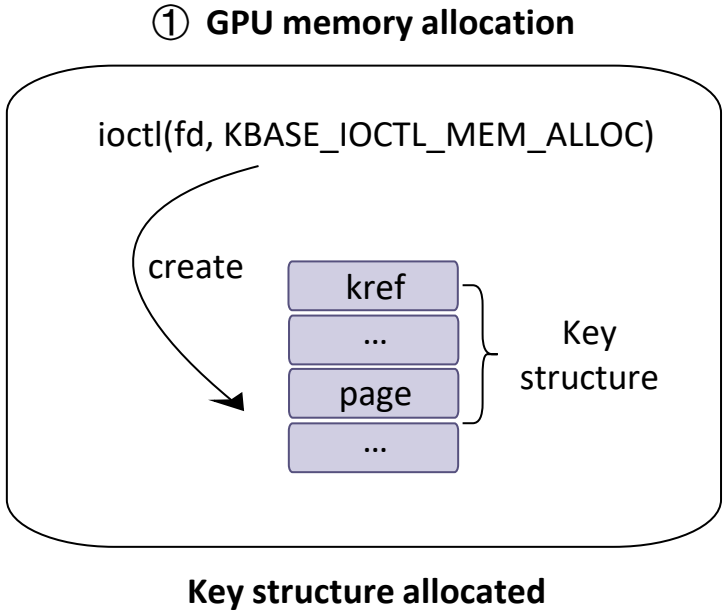

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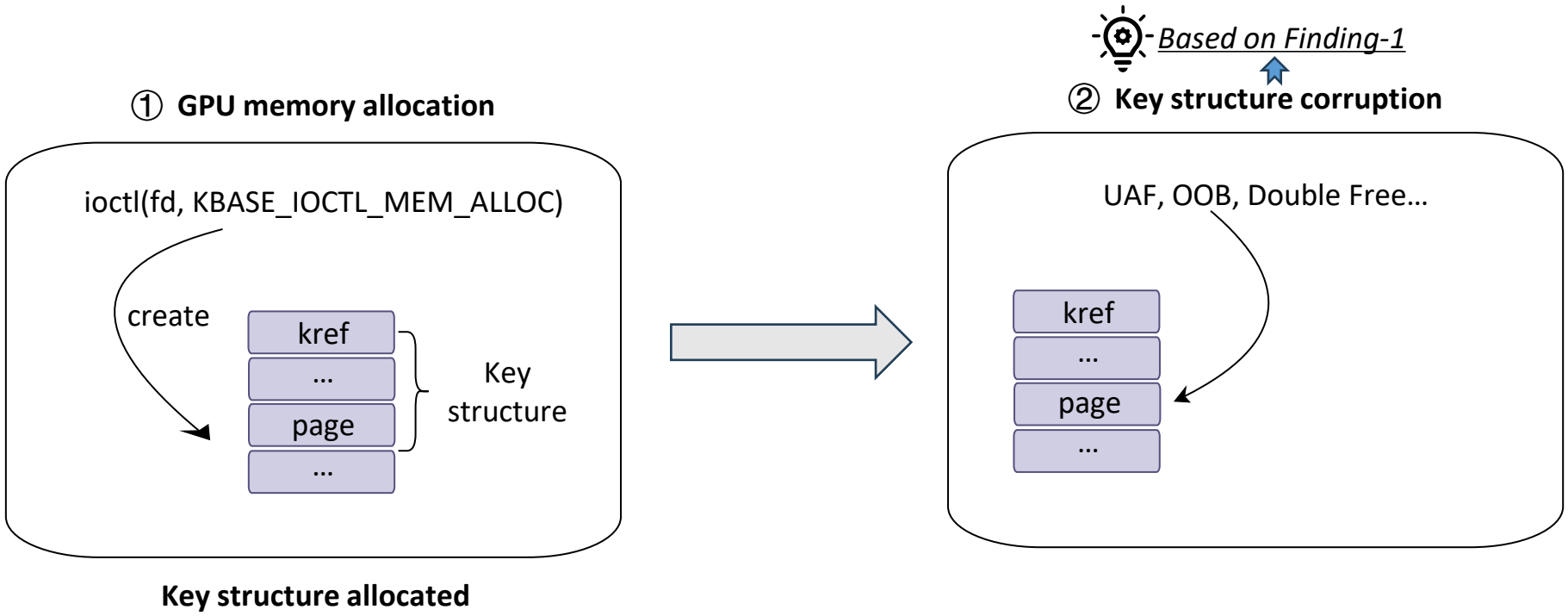

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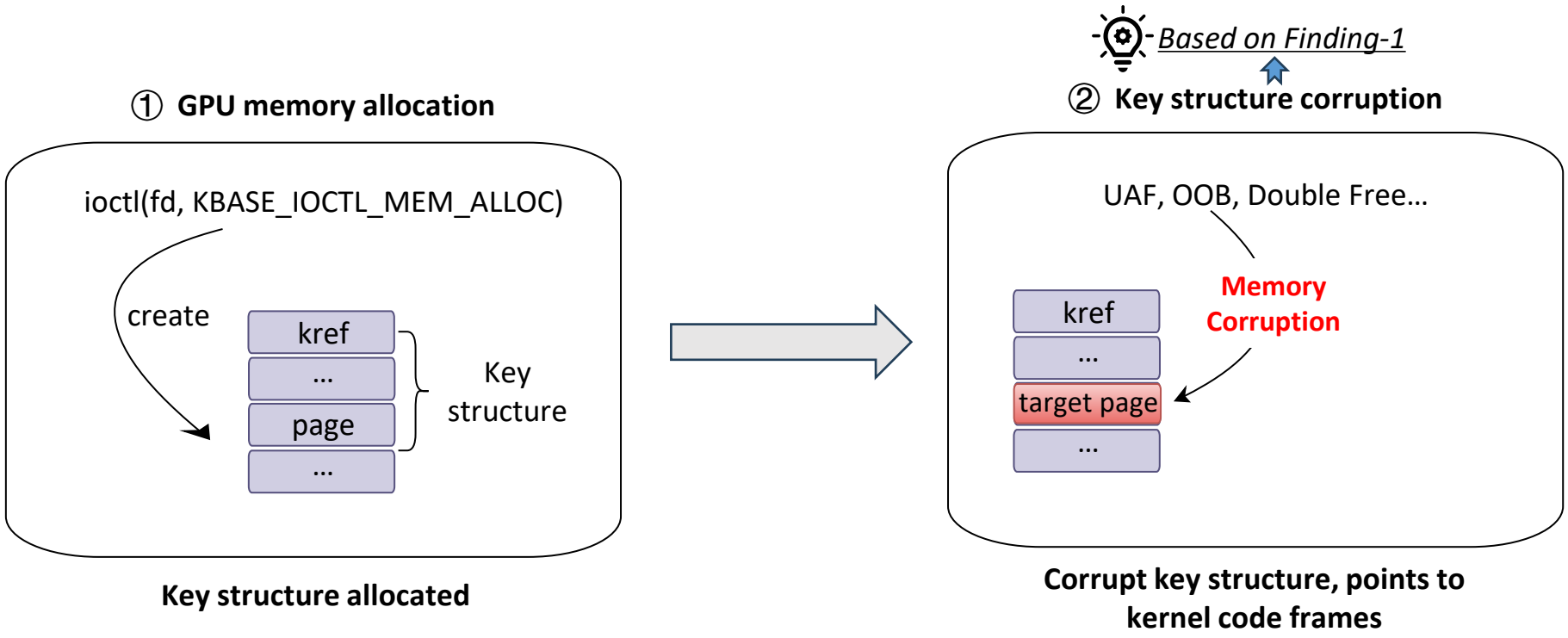

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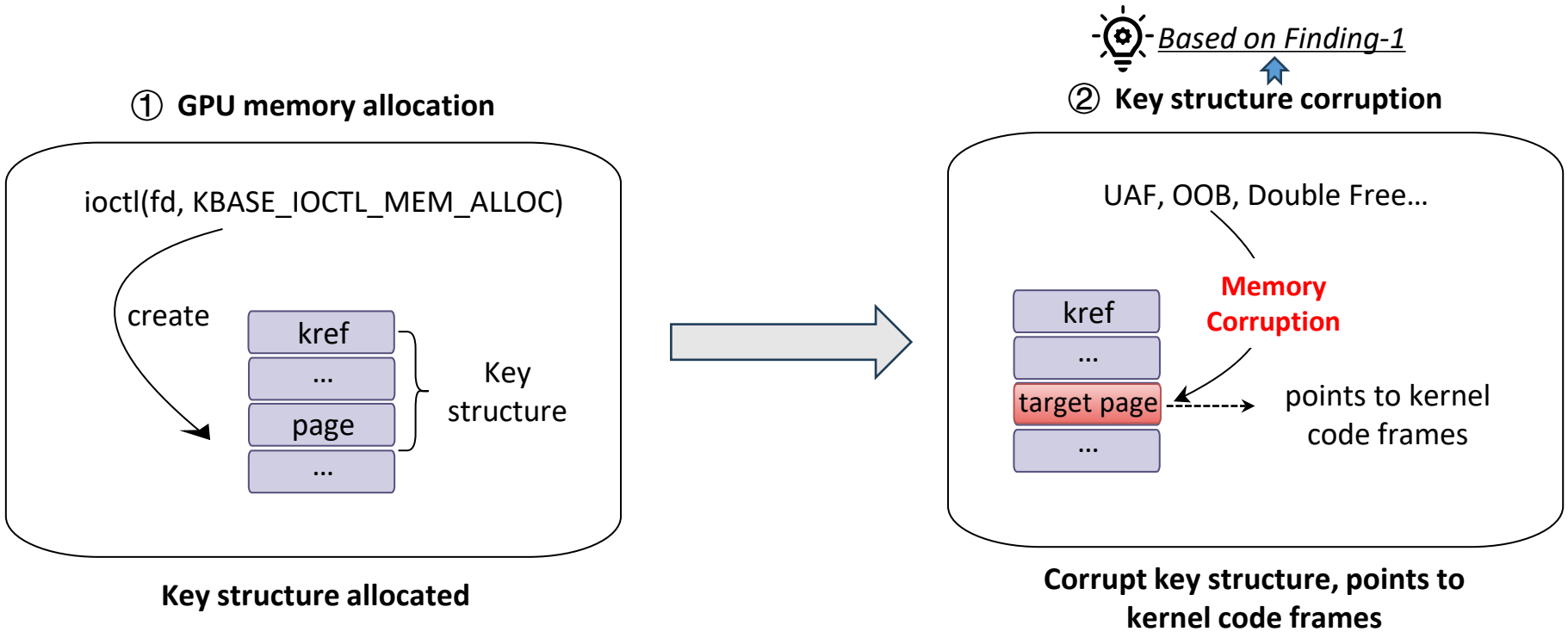

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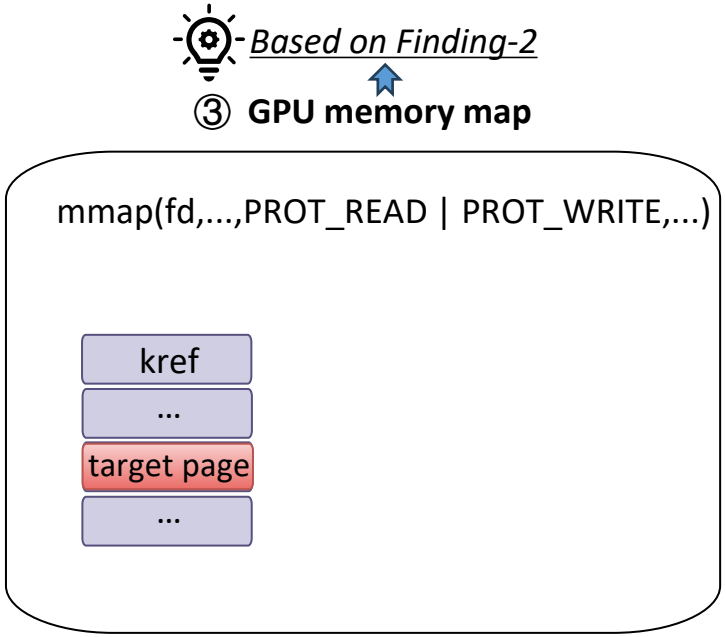

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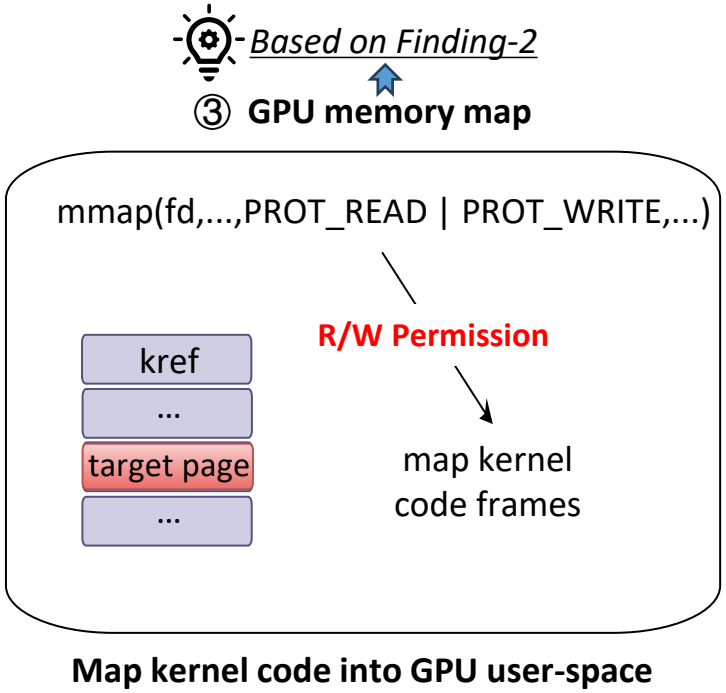

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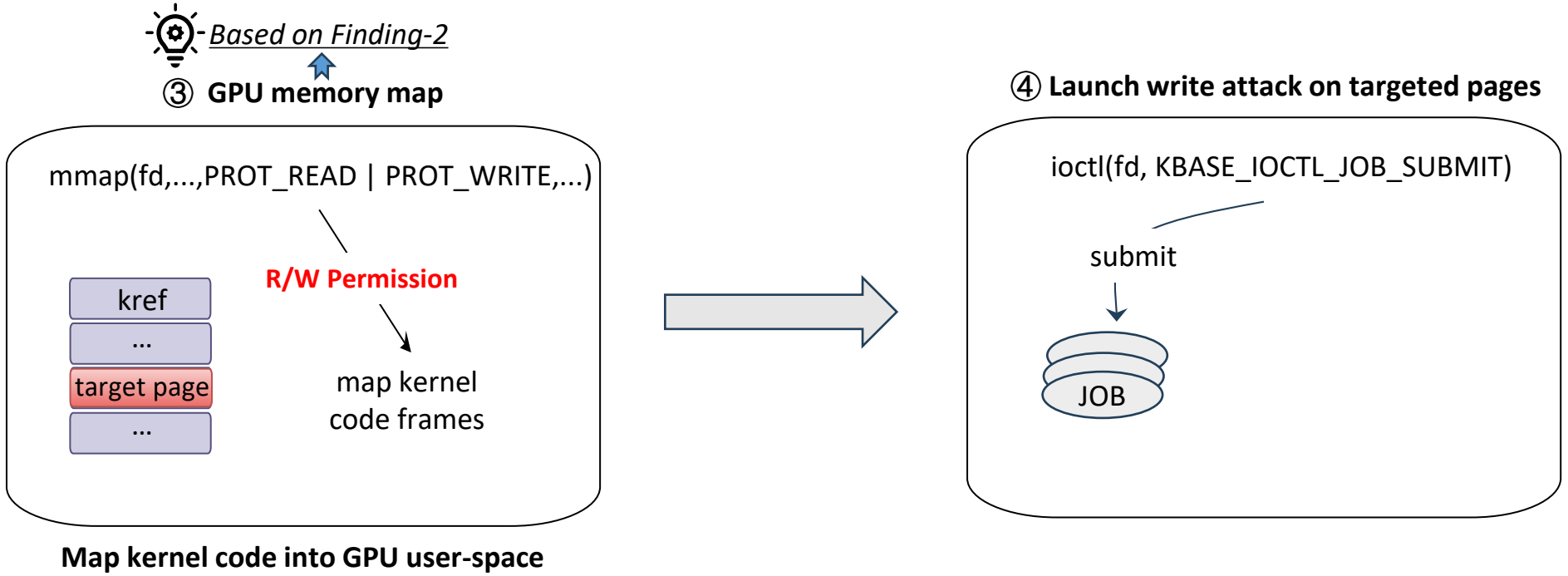

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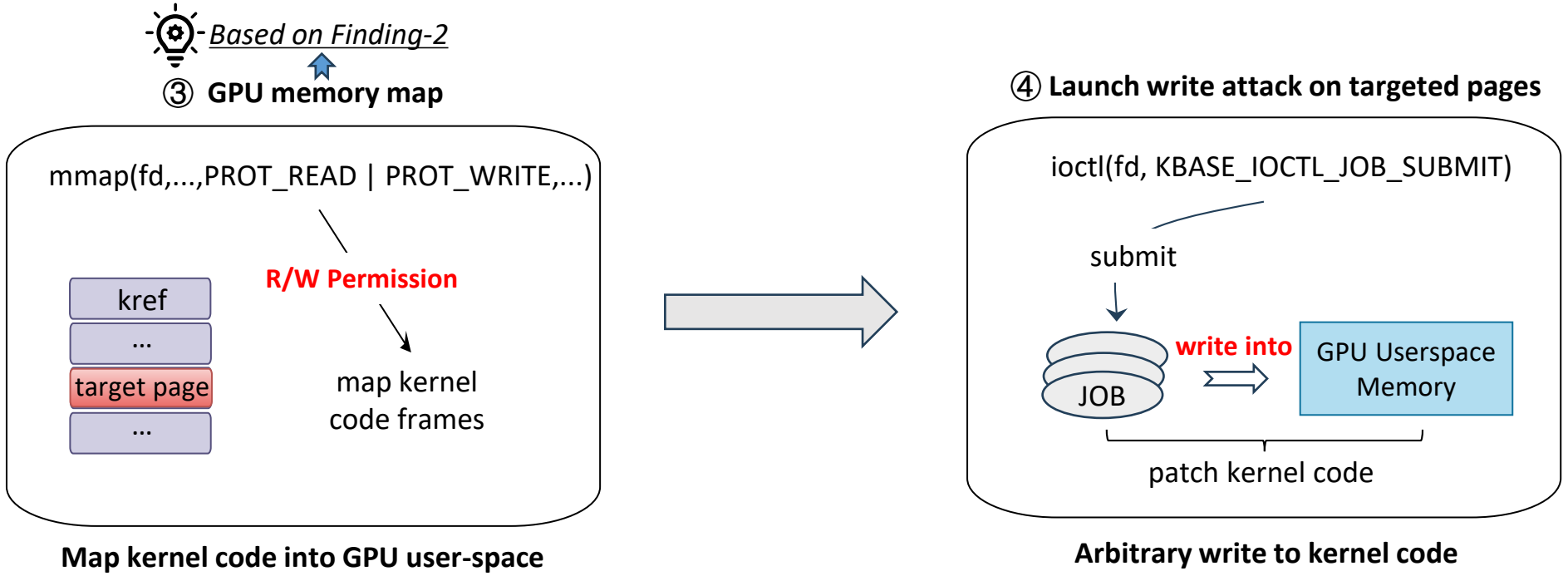

Map kernel code into GPU user-space

Arbitrary write to kernel code

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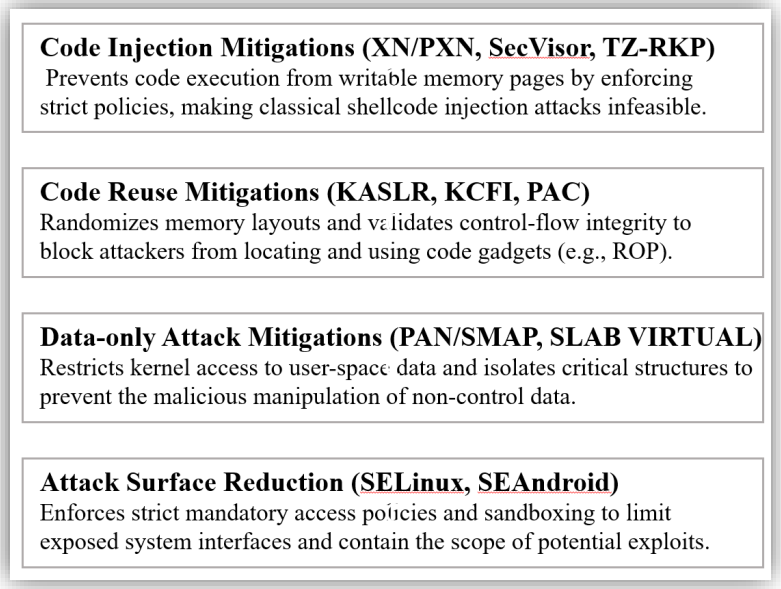

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- ***General !***
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- ***Reliable & Simpler !***
  - Don’t need any info-leak during exploitation.

Exploit Chains Identification

The dedicated analyzer identified **15 distinct end-to-end exploit chains** and **6 unique key structures**.

Allocation Entry	Syscall	Mapping Entry	Syscall	Related Key Structure	Read/Write
kbase_mem_alloc	ioctl	kbase_gpu_mmap	mmap	kbase_mem_phy_alloc	●
kbase_mem_alloc	ioctl	kbase_mem_commit	ioctl	kbase_mem_phy_alloc	●
kbase_mem_alloc	ioctl	kbase_cpu_mmap	ioctl	kbase_mem_phy_alloc	●
kbase_mem_import	ioctl	kbase_gpu_mmap	mmap	kbase_mem_phy_alloc	●
kbase_mem_import	ioctl	kbase_map_external_resource	ioctl	kbase_alloc_import_user_buf	●
kbase_mem_import	ioctl	kbase_mem_flags_change	ioctl	kbase_mem_phy_alloc	●
kbase_mem_import	ioctl	kbase_map_external_resource	ioctl	kbase_mem_phy_alloc	●
kbase_mem_alias	ioctl	kbase_gpu_mmap	mmap	kbase_mem_phy_alloc	●
kbase_mem_alias	ioctl	kbase_cpu_mmap	mmap	kbase_mem_phy_alloc	◐
kbase_create_context	open	kbase_gpu_mmap	mmap	kbase_context	◐
kbase_create_context	ioctl	kbase_map_external_resource	mmap	kbase_mem_phy_alloc	●
kbase_platform_device_probe†	—	kbase_csf_cpu_mmap_user_reg_page	mmap	kbase_device	◐
kbase_platform_device_probe†	—	kbase_csf_cpu_mmap_user_io_pages	mmap	kbase_device	●
kbase_csf_doorbell_mapping_init†	—	kbase_csf_cpu_mmap_user_io_pages	mmap	kbase_csf_device	●
kbase_csf_alloc_command_stream_user_pages†	ioctl	kbase_csf_cpu_mmap_user_io_pages	mmap	kbase_queue	●

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kbase_mem_alias	ioctl	kbase_gpu_mmap	mmap	kbase_mem_phy_alloc	●
kbase_mem_alias	ioctl	kbase_cpu_mmap	mmap	kbase_mem_phy_alloc	◐
kbase_create_context	open	kbase_gpu_mmap	mmap	kbase_context	◐
kbase_create_context	ioctl	kbase_map_external_resource	mmap	kbase_mem_phy_alloc	●
kbase_platform_device_probe†	—	kbase_csf_cpu_mmap_user_reg_page	mmap	kbase_device	◐
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R/W permission?

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kbase_create_context	open	kbase_gpu_mmap	mmap	kbase_context	◐
kbase_create_context	ioctl	kbase_map_external_resource	mmap	kbase_mem_phy_alloc	●
kbase_platform_device_probe†	—	kbase_csf_cpu_mmap_user_reg_page	mmap	kbase_device	◐
kbase_platform_device_probe†	—	kbase_csf_cpu_mmap_user_io_pages	mmap	kbase_device	●
kbase_csf_doorbell_mapping_init†	—	kbase_csf_cpu_mmap_user_io_pages	mmap	kbase_csf_device	●
kbase_csf_alloc_command_stream_user_pages†	ioctl	kbase_csf_cpu_mmap_user_io_pages	mmap	kbase_queue	●

R/W permission?

Attack window?

Exploit Chains Identification

The dedicated analyzer identified **15 distinct end-to-end exploit chains** and **6 unique key structures**.

Allocation Entry	Syscall	Mapping Entry	Syscall	Related Key Structure	Read/Write
kbase_mem_alloc	ioctl	kbase_gpu_mmap	mmap	kbase_mem_phy_alloc	●
kbase_mem_alloc	ioctl	kbase_mem_commit	ioctl	kbase_mem_phy_alloc	●
kbase_mem_alloc	ioctl	kbase_cpu_mmap	ioctl	kbase_mem_phy_alloc	●
kbase_mem_import	ioctl	kbase_gpu_mmap	mmap	kbase_mem_phy_alloc	●
kbase_mem_import	ioctl	kbase_map_external_resource	ioctl	kbase_alloc_import_user_buf	●
kbase_mem_import	ioctl	kbase_mem_flags_change	ioctl	kbase_mem_phy_alloc	●
kbase_mem_import	ioctl	kbase_map_external_resource	ioctl	kbase_mem_phy_alloc	●
kbase_mem_alias	ioctl	kbase_gpu_mmap	mmap	kbase_mem_phy_alloc	●
kbase_mem_alias	ioctl	kbase_cpu_mmap	mmap	kbase_mem_phy_alloc	◐
kbase_create_context	open	kbase_gpu_mmap	mmap	kbase_context	◐
kbase_create_context	ioctl	kbase_map_external_resource	mmap	kbase_mem_phy_alloc	●
kbase_platform_device_probe†	—	kbase_csf_cpu_mmap_user_reg_page	mmap	kbase_device	◐
kbase_platform_device_probe†	—	kbase_csf_cpu_mmap_user_io_pages	mmap	kbase_device	●
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Attack window?

Futhermore, we developed 15 end-to-end exploits for each of the exploit chains to confirm their real-world exploitability using CVE-2022-20409 and CVE-2023-48409.

Exploitability Evaluation

		Existing Exploits		PhantomMap Exploit	
CVE ID	Type	No Leak Required	Bypass Mitigations	No Leak Required	Bypass Mitigations
CVE-2025-21836	UAF	–	–	✔	✔
CVE-2024-46740	UAF	✔	✔	✔	✔
CVE-2024-26582	Double Free	✗	✔	✔	✔
CVE-2023-32882	OOB	✗	✔	✔	✔
CVE-2023-6560	OOB	✔	✗	✔	✔
CVE-2023-32837	OOB	✗	✗	✔	✔
CVE-2023-32832	UAF	✗	✔	✔	✔
CVE-2023-48409	OOB	✗	✔	✔	✔
CVE-2023-20938*	UAF	✗	✗	✔	✗
CVE-2023-0266	UAF	✗	✔	✔	✔
CVE-2022-38181	UAF	✔	✔	✔	✔
CVE-2022-20421*	UAF	✗	✗	✔	✗
CVE-2022-20409	Double Free	✗	✗	✔	✔

- 13 real-world CVEs, covering all common all common vulnerability types.
- 15 end-to-end privilege escalation exploits on Pixel6, Pixel7, Samsung A71.
- Successfully exploits CVE-2025-21836, for which no public exploit is known to date.

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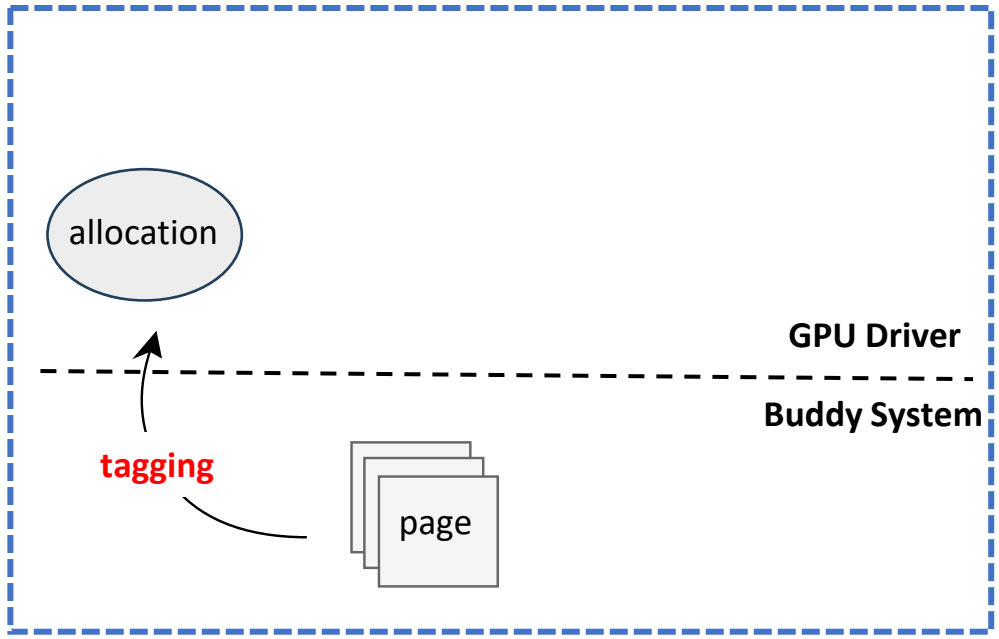
PhantomMap significantly outperforms existing methods: works without info-leak dependencies and bypasses stronger mitigations where prior exploits failed.

Lightweight Mitigation

Strategy



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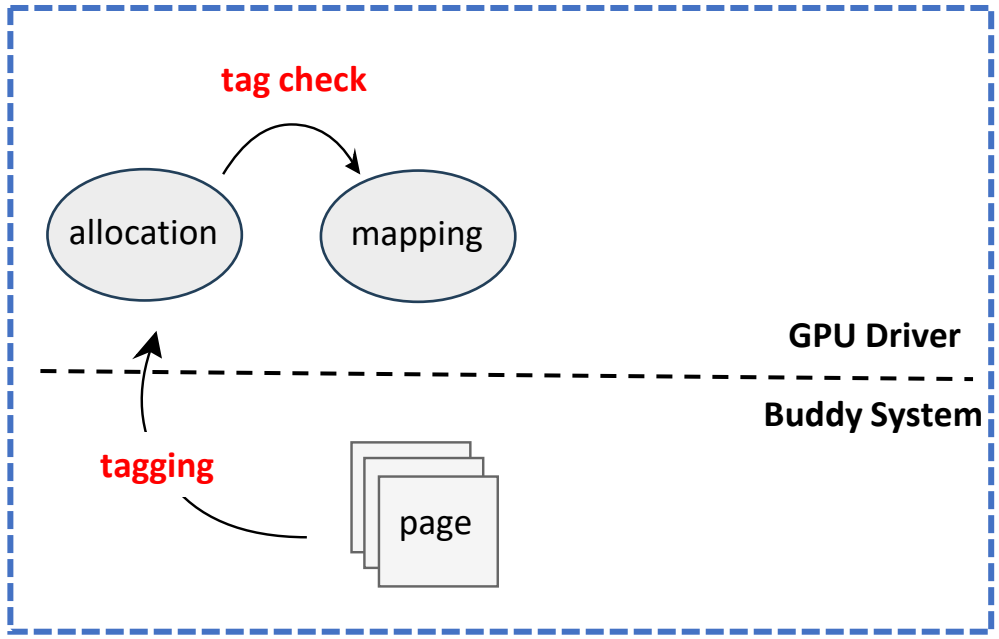

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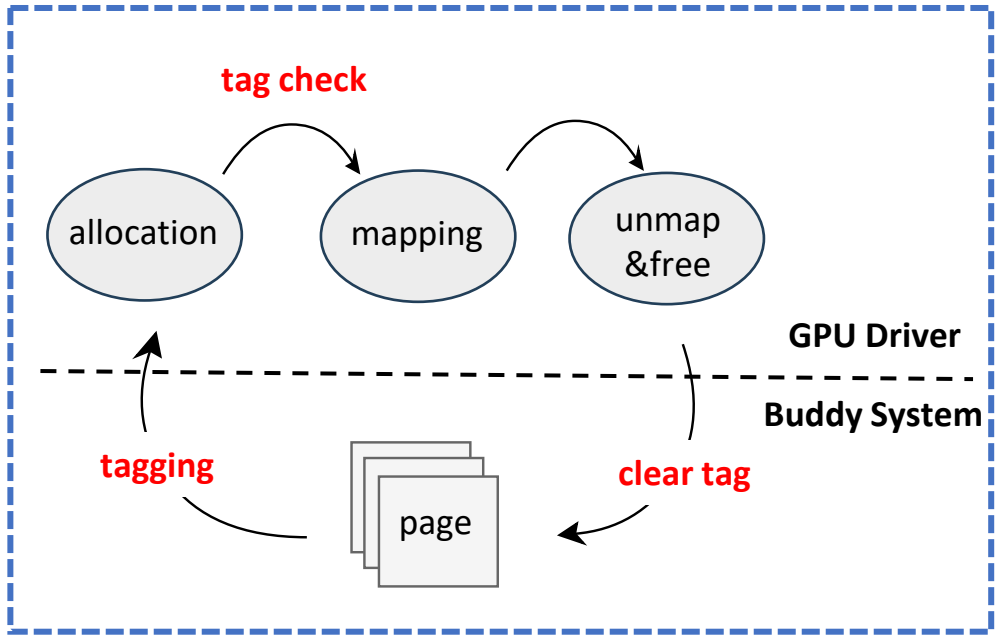

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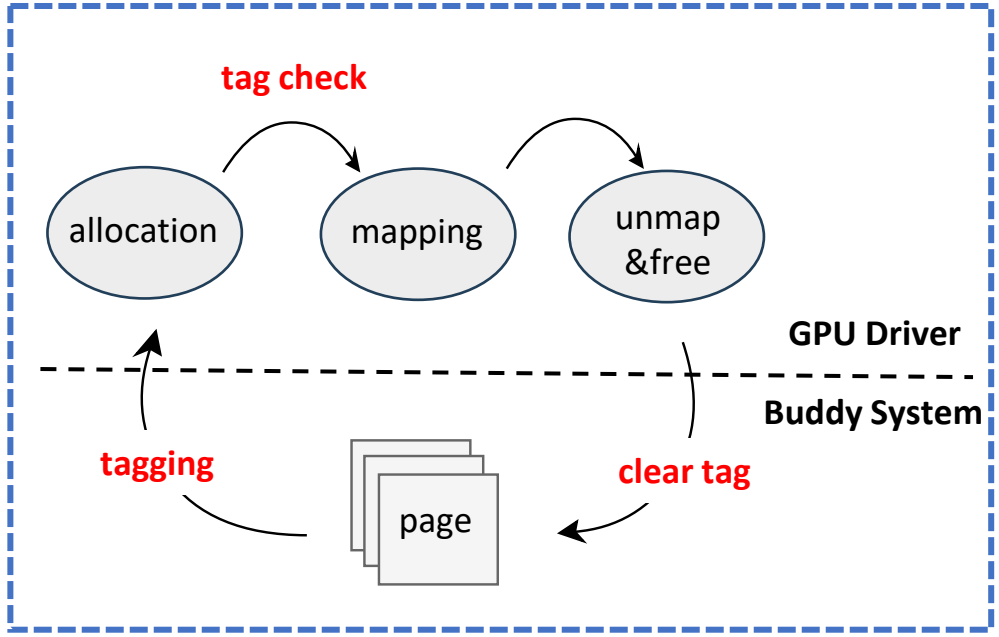

Implementation

```
**THE FIX**

// In kbase_csf_user_io_pages_vm_fault:


struct page *page = pfn_to_page(input_page_pfn);
if(!PageGpu(page)){
    ret = VM_FAULT_SIGBUS;
    goto exit;
}

// proceed to update GPU page table
ret = mgm_dev->ops.
mgm_vmf_insert_pfn_prot(..., input_page_pfn, ...);
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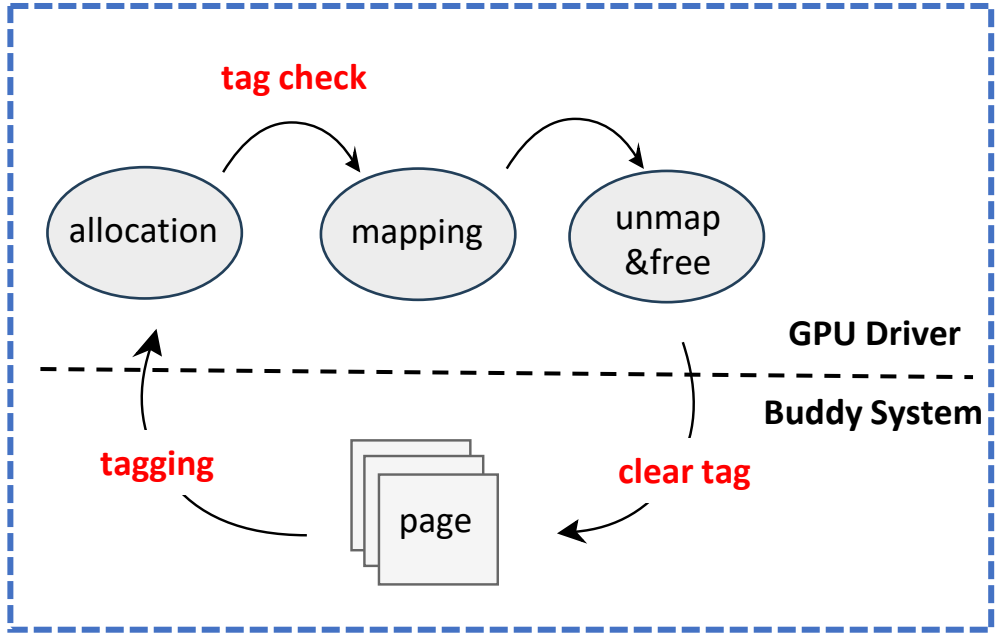

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Blocks mapping of any non-gpu memory

Lightweight Mitigation

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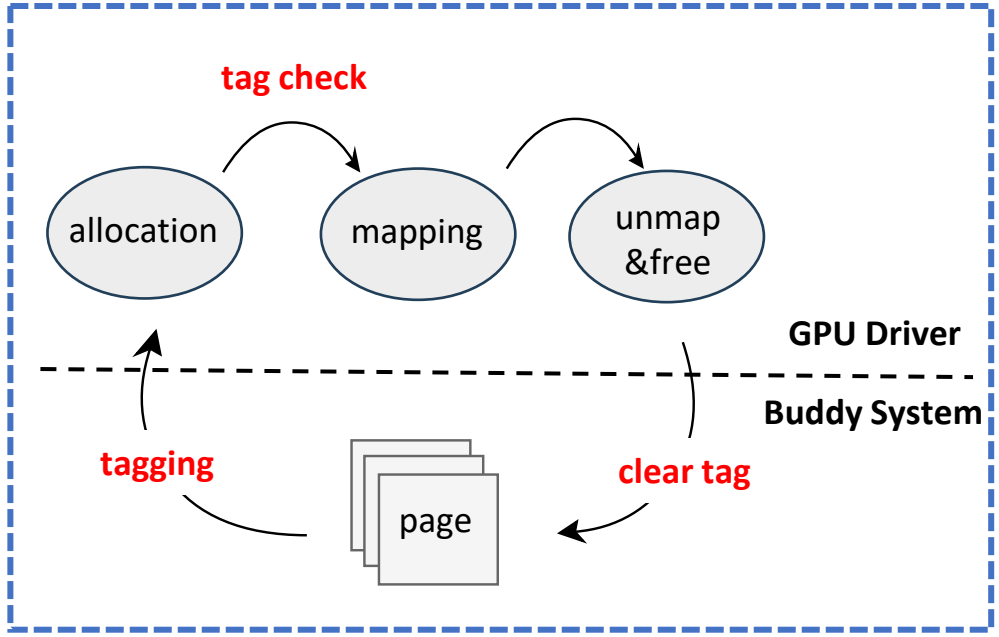

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```

Blocks mapping of any non-gpu memory

Re-enforcing stricter page validation !

Lightweight Mitigation

✅ **Lightweight**

- 21 representative GPU benchmarks tested.
- Evaluated on:
  - Pixel 6 (JM architecture)
  - Pixel 7 (CSF architecture)
- Performance Overhead:
  - Pixel 6: **0.56%** average overhead
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- Our mitigation introduces no functional regression.

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🥳 Powerful

- Strictly prevents mapping of **all non-GPU pages**, to effectively mitigate PhantomMap.

Takeaways

1. **First systematic analysis of the Mali GPU memory-mapping mechanism, revealing two security weaknesses.**
2. **A novel GPU-assisted kernel exploitation technique.**
3. **Comprehensive real-world exploitability evaluation.**
4. **A dedicated static analyzer to identify all viable exploit chains.**
5. **A lightweight and effective mitigation.**