SLUBStick:

Arbitrary Memory Writes through Practical Software Cross-Cache Attacks within the Linux Kernel

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Introduction

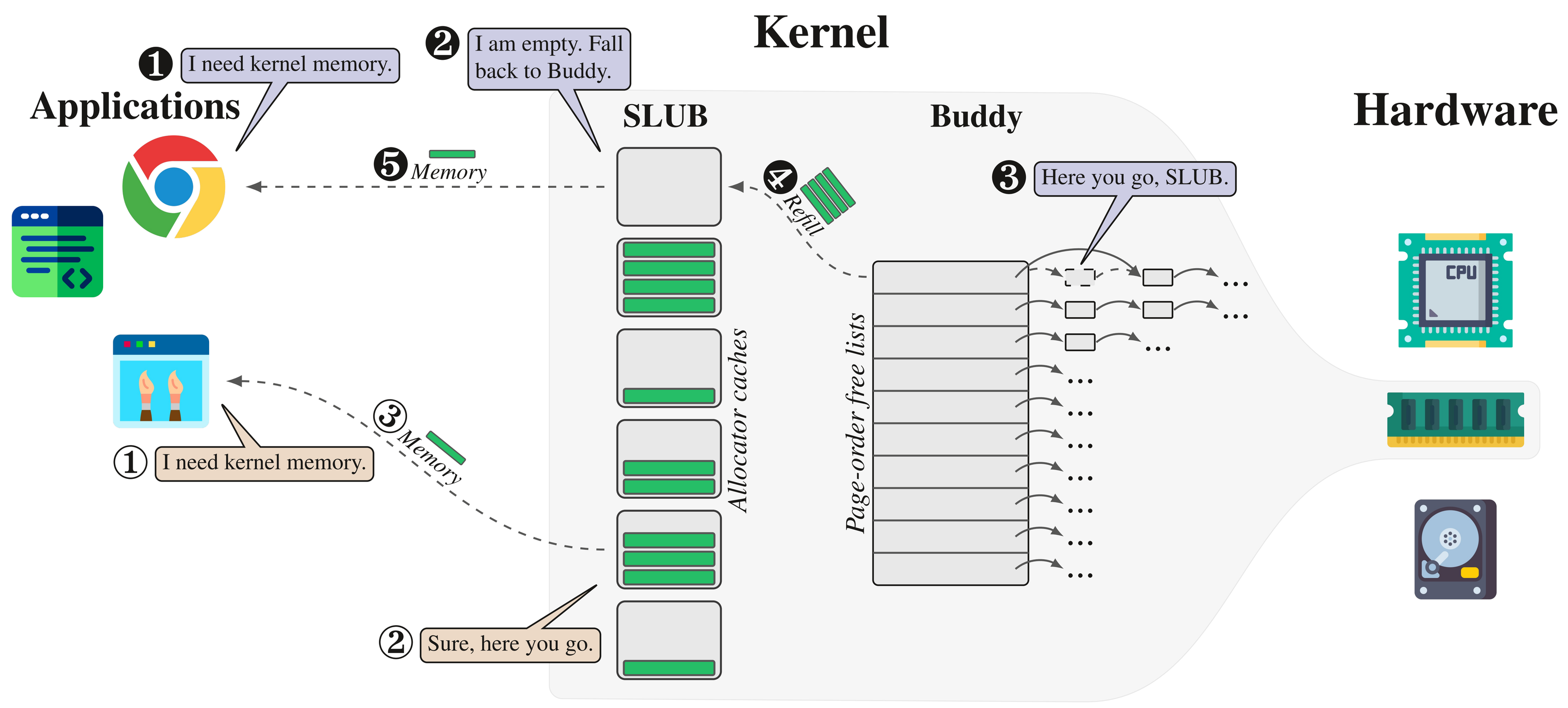
In recent years, the number of vulnerabilities as well as defenses in the Linux kernel has increased significantly. This results in a situation where many kernel vulnerabilities exist, while their exploitation is difficult.

We present a new kernel exploit technique, SLUBStick, which allows bad actors to fully compromise Linux systems with state-of-the-art kernel defenses enabled. We show the practicality of SLUBStick by implementing 9 exploits and compromising Ubuntu 22.04 LTS 9 times.

Background

Kernel Memory Management. Two allocators:

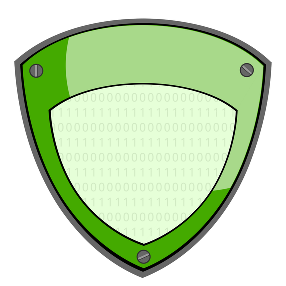
- Buddy allocator: splits the entire memory space into page-order memory chunks and stores them in *page-order free lists*.
- SLUB allocator: uses chunks from Buddy and stores free memory slots for object allocation in *allocator caches*.



Object Allocation. Applications use the SLUB allocator caches:

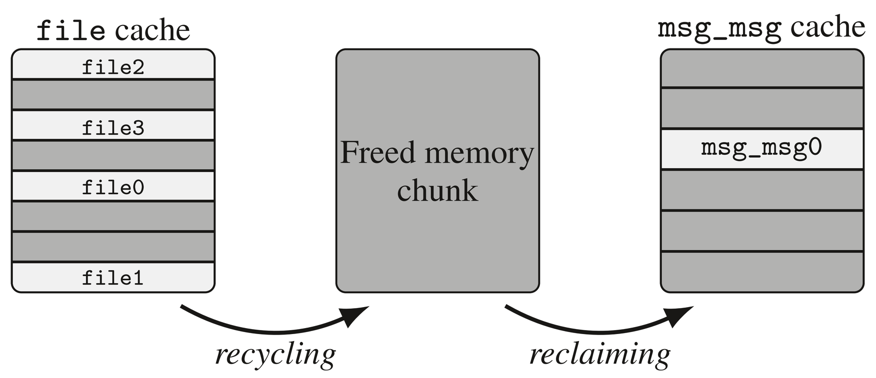
- Fast path: on a memory allocation (①), the allocator cache has free memory slots (②) and returns one slot (③).
- Slow path: on a memory allocation (❶), the allocator cache has no free memory slots (❷), so it resorts to Buddy (❸) and refills the memory slots (❹), returning one to the application (❺).

Heap Segregation. Linux uses different allocator caches for different security contexts, so vulnerable and security-critical objects never share the same cache. Hence, a UAF write to a vulnerable object cannot be directly exploited to overwrite security-critical objects.

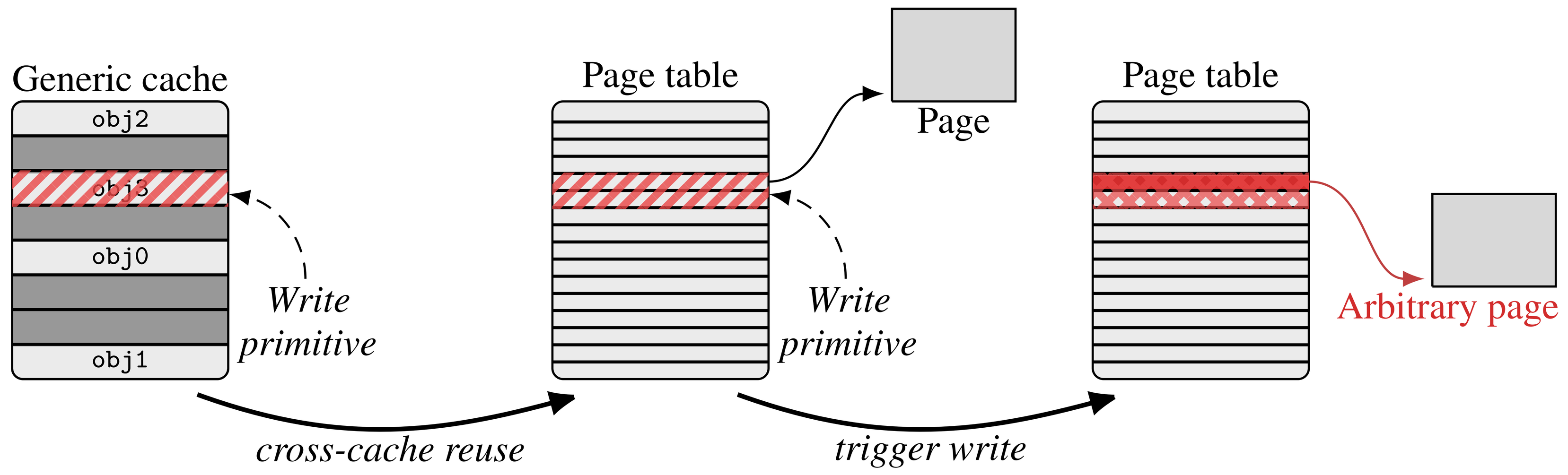


Cross-Cache Reuse. A bad actor exploits Buddy's memory reuse. They free all memory chunk slots from an allocator cache (e.g., `file`), causing to *recycle* this chunk. They then *reclaim* the chunk for security-critical objects (e.g., `msg_msg`).

This cross-cache reuse is mostly **unreliable and impractical**, with a success rate of 40%, where unsuccessful attempts may crash.



High-Level Overview



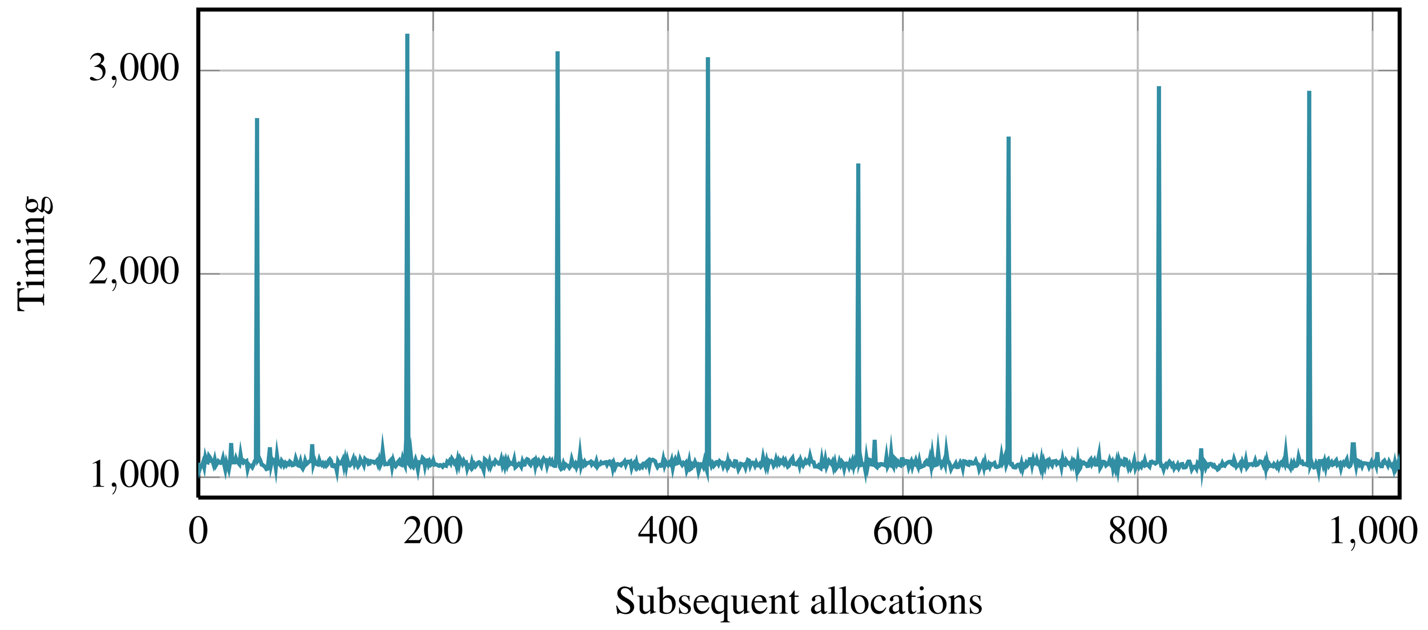
SLUBStick exploits a kernel heap vulnerability to obtain a *write primitive* for a vulnerable object at a given time. It then performs a *cross-cache reuse*, where the write primitive refers to a page table. Finally, it *triggers the write* to corrupt a page-table entry, granting its user address with arbitrary read/write access to the underlying physical page.

Technical Challenges. SLUBStick overcomes three challenges:

- **C1** Cross-cache reuse attacks on generic caches are unreliable.
- **C2** Most kernel heap vulnerabilities only grant weak write primitives.
- **C3** From page-table manipulation to an arbitrary read/write.

Timing Side Channel on the SLUB Allocator C1

SLUBStick **makes cross-cache reuse reliable and practical** by performing a timing side channel on SLUB. It measures the syscall timings of allocations and distinguishes between fast (①-③) from slow (❶-❺) paths, allowing objects to be grouped based on their chunk.



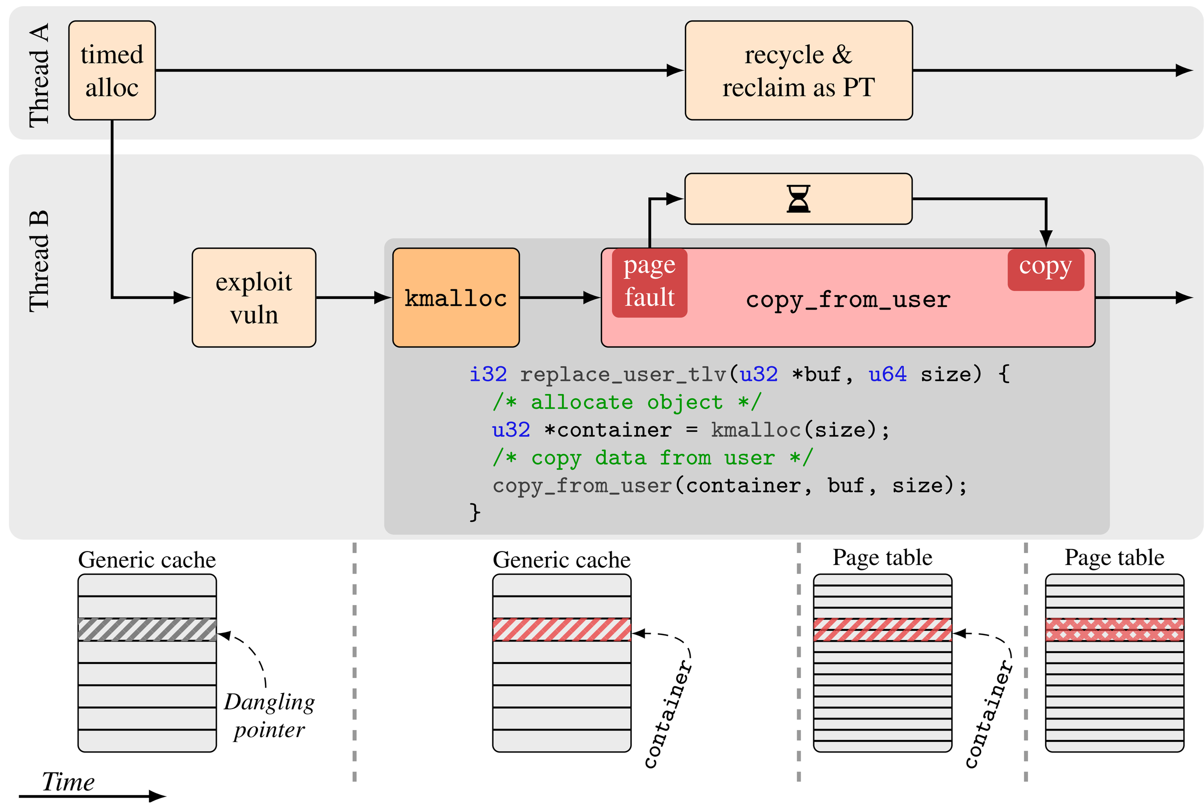
- Fast path (①-③): ~1,100 time stamps.
- Slow path (❶-❺): >2,500 time stamps.

Group allocated objects based on their chunk and free all grouped objects for cross-cache reuse.

- Ubuntu 22.04 LTS
- Linux kernel v6.2.
- Multiple generic caches.
- Tested on idle and noisy systems.
- **Success rates well above 40%.**

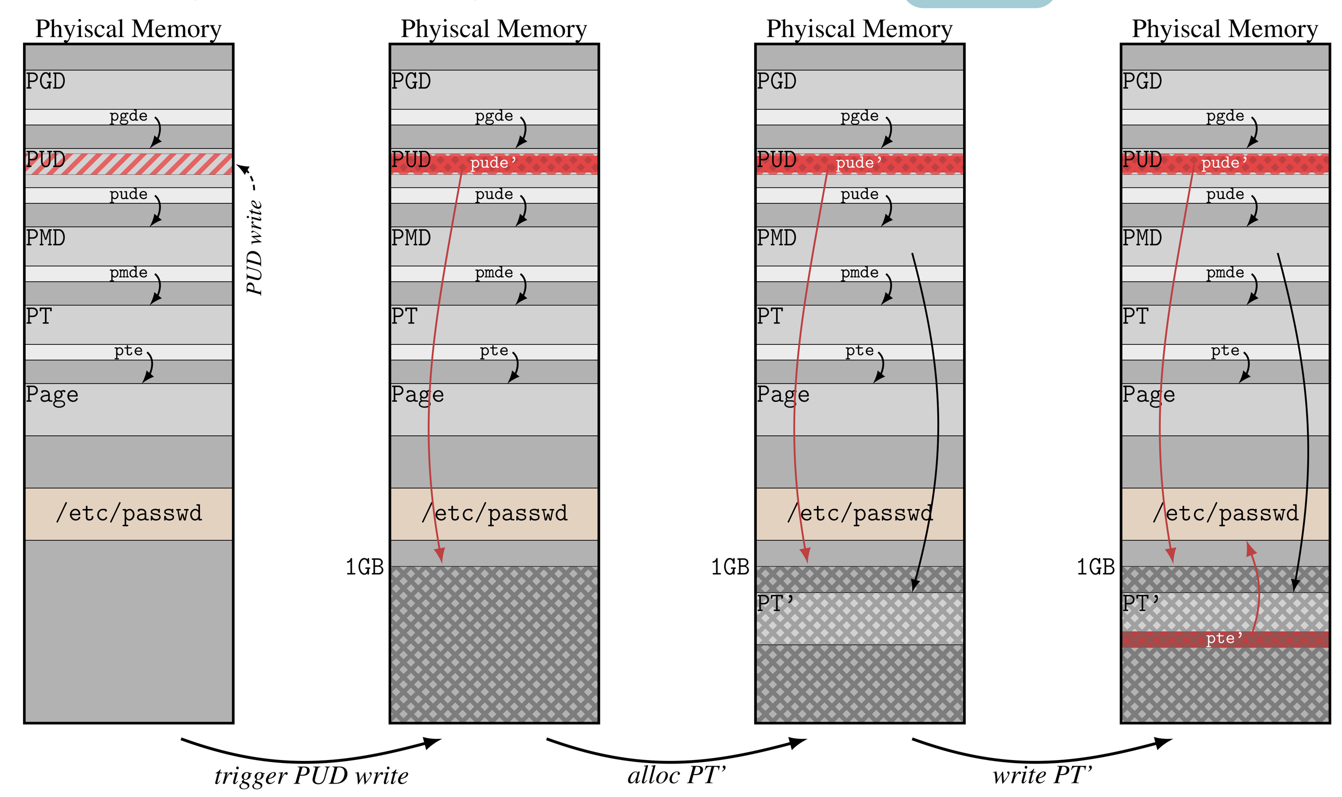
Generic Cache	#Pages	Success Rate		
		Idle	No CPU pinning	External noise
		%	%	%
`kmalloc-8`	1	99.9 ± 0.1	99.9 ± 0.1	99.6 ± 0.7
`kmalloc-16`	1	99.4 ± 0.6	98.9 ± 1.2	99.9 ± 0.4
`kmalloc-32`	1	99.4 ± 0.9	99.7 ± 0.5	99.9 ± 0.3
`kmalloc-64`	1	99.2 ± 1.3	99.2 ± 0.9	81.0 ± 6.4
`kmalloc-96`	1	99.9 ± 0.4	99.9 ± 0.1	99.8 ± 0.6
`kmalloc-128`	1	99.9 ± 0.4	99.8 ± 0.5	99.9 ± 0.3
`kmalloc-192`	1	99.9 ± 0.4	99.8 ± 0.4	99.3 ± 1.2
`kmalloc-256`	1	99.9 ± 0.3	99.9 ± 0.3	99.7 ± 0.7
`kmalloc-512`	2	90.2 ± 5.4	87.2 ± 3.1	65.2 ± 2.8
`kmalloc-1024`	4	88.1 ± 7.2	79.5 ± 3.3	70.3 ± 8.1
`kmalloc-2048`	8	83.1 ± 9.2	70.5 ± 16	57.8 ± 5.7
`kmalloc-4096`	8	82.1 ± 3.4	73.3 ± 19	53.8 ± 10

Pivoting Kernel Heap Vulnerabilities C2



SLUBStick exploits a **heap vulnerability for a page-table manipulation**, by first creating a *dangling pointer*. It then reclaims the pointer's memory for `container`, where writing via `copy_from_user` causes a slow page fault. SLUBStick recycles the cache's page and reclaims it as a page table, where copying then overwrites page-table entries.

Arbitrary Memory Read/Write C3



SLUBStick converts a **single-shot page-table manipulation to an arbitrary physical read/write**: It *triggers the PUD write* so that the user address with pude' refers to the first physical GB. It then *allocates PT'* and *overwrites* a PT' entry with pte'. The user address with pte' now refers to an arbitrary physical location, allowing the arbitrary physical read/write.

Conclusion

Timing side channel:
- Makes software cross-cache reuses practical.

Primitive conversions:
- Limited heap write to page-table manipulation.
- Single-shot page-table manipulation to an arbitrary physical read/write primitive.

Implemented 9 POC exploits.