Cross-Cache Attacks for the Linux Kernel via PCP Massaging

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Exploitation in the Linux Kernel

The Goal — what the attacker wants

Kernel memory (single pool)

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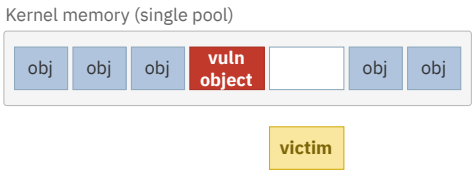

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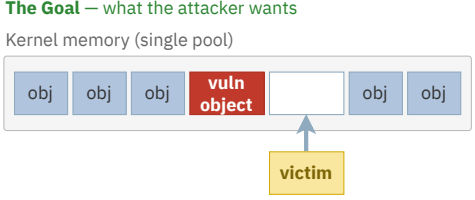

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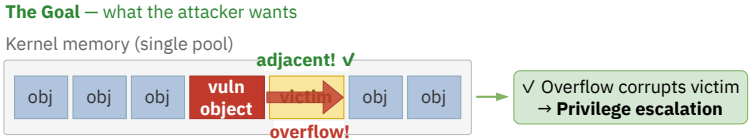

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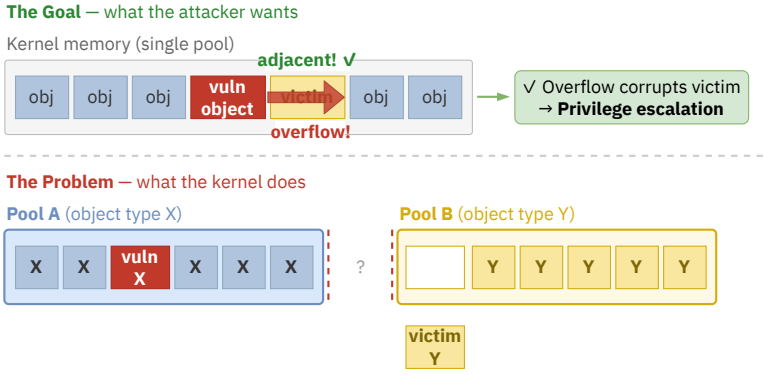

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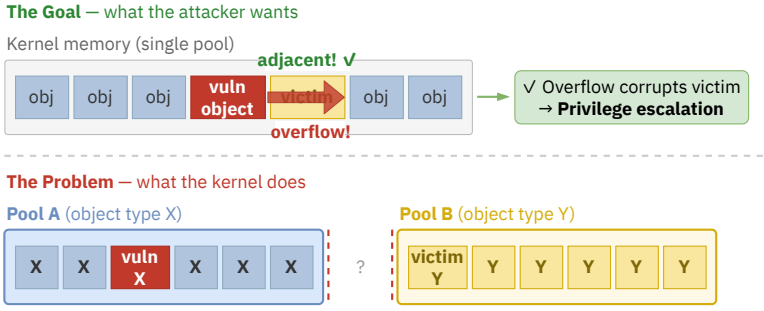

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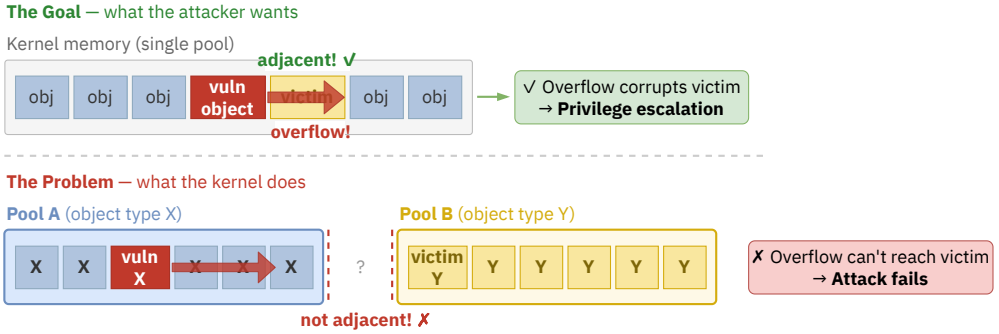

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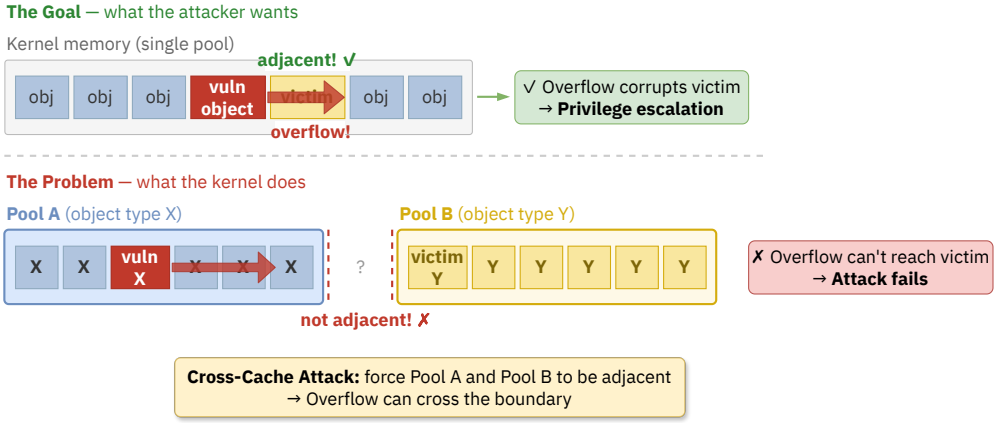

Previous Work

- Timing side-channels on SLUB: **PSPRAY** (USENIX 23)
- Cross-cache attacks for temporal vulnerabilities (page-recycling): **SLUBStick** (USENIX 24), **CROSS-X** (CCS 25)

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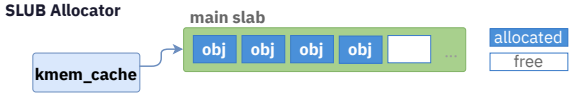
Previous work either focuses on SLUB or page-recycling cross-cache

PCPLost

This work:

- PCPLost is a cross-cache memory massaging technique for spatial vulnerabilities (page-adjacency)
- Exploits overlooked interactions between SLUB and Page Frame Allocator
- $\sim \mathbf{90}\%$ reliability in establishing adjacency, even under noise and mitigations

SLUB and Page Frame Allocator (PFA)



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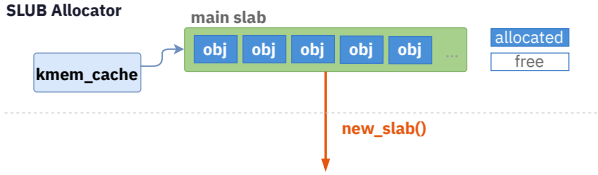

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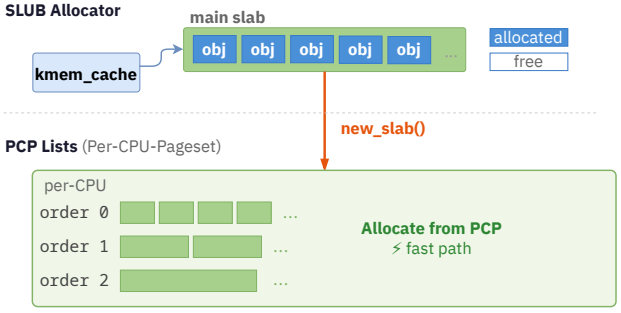

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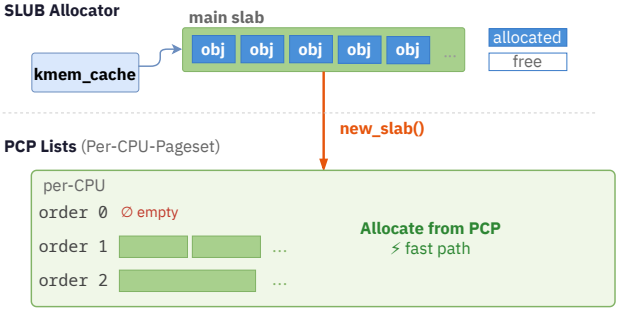

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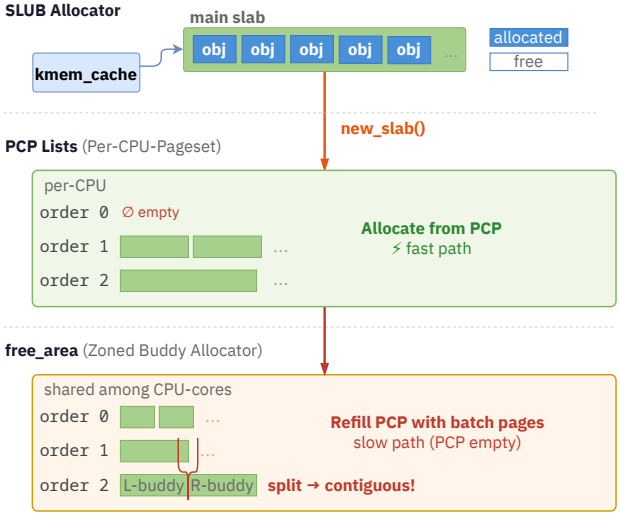

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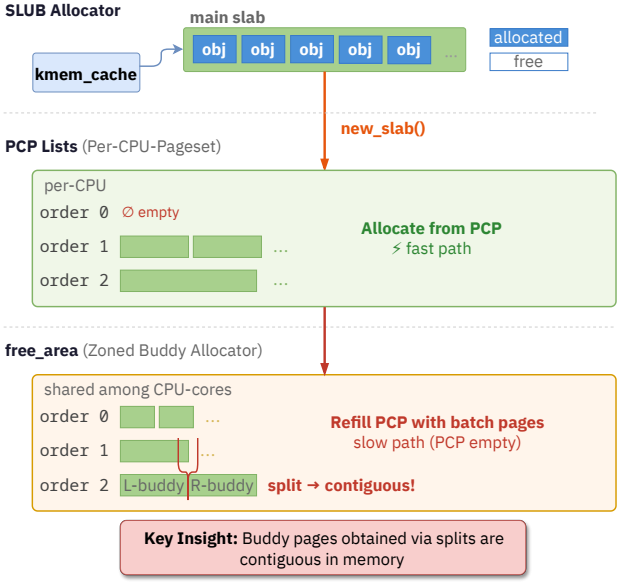
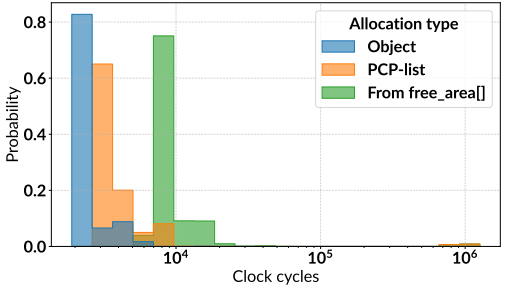
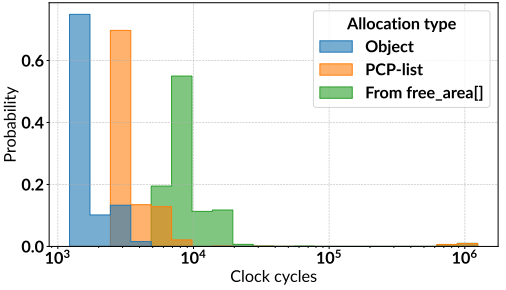


Timing side-channel on SLUB/PFA



(a) `kmalloc-4k`



(b) `kmalloc-2k`

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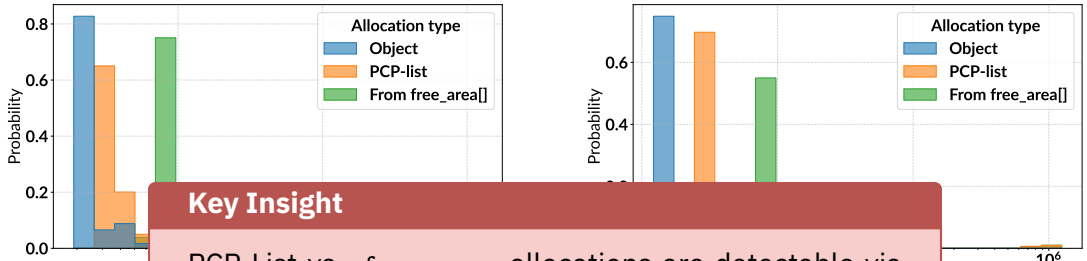

Key Insight

PCP List vs. `free_area` allocations are detectable via timing side-channel

PCPLost attack core steps

1. Repeatedly drain the PCP list for the target order (Probe & Drain)
    - Forces PFA page splits to create contiguous layouts in the PCP list

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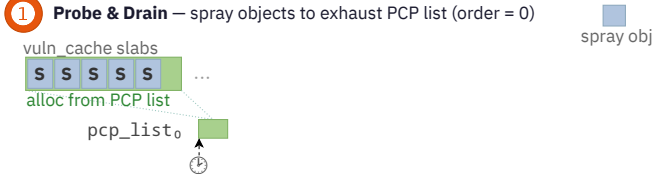
3. Trigger OOB write

Same-order PCP massaging



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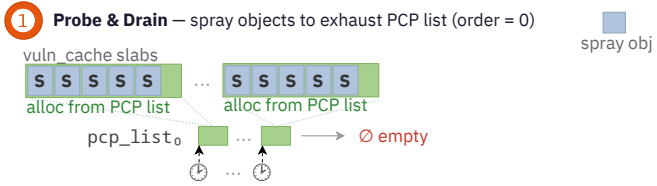

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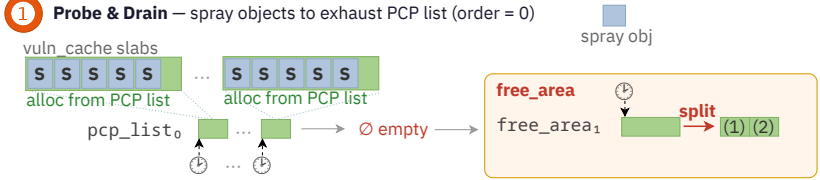

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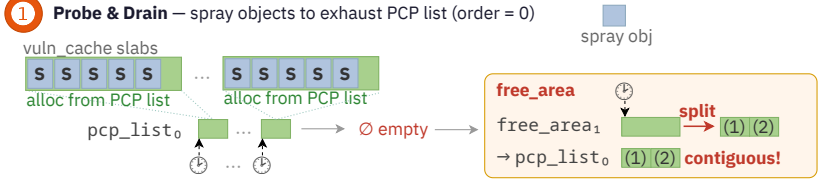

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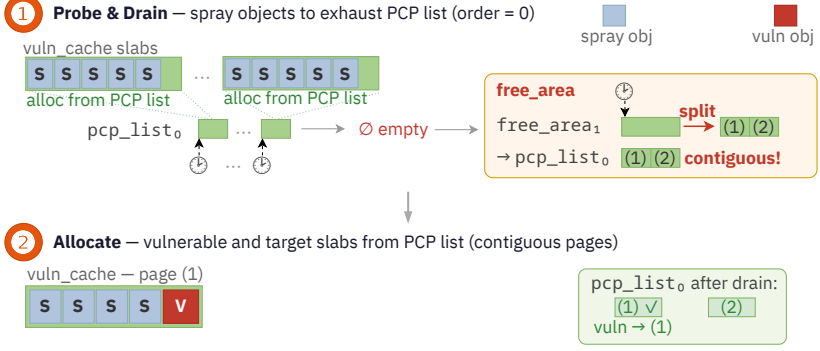

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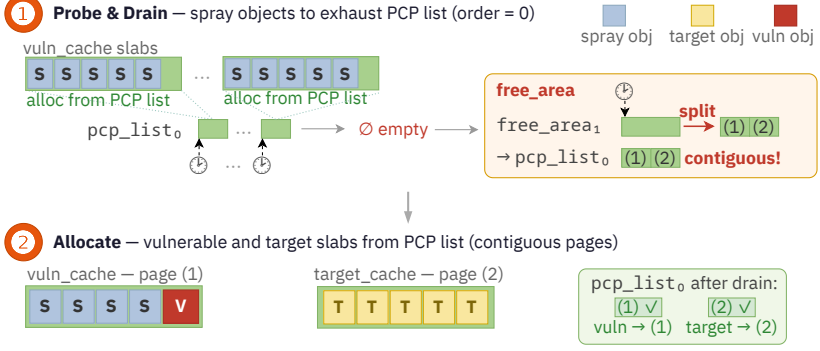

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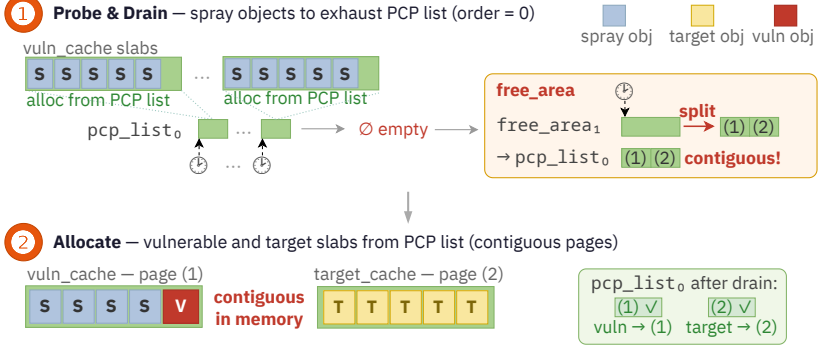

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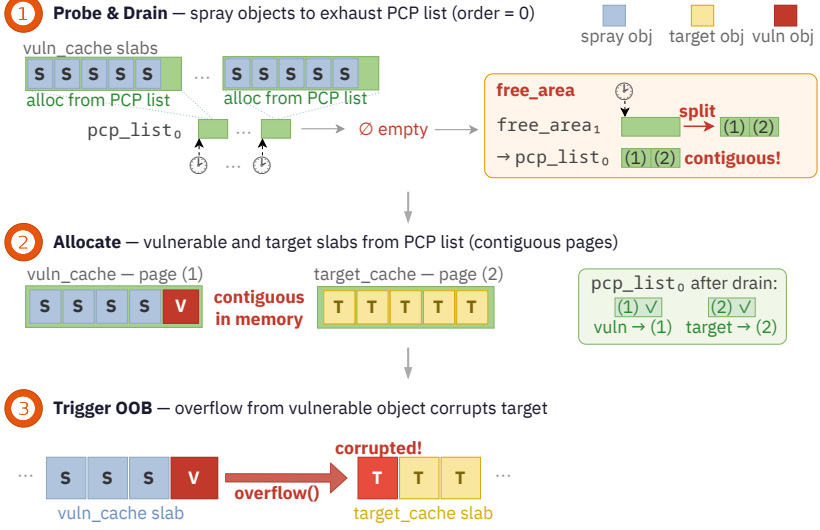

Evaluation

Reliability evaluation

Vuln. cache	Target cache	Idle (%)	Noise (%)
Same-order ($n_v = n_t$)			
`kmalloc-16`	`kmalloc-64`	98.83	97.42
`kmalloc-64`	`kmalloc-128`	96.80	90.94
`kmalloc-128`	`kmalloc-16`	99.84	98.28
Cross-order ($n_v > n_t$)			
`kmalloc-2k`	`kmalloc-16`	94.30	87.58
`kmalloc-4k`	`kmalloc-64`	93.20	92.42
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With CPU pinning. 800 runs per scenario.

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Real-world CVEs

- PCPLost validated on **6 CVEs**
  - **Spatial** bugs
  - **Temporal** bugs via pivoting
- Bypassing mainline mitigations
  `SLAB_FREELIST_RANDOM`
  `SLAB_FREELIST_HARDENED`
- Bypassing experimental `SLAB_VIRTUAL`

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  Mitigated by `SLAB_VIRTUAL_GP` (with guard pages)

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  - Cross-cache security requires mitigations at that level
- We disclosed PCPLost to kernel maintainers

Evaluation with real-world CVEs

CVE	Category	Vulnerable cache	Target cache	Mitgations bypassed
CVE-2024-53141	OOB	`kmalloc-cg-1k`	`kmalloc-cg-2k`	SV,FH
CVE-2021-22555	OOB/UAF	`kmalloc-cg-4k`	`kmalloc-cg-1k`	FR,SV,FH
CVE-2022-0185	OOB	`kmalloc-4k`	`kmalloc-cg-4k`	SV,FH
CVE-2023-0461	UAF	`kmalloc-512`	`kmalloc-cg-1k`	FR,SV,FH
CVE-2021-3715	UAF	`kmalloc-192`	`kmalloc-32`	FR,FH
CVE-2022-27666	OOB	–	`kmalloc-4k`	FR,FH

SLAB_FREELIST_RANDOM bypass