TU Graz

SCIENCE
PASSION
TECHNOLOGY

Kernel Security in the Wild:

Side-Channel-Assisted Exploit Techniques, Kernel-Level Defenses, and Real-World Analysis

Lukas Maar

September 26, 2025

PhD Defense

› isec.tugraz.at

Motivation

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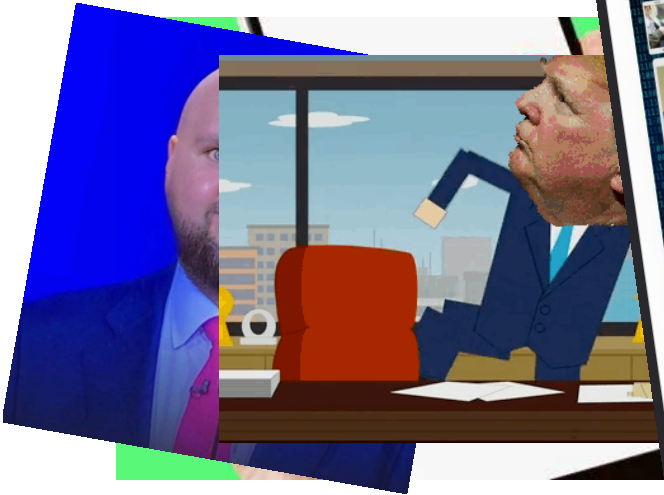

CELLEBRITE ZERO-DAY EXPLOIT USED TO TARGET PHONE OF SERBIAN STUDENT ACTIVIST
AMNESTY INTERNATIONAL
RESEARCH BRIEFING
CONTENTS

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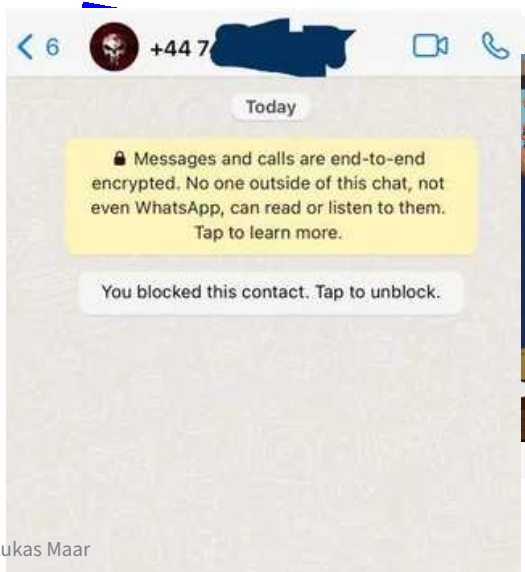
6
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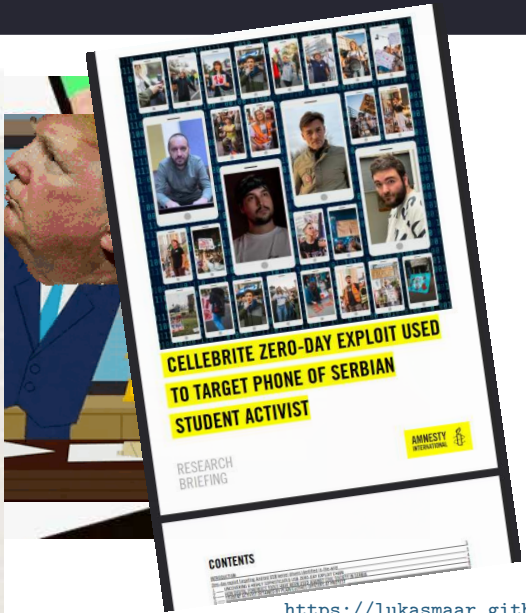
Today
Messages and calls are end-to-end encrypted. No one outside of this chat, not even WhatsApp, can read or listen to them. Tap to learn more.
You blocked this contact. Tap to unblock.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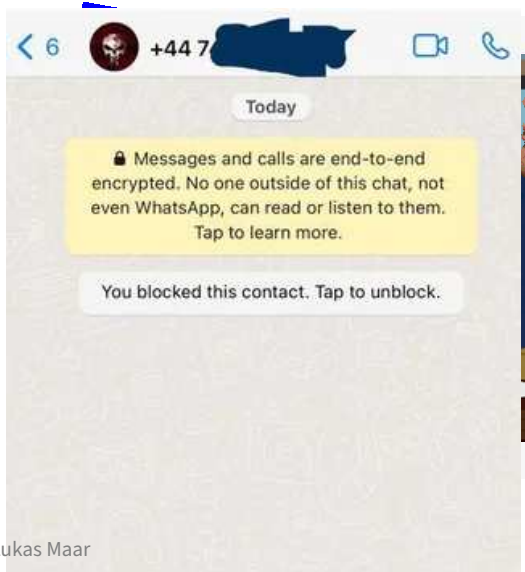
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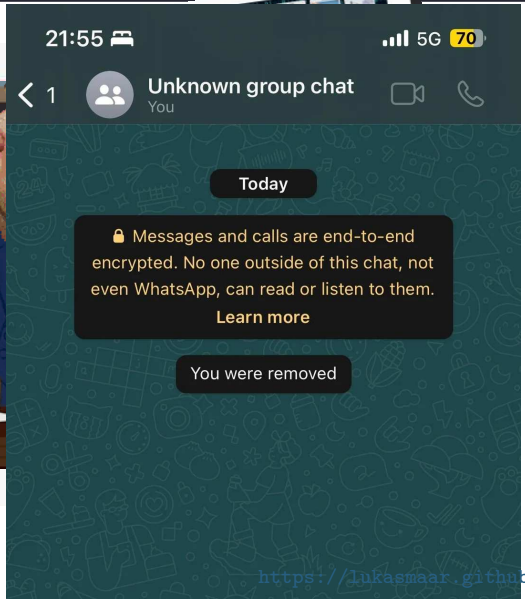
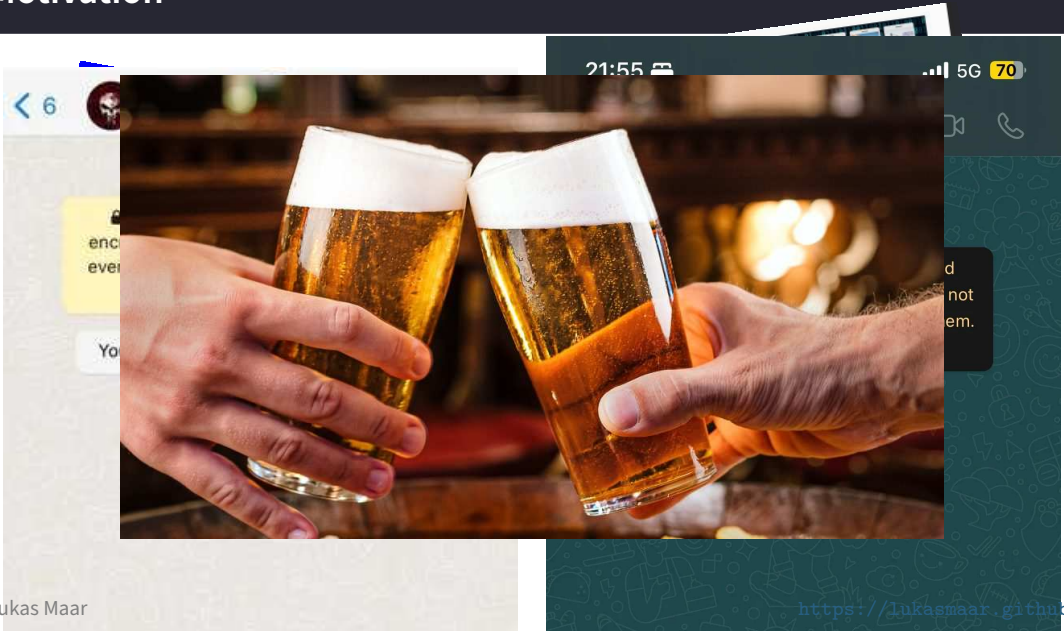

21:55
5G
70
1
Unknown group chat
You
Today
Messages and calls are end-to-end encrypted. No one outside of this chat, not even WhatsApp, can read or listen to them.
Learn more
You were removed

Motivation



Motivation of Next Morning

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How to Exploit?

Kernel *User*

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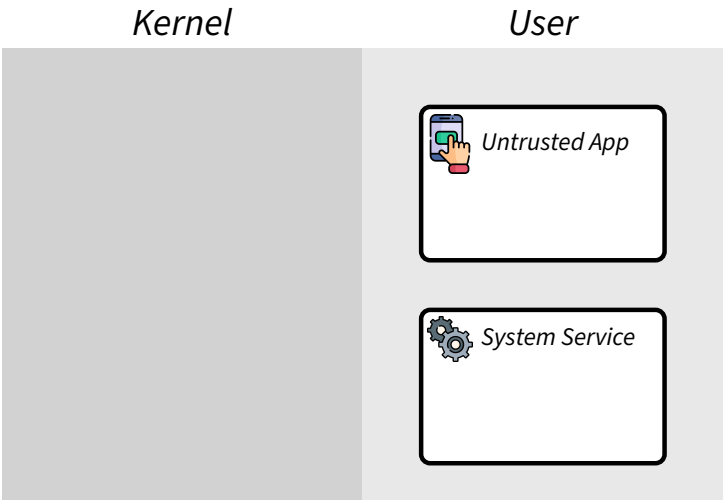

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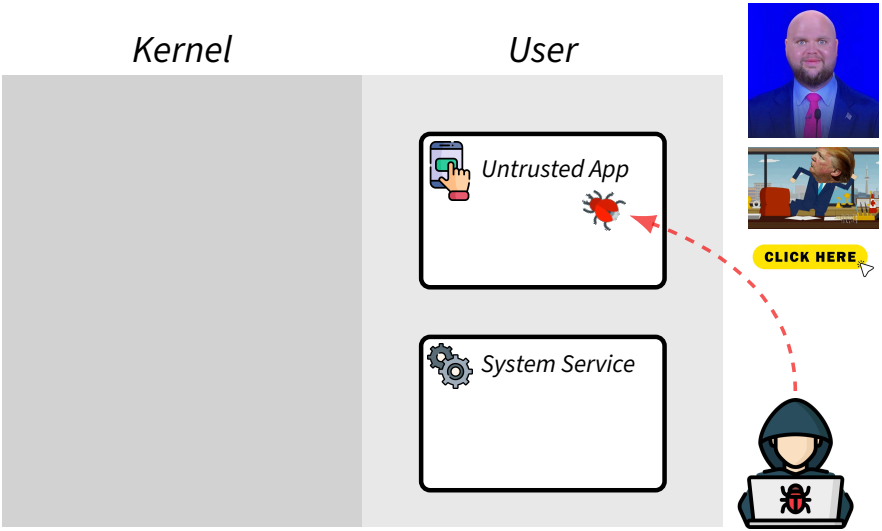

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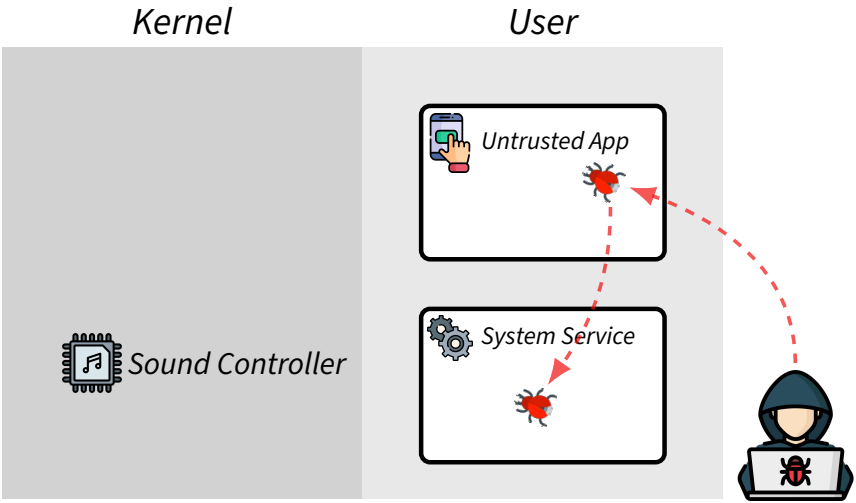

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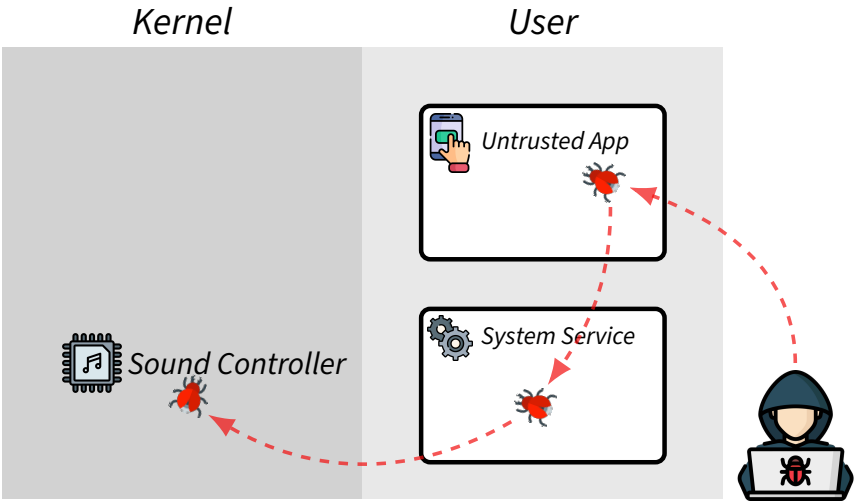

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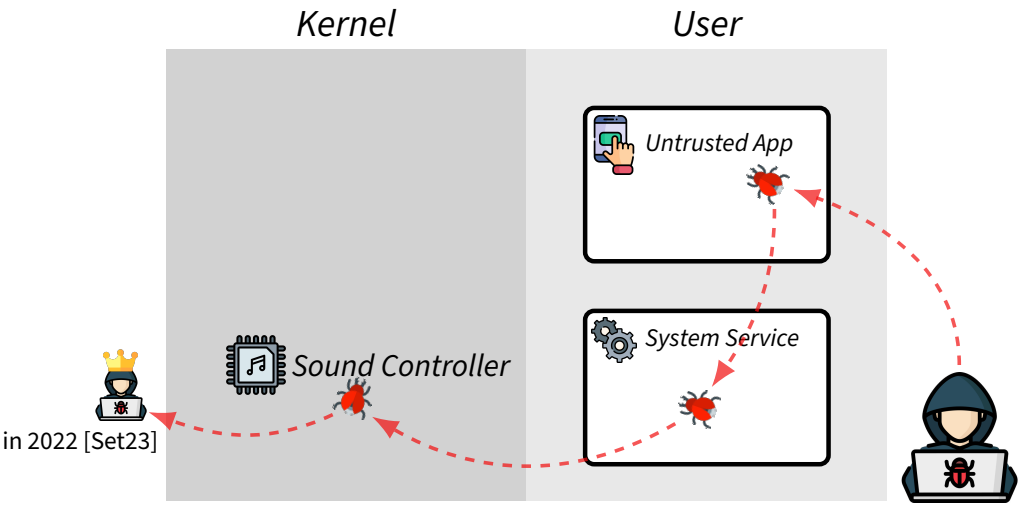

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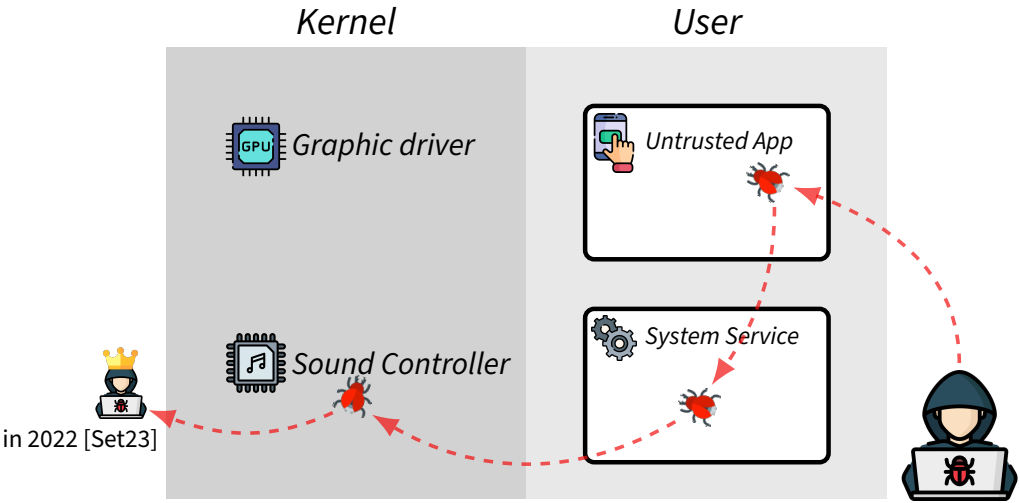

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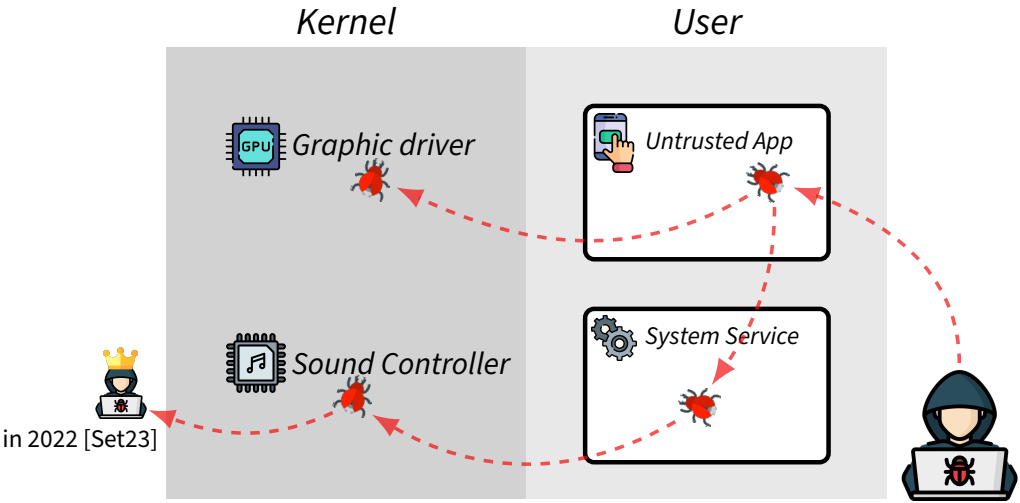

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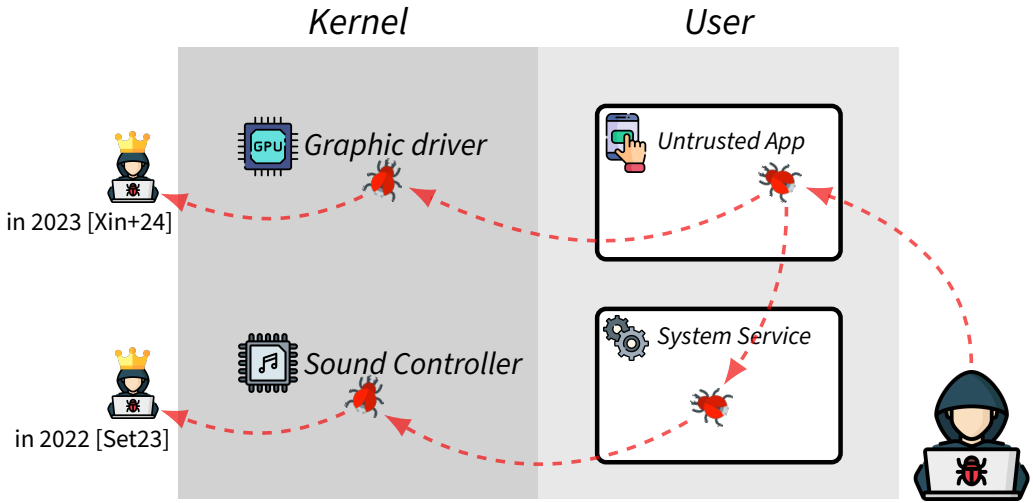

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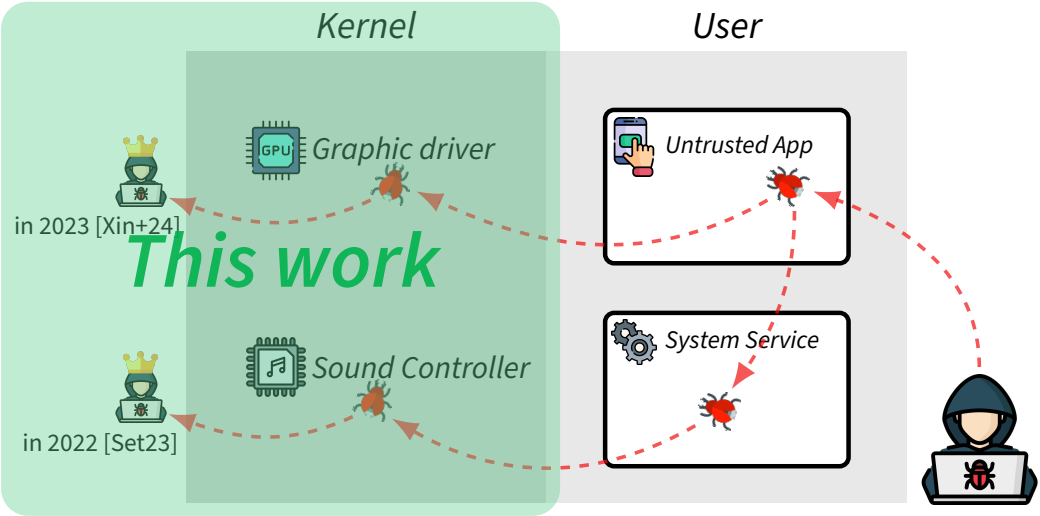
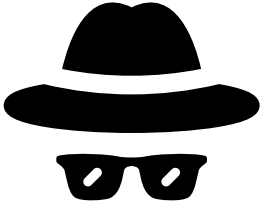


Threat Actor’s Goal



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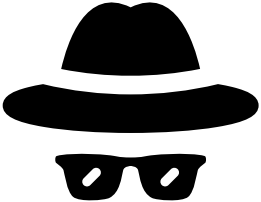

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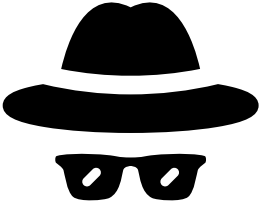

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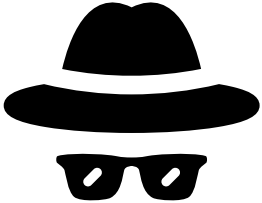
~~Threat Actor's~~ Defender's Goal



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~~Threat Actor's~~ Defender's Goal

Stealthy

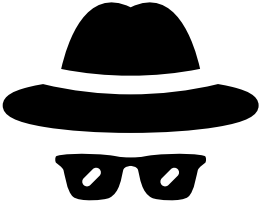
ed

usures

function across multiple devices

Make in-the-wild exploitation as hard as possible

My Main Contributions



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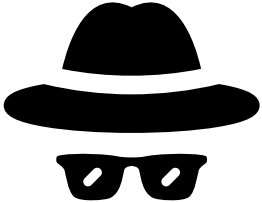

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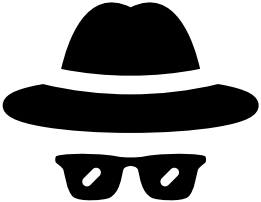

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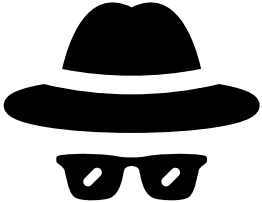

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  - Goal: Push defender site
- **Defenses**
  - *Increase Defense Effectiveness*
  - Goal: Direct resiliance improvement
- **Android Ecosystem**
  - *Reveal Shortcomings in the Android Ecosystem*
  - Goal: Push vendors

Enhance Exploit Reliability via Side Channels

Systematization of my Kernel Side-Channel Contributions

Side Channel	Type	Target	Goal

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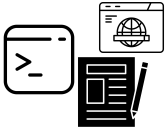
TLB disclosure	Hardware	TLB	Leakage of heap object locations Leakage of stack locations Leakage of page table locations

SLUBStick

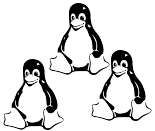
Kernel Memory Allocator

Kernel

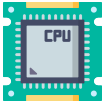
Applications



System Services



Hardware



Kernel Memory Allocator

Kernel

Applications

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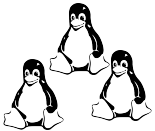
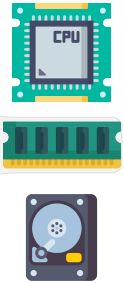


Slab

Buddy

Hardware



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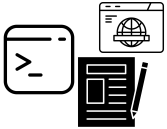

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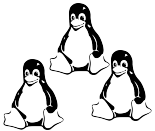

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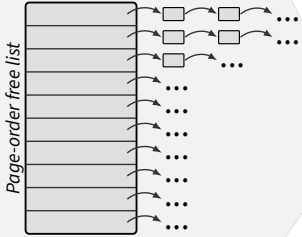

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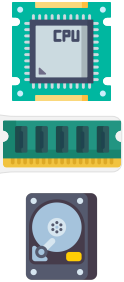

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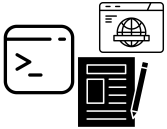

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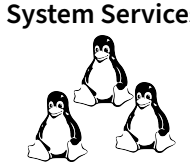

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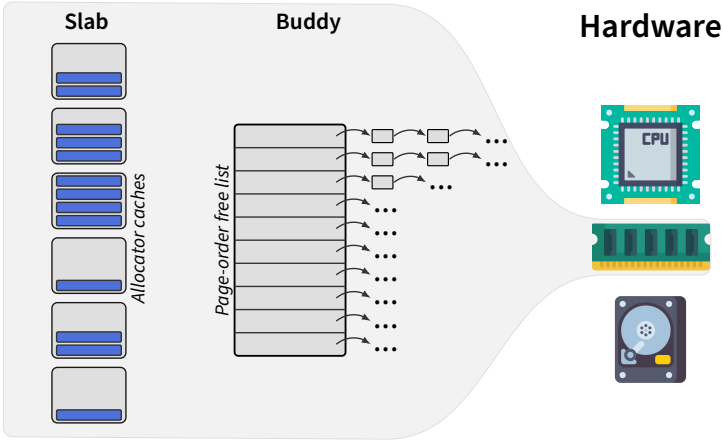

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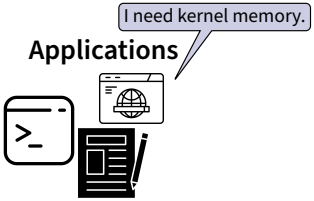

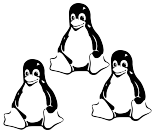

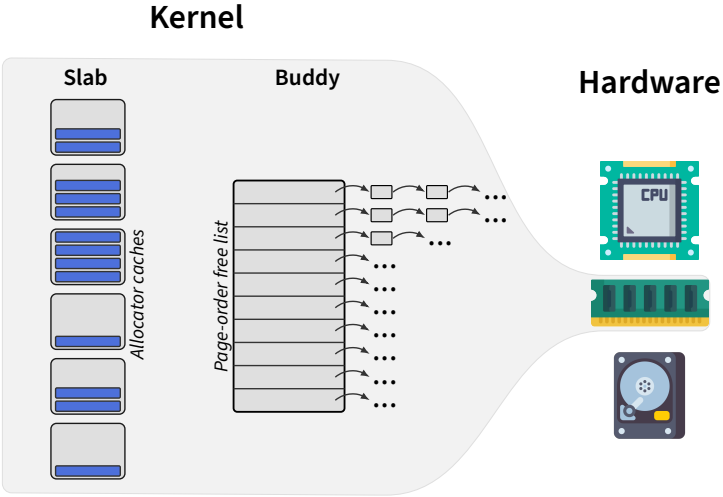

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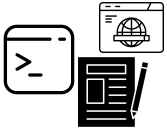

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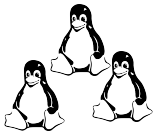
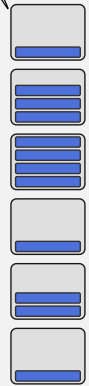


System Services

Kernel

Sure, here you go.

Slab



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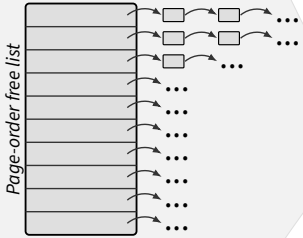

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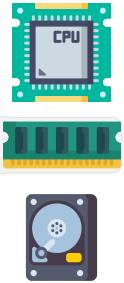

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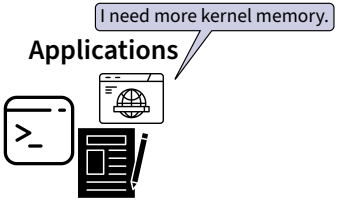

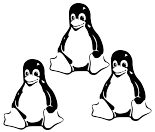

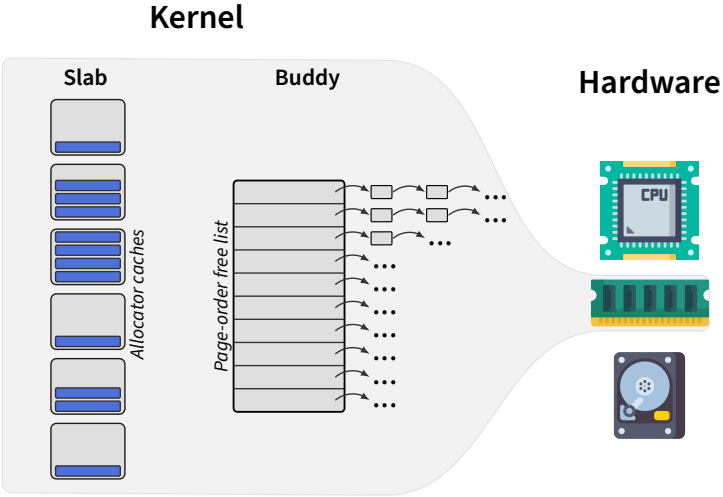

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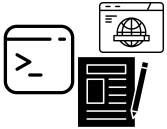
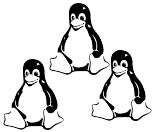
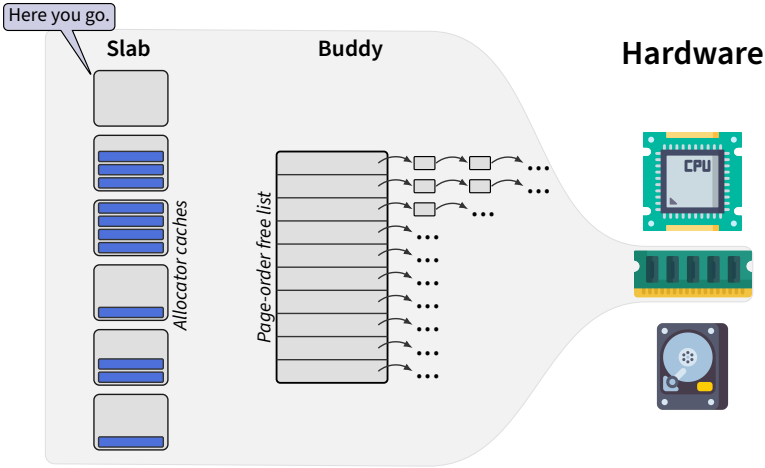


Applications

System Services

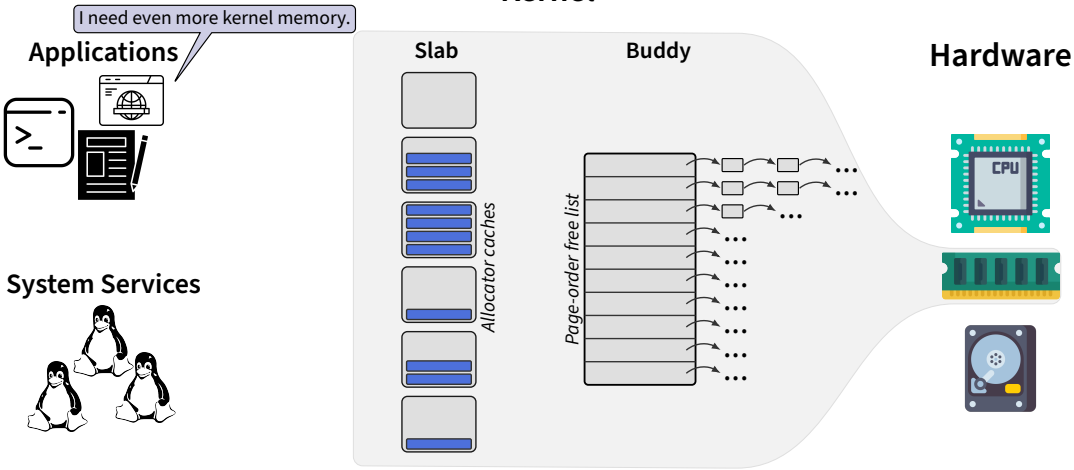


Kernel



Hardware

Kernel Memory Allocator



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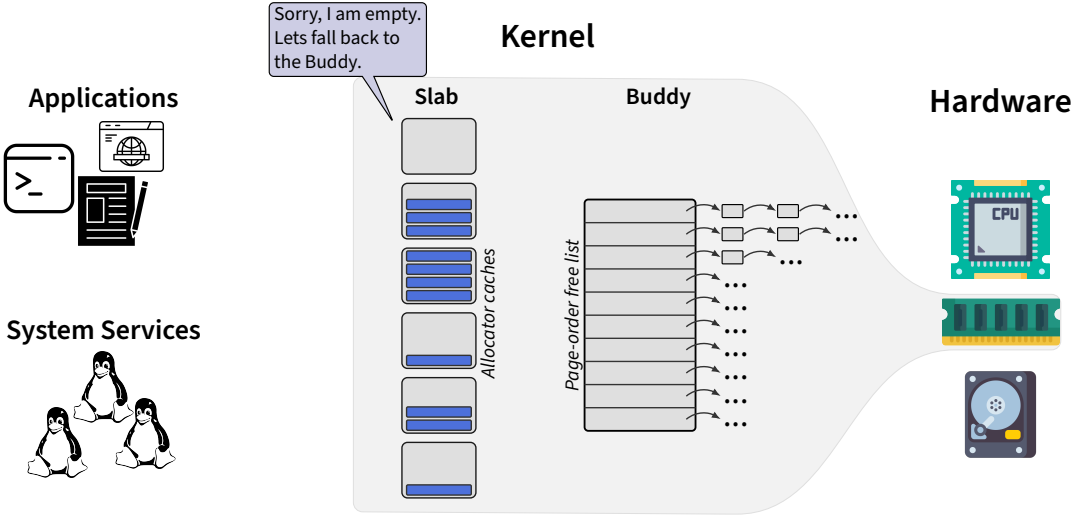
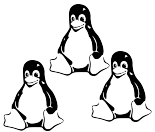


Kernel Memory Allocator

Applications



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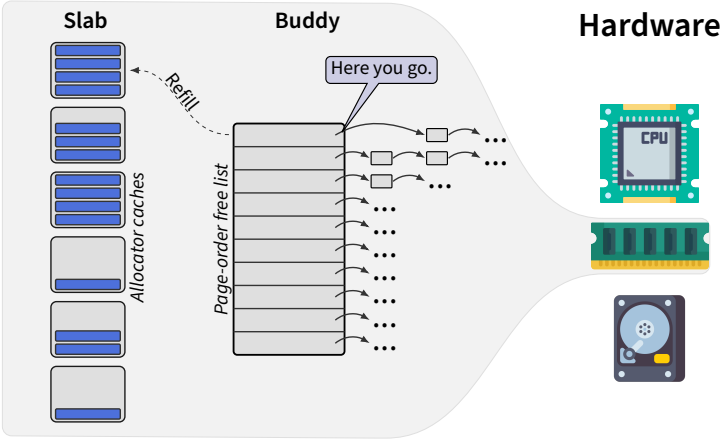

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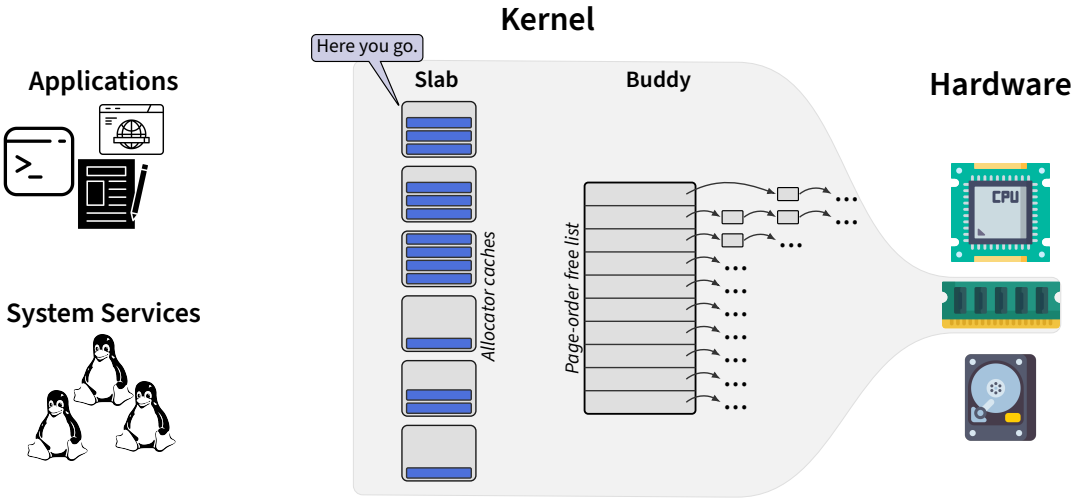

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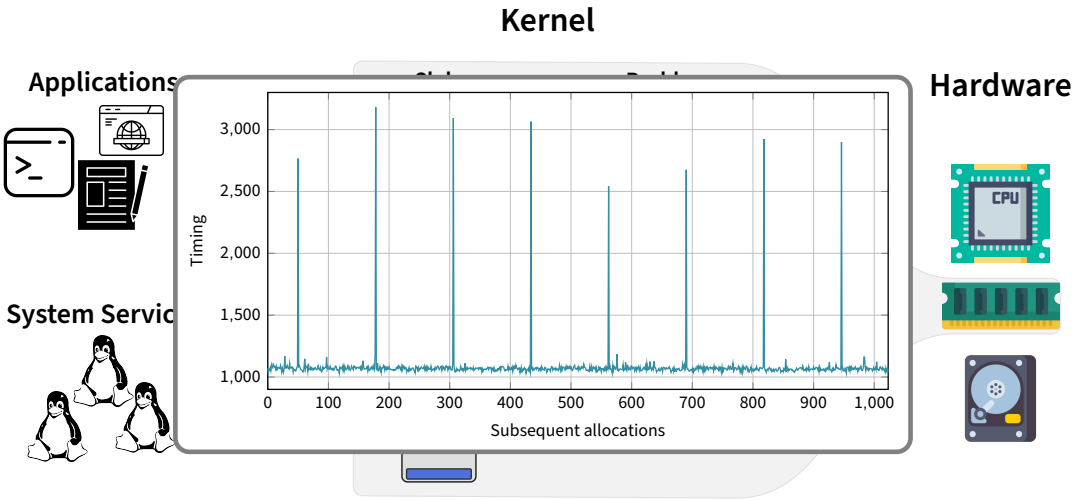

SLUBStick

Timing Allocator Side Channel:

- Measure syscall timing
- Increase reliability of heap manipulation

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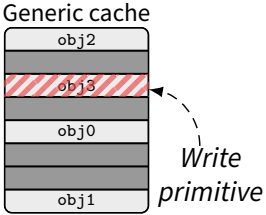
- **High Reliability:**
  - $\geq$ 99.2 % for single slab pages

Cross-Cache Reuse to Arbitrary Read and Write



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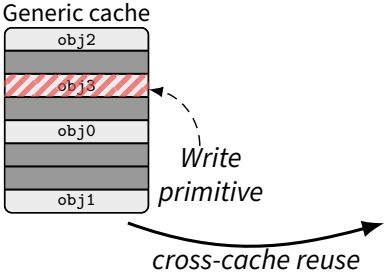

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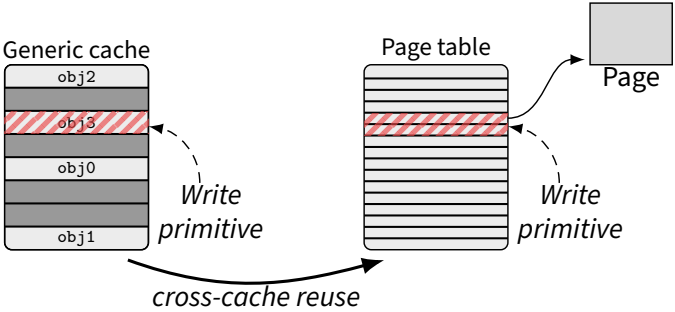

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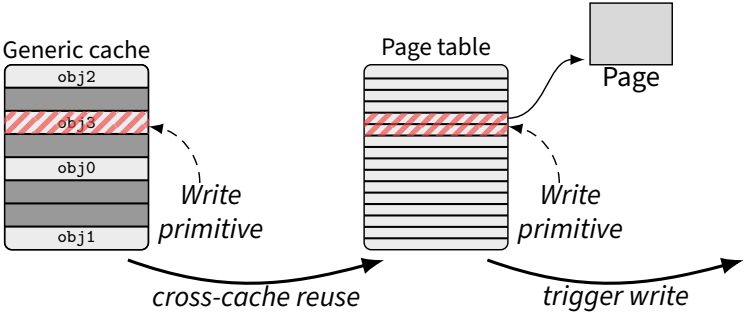

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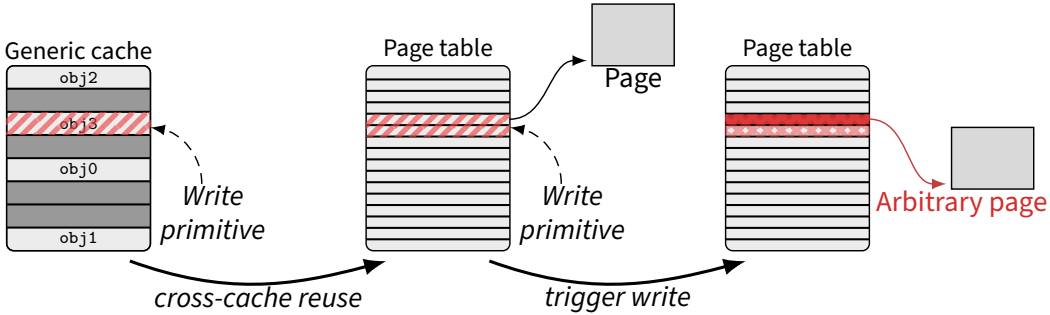

KernelSnitch

Linked List Access Timings

Empty list

List with
2 elements

List with
5 elements

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Fast access

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Empty list

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Fast access

Medium fast access

Slow access

Hash Table Access Timings

Hash Table Access Timings

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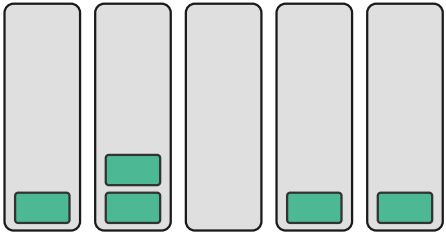

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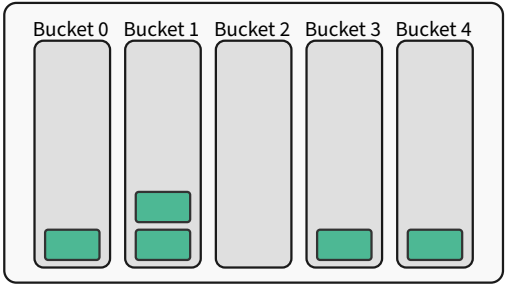

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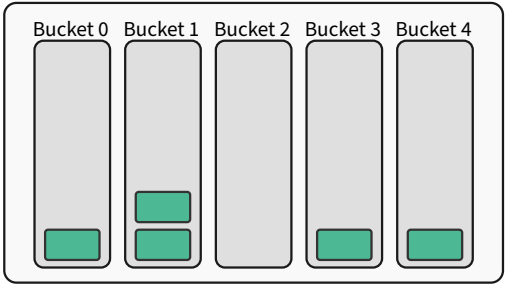
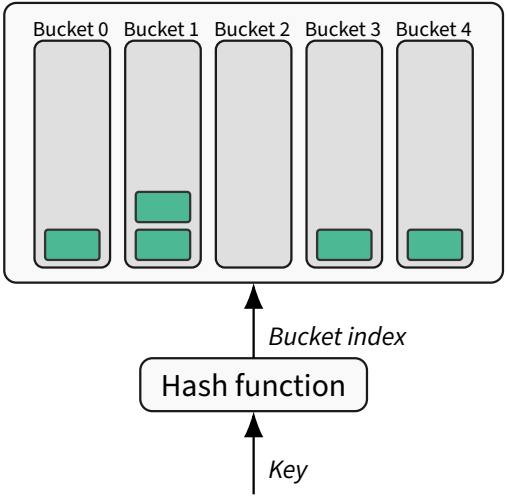


Hash function

Hash Table Access Timings



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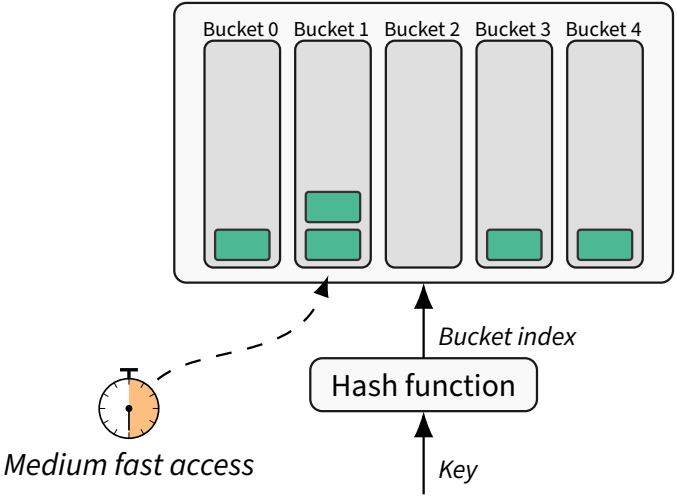

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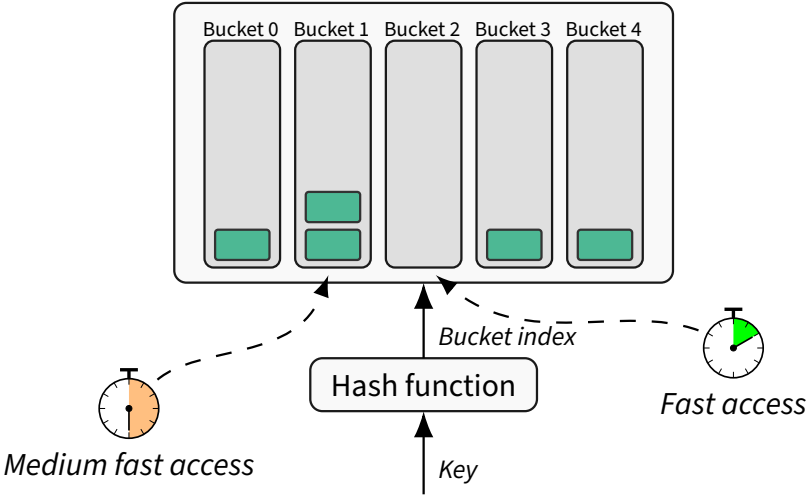

Timing Histogram

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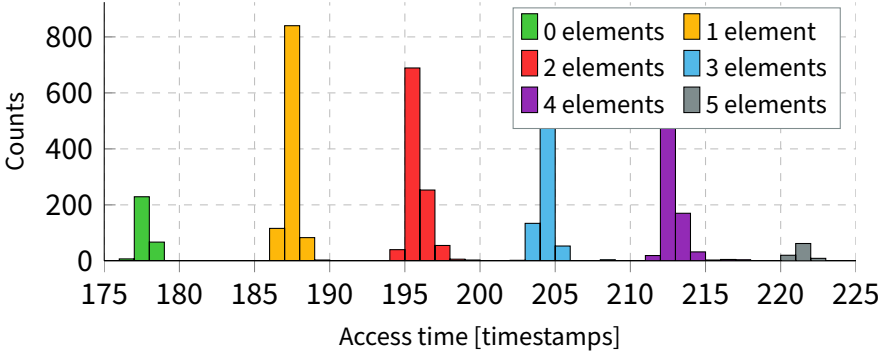

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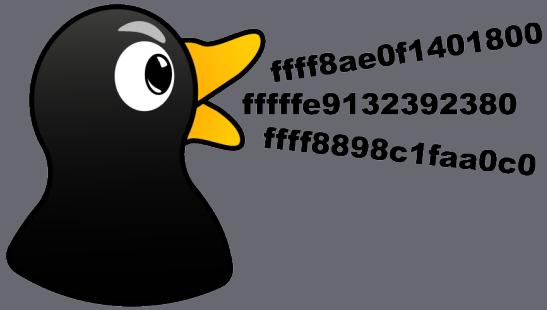
TLB Disclosure



Address Translation

virtual address:

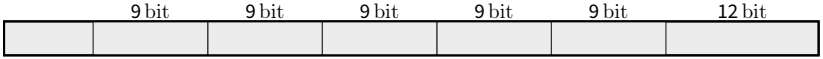
Address Translation

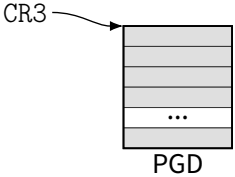
virtual address:

	9 bit	9 bit	9 bit	9 bit	9 bit	12 bit

Address Translation

virtual address:





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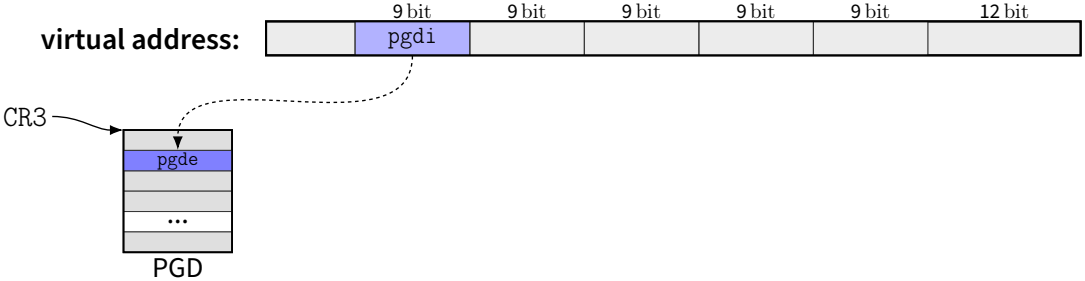

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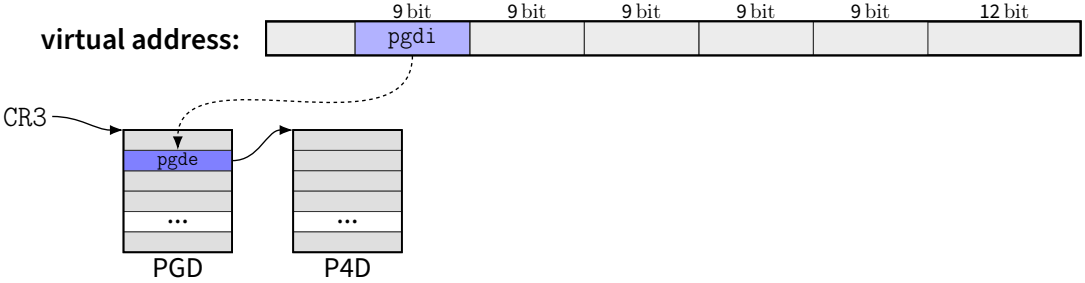

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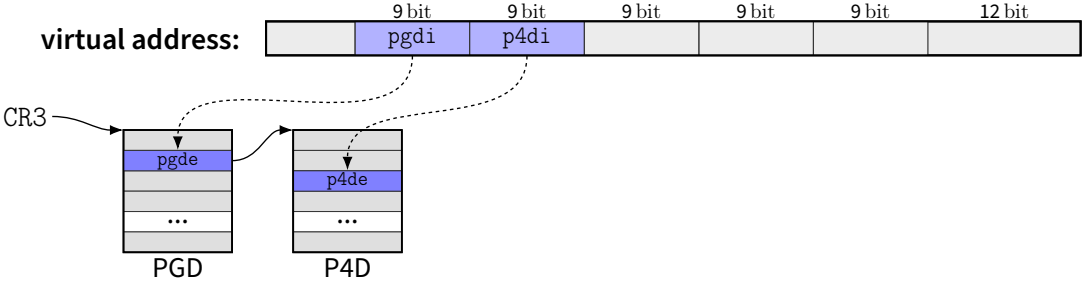

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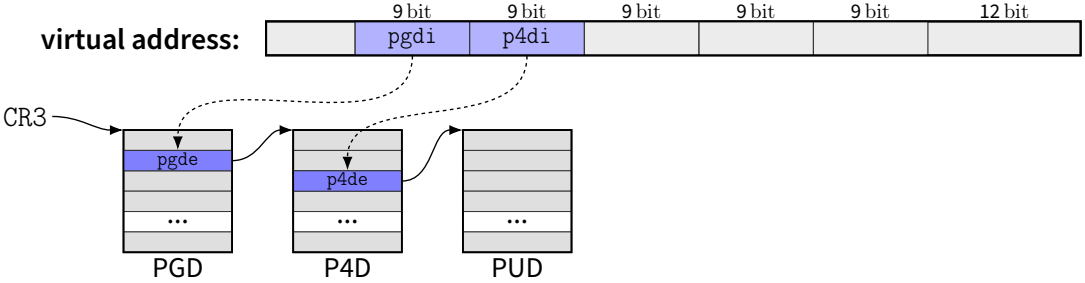

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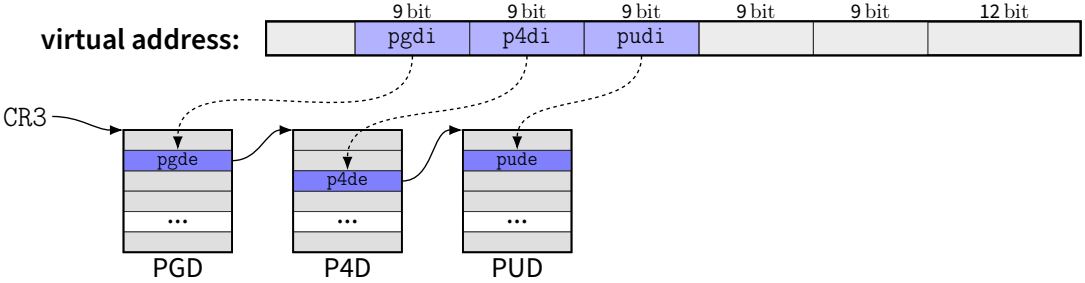

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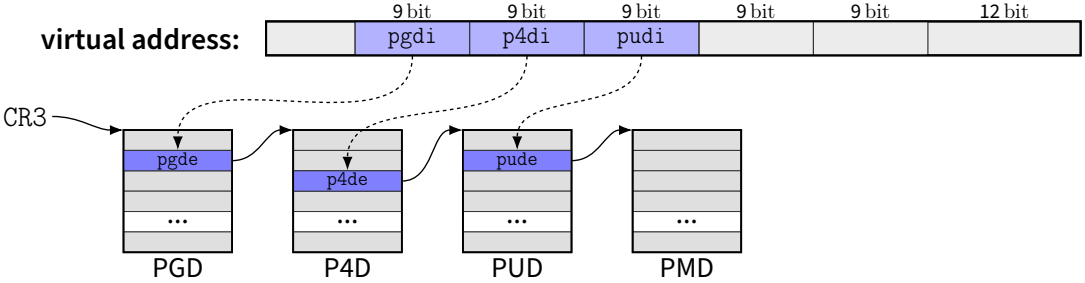

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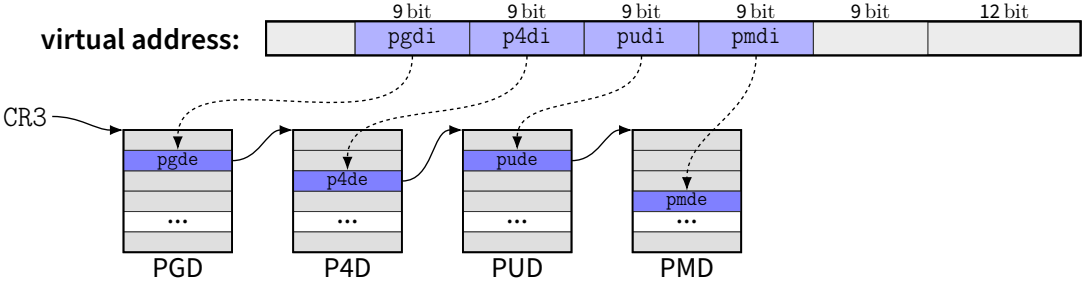

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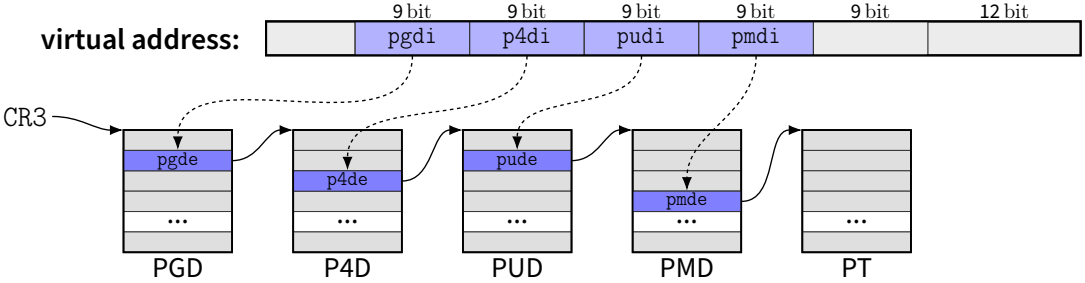

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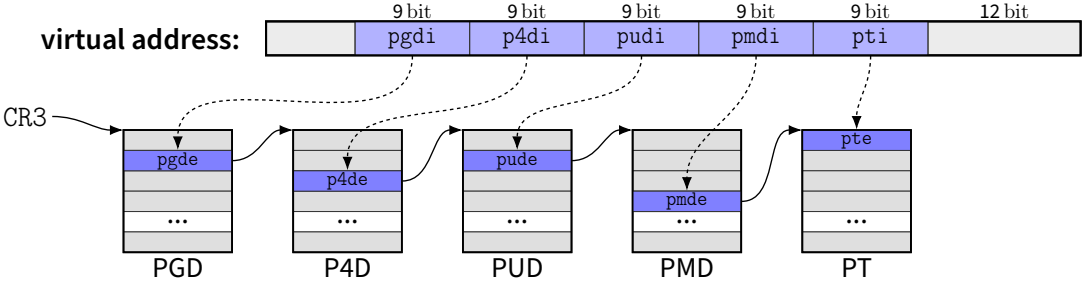

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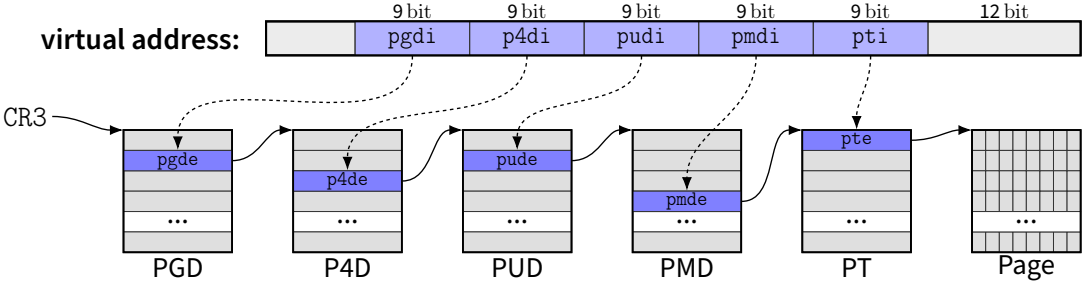

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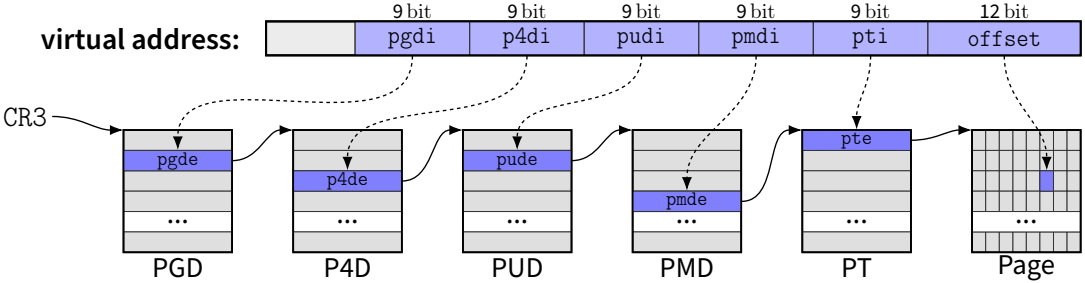
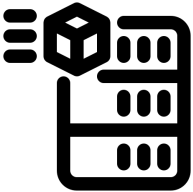


Translation Lookaside Buffer



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  - Slow!

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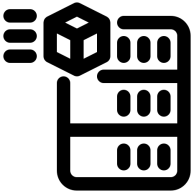

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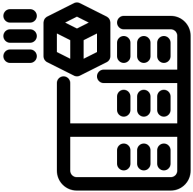

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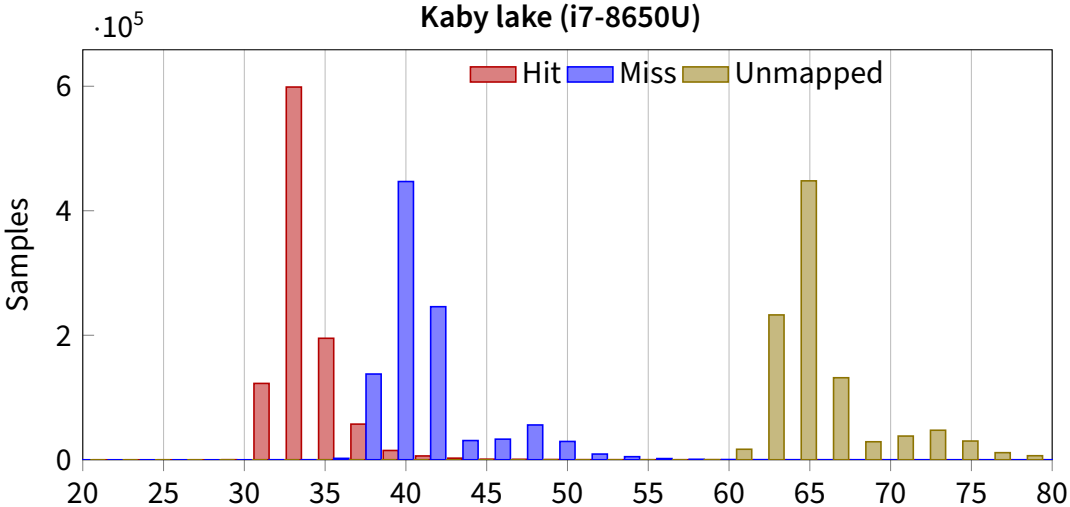
TLB Timing Histogram



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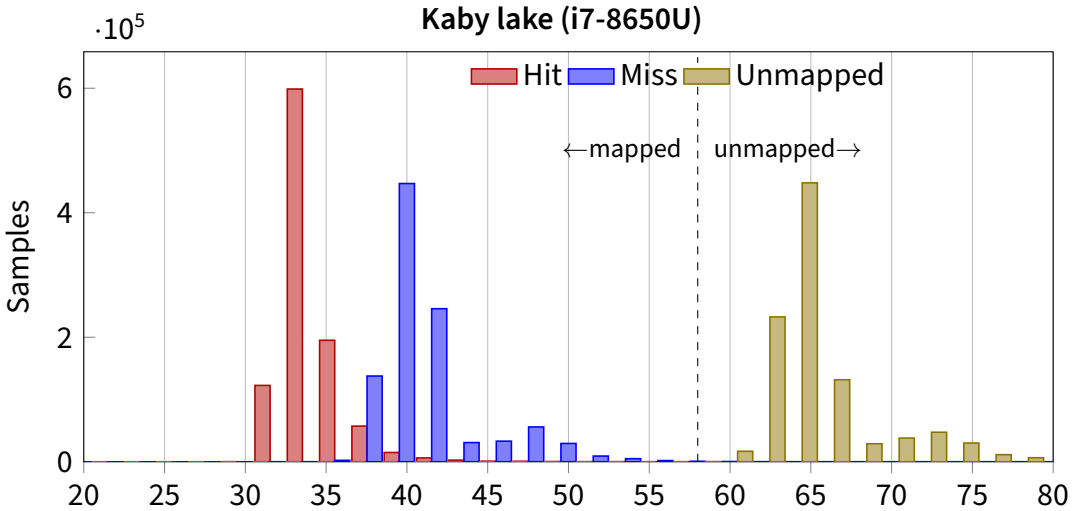

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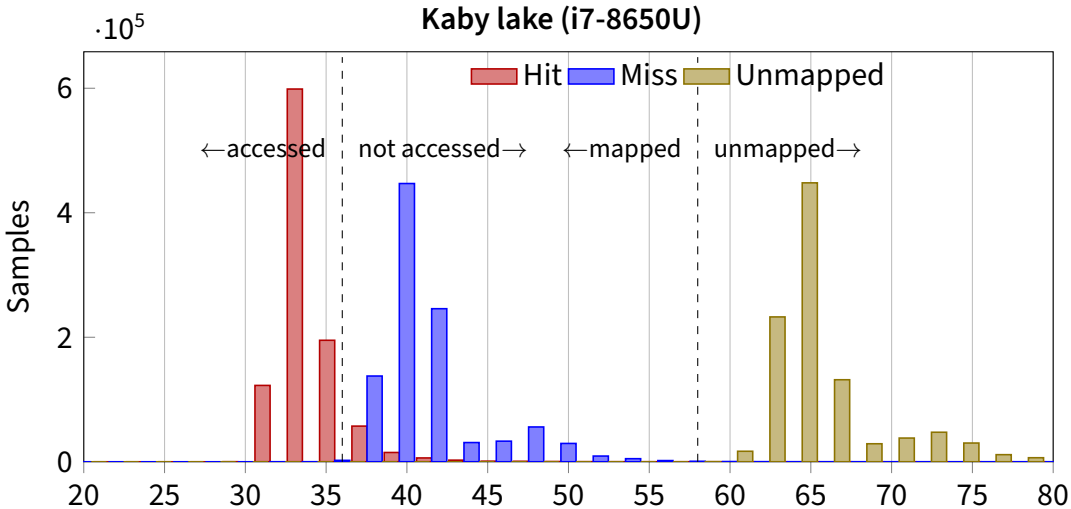

Advanced TLB Side Channel

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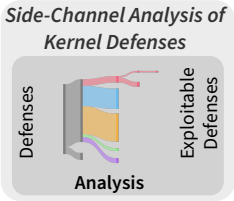
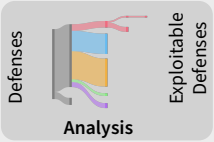


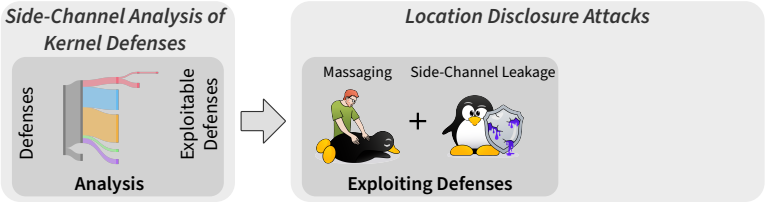
Advanced TLB Side Channel

Side-Channel Analysis of Kernel Defenses



Location Disclosure Attacks

Advanced TLB Side Channel



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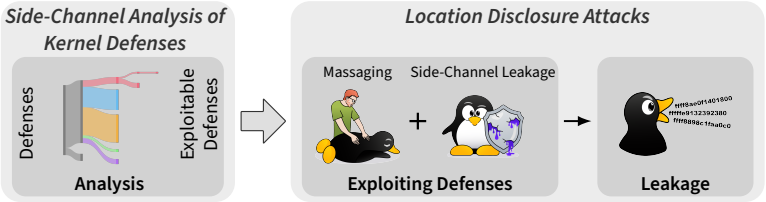

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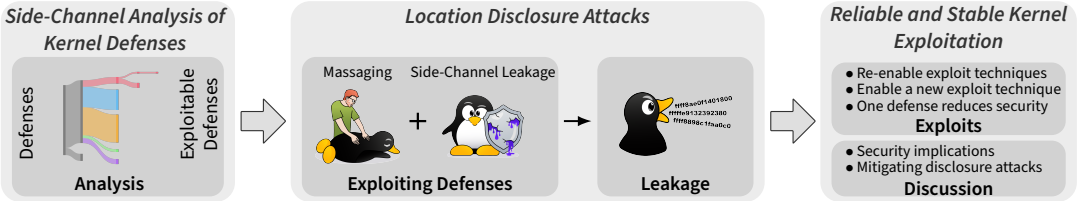

Advanced TLB Side Channel Results

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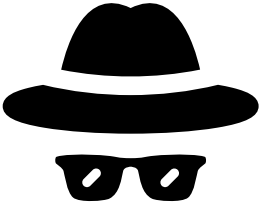
- **Results:**
  - Three side-channel-assisted exploit techniques
  - Near 100 % reliability
  - No system crashes

Increase Defense Effectiveness

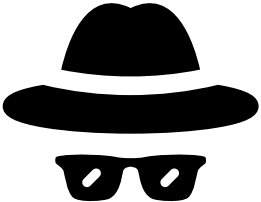
Attack Strategies

Attack Strategies



- **Control-Flow Hijacking Attacks:**

Attack Strategies



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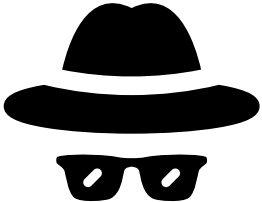

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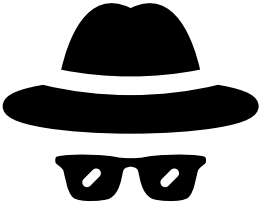
Attack Strategies



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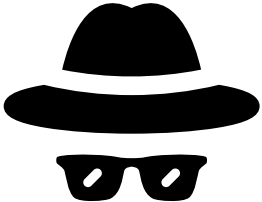
~~Attack~~ Defense Strategies



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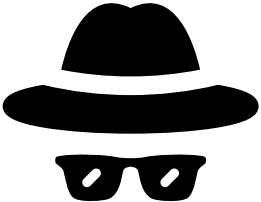

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HEK-CFI

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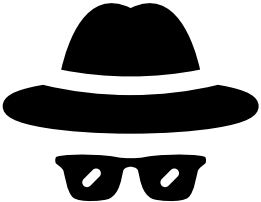

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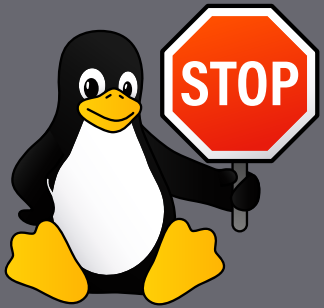
HEK-CFI

DOPE

HEK-CFI



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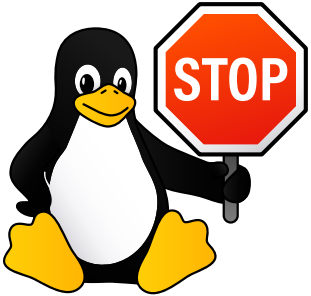

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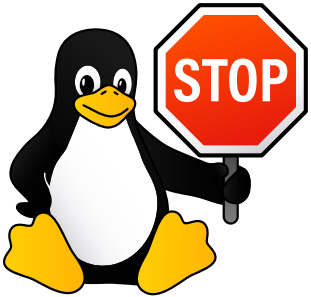
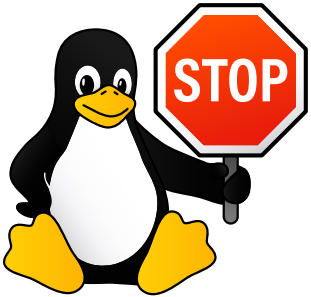


- **Hardware-Enforced Kernel Control-Flow Integrity:**
  - Intel CET, i.e., FineIBT and shadow stack
  - Safe areas

HEK-CFI



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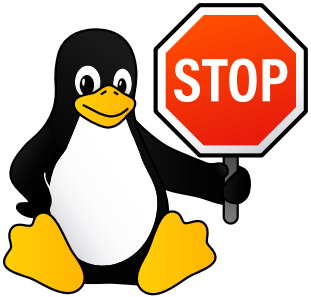
HEK-CFI



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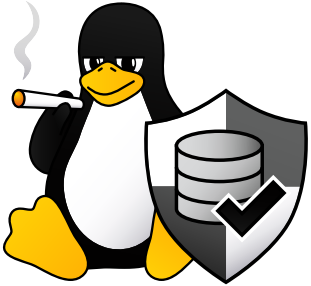
- **POC:**
  - Linux kernel 5.18 with compiler pass
  - $\approx$ 1.85 % overhead

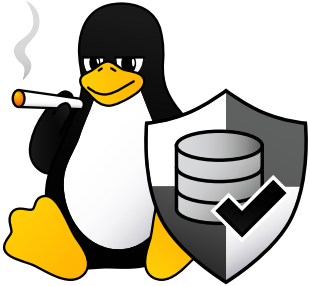
STOP

DOPE

DOPE



DOPE



- **DOmain Protection Enforcement:**
  - Memory Protection Keys, i.e., Intel PKS
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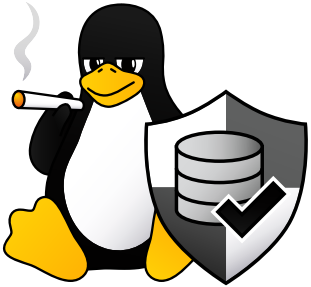
DOPE



- **DOmain Protection Enforcement:**
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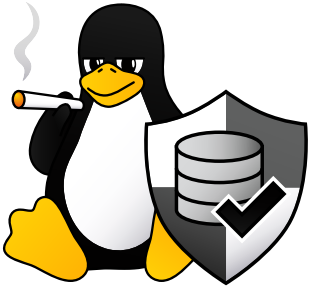
  - Credentials, page tables, ...

DOPE



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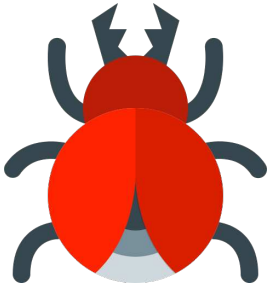
- **POC:**
  - Linux kernel 5.19 with compiler pass
  - $\approx$ 2.3 % overhead

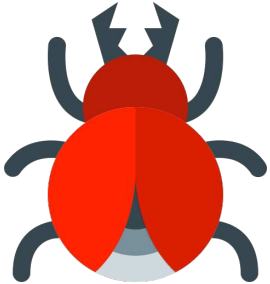
STOP

Reveal Shortcomings in the Android Ecosystem

In-the-Wild Exploits

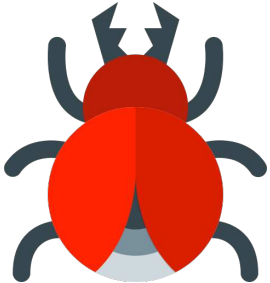


In-the-Wild Exploits



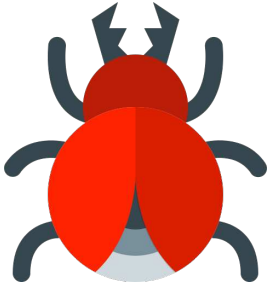
- Exploit vulnerabilities

In-the-Wild Exploits



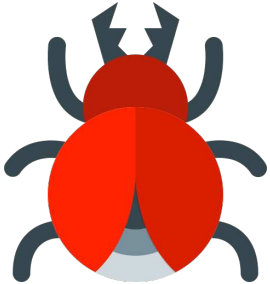
- Exploit vulnerabilities
- Escalate privileges

In-the-Wild Exploits



- Exploit vulnerabilities
- Escalate privileges
- Goal:
  - Compromise system
  - Install persistent spyware
  - ...

In-the-Wild Exploits



- Exploit vulnerab
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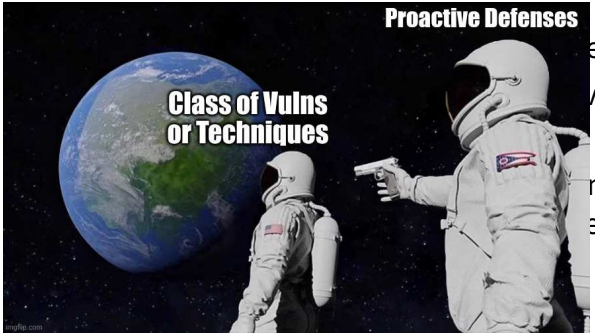
In-the-Wild Exploits

How Well Protected are Devices against In-the-Wild Exploits



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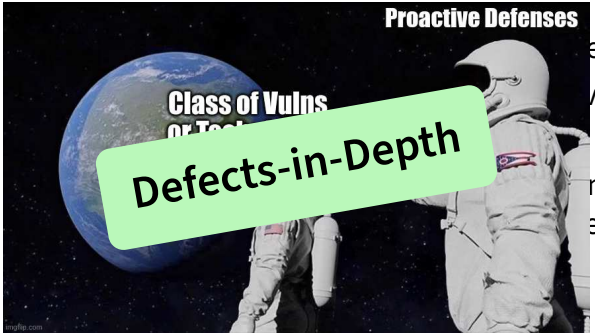

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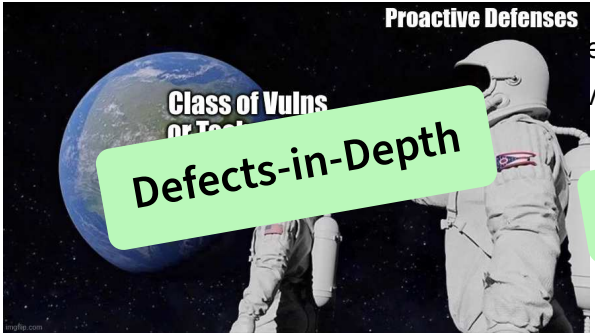
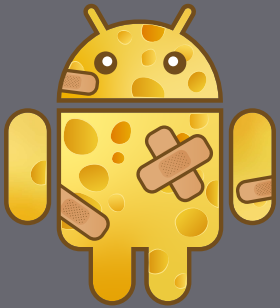


Defects-in-Depth



Defects-in-Depth

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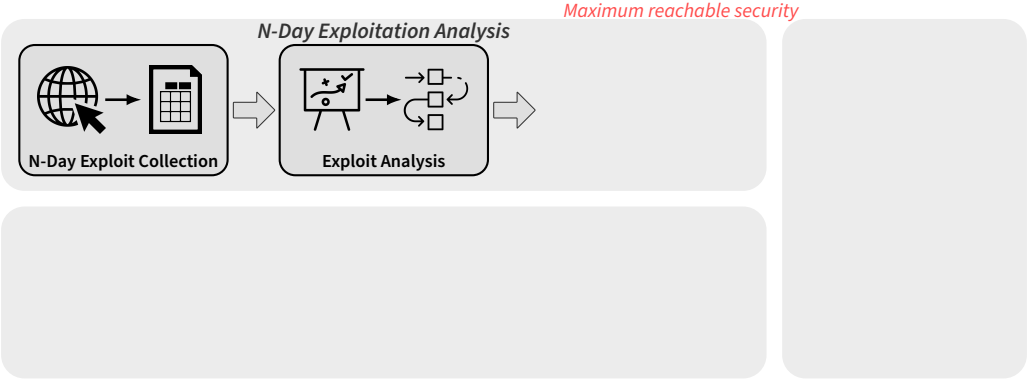
Maximum reachable security

N-Day Exploitation Analysis

Defects-in-Depth



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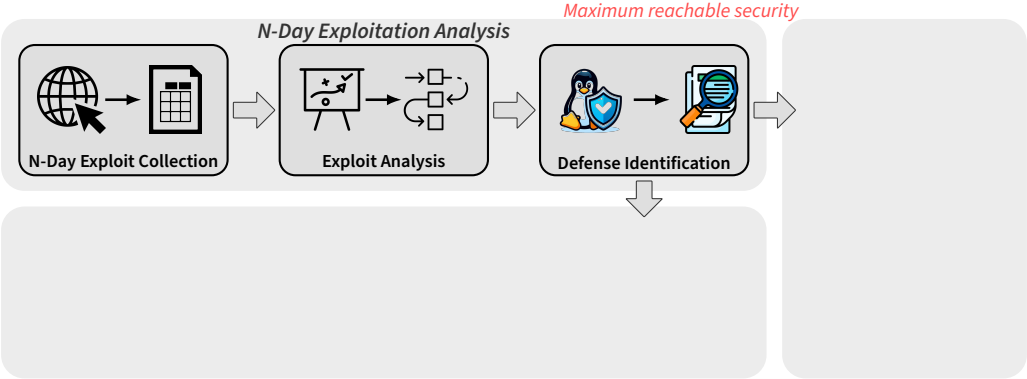

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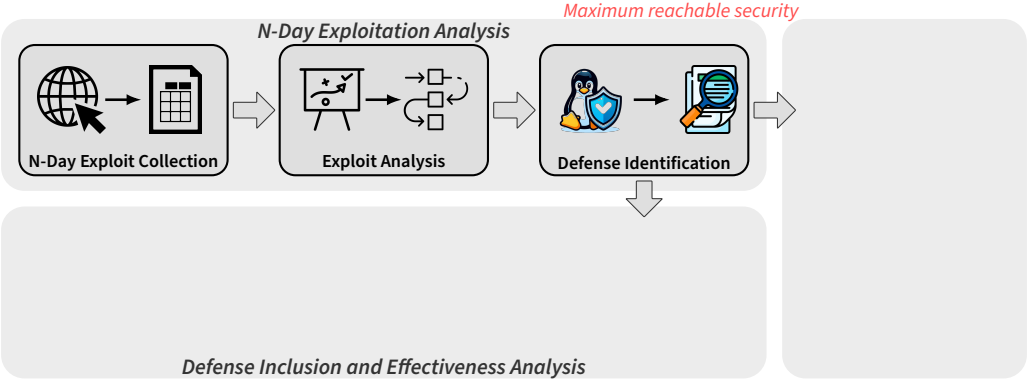

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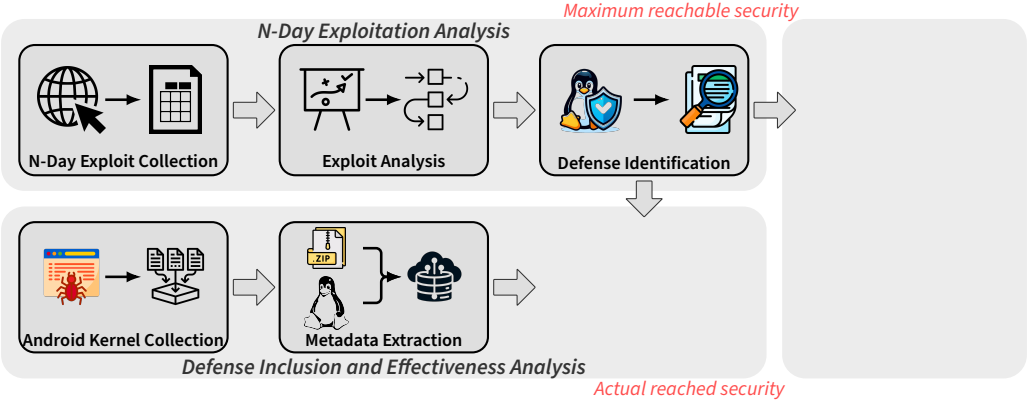

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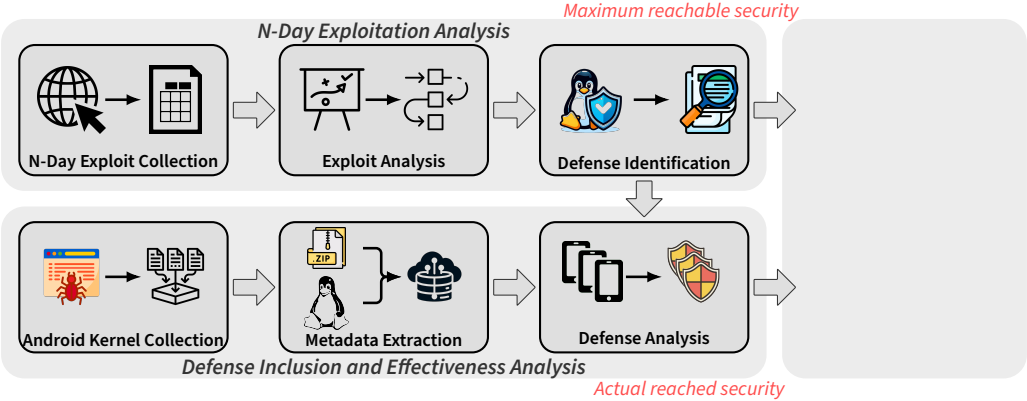

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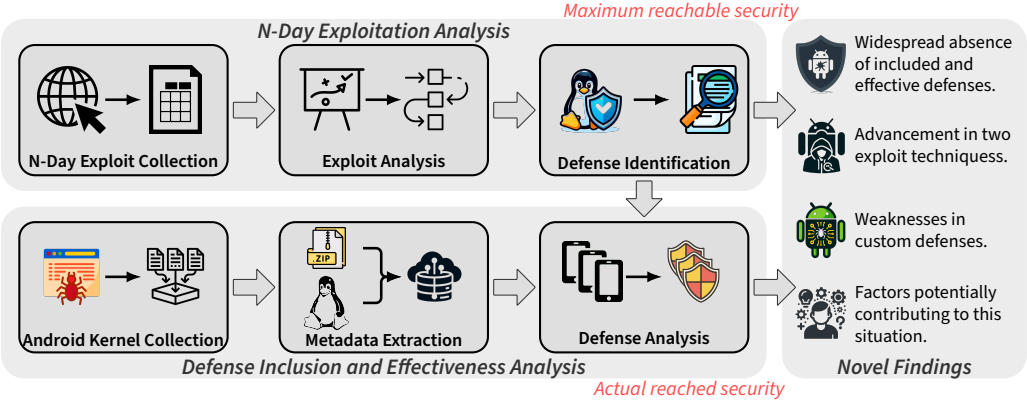

Maximum Reachable Security

Maximum Reachable Security

CVE	DM1	DM2	DM3	DM4	DM5	DM6	DM7	DM8	DM9	DM10
CVE-2019-2215	✓	✗	✓							✓
CVE-2019-2025	✓		✓							
CVE-2020-0030	✓	✗	✓							✓
CVE-2021-1968,-1969,-1940				✓	✓				✗	
CVE-2021-0920	✓		✓							
CVE-2021-1905				✓	✓				✗	
CVE-2022-22265			✓							
CVE-2021-25369,-25370		✗	✓	✗					✗	✓
CVE-2016-3809,-2021-0399			✓	✓	✓				✗	
CVE-2022-20409			✓							
CVE-2023-21400			✓						✶	✗
CVE-2022-28350									✶	✗
CVE-2020-29661									✶	✗
CVE-2021-22600			✓							
CVE-2020-0423	✓							✗	✓	✓
CVE-2022-22057						✓		✗	✓	✓
CVE-2023-26083,-0266				✗					✗	
CVE-2020-0041	✓		✓							
CVE-2019-2205	✓		✓							
CVE-2019-2025	✓		✓					✗	✓	✓
CVE-2020-3680	✓		✓					✗	✓	✓
CVE-2022-20421			✓							
CVE-2022-0847							✓			
CVE-2021-4154										
CVE-2021-38001				✓	✓				✗	
NO_NUMBER (∼2021)			✓			✓				

DM1: `CONFIG_DEBUG_LIST` **DM2:** `CONFIG_ARM64_UAO` **DM3:** `kmalloc-cg-*` **DM4:** `CONFIG_CFI_CLANG`
DM5: `CONFIG_BPF_JIT_ALWAYS_ON` **DM6:** `CONFIG_SLAB_FREELIST_HARDENED` **DM7:** `CONFIG_INIT_ON_ALLOC_DEFAULT_ON`
DM8: KSMA protection **DM9:** Samsung RKP **DM10:** Huawei HKIP

Maximum Reachable Security

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CVE-2019-2025	✓		✓							
CVE-2020-0030	✓	✗	✓							✓
CVE-2021-1968,-1969,-1940				✓	✓				✗	
CVE-2021-0920	✓		✓							
CVE-2021-1905				✓	✓				✗	
CVE-2022-22265			✓							
CVE-2021-25369,-25370		✗	✓	✗					✗	✓
CVE-2016-3809,-2021-0399			✓	✓	✓				✗	
CVE-2022-20409			✓							
CVE-2023-21400			✓						✶	✗
CVE-2022-28350									✶	✗
CVE-2020-29661									✶	✗
CVE-2021-22600			✓							
CVE-2020-0423	✓							✗	✓	✓
CVE-2022-22057						✓		✗	✓	✓
CVE-2023-26083,-0266				✗					✗	
CVE-2020-0041	✓		✓							
CVE-2019-2205	✓		✓							
CVE-2019-2025	✓		✓					✗	✓	✓
CVE-2020-3680	✓		✓					✗	✓	✓
CVE-2022-20421			✓							
CVE-2022-0847							✓			
CVE-2021-4154										
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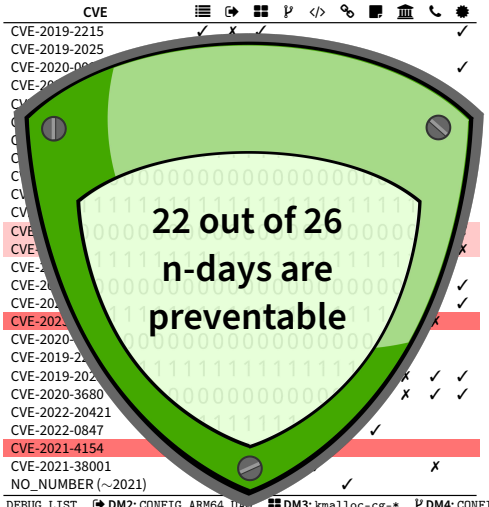
Maximum Reachable Security



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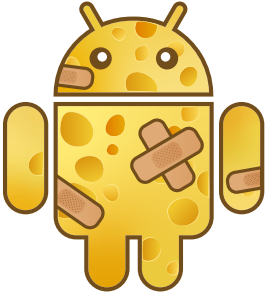
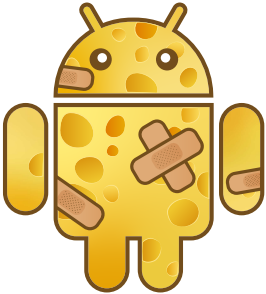
Actual Reached Security



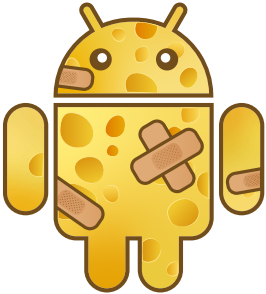
Actual Reached Security



Exploit Flows Still Feasible:

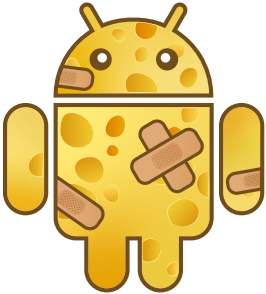
- *Ground Truth:* **4** of 26

Actual Reached Security



- **Exploit Flows Still Feasible:**
  - *Ground Truth:* **4** of 26
- **Evaluation:**
  - 994 devices
  - From 10 vendors

Actual Reached Security



- **Exploit Flows Still Feasible:**
  - *Ground Truth:* **4** of 26
- **Evaluation:**
  - 994 devices
  - From 10 vendors
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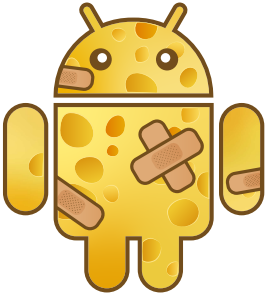
Actual Reached Security



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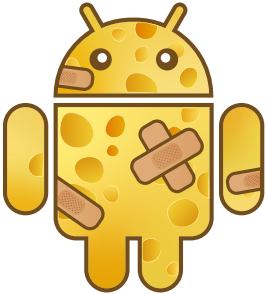

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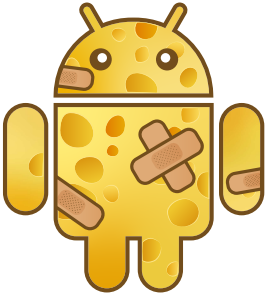

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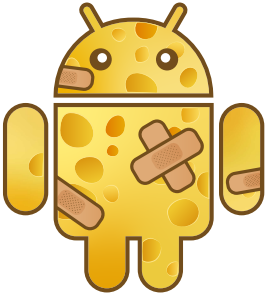

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STOP

The Doom of Device Drivers

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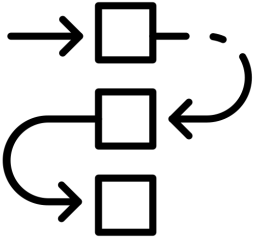

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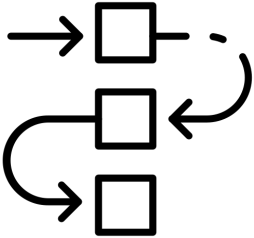

Identify N-Day Vulnerabilities:

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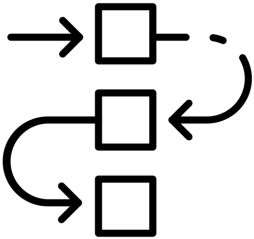

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- Affect a wide range of Android devices.

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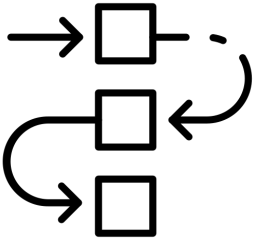

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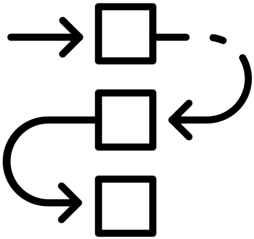

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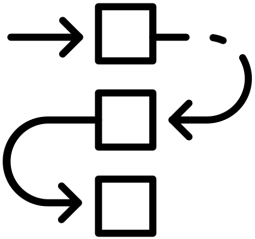

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Patch Inclusion Analysis:

- 131 Android devices
- 7 device vendors
- 3 chipset vendors

Devices Susceptibility to at least 1 N-Day

Device Vendor	All Devices Analyzed	
	Crit Vuln	Any Vuln
	%	%
Samsung		
Xiaomi		
Asus		
Realme		
Vivo		
Oppo		
OnePlus		

in December 2024

Devices Susceptibility to at least 1 N-Day

Device Vendor	All Devices Analyzed	
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Samsung	45.5	45.5
Xiaomi	67.3	71.4
Asus	75.0	100.0
Realme	56.2	62.5
Vivo	40.0	40.0
Oppo	42.9	42.9
OnePlus	85.7	85.7

in December 2024

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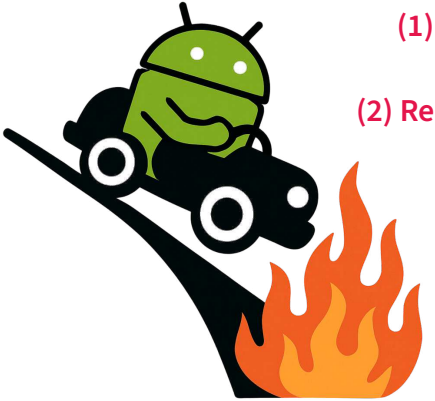

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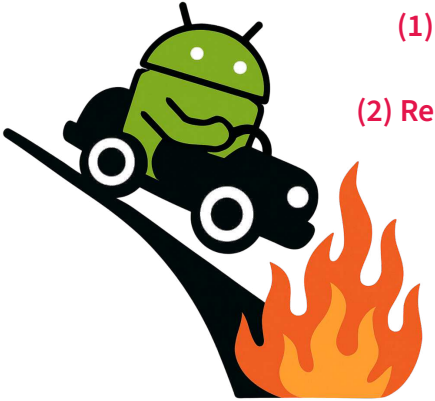

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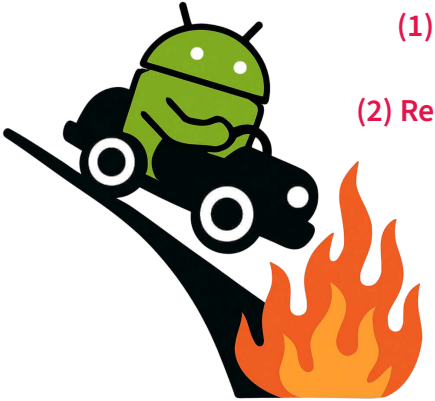

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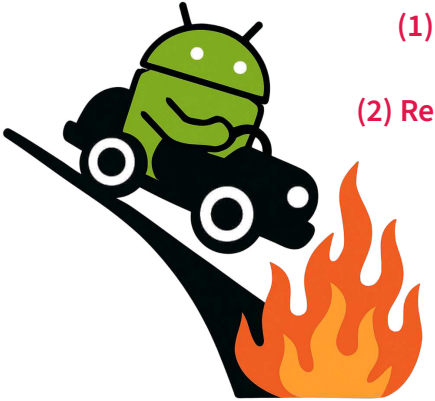

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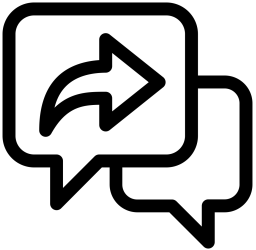
(5) Exploit: Threat actors can weaponize n-day vulns, avoiding costly zero-days.

STOP

Outlook

Top Responses



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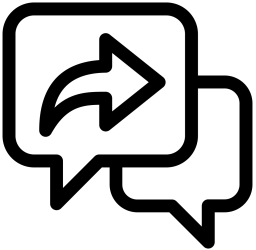

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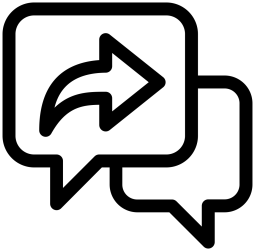

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- Supervised 2 Master and 1 Bachelor students

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Increase Defense Effectiveness

Reveal Shortcomings in the Android Ecosystem

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Increase Defense
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TU Graz

SCIENCE
PASSION
TECHNOLOGY

Kernel Security in the Wild:

Side-Channel-Assisted Exploit Techniques, Kernel-Level Defenses, and Real-World Analysis

Lukas Maar

September 26, 2025

PhD Defense

› isec.tugraz.at

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