SCIENCE
PASSION
TECHNOLOGY

Artifacts Evaluated acm Functional V1.1

DOPE: DOmain Protection Enforcement with PKS

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7 December 2023

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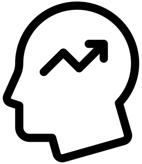
Motivation

Exploitation



Goals of adversaries

- Leaking sensitive informations, e.g., , , or
- Resource compromising
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Kernel security

- Isolate different entities

Kernel vulnerabilities

- Exploitation to bypass isolation primitives

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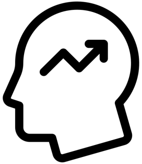

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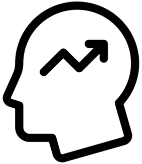

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CVEs in the Linux Kernel

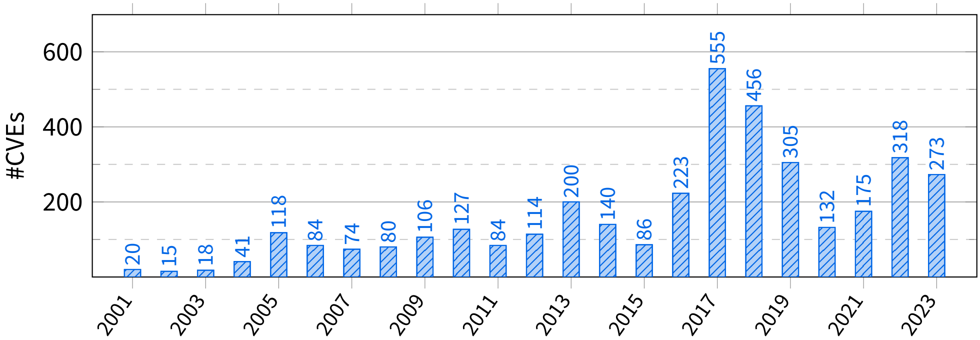

Figure: Found Linux kernel CVEs from NIST NVD.

Kernel Attacks

Control-flow hijacking attacks

- Corrupt control data to redirect control flow
- ROP or JOP chain
- Code execution → escalate privileges

Kernel Control-Flow Integrity (CFI) [CDA14, Edg20, ABEL05] prevents control-flow hijacking attacks

What about corrupting non-control data?

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Data-Oriented Attacks

Overview

Goal of adversaries to overwrite sensitive non-control data

Does not violate control flow's integrity

Sensitive data objects in the kernel

- Credentials
- Inode
- Page tables
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```
struct cred {
  kuid_t uid;
  kgid_t gid;
  ...
  kernel_cap_t cap_permitted;
  kernel_cap_t cap_effective;
  ...
  struct key *thread_keyring;
  ...
  struct user_namespace *user_ns;
  ...
} __randomize_layout;
```

Overview

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```c
struct inode {
  umode_t i_mode;
  kuid_t i_uid;
  kgid_t i_gid;
  unsigned int i_flags;
  ...
} __randomize_layout;
```

Overview

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```
#define _PAGE_BIT_PRESENT 0
#define _PAGE_BIT_RW 1
#define _PAGE_BIT_USER 2
...
#define _PAGE_BIT_PAT_LARGE 12
...
#define _PAGE_BIT_NX 63
```

Data-Oriented Attacks in the Wild

- Data-oriented attacks are very common
  - DirtyCred [LWX22], Dirty PageTable [Nic23], ...
  - Numerous public exploits and one-day attacks [Goo19, Goo21, Ale21]
  - Enormous threat to system security
- *RQ1: How can we enhance kernel security to provide effective protection against data-oriented attacks with reasonable performance overhead for multiple sensitive data objects?*
- *RQ2: How does our solution scale and perform when compared to state-of-the-art solutions?*

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Sensitive Data Portection

DOPE: DOmain Protection Enforcement with PKS

- Novel kernel mitigation to protect sensitive data objects
- Enforces domain protection leveraging Intel PKS [Int16]
  - Moves sensitive data to distinct security domains
  - Restricts memory access to these domains
  - Based on the principle of least privilege
- Protects 8 sensitive data objects with an average runtime overhead of ≈2.3 %
- Systematically analyze 11 state-of-the-art data protection schemes

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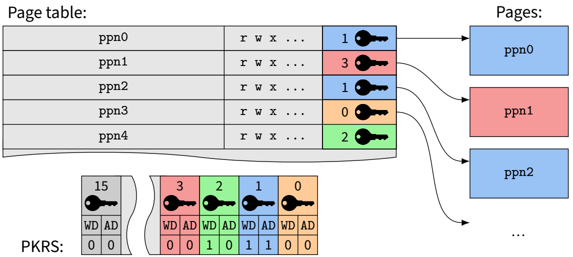
Intel Protection Keys for Supervisor (PKS)



- Intel's implementation of MPK
- Tags page with key
- Access only allowed if permission is set in the PKRS
  - WD Write Disabled
  - AD Access Disabled
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- No TLB flush or page table walk

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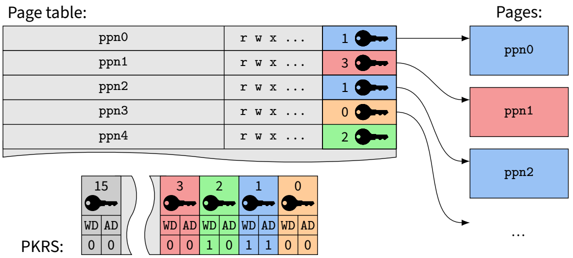

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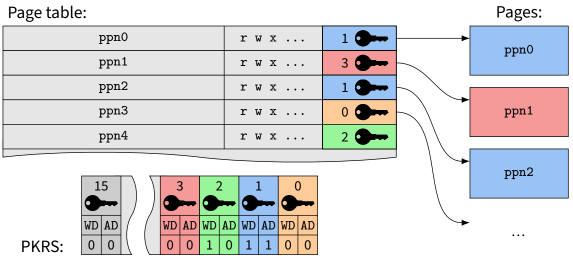

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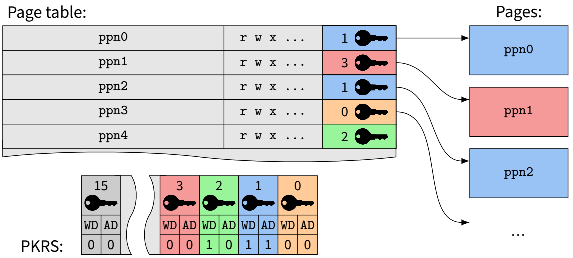

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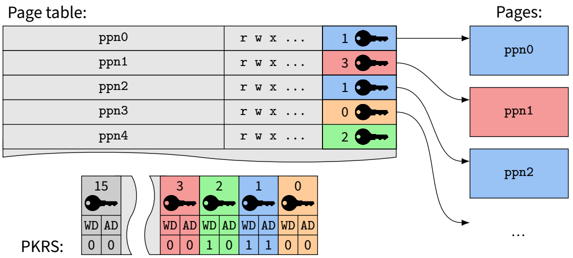

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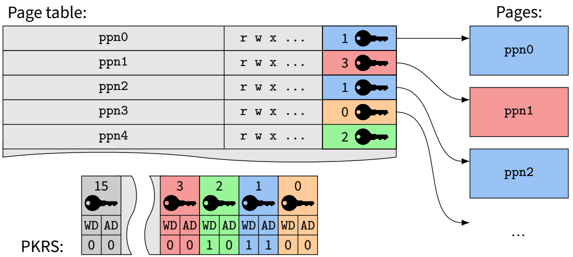

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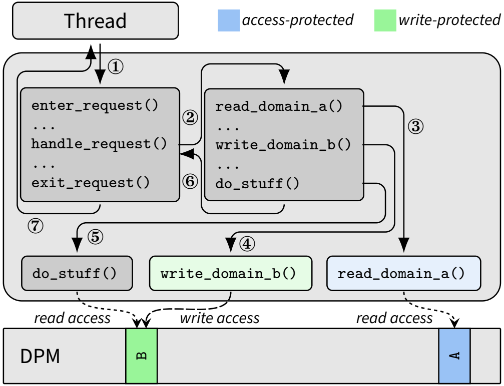

① Enters a kernel execution request and obtains restricted access permissions

② Handles the execution request

③ Legally reads access-protected data

- By switching to domain A

④ Legally writes write-protected data

- By switching to domain B

⑤ Reads write-protected data

⑥/⑦ Exits the execution request

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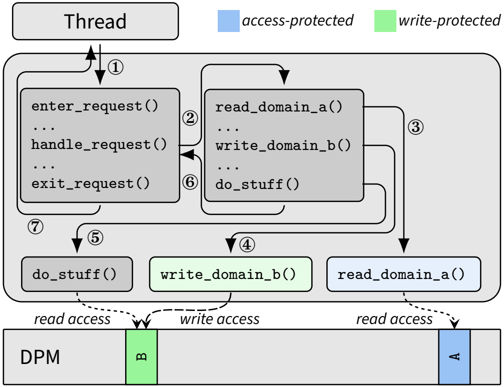

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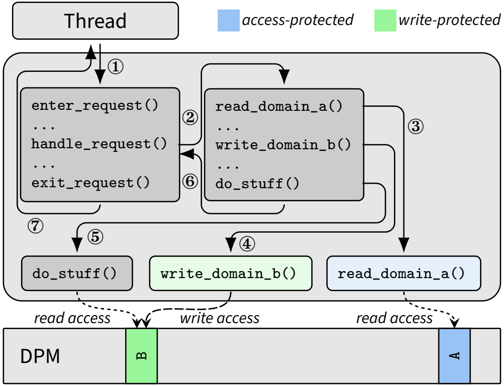

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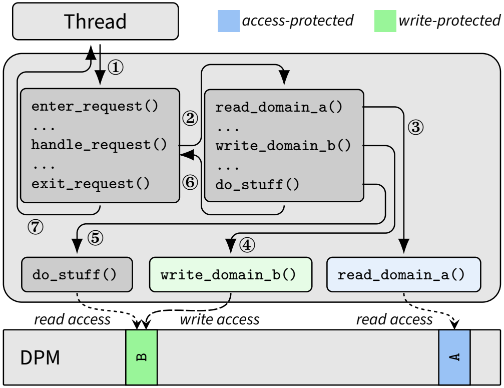

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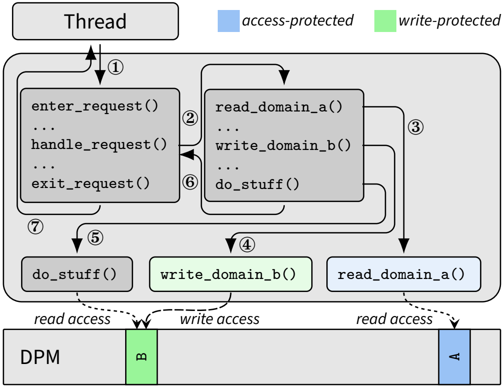

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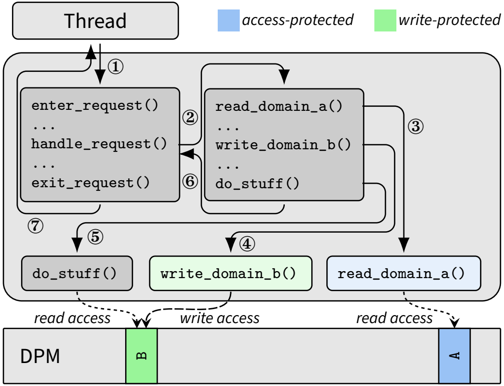

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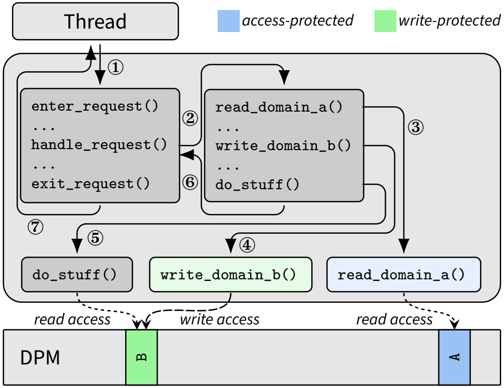

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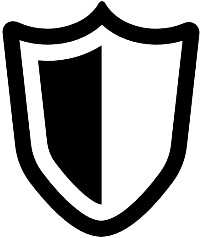

- Predefined restricted access permissions
- Sensitive data access in trusted code locations
  - Predefined before compile-time
  - Semi-automatic approach with compiler pass
- Three variants of enforcing domain protection with PKS
  - Entire data object protection
  - Shadow memory protection
  - Sensitive data protection
- Pointer integrity through ownership

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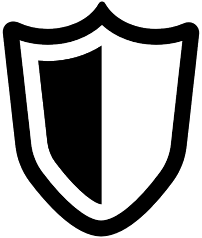

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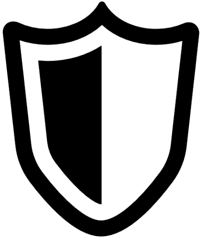

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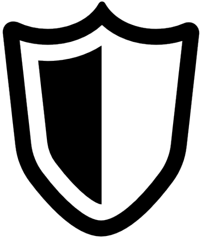

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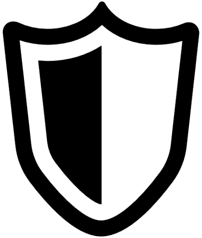

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Trusted Code

```
/* get ext4 inode */
struct inode *ext4_iget(){
  struct ext4_inode *ei;
  struct inode *ino;
  ...
  ino = dentry->inode;


  ino->i_uid = i_uid;
  ino->i_gid = i_gid;

  ei->i_data[blk] = data;
  ...
  return ino;
}
```

- ext4_iget function returns ext4 inode
  - Access inode from its owner dentry
  - Legally overwrites sensitive data i.e., i_*id
- Code analyzer detects accesses, i.e., owner and sensitive data
- Insert domain switches
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struct inode *ext4_iget(){
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  struct inode *ino;
  ...
  ino = dentry->inode;
+ owner_check(dentry, ino);
+ enter_inode_wr();
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Ownership

- Sensitive data object comprises the owner's address
- Validation check
  - Owner same
  - Sensitive data object correctly tagged
- Multiple ownership
  - Store both addresses in hashtable
  - Hashtable tagged same domain

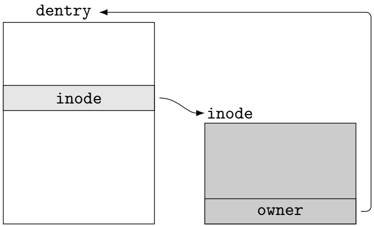

Figure: Ownership-based protection is employed to protect the sensitive pointer to `inode` within its owner `dentry`.

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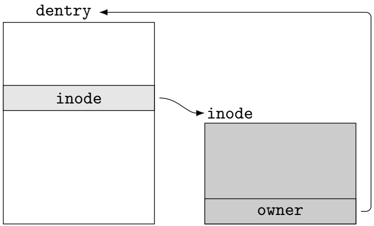

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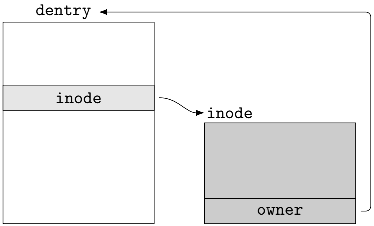


Figure: Ownership-based protection is employed to protect the sensitive pointer to `inode` within its owner `dentry`.

Ownership

- Sensitive data object comprises the owner's address
- Validation check
  - Owner same
  - Sensitive data object correctly tagged
- Multiple ownership
  - Store both addresses in hashtable
  - Hashtable tagged same domain

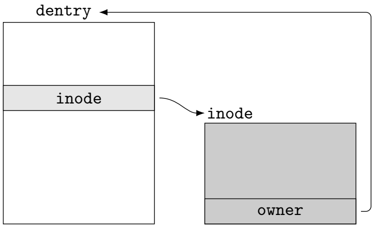


Figure: Ownership-based protection is employed to protect the sensitive pointer to `inode` within its owner `dentry`.

Enforcing Domain Protection with PKS

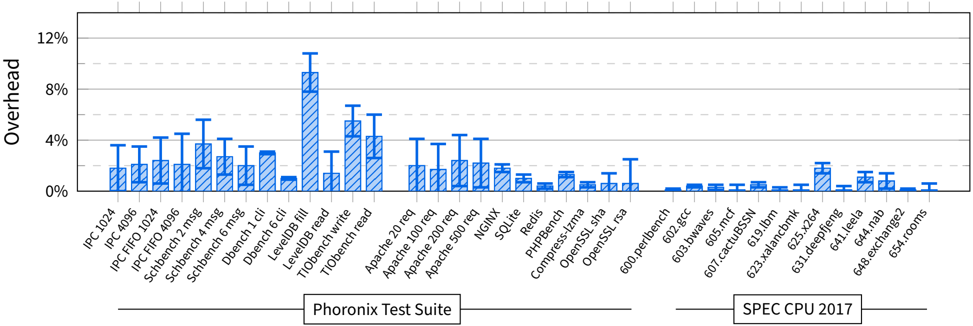
Table: Applied protection variant for our sensitive data objects.

Variant	User-accessible pages	Credentials	Inodes	Page tables	Virtual memory areas	Virtual memory	Filesystem mount	Stored registers	Sensitive state
Entire date object protection	●	●	○	●	○	○	○	●	●
Shadow memory protection	○	○	○	○	●	●	●	○	○
Sensitive data protection	○	○	●	○	○	○	○	○	○

● Applied ○ Not applied

Performance Overhead

Figure: We implement our DOPE proof-of-concept in Linux kernel v5.19 and run it on Ubuntu 22.04.1 LTS with a recent Intel Alder Lake processor.



Systematic Analysis

Table: Systematic overview of mitigations against data-oriented attacks in the Linux kernel.

Mitigations	Sensitive Data Objects									Overhead
	Credentials	Virtual memory	Virtual memory areas	Inodes	Page tables	Filesystem mount	Other non-control data	User-accessible pages	Stored registers	
PrivGuard [QYJS18]	○	○	-	-	-	-	-	-	-	⧖
AKO [YAY+21]	○	-	-	-	-	-	-	-	-	⧖
PrivWatcher [CAGN17]	●	●	-	-	-	-	-	-	-	⌛[1]
SALADS [CXL+15]	●	-	-	●	-	-	●[2]	-	-	⌛
PT-Rand [DGLS17]	-	-	-	-	●	-	-	-	-	⧖
Mondrix [WRA05]	-	-	-	-	-	-	●	-	●	⌛[1]
HAKC [MGP+22]	○	○	●	○	●	○	●	○	◐	⌛
KDPM [KY22a]	○	-	-	-	-	-	-	-	-	⧖[1]
KPRM [KY22b]	○	-	-	-	-	-	○	-	-	⌛
KENALI [SLL+16]	◐	●	◐	◐	●	◐	●	-	●	⌛
xMP [PMG+20]	◐	●	-	-	●	-	●[3]	-	-	⌛
DOPE [**our solution**]	●	●	●	●	●	●	-	●	●	⏳

● Strong protection ◐ Partial protection ○ Insufficient protection - Not protected

⧖ Low overhead ⏳ Reasonable overhead ⌛ High overhead

[1] Not tested on hardware [2] Non-sensitive data [3] User space data

Conclusion

- Presented DOPE, a novel kernel mitigation to protect sensitive data objects
- Implementation and case study to protect 8 sensitive data objects
  - Opensource: https://extgit.iaik.tugraz.at/sesys/dope
- Performance evaluation on real hardware shows an average runtime overhead of $\approx 2.3\,\%$
- Systematically analyze 11 state-of-the-art data protection schemes

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Thank you for your attention!

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