


TU Graz
SCIENCE
PASSION
TECHNOLOGY

# Derandomizing Kernel Object Locations with Software- and Hardware-Induced Side Channels

**Lukas Maar**

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Nullcon Berlin

› isec.tugraz.at

# Who Am I?

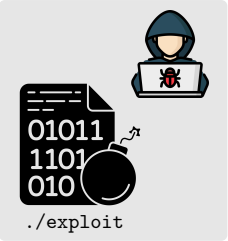
**Lukas Maar**

- PhD candidate at Graz University of Technology
  - System Security
  - Kernel Security
  - Side-Channel Security
- Looking for a job (end 2025)

# Motivation

# Kernel Exploitation

## User Space




## Kernel Space

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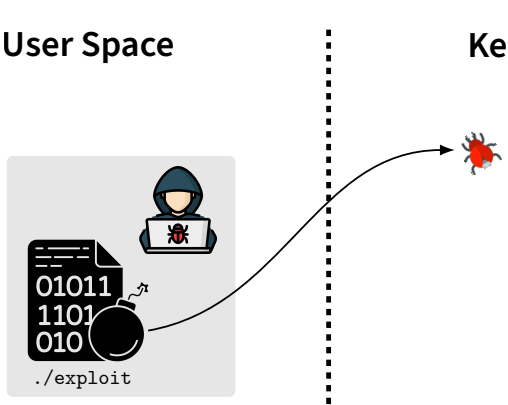

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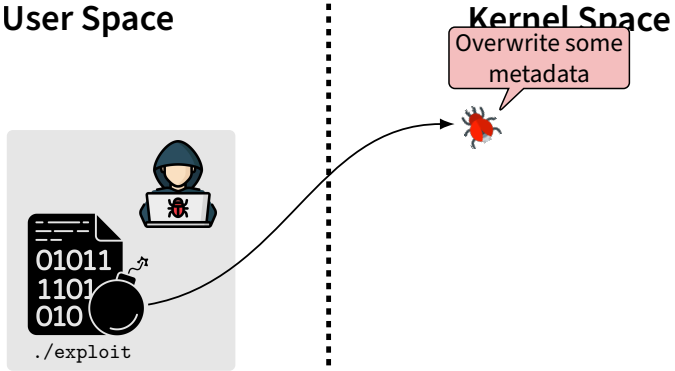

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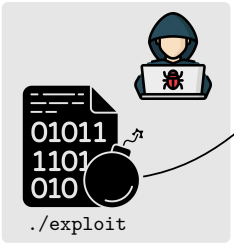


## Kernel Space

**Read primitive**

```
1 def information_leak():
2   return kaddr
```

# Kernel Exploitation

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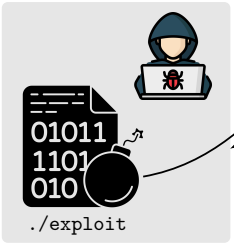


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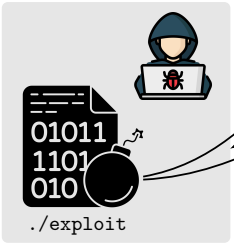


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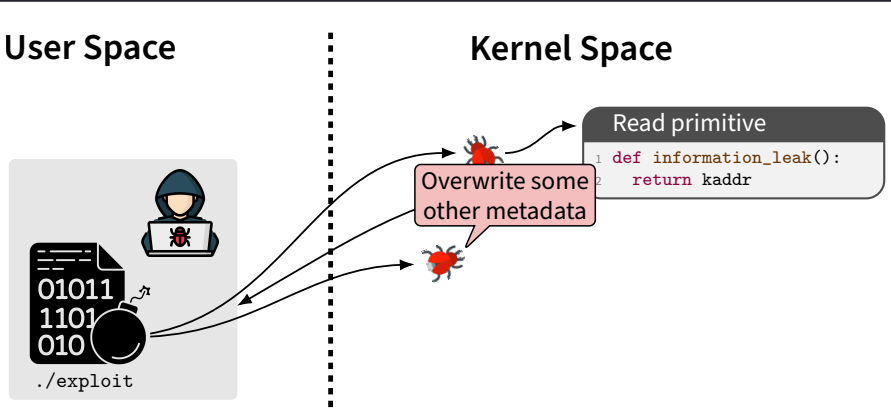

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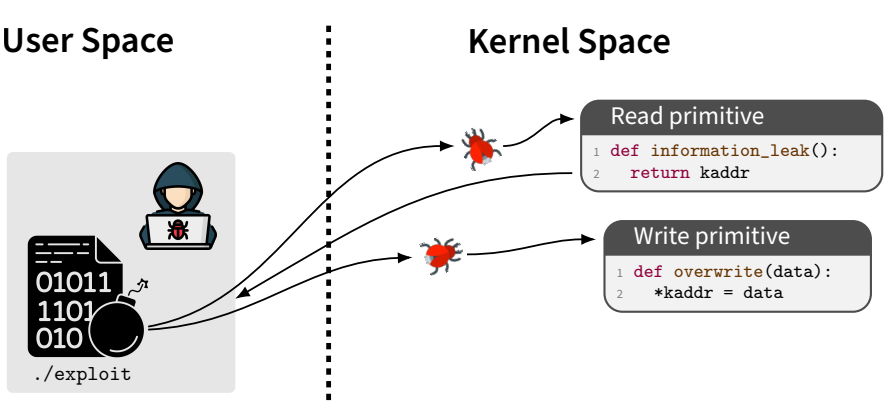

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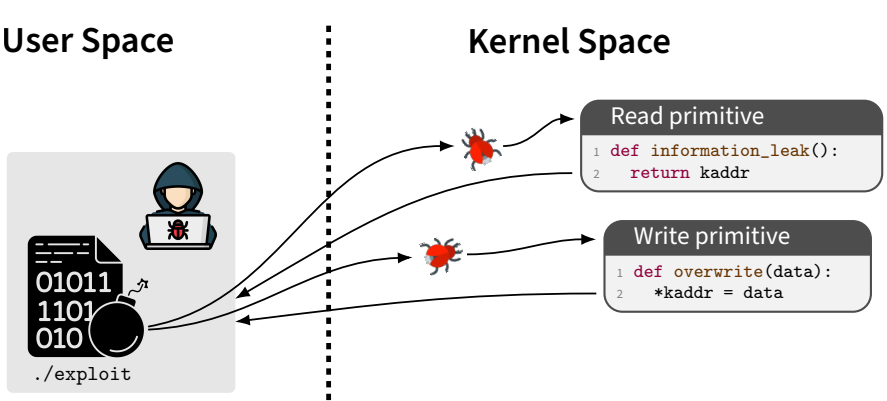

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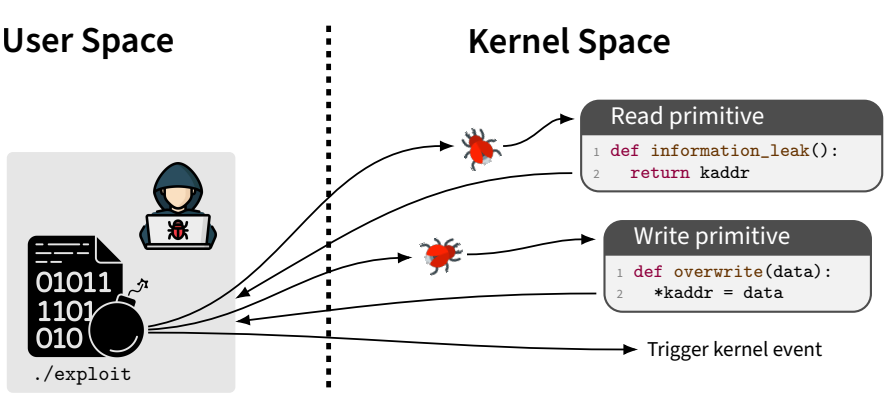

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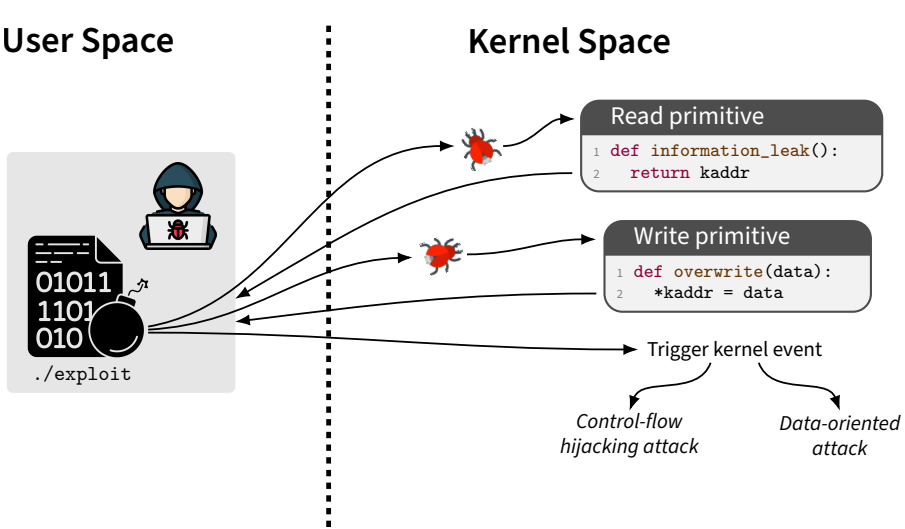

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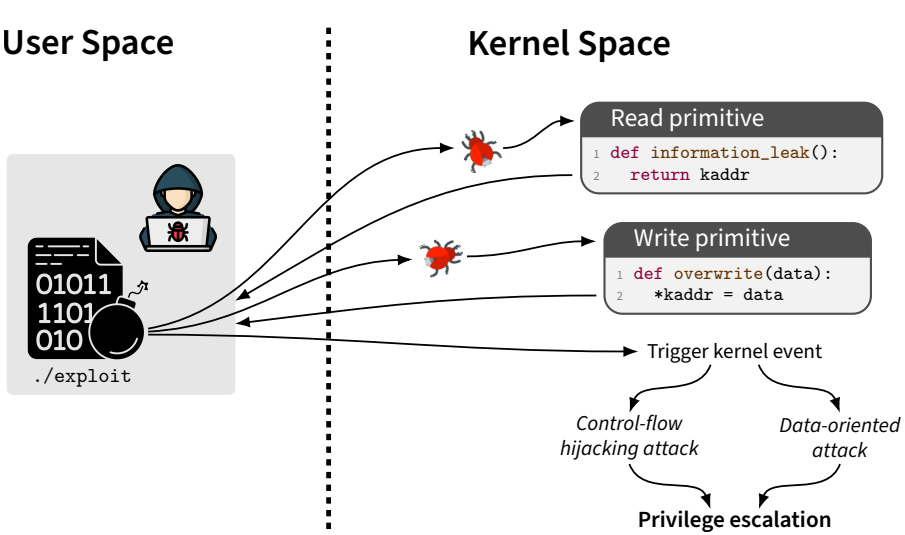

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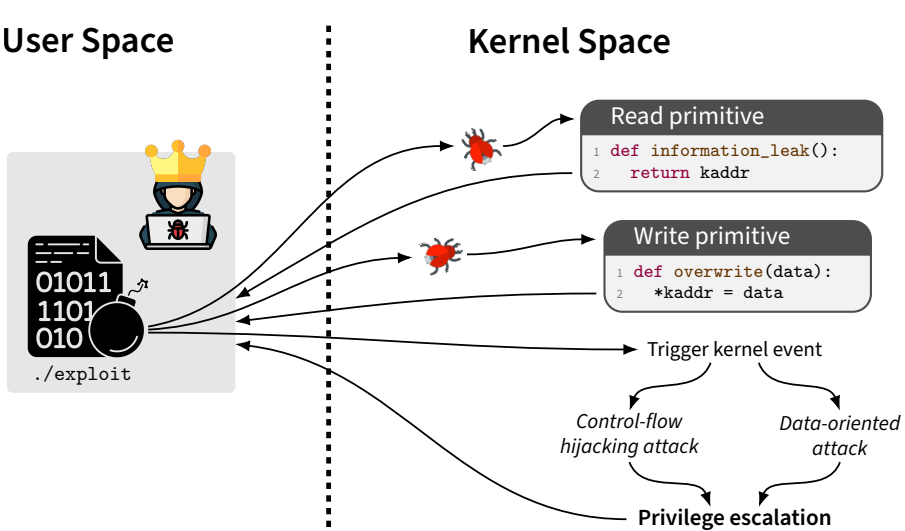

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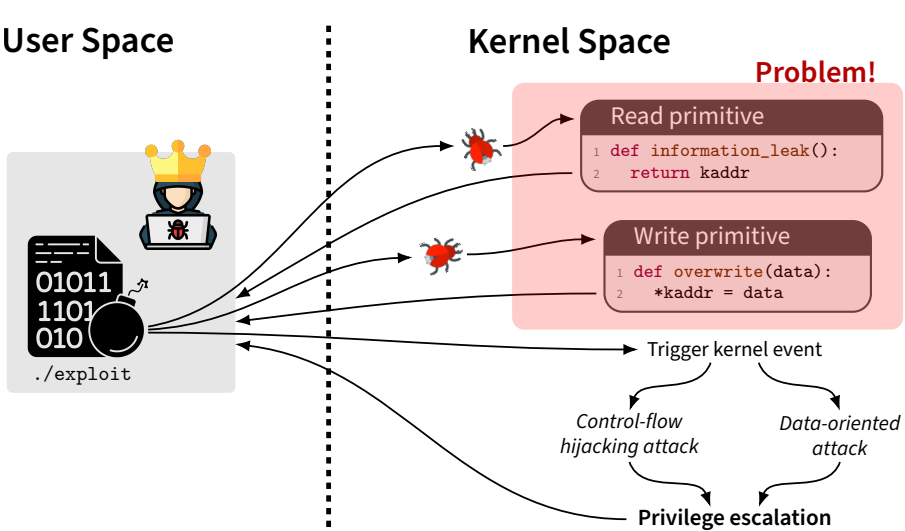

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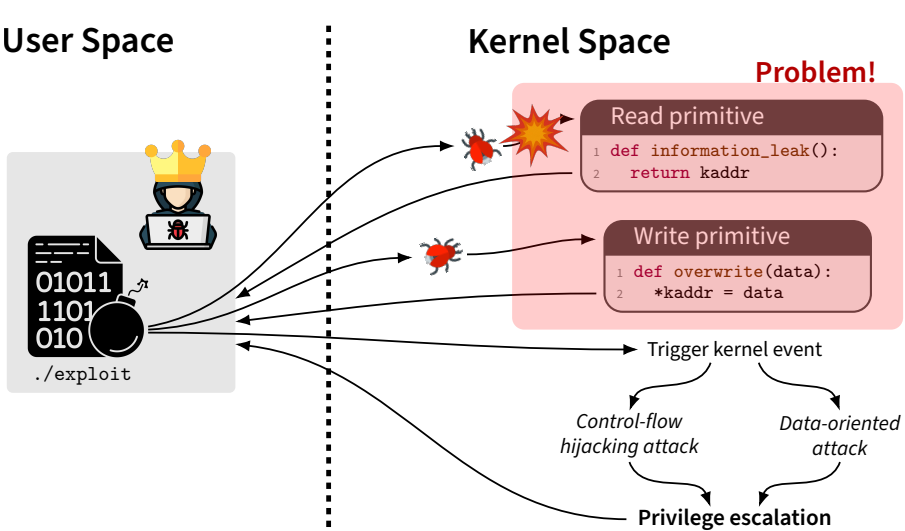

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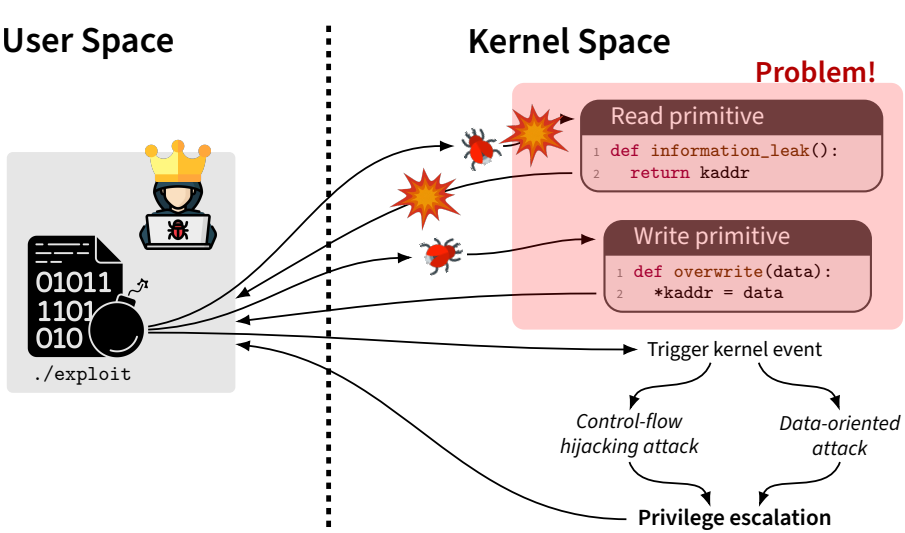

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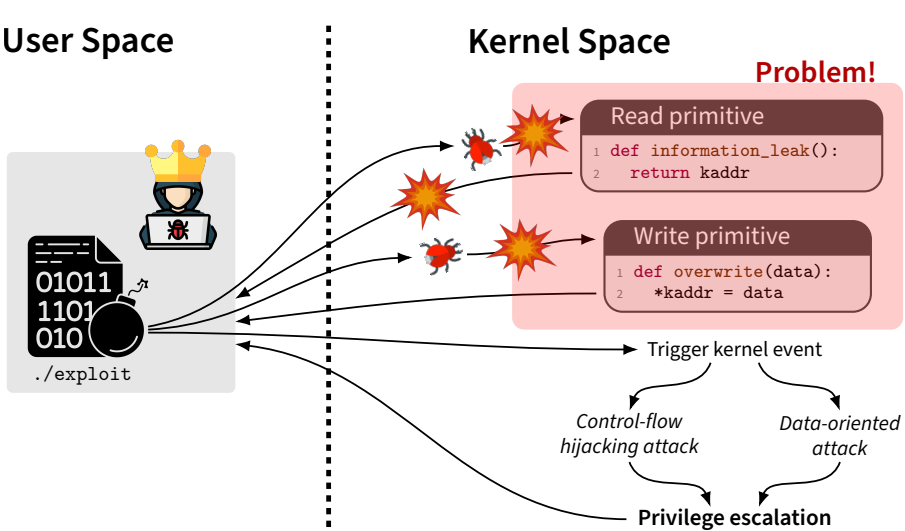

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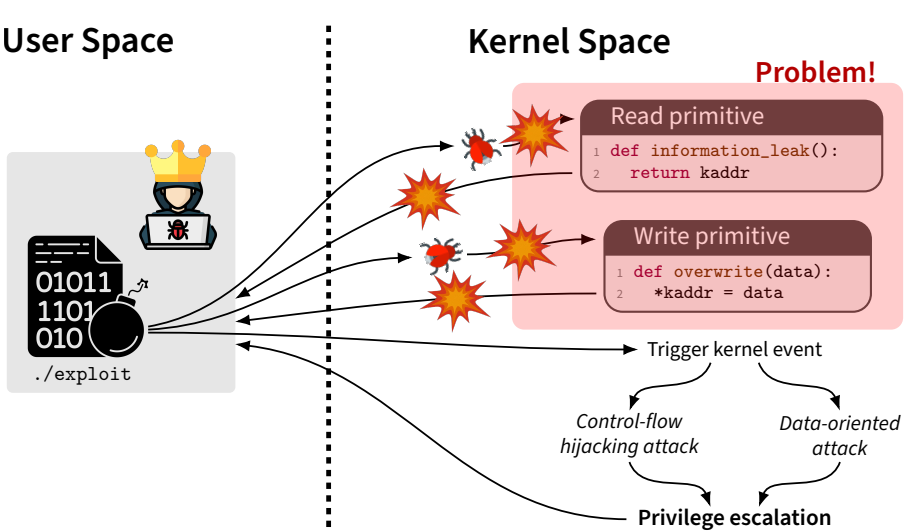

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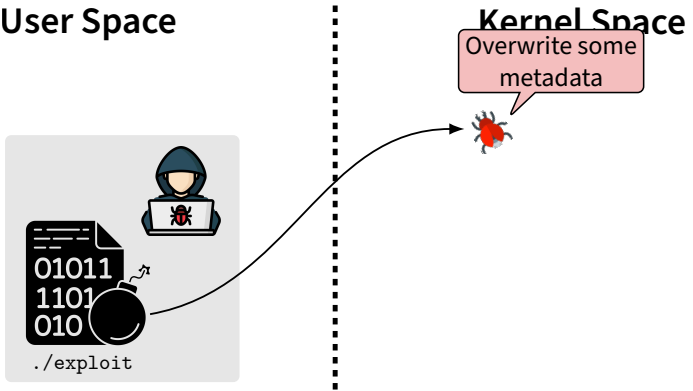
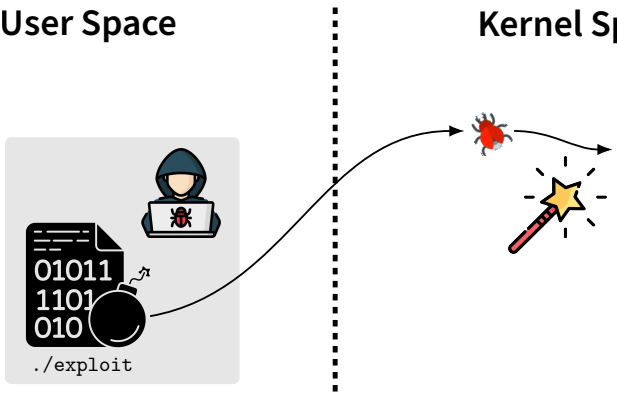
  - Potential immiate system crash
  - Potential system crash later
- **So, worst case a reboot?**
- **No, potentially triggers forensic investigation!**
  - Undermines stealth
  - Potentially burns zero-day vulnerabilities

# Magic Wand


User Space
Kernel Space
Overwrite some metadata
01011
1101
010
./exploit

# Magic Wand



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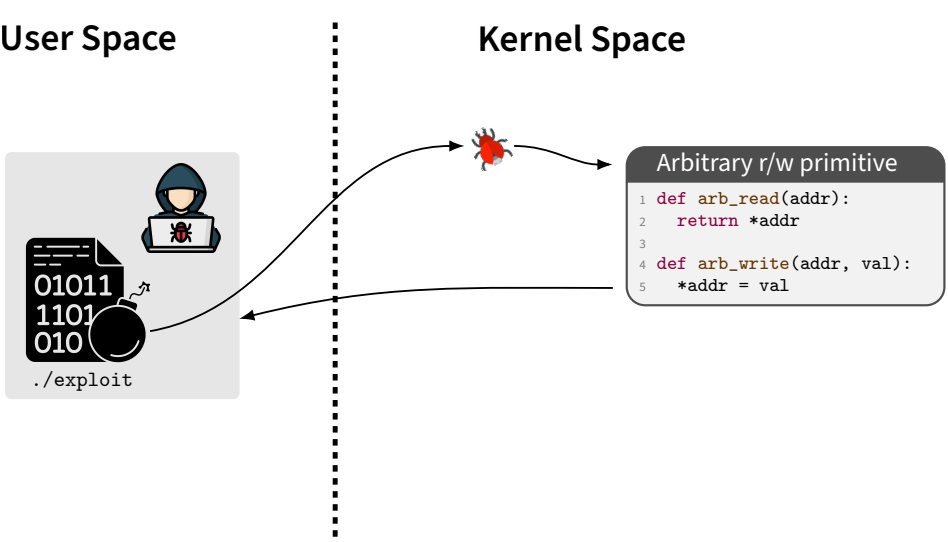
User Space
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Arbitrary r/w primitive
1 def arb_read(addr):
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4 def arb_write(addr, val):
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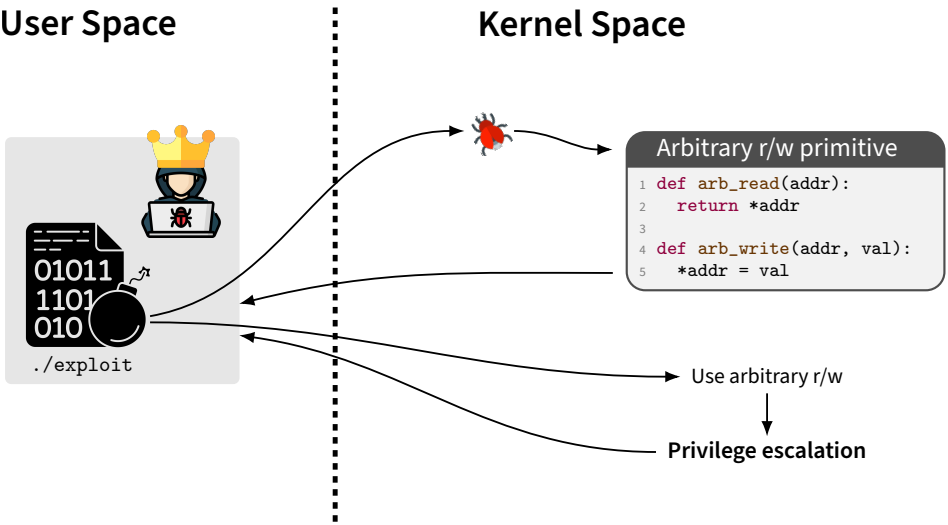
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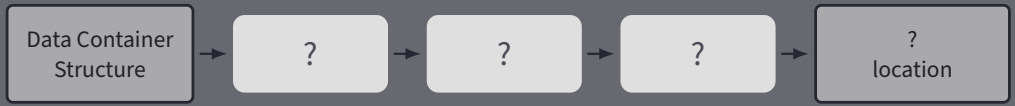
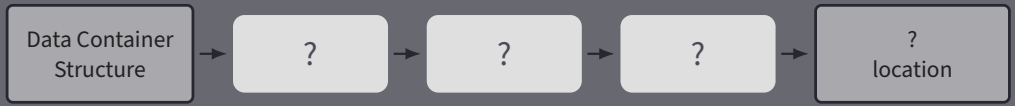
Use arbitrary r/w
Privilege escalation


Data Container Structure
?
?
?
? location


Hardware Cache
?
?
?
? location


Data Container
Structure
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location


Hardware
Cache
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location

# Linked Lists

Empty list

List with
2 elements

List with
5 elements

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*Fast access*

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*Fast access*

*Medium fast access*

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*Fast access*

*Medium fast access*

*Slow access*

# Hash Tables

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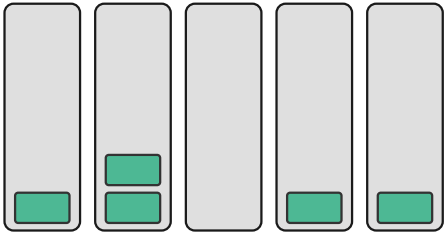

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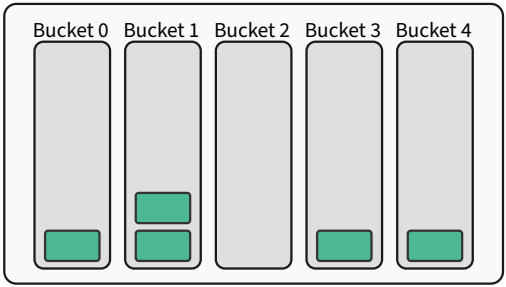

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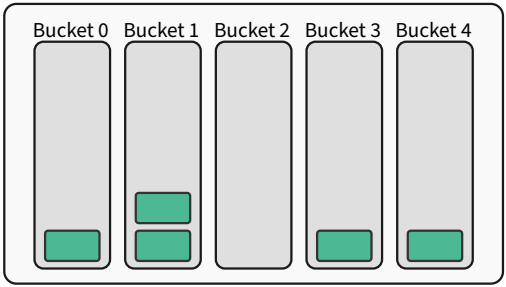

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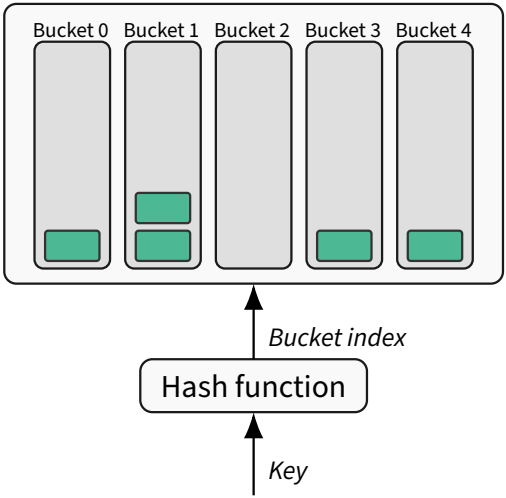
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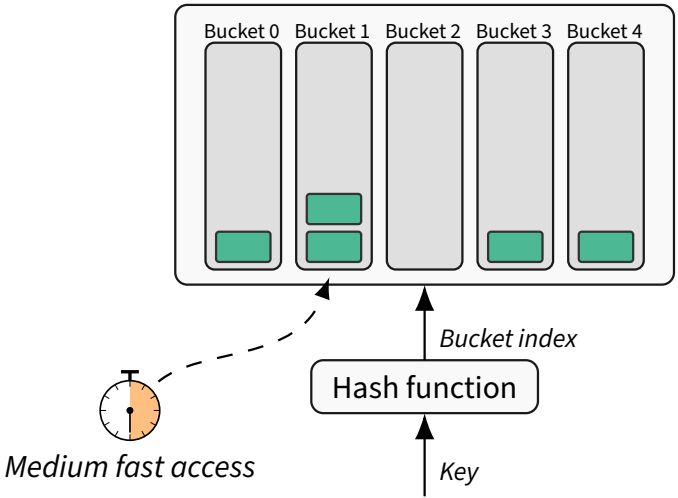
Bucket 1
Bucket 2
Bucket 3
Bucket 4
Bucket index
Hash function
Key

# Hash Tables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Medium fast access

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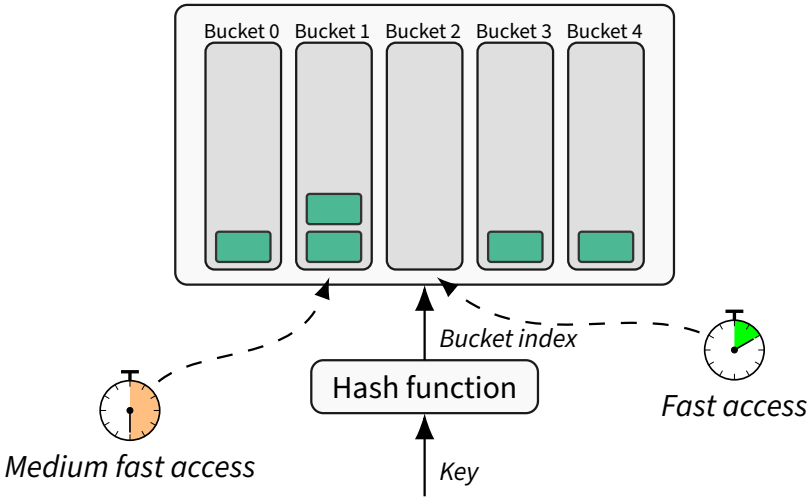
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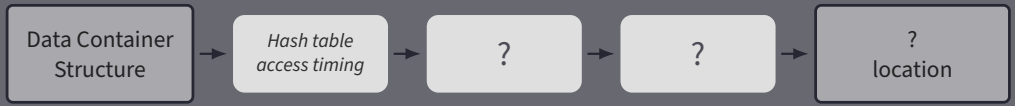
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Hash table access timing
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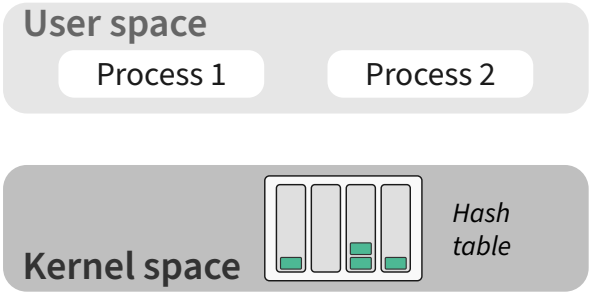
# Software-Induced Side Channel



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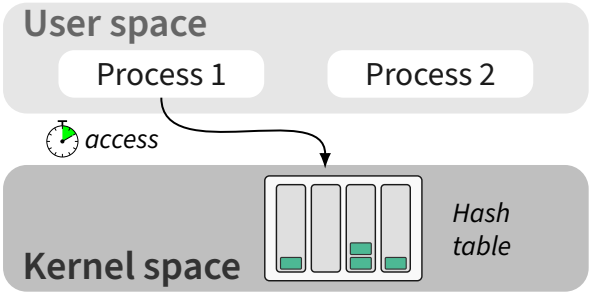


Process 1 $\rightarrow$ syscall accesses the hash table

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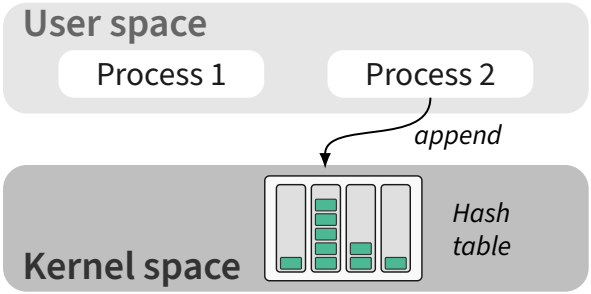


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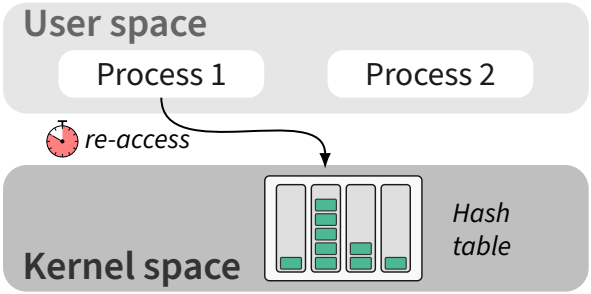


Process 1 $\rightarrow$ syscall accesses the hash table

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Process 1 $\rightarrow$ syscall re-accesses the hash table

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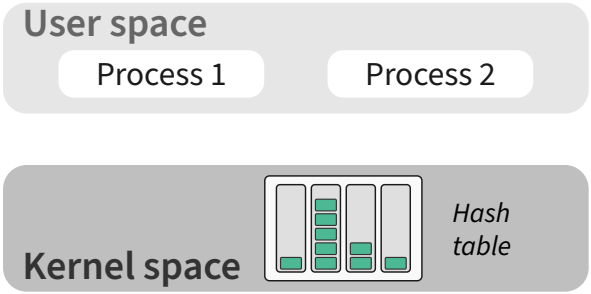


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**Deduce security-critical information**

# Primitives

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## Access primitive

## Append/remove primitive

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**Access primitive**

- Syscalls that access structures

**Append/remove primitive**

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- Syscalls that access structures
- Such as:

**Get POSIX time**

```
def sys_clock_gettime(id):
  sign = current.signal
  h = timer_hash(id, sign)
  hbucket =
    posix_timers_htable[h]
  for tim in hbucket:
    if tim.sign == sign and
       tim.id == id:
      return tim.get_time()
  return ERROR
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**Append/remove primitive**

Hash
Bucket

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Timing leak

**Append/remove primitive**

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Create new POSIX timer

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6   tim = k_itimer(sign, id)
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8     return id
```

# Timing Side Channel

Timing measurement of syscall

**Side-channel attack**

```
def side_channel_attack():
  times = []
  for id in ids:
    t0 = get_time()
    sys_clock_gettime(id)
    t1 = get_time()
    times.append(t1-t0)
```

# Timing Side Channel

Timing measurement of syscall

**Side-channel attack**

```
1 def side_channel_attack():
2   times = []
3   for id in ids:
4     t0 = get_time()
5     sys_clock_gettime(id)
6     t1 = get_time()
7     times.append(t1-t0)
```

**Invalid IDs**

# Timing Side Channel

Timing measurement of syscall

**Side-channel attack**

```
1 def side_channel_attack():
2   times = []
3   for id in ids:
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5     sys_clock_gettime(id)
6     t1 = get_time()
7     times.append(t1-t0)
```

**Invalid IDs**

**Leaks occupancy level**

Via syscall timing

# Timing Histogram

Perform $\sim$ 4000 bucket accesses

- Hash table storing POSIX timers
- Buckets between 0 and 5 timers

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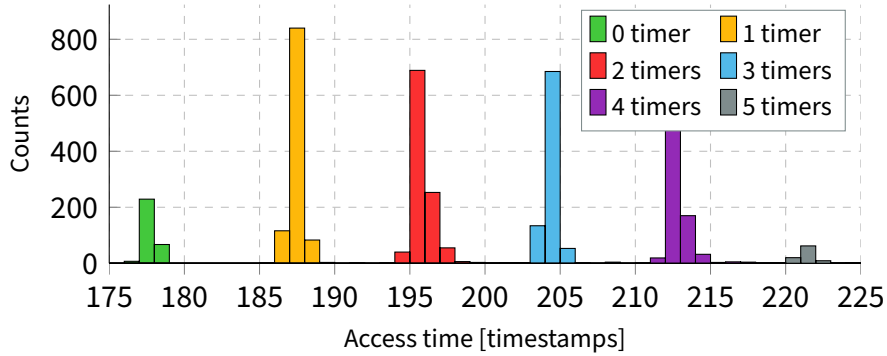

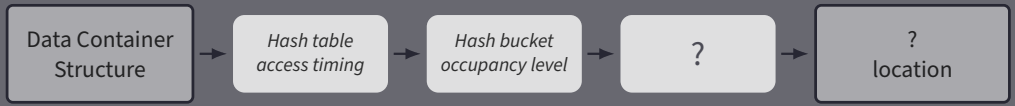
Data Container Structure
Hash table access timing
Hash bucket occupancy level
?
? location


Hardware Cache
?
?
?
? location

# Hash Collision Identifier

**Access primitive**

```
index = hash_fn(kaddr, user_id)
bucket = hash_table[index]
for e in bucket
```

# Hash Collision Identifier

**Hash:**

- Known: `hash_fn`, `user_id`
- Unkown: `kaddr`

**Access primitive**

```
1 index = hash_fn(kaddr, user_id)
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- Same `kaddr`, but different `user_ids`
- Use our side channel to detect hash collisions

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**Hash:**

- Known: `hash_fn`, `user_id`
- Unkown: `kaddr`

**Exploit strategy (online phase):**

- Same `kaddr`, but different `user_ids`
- Use our side channel to detect hash collisions

**Bruteforce (offline phase):**

- Test all possible `kaddrs`
- Match hash collisions

# Attack Scenario

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- Target data structure: futex hash table
  - Stores kernel metadata for fast userspace mutexes
  - `user_id`: user address
  - `kaddr`: `mm_struct`

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  - Similar applies to AArch64 and RISC-V

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- Target data structure: futex hash table
  - Stores kernel metadata for fast userspace mutexes
  - `user_id`: user address
  - `kaddr`: `mm_struct`
- Target system: x86_64
  - Similar applies to AArch64 and RISC-V
- Leak in less than 1 min

# Primitives

**Access primitive**

**Append/remove primitive**

# Primitives

## Access primitive

**Wake up thread**

```
1 def sys_futex_wake(uaddr):
2   mm = current.mm
3   h = futex_hash(uaddr, mm)
4   hbucket = futex_hash_tables[h]
5   for fqueue in hbucket:
6     if fqueue.mm == mm and
7        fqueue.uaddr == uaddr:
8       fqueue.wake()
```

## Append/remove primitive

# Primitives

## Access primitive

**Wake up thread**

```
def sys_futex_wake(uaddr):
  mm = current.mm
  h = futex_hash(uaddr, mm)
  hbucket = futex_hash_tables[h]
  for fqueue in hbucket:
    if fqueue.mm == mm and
       fqueue.uaddr == uaddr:
      fqueue.wake()
```

## Append/remove primitive

**Wait for thread**

```
def sys_futex_wait(uaddr):
  mm = current.mm
  h = futex_hash(uaddr, mm)
  hbucket = futex_hash_tables[h]
  fqueue = futex_q(uaddr, mm)
  hbucket.append(fqueue)
  fqueue.wait()
```

# Hash Collision Detection

Find 15 ids that cause a hash collision

```
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
```

# Hash Collision Detection

## Find 15 ids that cause a hash collision

```
1  futexes = new array(1<<30) // user identifiers for primitives
2  collisions = []            // found collisions
3  def find_collisions():
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
```

# Hash Collision Detection

## Find 15 ids that cause a hash collision

```
1  futexes = new array(1<<30) // user identifiers for primitives
2  collisions = []            // found collisions
3  def find_collisions():
4
5    flush_cpu_caches()
6    t0 = get_time()
7    sys_futex_wake(0xdeadbeef)
8    t1 = get_time()
9    threshold_time = 10*(t1-t0)
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
```

# Hash Collision Detection

## Find 15 ids that cause a hash collision

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futexes = new array(1<<30) // user identifiers for primitives
collisions = []            // found collisions
def find_collisions():

  flush_cpu_caches()
  t0 = get_time()
  sys_futex_wake(0xdeadbeef)
  t1 = get_time()
  threshold_time = 10*(t1-t0)

  for i in range(4096):
    sys_futex_wait(futexes[0])
  collisions.append(futexes[0])
```

# Hash Collision Detection

## Find 15 ids that cause a hash collision

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1  futexes = new array(1<<30) // user identifiers for primitives
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8    t1 = get_time()
9    threshold_time = 10*(t1-t0)
10
11   for i in range(4096):
12     sys_futex_wait(futexes[0])
13   collisions.append(futexes[0])
14
15   fid = 1
16   while sizeof(collisions) < 16:
17
18
19
20
21
22
23
24
25
26     fid++
```

# Hash Collision Detection

## Find 15 ids that cause a hash collision

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1  futexes = new array(1<<30) // user identifiers for primitives
2  collisions = []            // found collisions
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23
24
25
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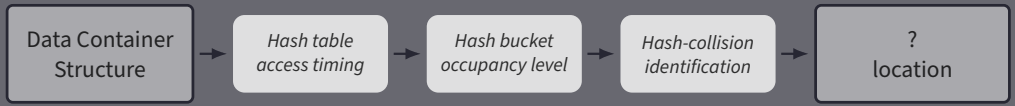
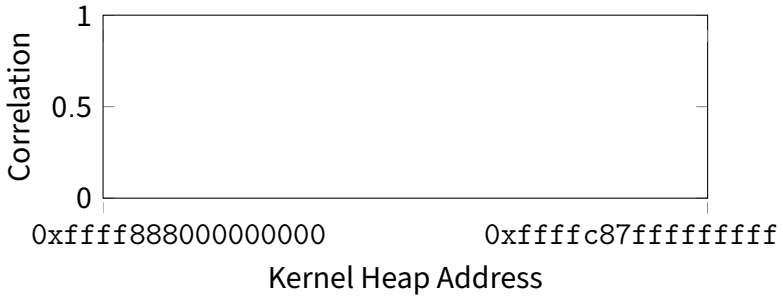
20     sys_futex_wake(futexes[fid])
21     t1 = get_time()
22
23     if (t1-t0) > threshold_time:
24       collisions.append(futexes[fid])
25
26     fid++
```


Data Container Structure
Hash table access timing
Hash bucket occupancy level
Hash-collision identification
? location


Hardware Cache
?
?
?
? location

# Bruteforce Kernel Address

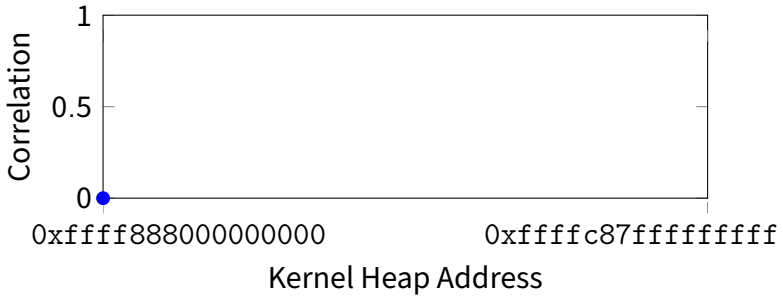



| uaddr | coll. |
|---|---|
| 0x501008 | - |
| 0x503010 | - |
| 0x5041f0 | - |
| 0x507b10 | - |
| 0x5090a8 | - |
| ... | ... |

**Bruteforce attack**

```
1 for uaddr in uaddrs:
2   found &= (index == futex_hash(kaddr, uaddr))
```

# Bruteforce Kernel Address

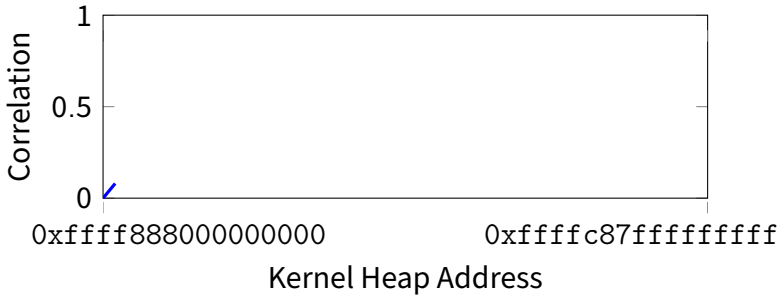



| uaddr | coll. |
|---|---|
| 0x501008 | ✗ |
| 0x503010 | ✗ |
| 0x5041f0 | ✗ |
| 0x507b10 | ✗ |
| 0x5090a8 | ✗ |
| ... | ... |

**Bruteforce attack**

```
1 for uaddr in uaddrs:
2   found &= (index == futex_hash(0xffff888000000000, uaddr))
```

# Bruteforce Kernel Address

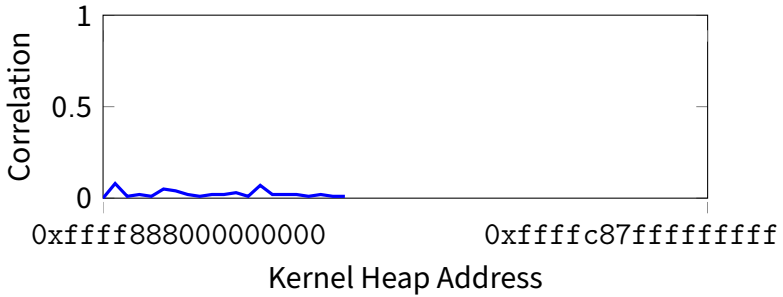



| uaddr | coll. |
|---|---|
| 0x501008 | ✓ |
| 0x503010 | ✓ |
| 0x5041f0 | ✗ |
| 0x507b10 | ✗ |
| 0x5090a8 | ✗ |
| ... | ... |

**Bruteforce attack**

```
1 for uaddr in uaddrs:
2   found &= (index == futex_hash(0xffff888000000580, uaddr))
```

# Bruteforce Kernel Address

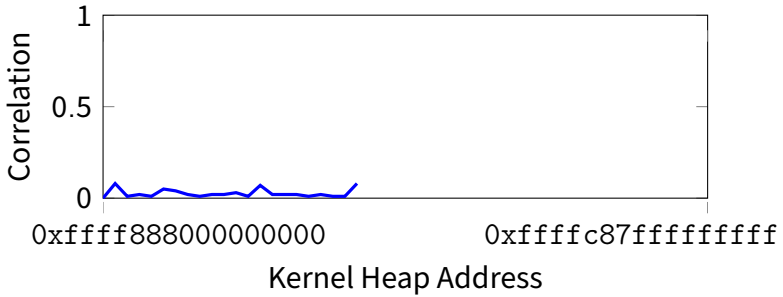



| uaddr | coll. |
|---|---|
| 0x501008 | ✗ |
| 0x503010 | ✗ |
| 0x5041f0 | ✗ |
| 0x507b10 | ✗ |
| 0x5090a8 | ✗ |
| ... | ... |

**Bruteforce attack**

```
1 for uaddr in uaddrs:
2   found &= (index == futex_hash(0xffff8880017cf080, uaddr))
```

# Bruteforce Kernel Address

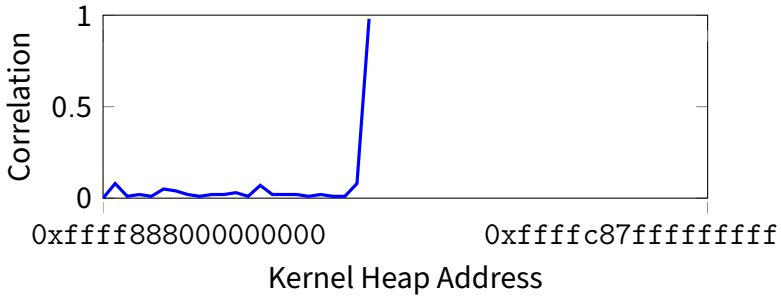



| uaddr | coll. |
|---|---|
| 0x501008 | ✗ |
| 0x503010 | ✓ |
| 0x5041f0 | ✗ |
| 0x507b10 | ✗ |
| 0x5090a8 | ✓ |
| ... | ... |

**Bruteforce attack**

```
1 for uaddr in uaddrs:
2   found &= (index == futex_hash(0xffff8880017cf600, uaddr))
```

# Bruteforce Kernel Address

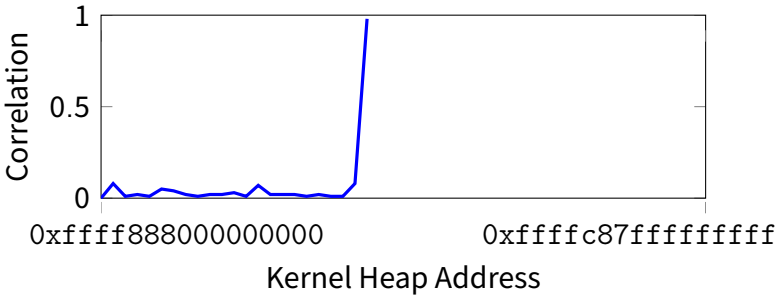



| uaddr | coll. |
|---|---|
| 0x501008 | ✓ |
| 0x503010 | ✓ |
| 0x5041f0 | ✓ |
| 0x507b10 | ✓ |
| 0x5090a8 | ✓ |
| ... | ... |

**Bruteforce attack**

```
1 for uaddr in uaddrs:
2   found &= (index == futex_hash(0xffff8880017cfb80, uaddr))
```

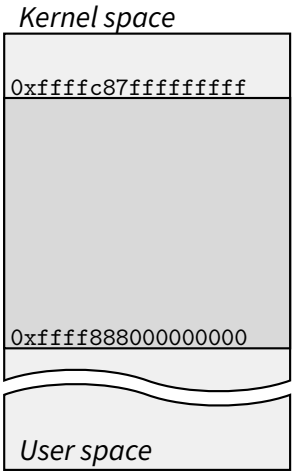
# Bruteforce Kernel Address




**Bruteforce attack**

```
1 for uaddr in uaddrs:
2   found &= (index == futex_hash(0xffff8880017cfb80, uaddr))
```

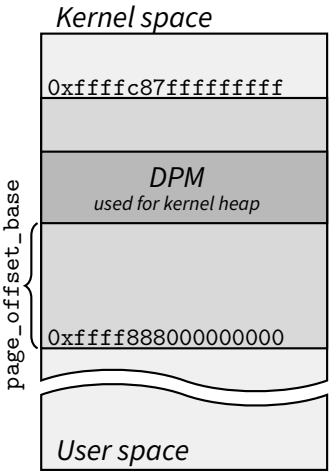
# Search Space Reduction




*Entropy:*

$2^{46}$

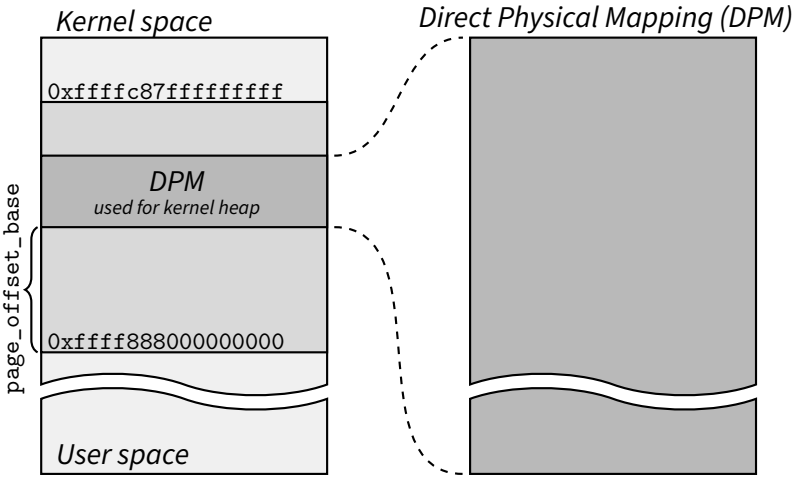
# Search Space Reduction




*Entropy:*

$2^{46}$

# Search Space Reduction

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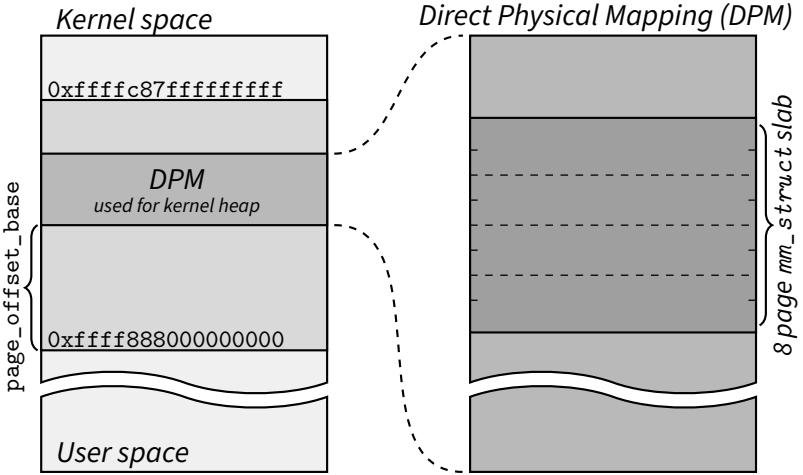
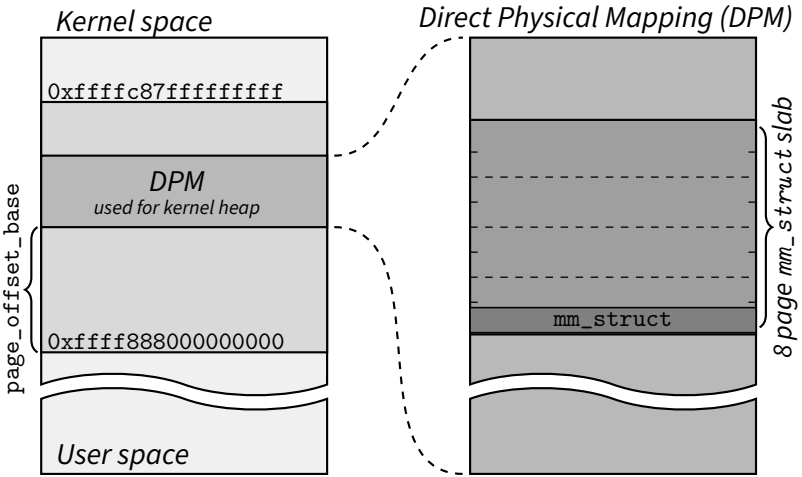



*Entropy:*

$$2^{46-3-12} \cdot x$$

# Search Space Reduction




*Entropy:*

$$2^{46-3-12} \cdot x$$

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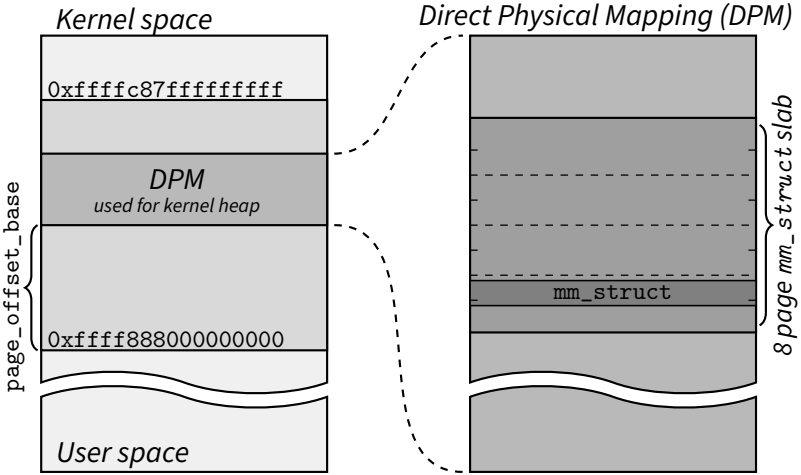
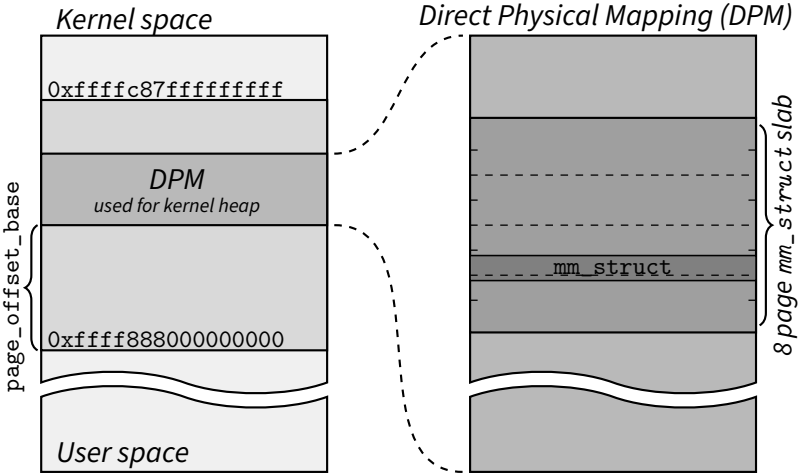



*Entropy:*

$$2^{46-3-12} \cdot x$$

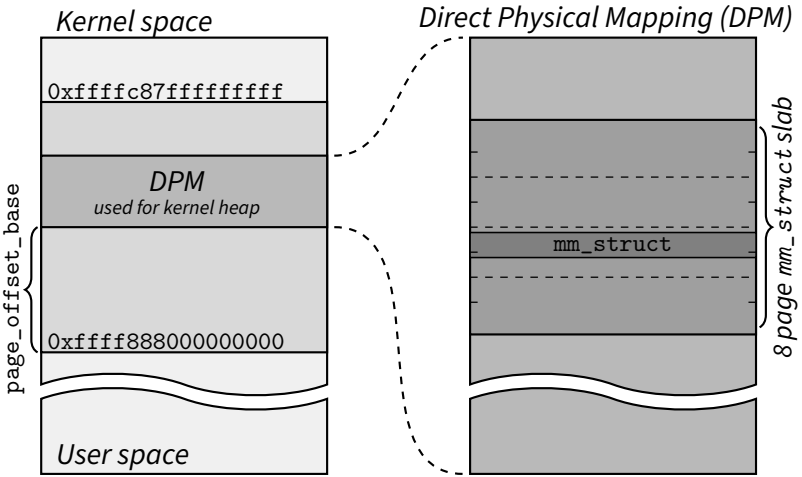
# Search Space Reduction




*Entropy:*

$$2^{46-3-12} \cdot x$$

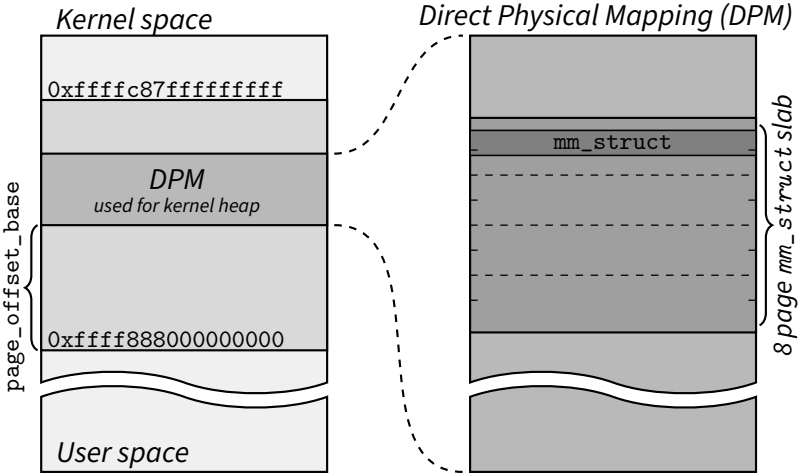
# Search Space Reduction




*Entropy:*

$$2^{46-3-12} \cdot x$$

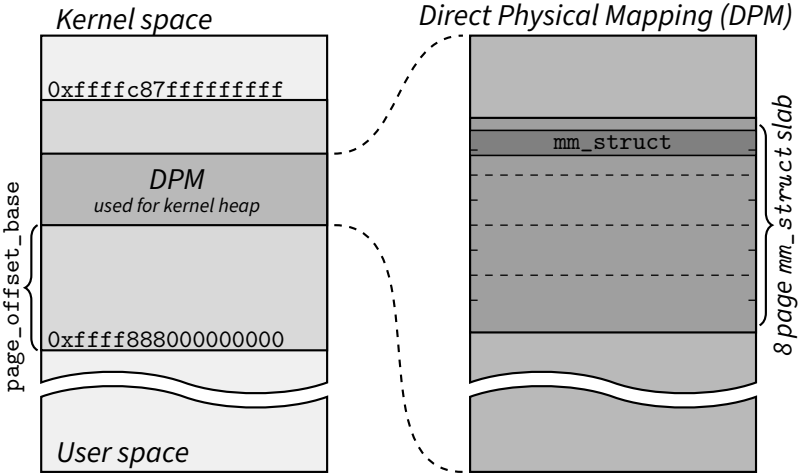
# Search Space Reduction




*Entropy:*

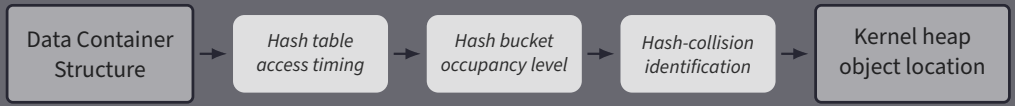
$2^{46-3-12} \cdot 23$

# Search Space Reduction




*Entropy:*

$2^{35.5}$


Data Container Structure
Hash table access timing
Hash bucket occupancy level
Hash-collision identification
Kernel heap object location


Hardware Cache
?
?
?
? location

# System Dependencies

# System Dependencies

- Target: Ubuntu kernel `6.8.0-52-generic`

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- Target: Ubuntu kernel ~~`6.8.0-52-generic`~~ `6.8.0-79-generic`
- **Slab page order size?**
- `mm_struct` **size?**

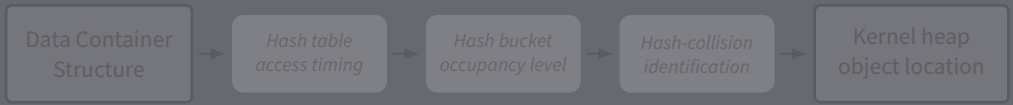
# System Dependencies

- Target: Ubuntu kernel ~~`6.8.0-52-generic`~~ `6.8.0-79-generic`
- **Slab page order size?**
- `mm_struct` **size?**
- `/sys/kernel/slab/mm_struct> grep .* *`

**Output**

```
...
objs_per_slab:23 # objects per slab
order:3          # page order
...
slab_size:1408   # size of mm_struct
...
```

# Let’s leak some kernel addresses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Hash table access timing
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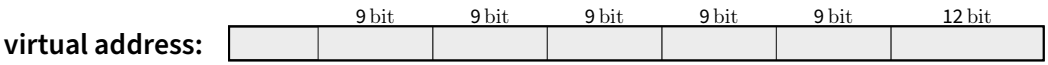
?
?
?
? location

# Address Translation

**virtual address:** 

# Address Translation



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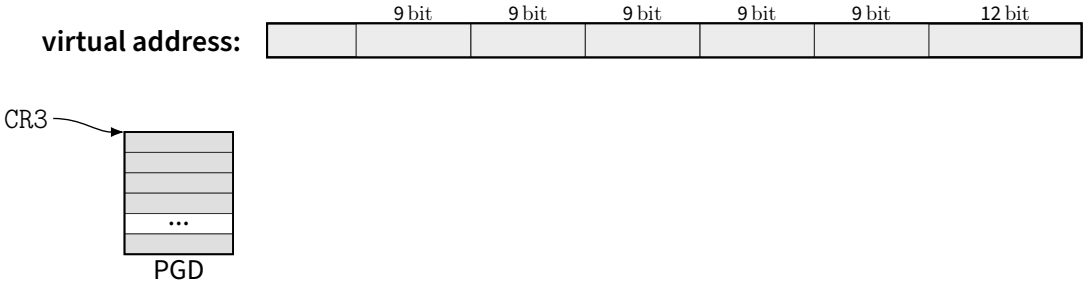

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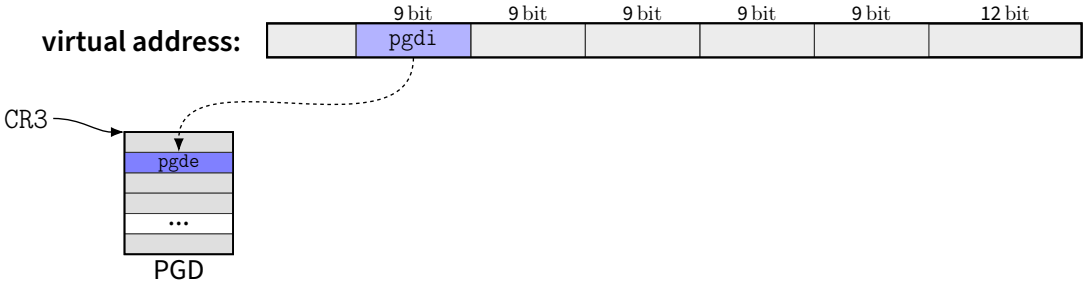

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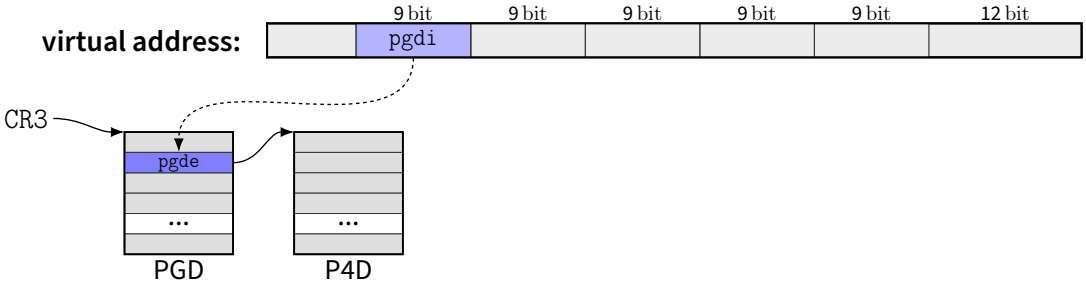
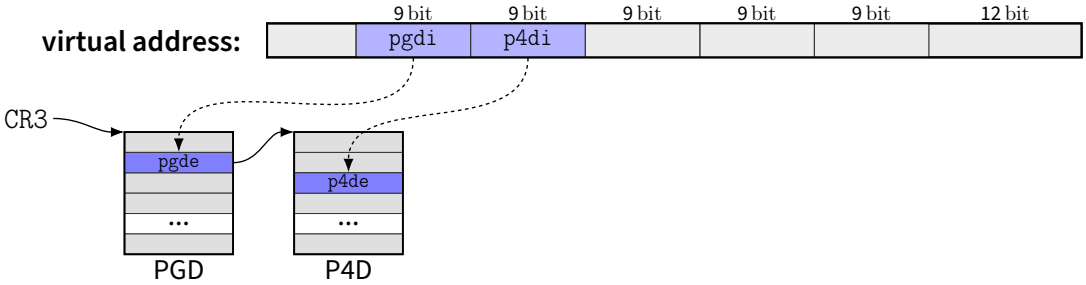
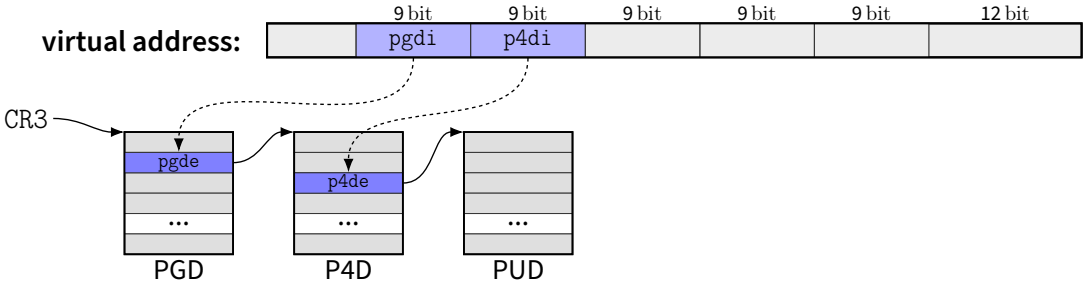


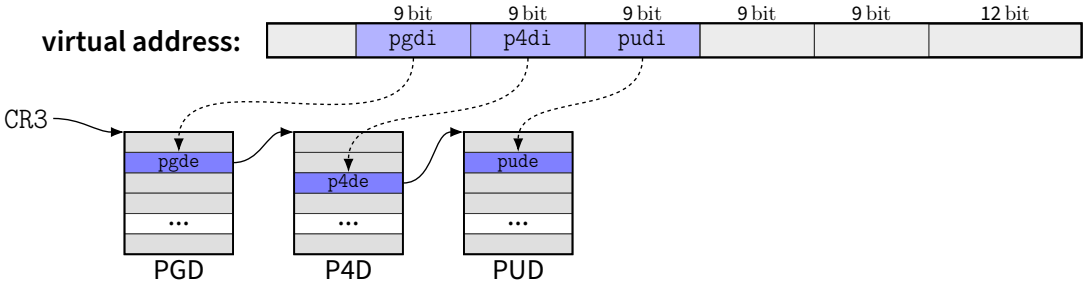
# Address Translation



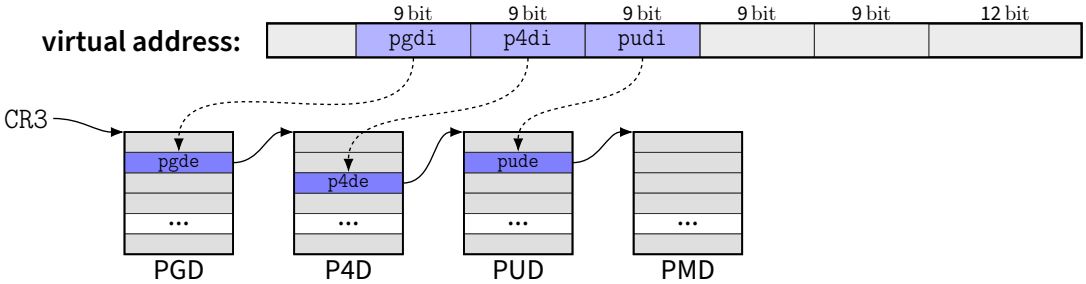
# Address Translation



# Address Translation



# Address Translation



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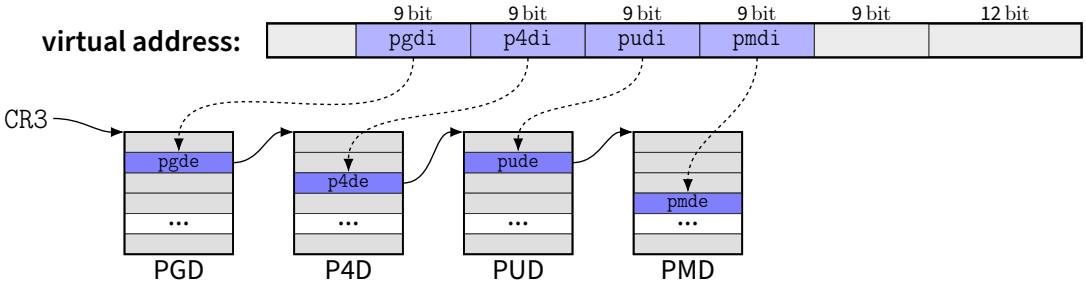

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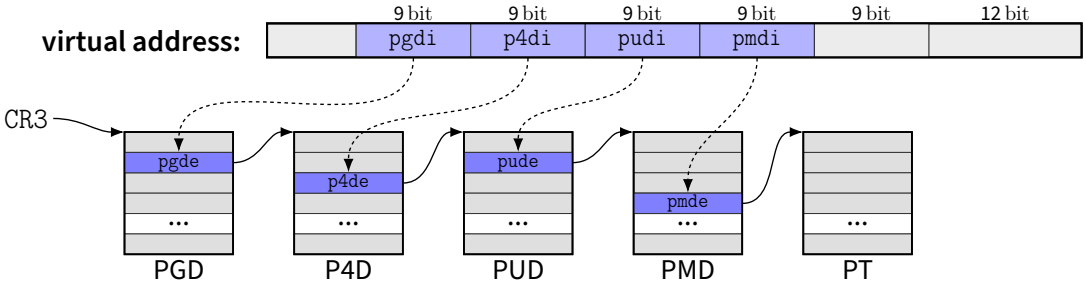

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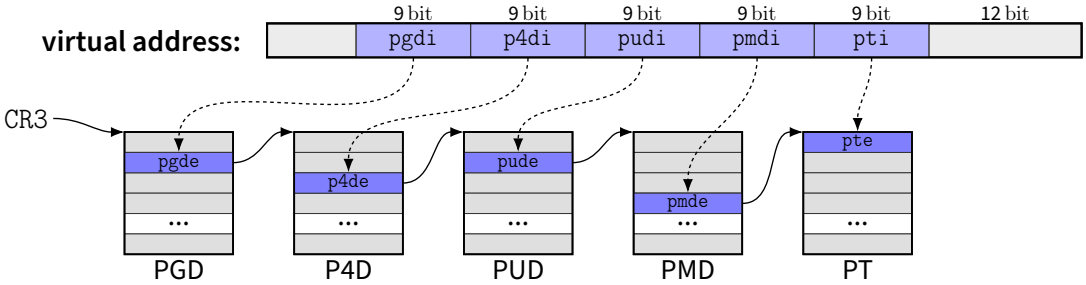

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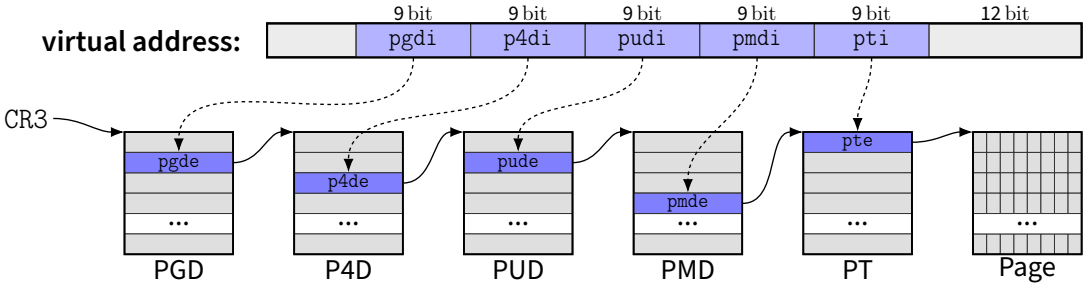

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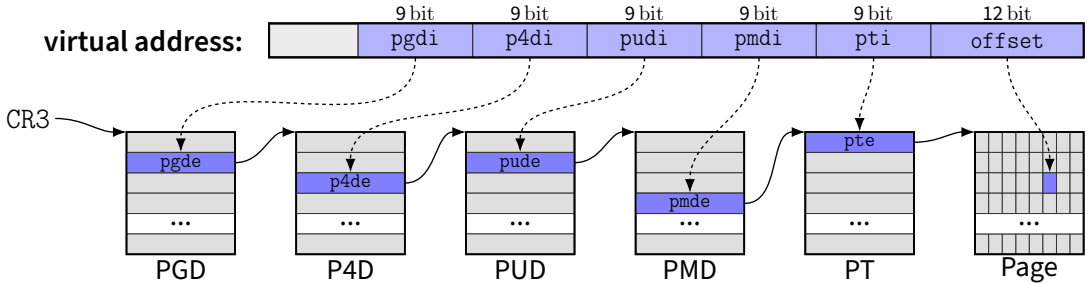
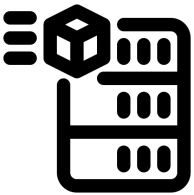


# Translation Lookaside Buffer



- Each page-table access $\rightarrow$ memory fetch
  - Slow!

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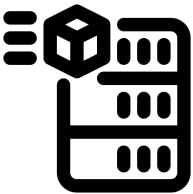

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- TLB
  - CPU cache
  - Stores page-table entries

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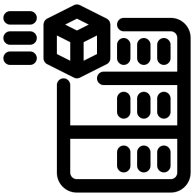
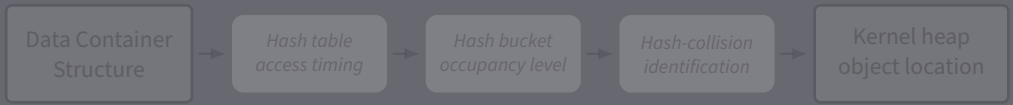
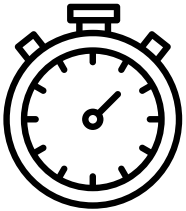


- Each page-table access $\rightarrow$ memory fetch
  - Slow!
- TLB
  - CPU cache
  - Stores page-table entries
- Faster!


Data Container Structure
Hash table access timing
Hash bucket occupancy level
Hash-collision identification
Kernel heap object location


Hardware Cache
TLB access timings
?
?
? location

# TLB Timing Side Channel



- Measure an access:

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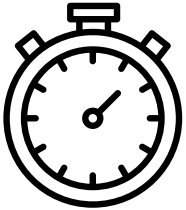

- Measure an access:

```
start = time();
```

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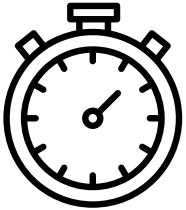

- Measure an access:

```
start = time();
access(test_address);
```

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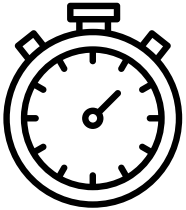
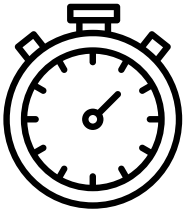


- Measure an access:

```
start = time();
access(test_address);
time = time() - start;
```

# TLB Timing Side Channel



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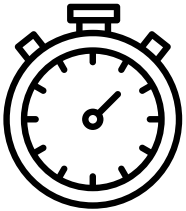
# TLB Timing Side Channel



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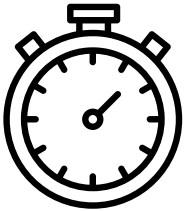

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prefetch(kernel_address);
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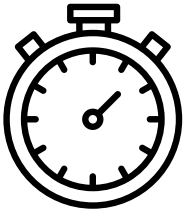

- Measure an access:

```
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access(test_address);
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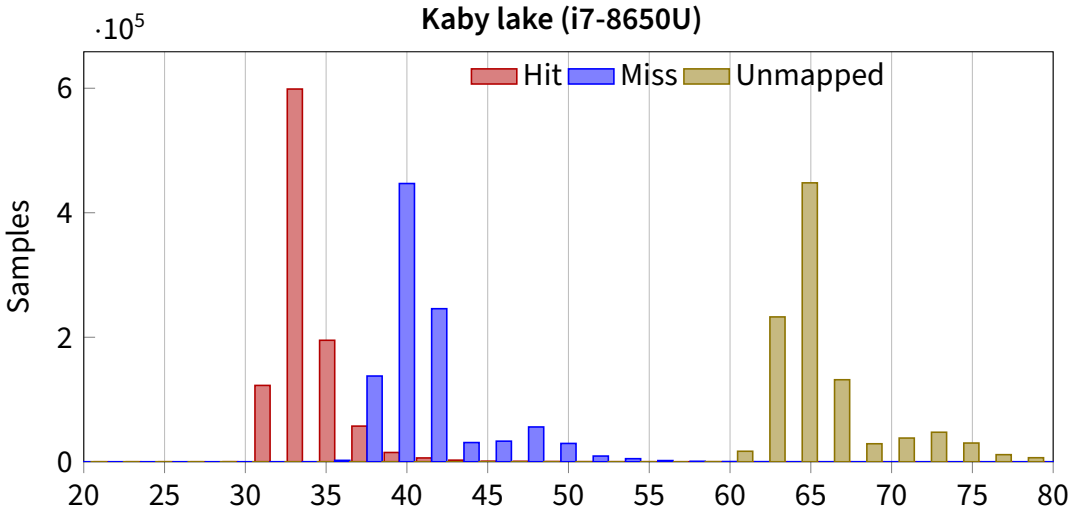
```

- How to measure kernel pages?

```
start = time();
prefetch(kernel_address);
time = time() - start;
```

# TLB Timing Histogram



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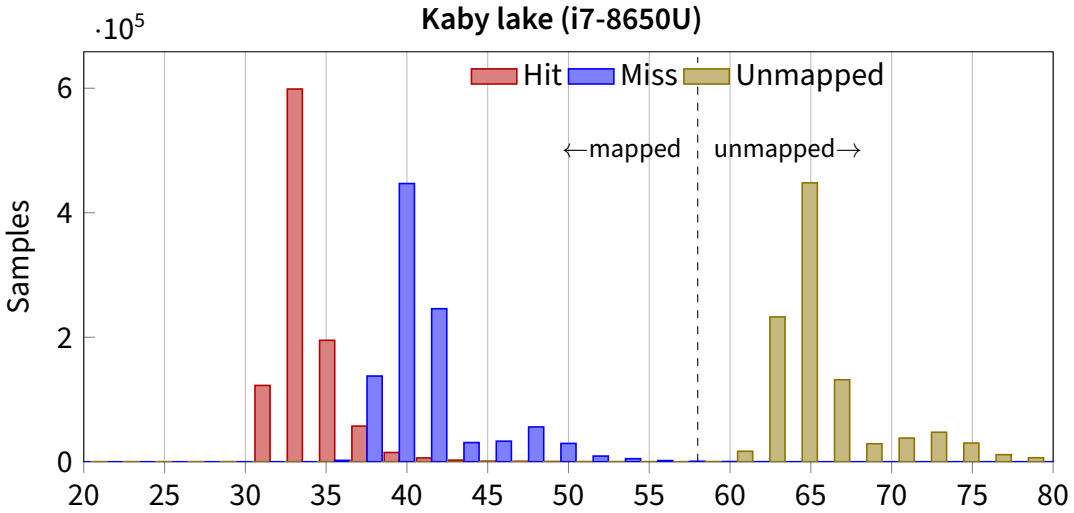

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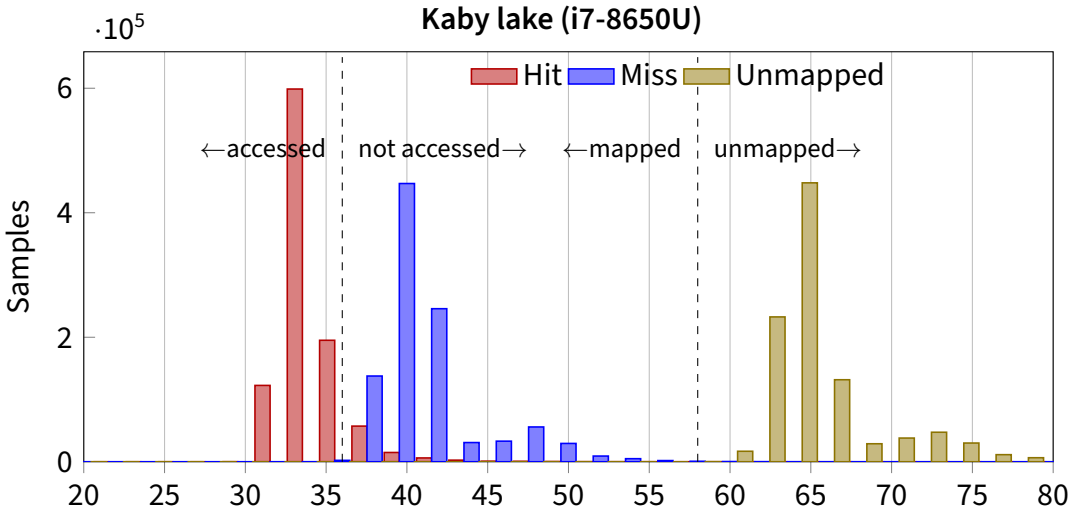
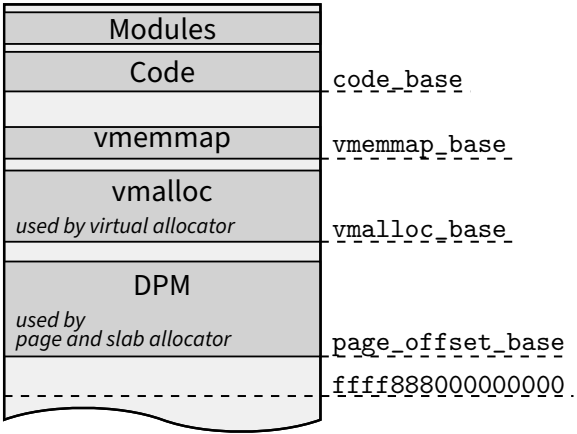


# TLB Memory Mapping Leakage



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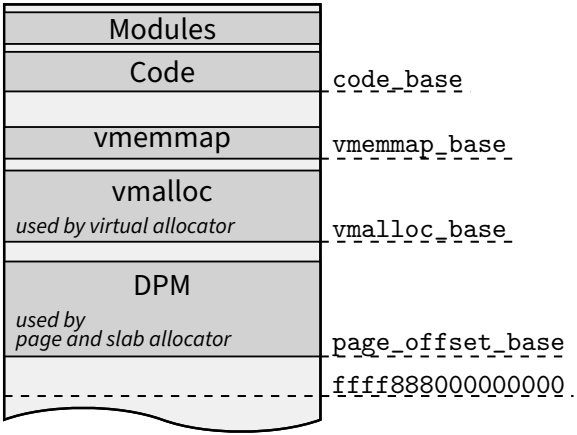
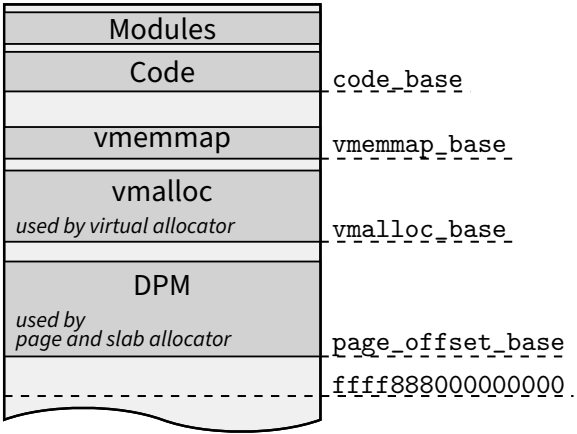


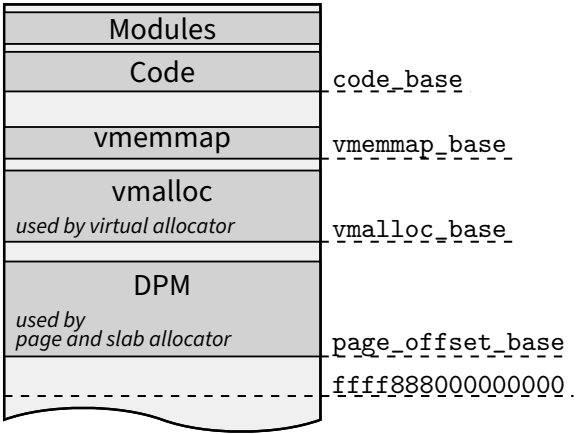

- Leak region bases

# TLB Memory Mapping Leakage

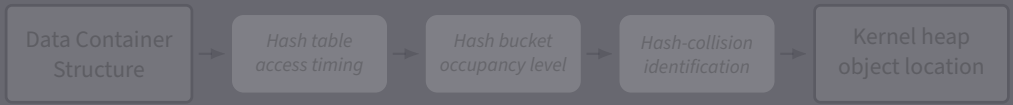



- Leak region bases
- Leak access location

# TLB Memory Mapping Leakage




- Leak region bases
- Leak access location
- Page granularity, 2 MB?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Hash table access timing
Hash bucket occupancy level
Hash-collision identification
Kernel heap object location


Hardware Cache
TLB access timings
2 MB-aligned memory sections
?
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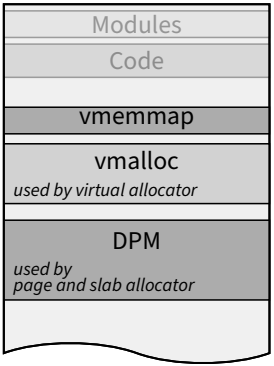
# Enforcing 4 kB Memory Mappings




No Mapping
4kB Mapping
2MB Mapping

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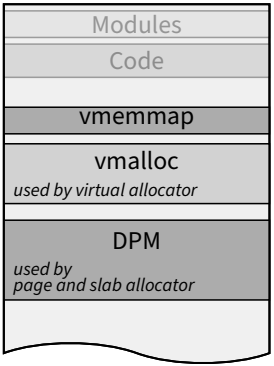


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- Use memory allocated with `vmalloc`.
  - E.g., bytecode for eBPF.

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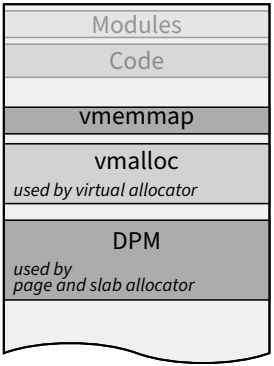


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- Use defenses:

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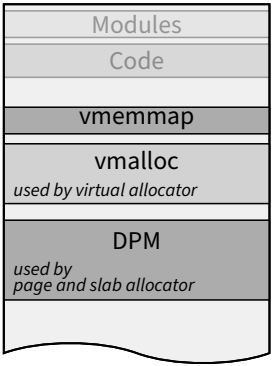


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  - `CONFIG_VMAP_STACK`:
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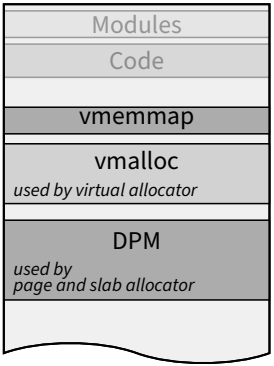
# Enforcing 4 kB Memory Mappings

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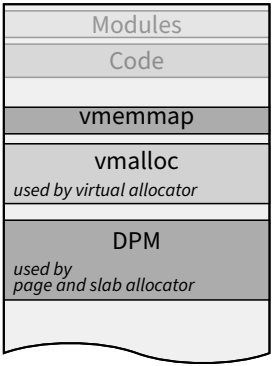
    Virtualize heap on 4 kB mappings.

# Enforcing 4 kB Memory Mappings

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  - E.g., bytecode for eBPF.
- Use defenses:
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    Stack allocated with `vmalloc`.
  - `CONFIG_SLAB_VIRTUAL`:
    Virtualize heap on 4 kB mappings.
  - `CONFIG_STRICT_MODULE_RWX`:
    Split DPM to 4 kB mappings.

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- Syscalls to load 4 kB-aligned kernel address:

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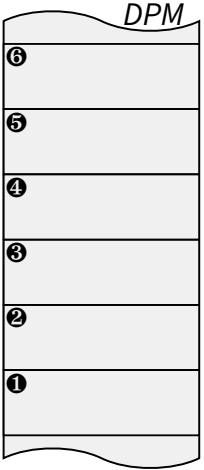
  - `pipe_buffer`:
    `sys_read`
  - Page tables:
    `sys_mprotect`
  - ...
- Multiple addresses are loaded to the TLB ☹

# Leaking 4 kB-Aligned Address




```
sys_msgrcv(id, mtext, mtype):
  queue = ipc_ns.root_rt[id]
  msg = find_msg(queue, mtype)
  copy_to_user(mtext, msg.mtext)
```

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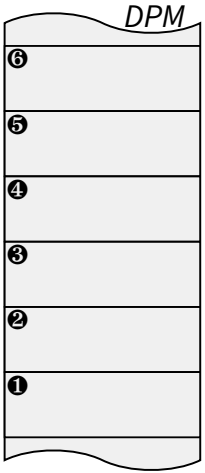


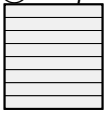


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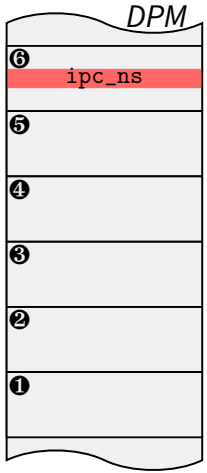
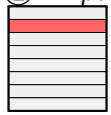
```

```
mtext = char[]
mtype = 0x41

// access msg0, queue0, ipc_ns
sys_msgrcv(0, mtext, mtype) ①
```

# Leaking 4 kB-Aligned Address

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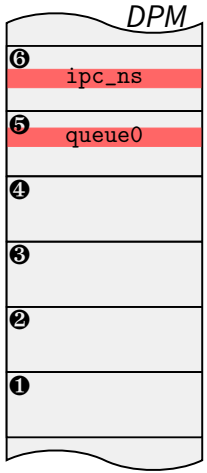


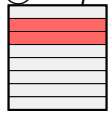


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# Leaking 4 kB-Aligned Address


①TLB pattern

```
sys_msgrcv(id, mtext, mtype):
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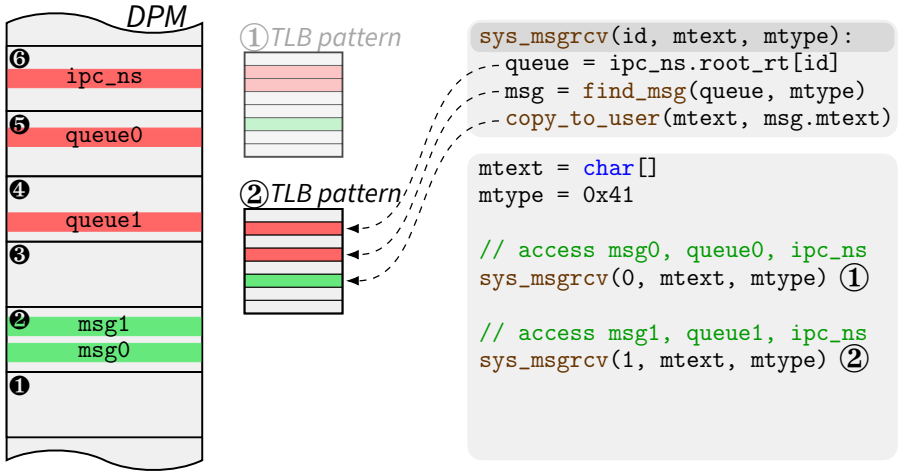

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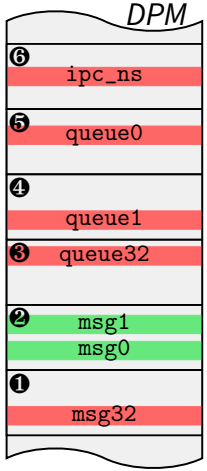



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```
mtext = char[]
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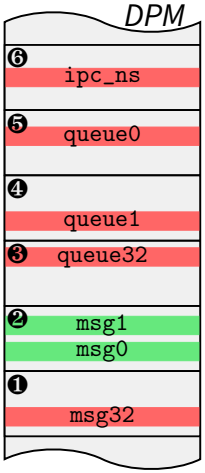
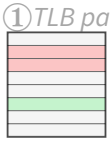
// access msg0, queue0, ipc_ns
sys_msgrcv(0, mtext, mtype) ①

// access msg1, queue1, ipc_ns
sys_msgrcv(1, mtext, mtype) ②

// access msg32, queue32, ipc_ns
sys_msgrcv(32, mtext, mtype) ③
```

# Leaking 4 kB-Aligned Address



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```
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```

①*TLB pattern* ∩
②*TLB pattern* \
③*TLB pattern*

```
sys_msgrcv(32, mtext, mtype) ③
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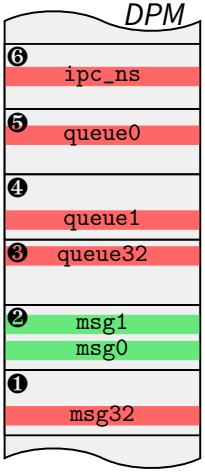


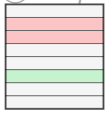




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$$[❷, ❺, ❻] \cap$$
$$[❷, ❹, ❻] \setminus$$
$$[❶, ❸, ❻]$$

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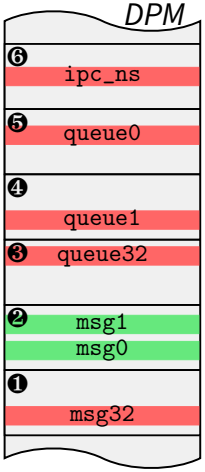


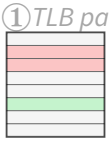



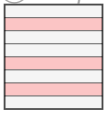


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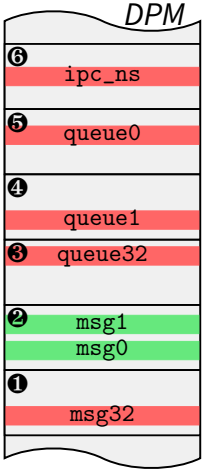


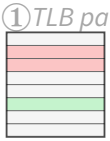




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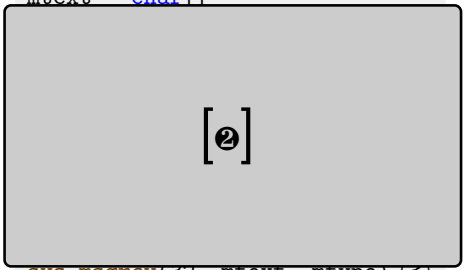


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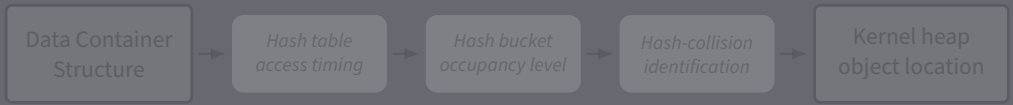
Data Container Structure
Hash table access timing
Hash bucket occupancy level
Hash-collision identification
Kernel heap object location


Hardware Cache
TLB access timings
2 MB-aligned memory sections
4 kB-aligned slab pages
? location

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- **Leaked all object locations**
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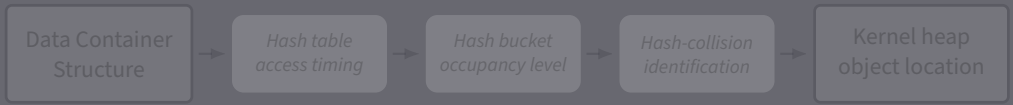
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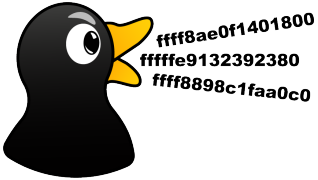
# Location Disclosure Attacks



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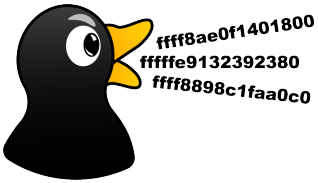


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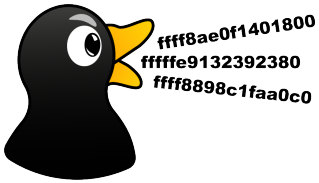


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  - Page tables:
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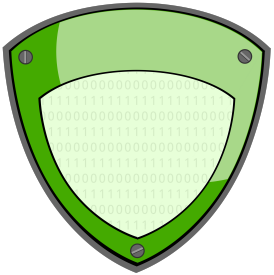
# Let’s leak some more kernel addresses

# Discussion & Takeaways

# Mitigations



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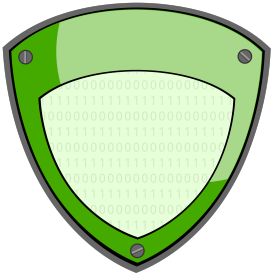

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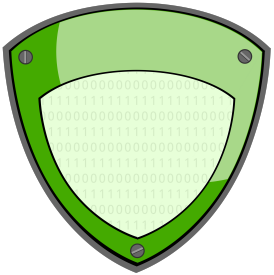

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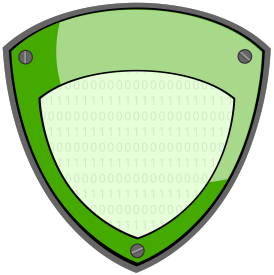

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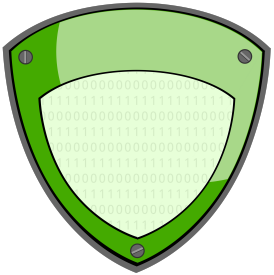

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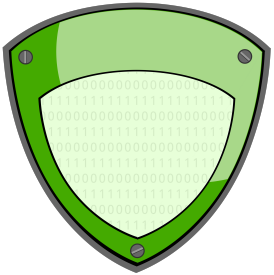

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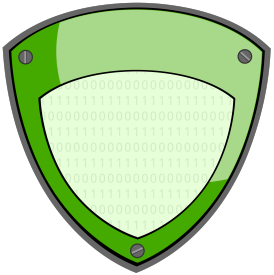

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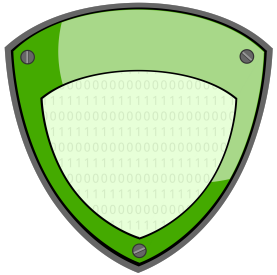

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- **Exploitation:**
  Leakages enhance kernel exploit reliability

# Acknowledgments

This research was made possible by generous funding from:





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TECHNOLOGY

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**Lukas Maar**

September 4-5, 2025

Nullcon Berlin

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