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BRIEFINGS

Cautious! A New Exploitation Method! No Pipe but as Nasty as Dirty Pipe

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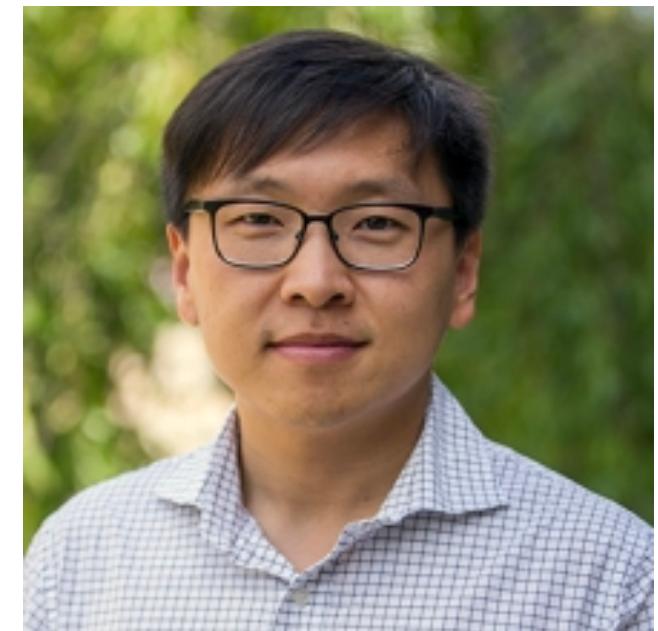
Who Are We



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Xinyu Xing
Associate Professor
xinyuxing.org

Recap About Dirty Pipe

- CVE-2022-0847
- An uninitialized bug in Linux kernel's pipe subsystem
- Affected kernel v5.8 and higher
- Data-only, no effective exploitation mitigation
- Overwrite any files with read permission
- Demonstrated LPE on Android

What We Learned

- **Data-only is powerful**
 - Universal exploit
 - Bypass CFI (enabled in Android kernel)
 - New mitigation required

What We Learned

- **Data-only is powerful**
 - Universal exploit
 - Bypass CFI (enabled in Android kernel)
 - New mitigation required
- **Dirty Pipe is not perfect**
 - Cannot actively escape from container
 - Not a generic exploitation method

Introducing DirtyCred

- **High-level idea**
 - Swapping Linux kernel *Credentials*
- **Advantages**
 - A generic exploitation method, simple and effective
 - Write a data-only, universal (i.e., Dirty-Pipe-liked) exploit
 - Actively escape from container

Comparison with Dirty Pipe

	Dirty Pipe	DirtyCred
• A generic exploitation method?	✗	✓
• Write a data-only, universal exploit?	✓	✓
• Attack with CFI enabled (on Android)?	✓	✓
• Actively escape from container?	✗	✓
• Threat still exists?	✗	✓

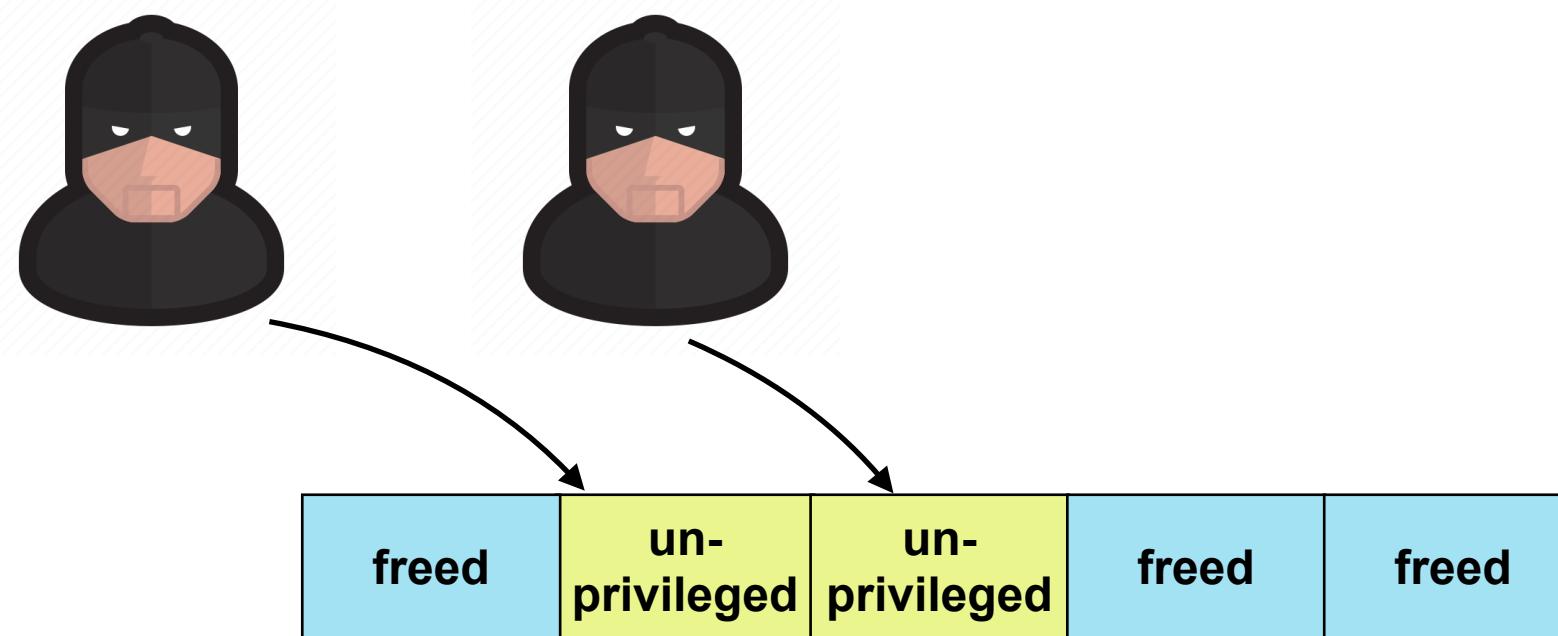
Kernel Credential

- Properties that carry privilege information in kernel
 - Defined in kernel documentation
 - Representation of **privilege** and **capability**
 - Two main types: ***task credentials*** and ***open file credentials***
 - Security checks act on credential objects

Source: <https://www.kernel.org/doc/Documentation/security/credentials.txt>

Task Credential

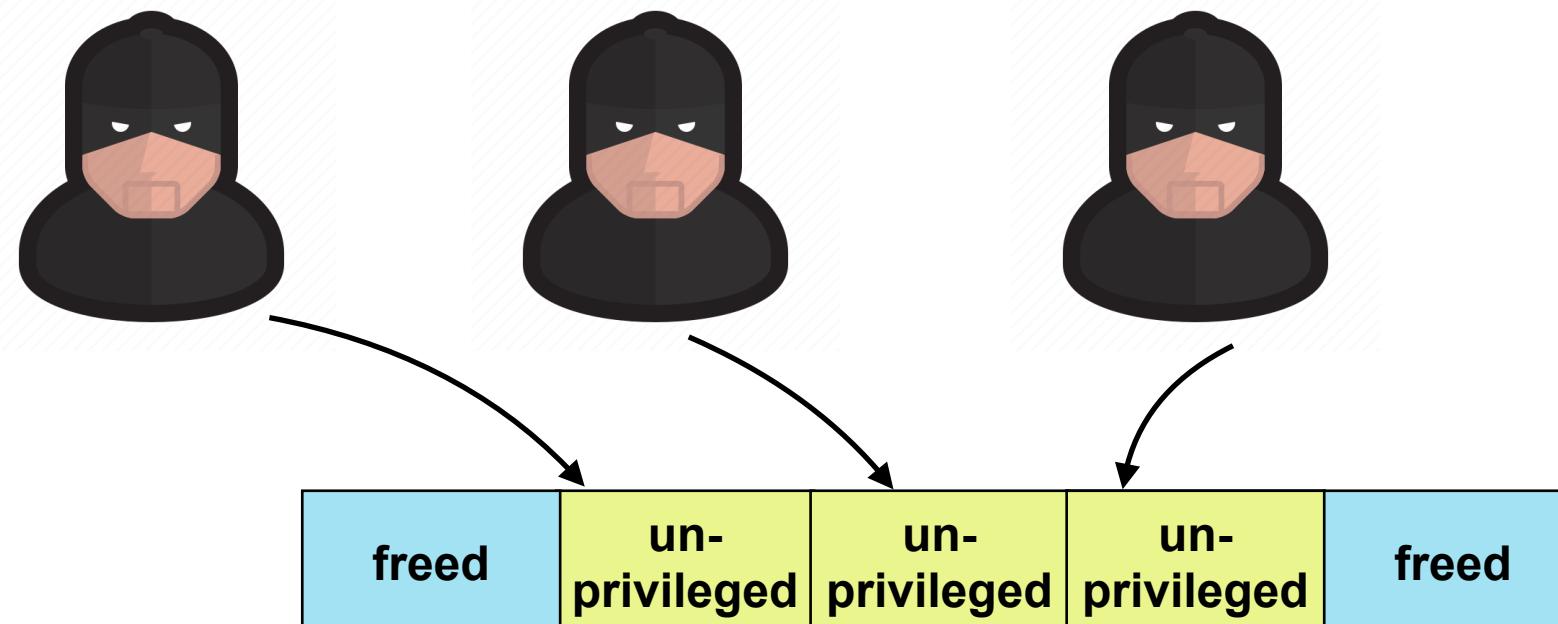
- **Struct cred** in kernel's implementation



struct cred on kernel heap

Task Credential

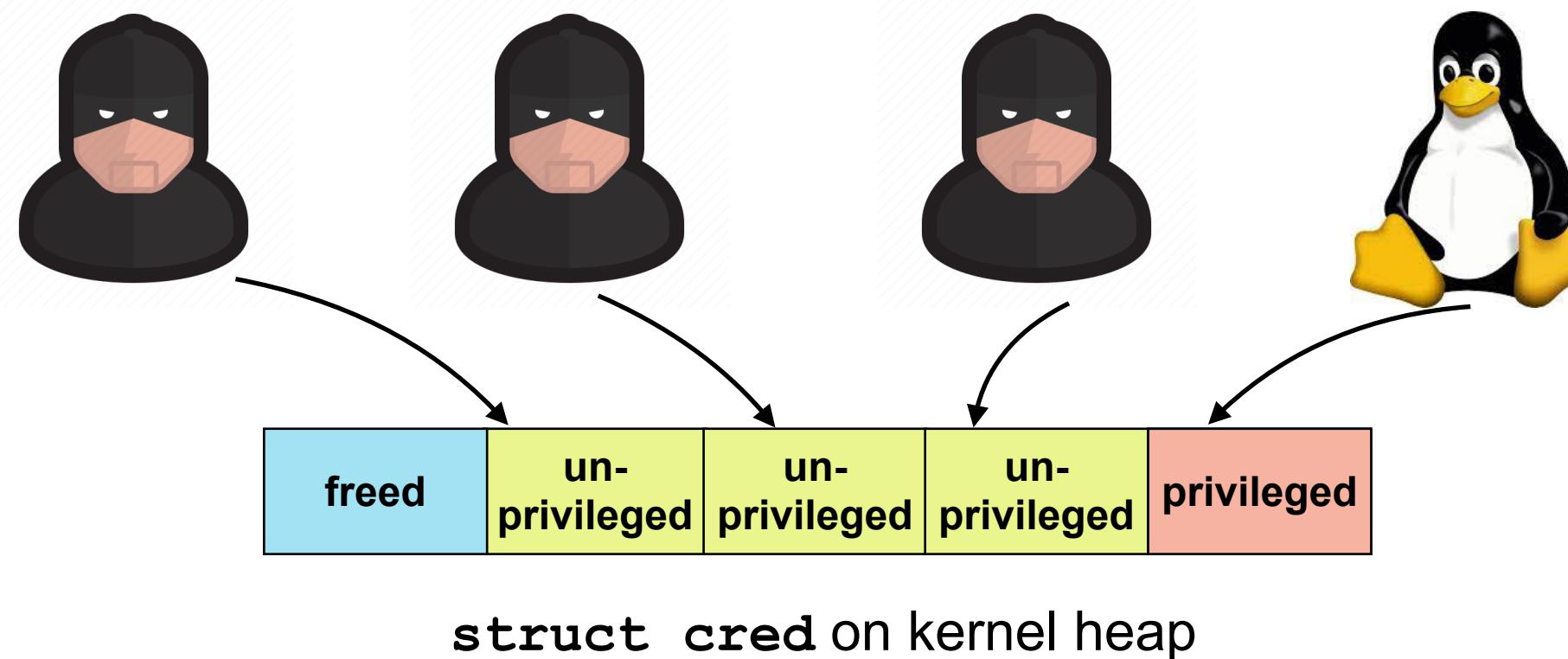
- **Struct cred** in kernel's implementation



`struct cred` on kernel heap

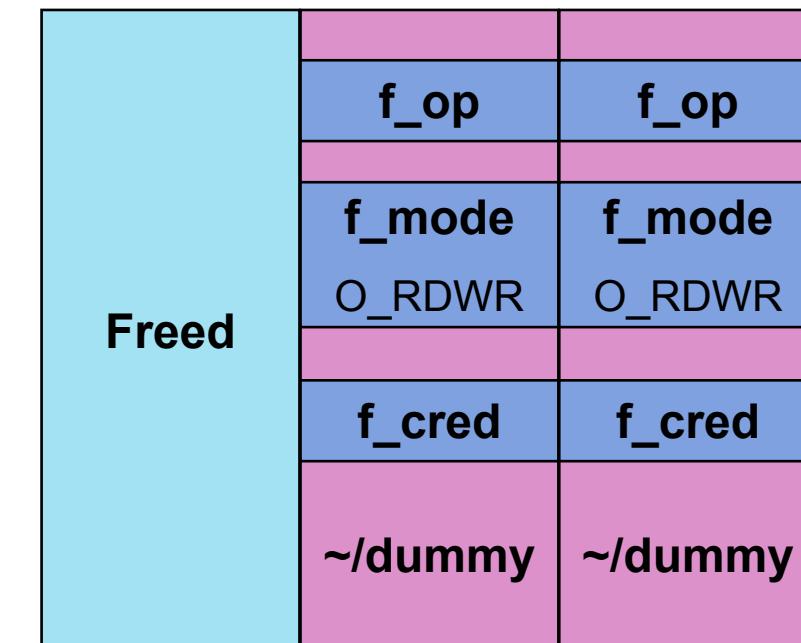
Task Credential

- **Struct cred** in kernel's implementation



Open File Credentials

- **Struct file** in kernel's implementation

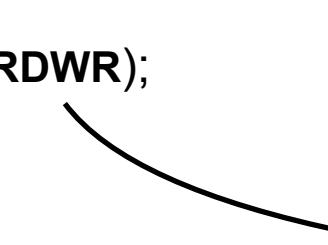


`struct file` on kernel heap

Open File Credentials

- **Struct file** in kernel's implementation

```
int fd = open("~/dummy", O_RDWR);
```



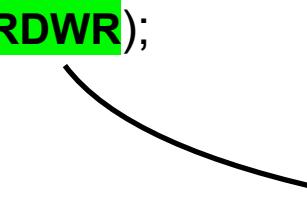
f_op	f_op	f_op
f_mode	f_mode	f_mode
O_RDWR	O_RDWR	O_RDWR
f_cred	f_cred	f_cred
~/dummy	~/dummy	~/dummy

struct file on kernel heap

Open File Credentials

- **Struct file** in kernel's implementation

```
int fd = open("~/dummy", O_RDWR);
```



f_op	f_op	f_op
f_mode	f_mode	f_mode
O_RDWR	O_RDWR	O_RDWR
f_cred	f_cred	f_cred
~/dummy	~/dummy	~/dummy

struct file on kernel heap

Open File Credentials

- Kernel checks permission on the `file` object when accessing

```
int fd = open("~/dummy", O_RDWR);
```

```
write(fd, "HACKED", 6);
```

check perm

f_op	f_op	f_op
f_mode	f_mode	f_mode
O_RDWR	O_RDWR	O_RDWR
f_cred	f_cred	f_cred
~/dummy	~/dummy	~/dummy

`struct file` on kernel heap

Open File Credentials

- Write content to file on disk if permission is granted

```
int fd = open("~/dummy", O_RDWR);
```

```
write(fd, "HACKED", 6);
```

check perm



Write to disk

f_op	f_op	f_op
f_mode	f_mode	f_mode
O_RDWR	O_RDWR	O_RDWR
f_cred	f_cred	f_cred
~/dummy	~/dummy	~/dummy

struct file on kernel heap

Open File Credentials

- Write *denied* if the file is opened *read-only*

```
int fd = open("~/dummy", O_RDONLY);
```

```
write(fd, "HACKED", 6);
```

check perm

f_op	f_op	f_op
f_mode	f_mode	f_mode
O_RDONLY	O_RDWR	O_RDWR
f_cred	f_cred	f_cred
~/dummy	~/dummy	~/dummy

struct file on kernel heap

Open File Credentials

- Write *denied* if the file is opened *read-only*

```
int fd = open("~/dummy", O_RDONLY);
```

```
write(fd, "HACKED", 6);
```

check perm



Failed write to
disk

f_op	f_op	f_op
f_mode	f_mode	f_mode
O_RDONLY	O_RDWR	O_RDWR
f_cred	f_cred	f_cred
~/dummy	~/dummy	~/dummy

struct file on kernel heap

DirtyCred: Swapping Linux Kernel Credentials

High-level idea

- Swapping *unprivileged* credentials with *privileged* ones

Two-Path attacks

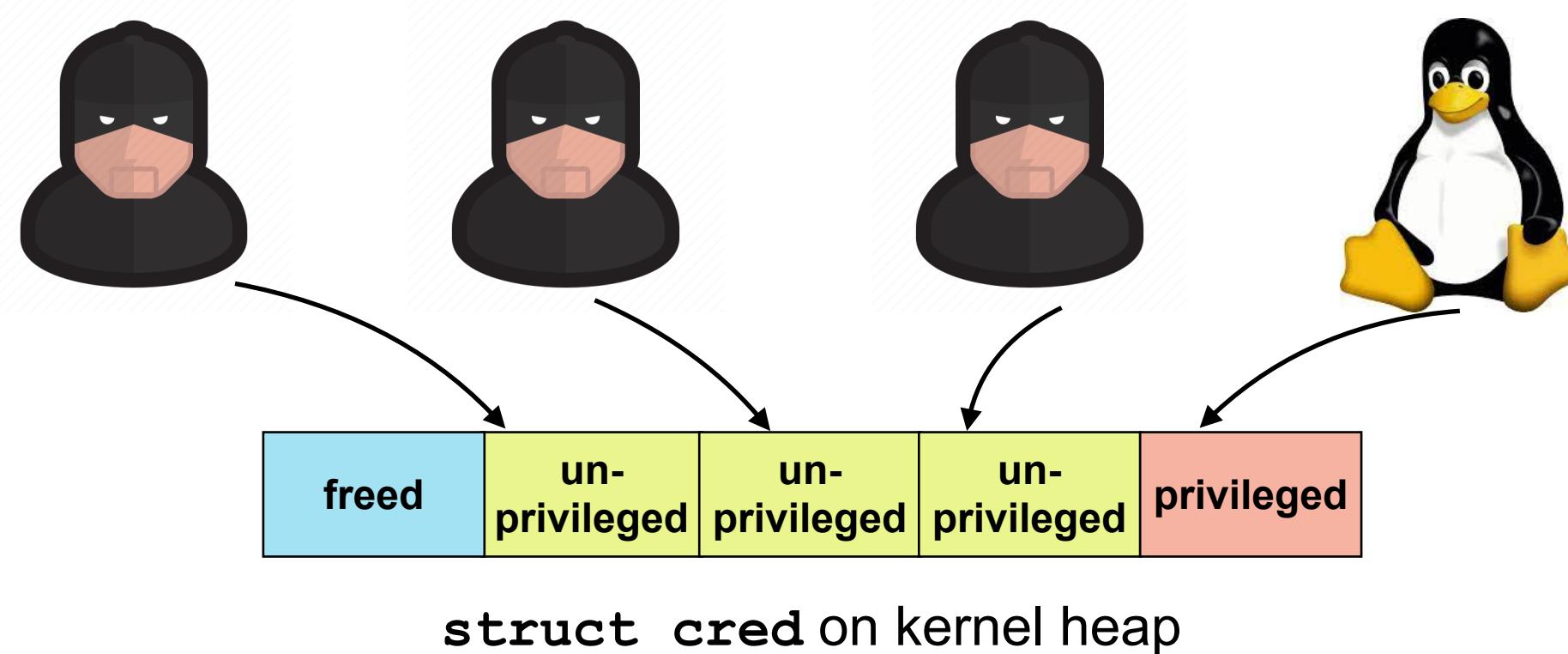
- Attacking *task credentials* (**struct cred**)
- Attacking *open file credentials* (**struct file**)

DirtyCred: Swapping Linux Kernel Credentials

Two-Path attacks

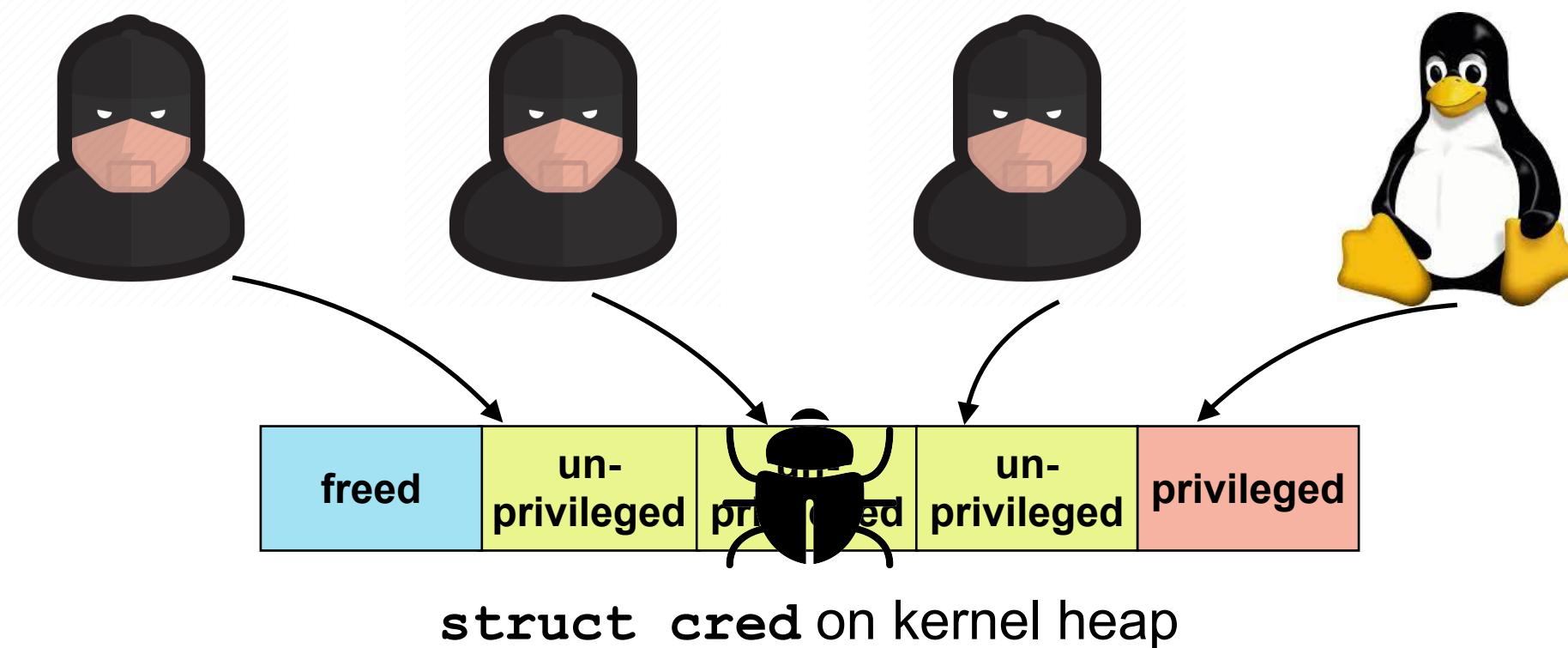
- Attacking *task credentials* (`struct cred`)
- Attacking *open file credentials* (`struct file`)

Attacking Task Credentials



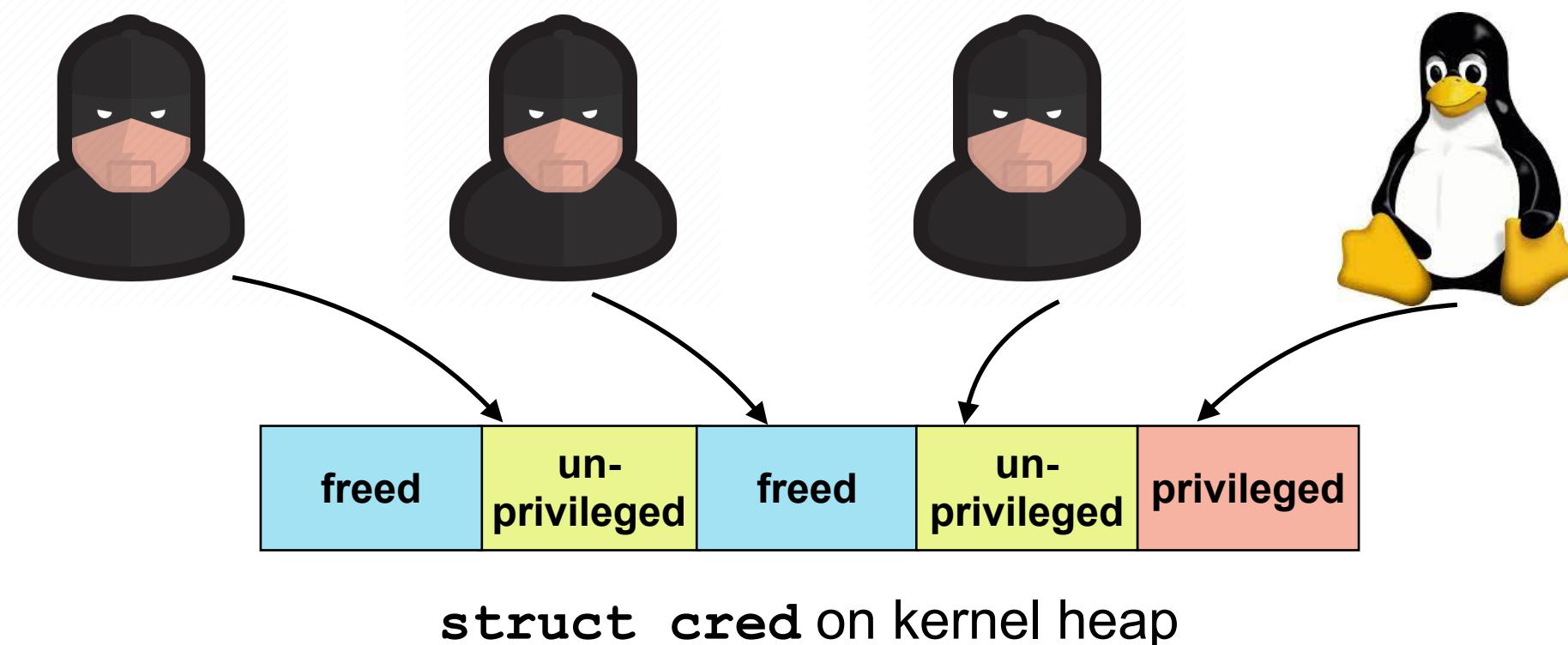
Attacking Task Credentials

Step 1. Free a *unprivileged* credential with the vulnerability



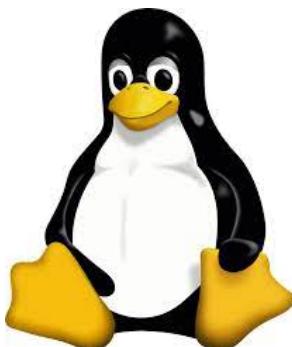
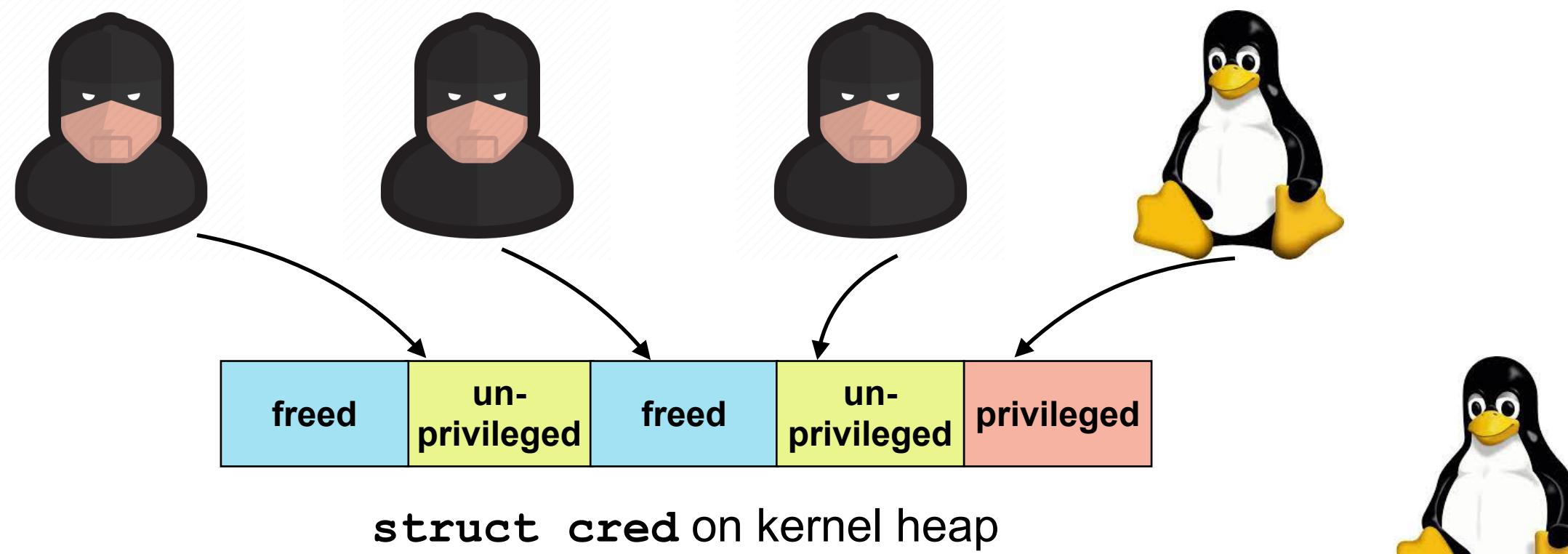
Attacking Task Credentials

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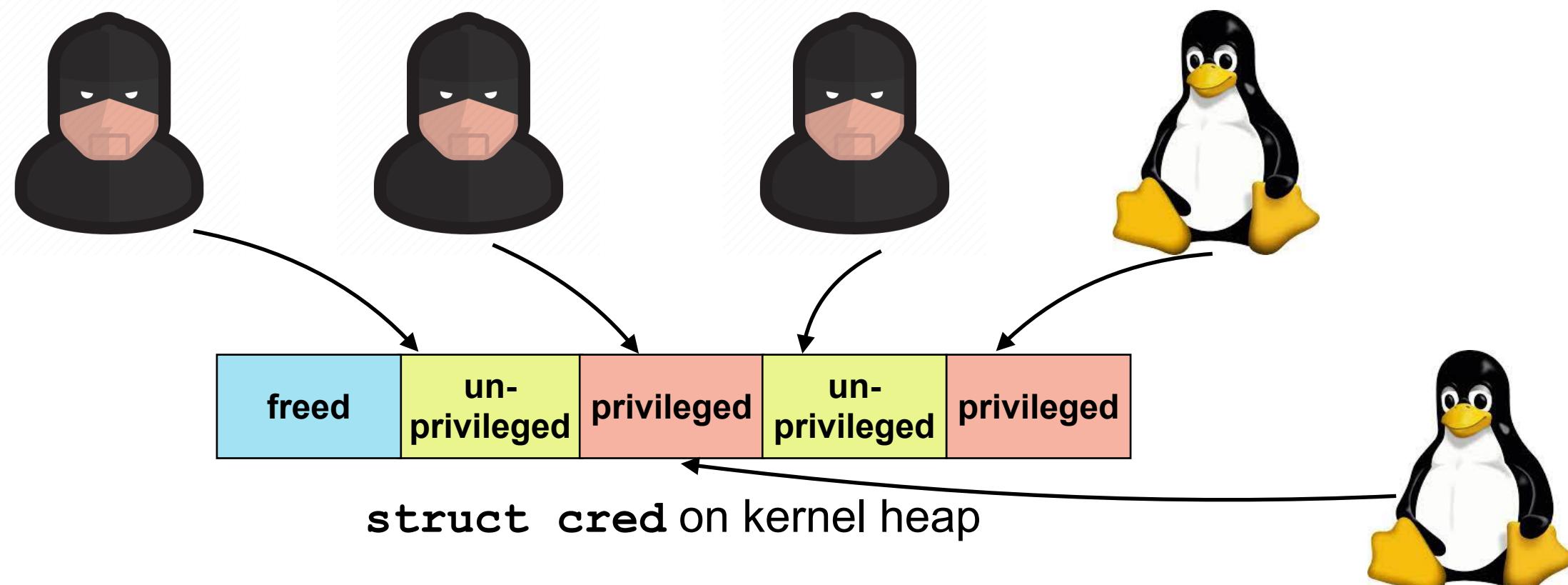
Attacking Task Credentials

Step 2. Allocate *privileged* credentials in the *freed* memory slot



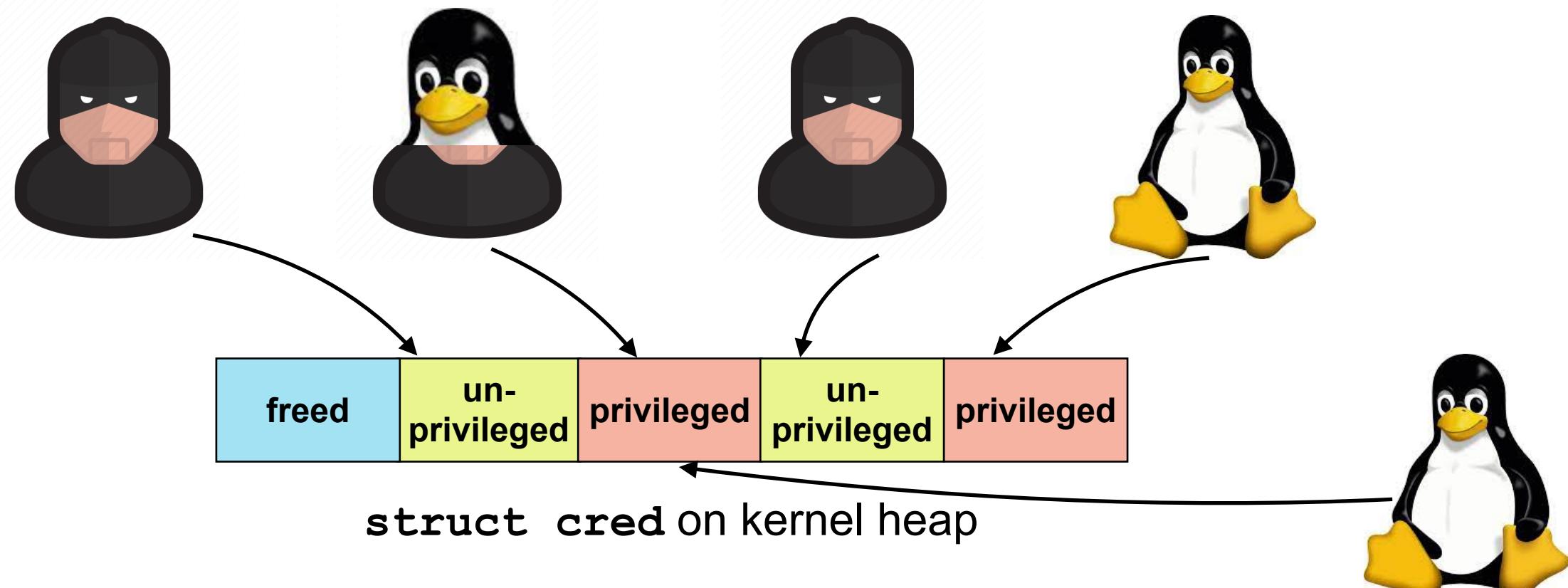
Attacking Task Credentials

Step 2. Allocate *privileged* credentials in the *freed* memory slot



Attacking Task Credentials

Step 3. Operate as *privileged* user



DirtyCred: Swapping Linux Kernel Credentials

Two-Path attacks

- Attacking *task credentials* (`struct cred`)
- Attacking *open file credentials* (`struct file`)

Attacking Open File Credentials

- Write content to file on disk if permission is granted

```
int fd = open("~/dummy", O_RDWR);
```

```
write(fd, "HACKED", 6);
```

check perm

f_op	f_op	f_op
f_mode	f_mode	f_mode
O_RDWR	O_RDWR	O_RDWR
f_cred	f_cred	f_cred
~/dummy	~/dummy	~/dummy

struct file on kernel heap

Attacking Open File Credentials

Step 1. Free file obj *after* checks, but *before* writing to disk

```
int fd = open("~/dummy", O_RDWR);
```

```
write(fd, "HACKED", 6);
```

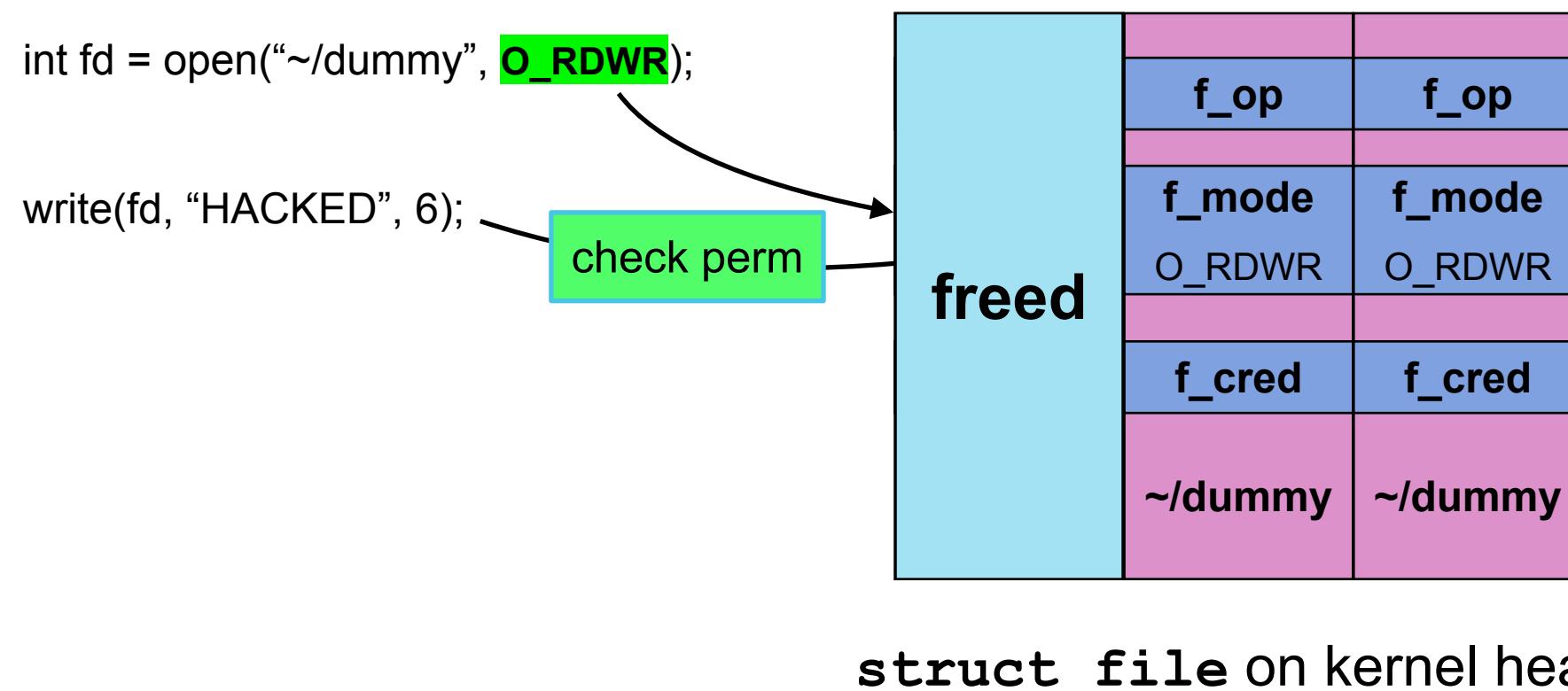
check perm

f_op	f_op	f_op
f_mode	f_mode	f_mode
O_RDWR	O_RDWR	O_RDWR
f_cred	f_cred	f_cred
~/dummy	~/dummy	~/dummy

struct file on kernel heap

Attacking Open File Credentials

Step 1. Free file obj *after* checks, but *before* writing to disk



Attacking Open File Credentials

Step 2. Allocate a *read-only* file obj in the freed memory slot

```
int fd = open("~/dummy", O_RDWR);
```

```
write(fd, "HACKED", 6);
```

check perm

freed	
f_op	f_op
f_mode	f_mode
O_RDWR	O_RDWR
f_cred	f_cred
~/dummy	~/dummy

```
open("/etc/passwd", O_RDONLY);
```

struct file on kernel heap

Attacking Open File Credentials

Step 2. Allocate a *read-only* file obj in the freed memory slot

```
int fd = open("~/dummy", O_RDWR);
```

```
write(fd, "HACKED", 6);
```

check perm

f_op	f_op	f_op
f_mode	f_mode	f_mode
O_RDONLY	O_RDWR	O_RDWR
f_cred	f_cred	f_cred
<u>/etc/</u> <u>passwd</u>	~/dummy	~/dummy

```
open("/etc/passwd", O_RDONLY);
```

struct file on kernel heap

Attacking Open File Credentials

Step 3. Operate as *privileged* user — Writing content to the file

```
int fd = open("~/dummy", O_RDWR);
```

```
write(fd, "HACKED", 6);
```

check perm



Write to /etc/
passwd on disk

f_op	f_op	f_op
O_RDONLY	O_RDWR	O_RDWR
f_cred	f_cred	f_cred
<u>/etc/ passwd</u>	~/dummy	~/dummy

```
open("/etc/passwd", O_RDONLY);
```

struct file on kernel heap

DirtyCred: Swapping Linux Kernel Credentials

Three Steps:

1. **Free** an inuse *unprivileged* credential with the vulnerability
2. **Allocate** *privileged* credentials in the *freed* memory slot
3. **Operate** as *privileged* user

Three Challenges

1. How to **free** credentials.
2. How to **allocate** privileged credentials as unprivileged users.
(attacking *task* credentials)
3. How to **stabilize** file exploitation. (attacking *open file* credentials)

Challenge 1: Free Credentials

- Both ***cred*** and ***file*** object are in **dedicated** caches
- Most vulnerabilities happens in **generic** caches
- Most vulnerabilities may not have free capability

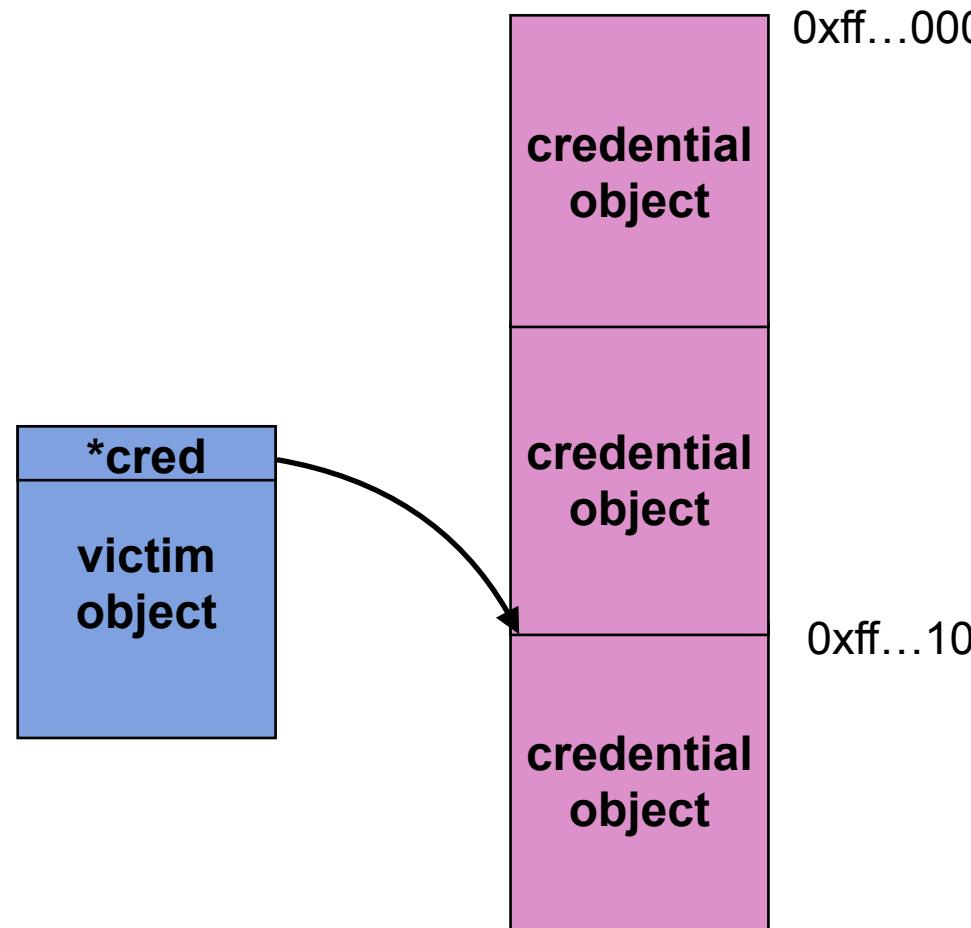
Challenge 1: Free In-use Credentials Invalidly

- **Solution: Pivoting Vulnerability Capability**
 - Pivoting Invalid-Write (e.g., OOB & UAF write)
 - Pivoting Invalid-Free (e.g., Double-Free)

Pivoting Invalid-Write

Pivoting Invalid-Write

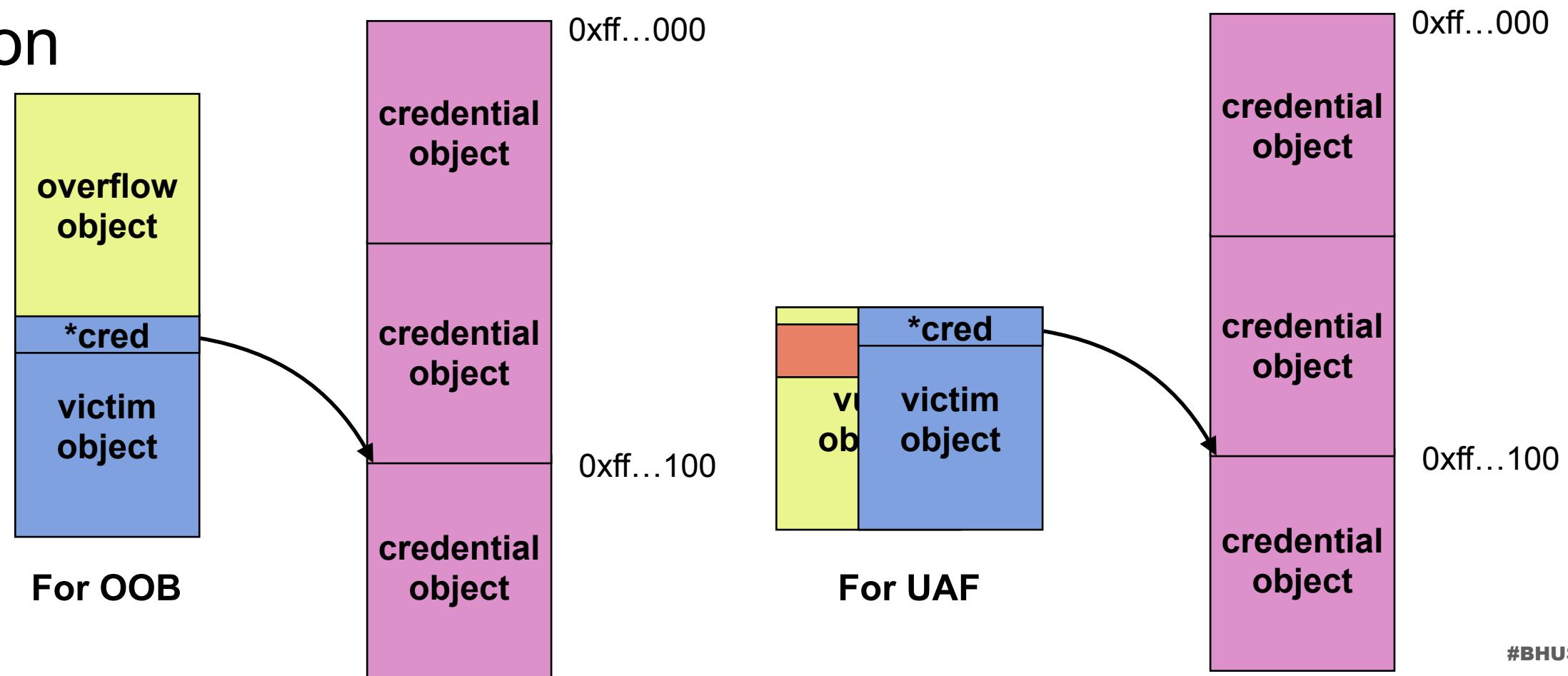
- Leverage victim objects with a reference to credentials



```
struct request_key_auth {
    struct rcu_head
    struct key
    struct key
    const struct cred
    void
    size_t
    pid_t
    char
} __randomize_layout;
```

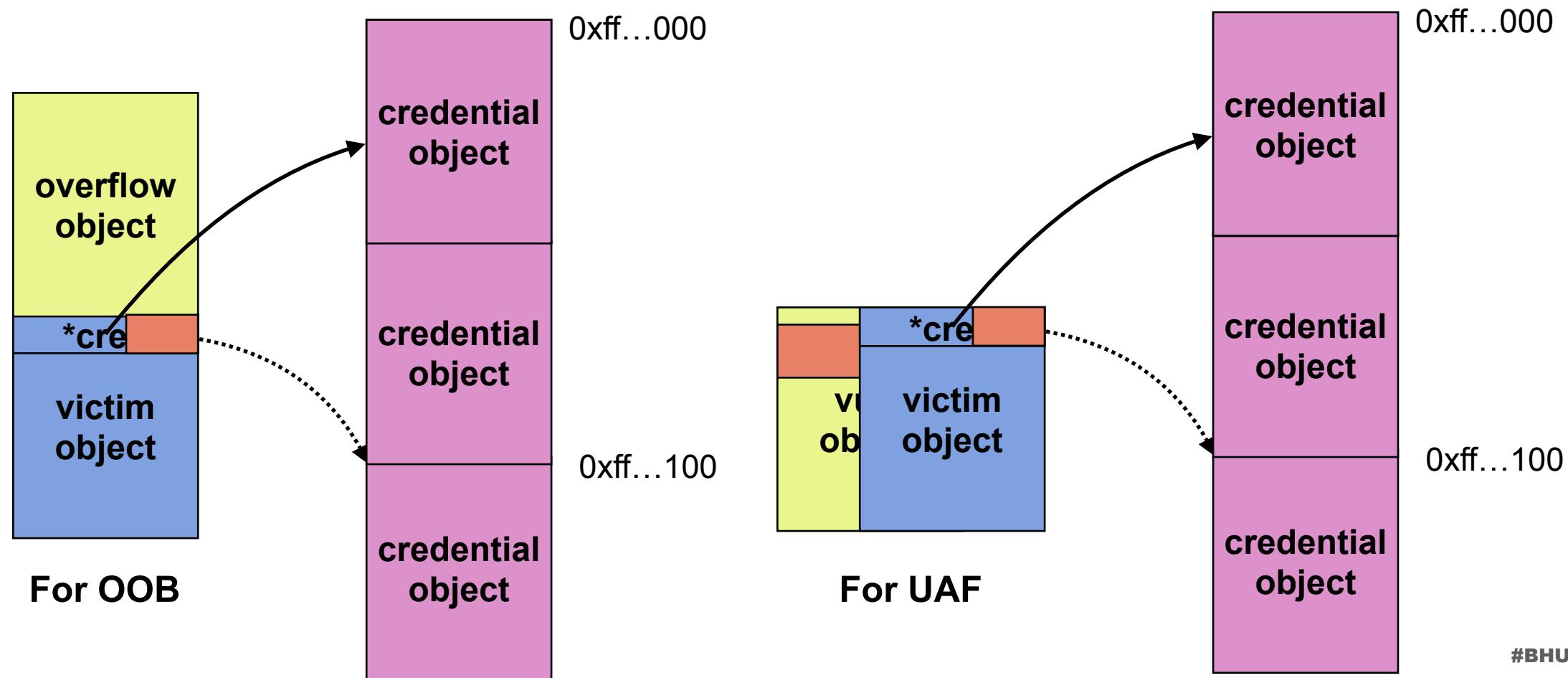
Pivoting Invalid-Write

- Manipulate the memory layout to put the *cred* in the overwrite region



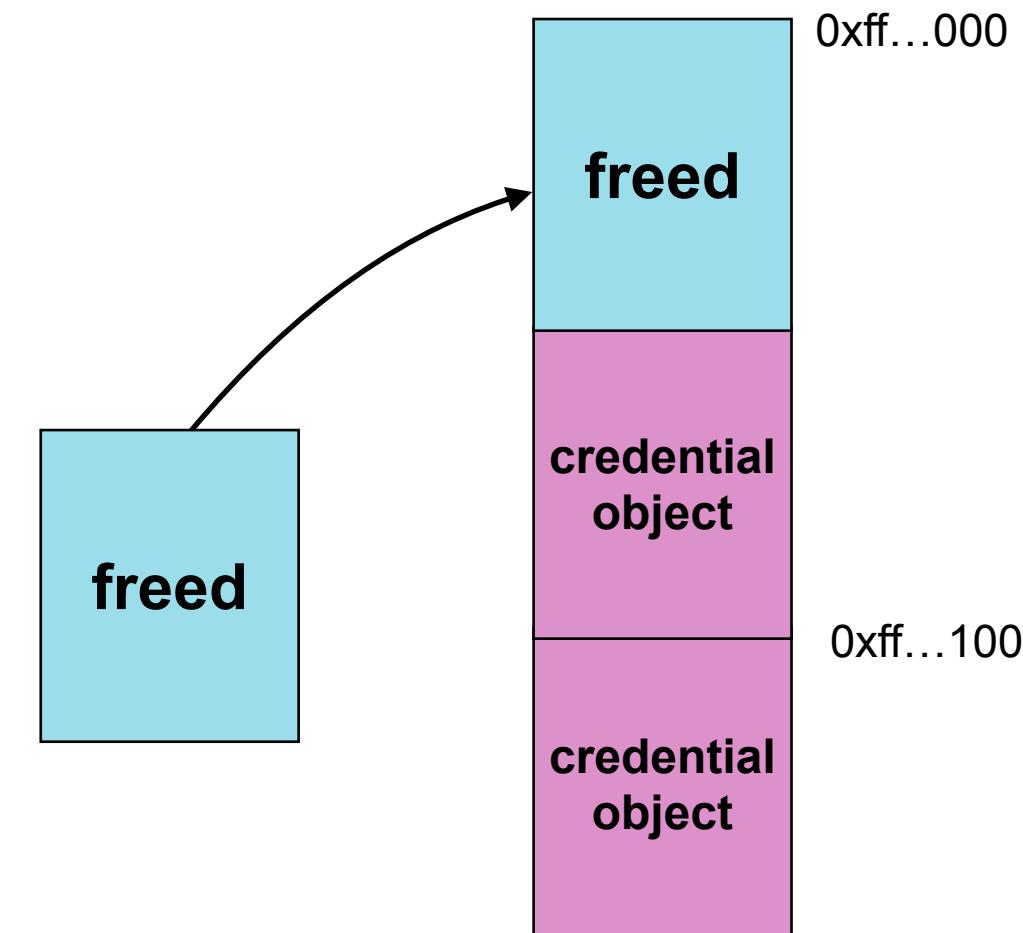
Pivoting Invalid-Write

- *Partially* overwrite the pointer to cause a reference unbalance



Pivoting Invalid-Write

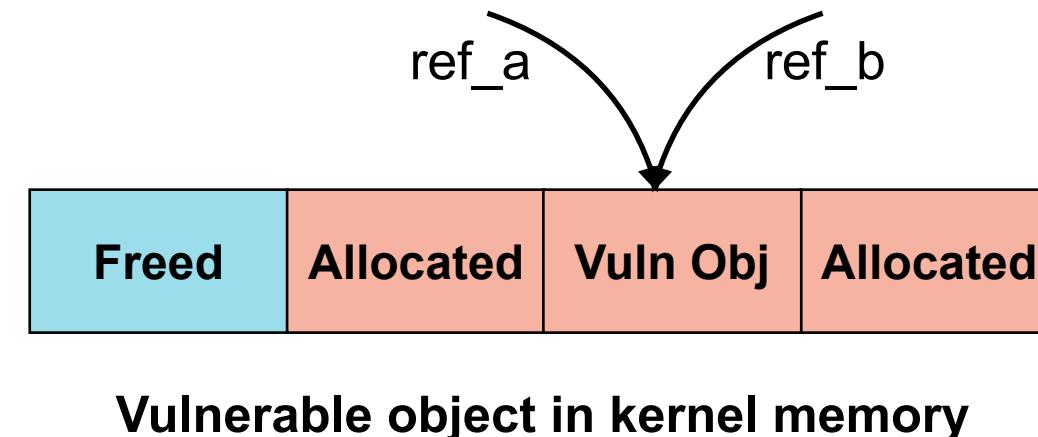
- Free the credential object when freeing the victim object



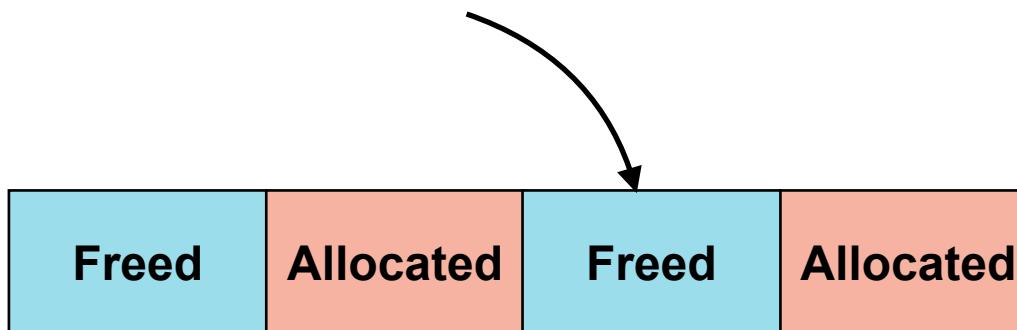
Pivoting Invalid-Free

Pivoting Invalid-Free

- Two references to free the same object

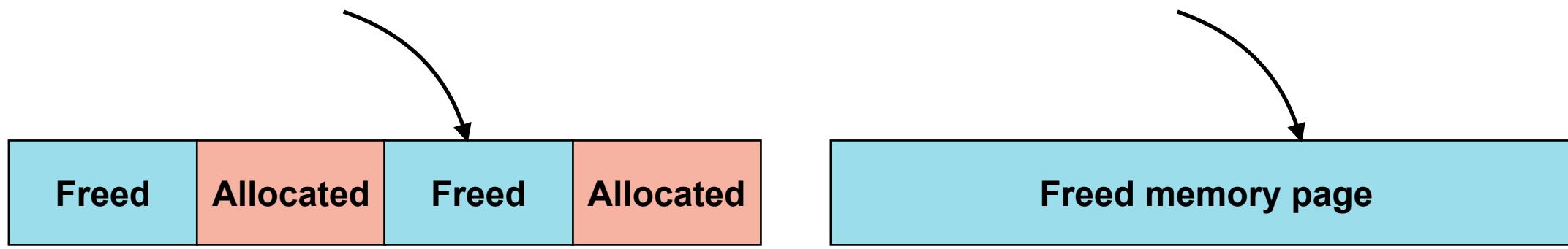


Pivoting Invalid-Free



Step 1. Trigger the vuln, free the vuln object with one reference

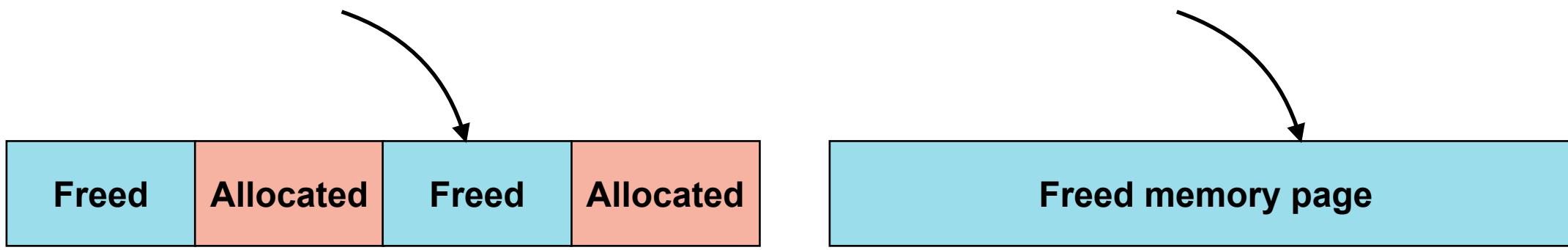
Pivoting Invalid-Free



Step 1. Trigger the vuln, free the vuln object with one reference

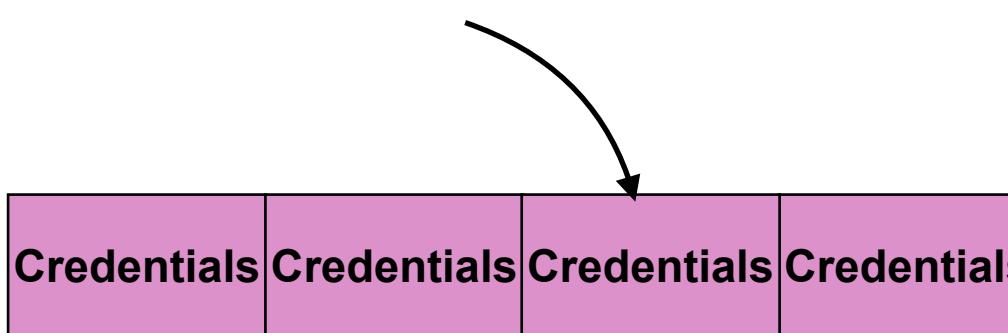
Step 2. Free the object in the memory cache to free the memory page

Pivoting Invalid-Free



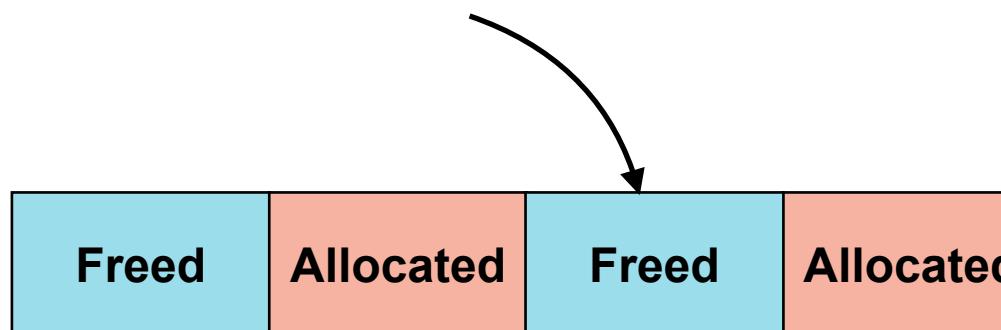
Step 1. Trigger the vuln, free the vuln object with one reference

Step 2. Free the object in the memory cache to free the memory page

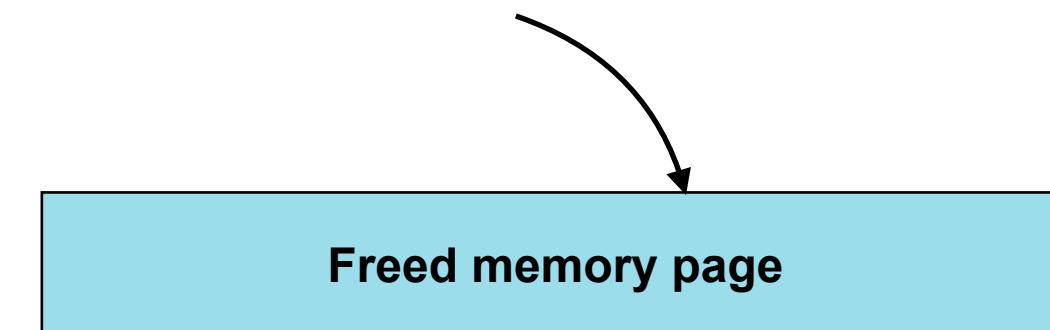


Step 3. Allocate credentials to reclaim the freed memory page (*Cross Cache Attack*)

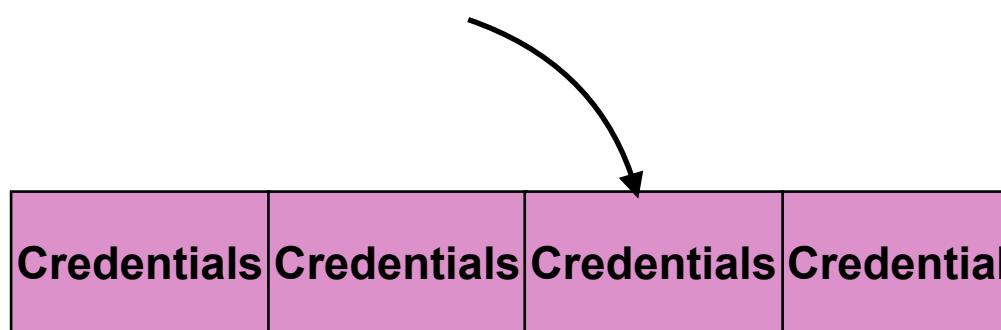
Pivoting Invalid-Free



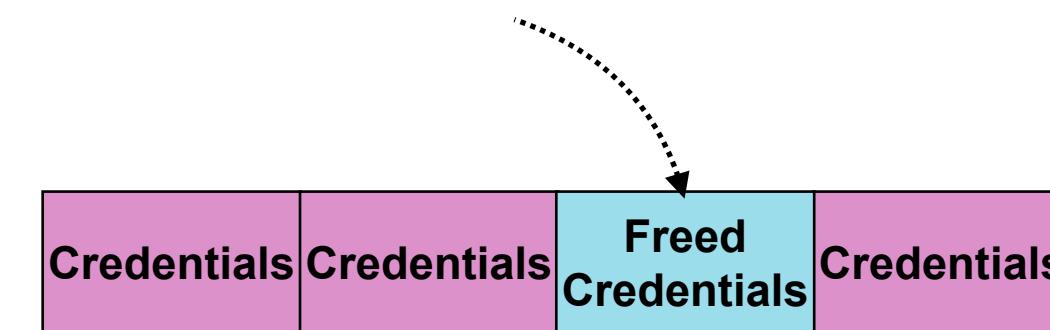
Step 1. Trigger the vuln, free the vuln object with one reference



Step 2. Free the object in the memory cache to free the memory page



Step 3. Allocate credentials to reclaim the freed memory page (Cross Cache Attack)



Step 4. Free the credentials with the left dangling reference

Three Challenges

1. How to **free** credentials.
2. How to **allocate** privileged credentials as unprivileged users.
(attacking *task* credentials)
3. How to **stabilize** file exploitation. (attacking *open file* credentials)

Challenge 2: Allocating Privileged Task Credentials

- *Unprivileged* users come with *unprivileged* task credentials
- Waiting privileged users to allocate task credentials influences the success rate

Challenge 2: Allocating Privileged Task Credentials

- **Solution I: Trigger Privileged Userspace Process**
 - Executables with root SUID (e.g. su, mount)
 - Daemons running as root (e.g. sshd)

Challenge 2: Allocating Privileged Task Credentials

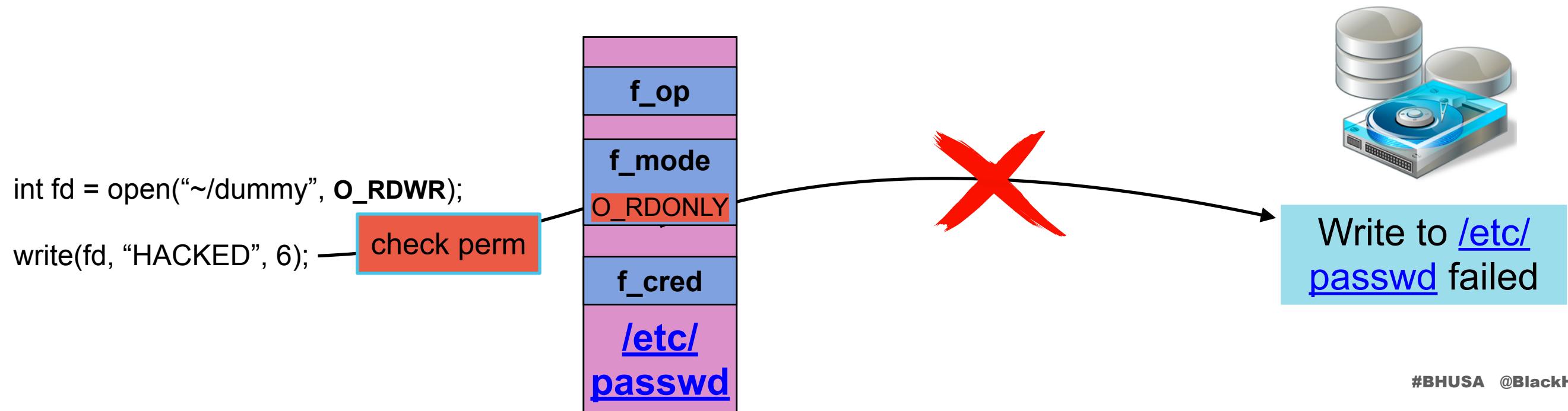
- **Solution I: Trigger Privileged Userspace Process**
 - Executables with root SUID (e.g. su, mount)
 - Daemons running as root (e.g. sshd)
- **Solution II: Trigger Privileged Kernel Thread**
 - Kernel Workqueue — spawn new workers
 - Usermode helper — load kernel modules from userspace

Three Challenges

1. How to **free** credentials.
2. How to **allocate** privileged credentials as unprivileged users.
(attacking *task* credentials)
3. How to **stabilize** file exploitation. (attacking *open file* credentials)

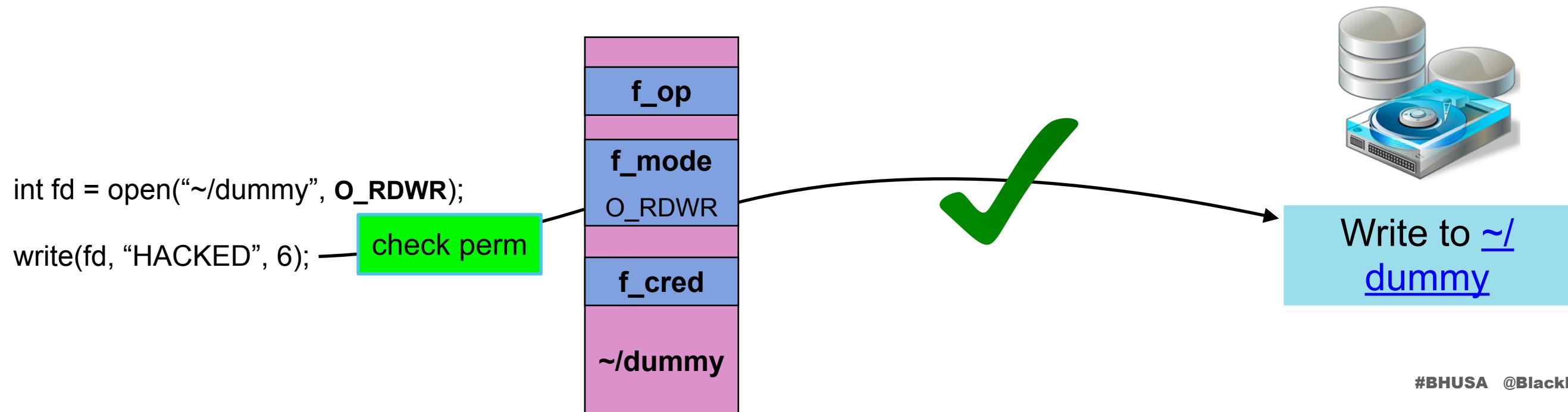
Challenge 3: Stabilizing File Exploitation

- The swap of *file* object happens before permission check



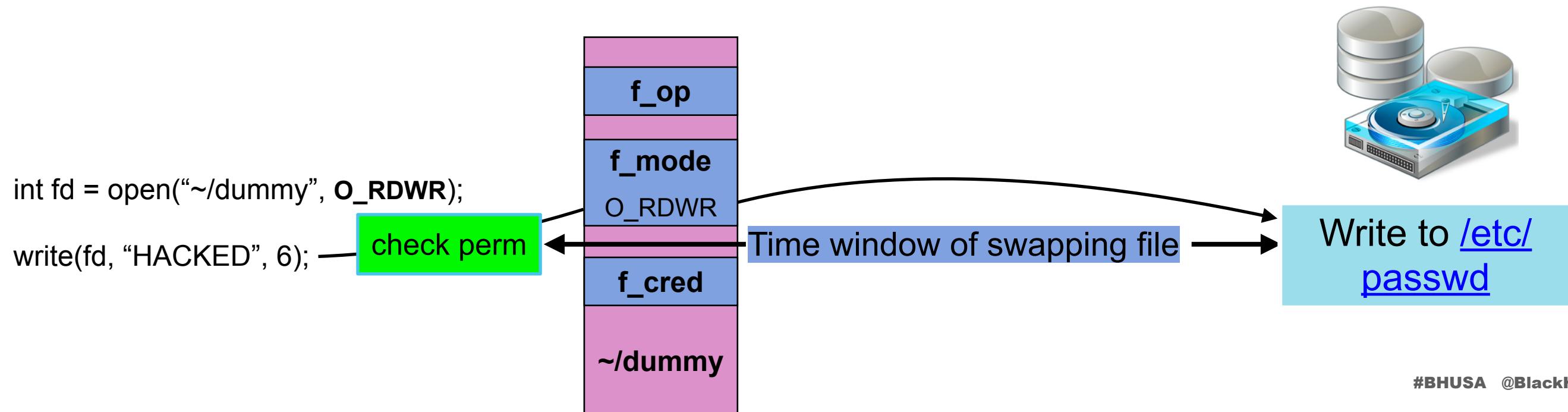
Challenge 3: Stabilizing File Exploitation

- The swap of *file* object happens after *file write*.



Challenge 3: Stabilizing File Exploitation

- The swap of *file* object should happen between permission check and actual file write
- The desired time window is small



Challenge 3: Stabilizing File Exploitation

- **Solution I: Extend with Userfaultfd or FUSE**
 - *Pause kernel execution when accessing userspace memory*

Solution I: Userfaultfd & FUSE

- Pause at *import_iovec* before v4.13
 - *import_iovec* copies userspace memory

```
ssize_t vfs_writev(...)  
{  
    // permission checks  
    if (!(file->f_mode & FMODE_WRITE))  
        return -EBADF;  
    if (!(file->f_mode & FMODE_CAN_WRITE))  
        return -EINVAL;  
  
    ...  
    // import iovec to kernel, where kernel would be paused  
    // using userfaultfd & FUSE  
    res = import_iovec(type, uvector, nr_segs,  
                      ARRAY_SIZE(iovstack), &iov, &iter);  
    ...  
    // do file writev  
}
```

Solution I: Userfaultfd & FUSE

- Pause at *import_iovec* before v4.13
 - *import_iovec* copies userspace memory
 - Used in Jann Horn's exploitation for [CVE-2016-4557](#)
 - *Dead after v4.13*

Solution I: Userfaultfd & FUSE

- **vfs_writev after v4.13**

```
ssize_t vfs_writev(...)  
{  
    ...  
    // import iovec to kernel, where kernel would be paused  
    // using userfaultfd  
    res = import_iovec(type, uvector, nr_segs,  
                      ARRAY_SIZE(iovstack), &iov, &iter);  
    ...  
    // permission checks  
    if (!(file->f_mode & FMODE_WRITE))  
        return -EBADF;  
    if (!(file->f_mode & FMODE_CAN_WRITE))  
        return -EINVAL;  
    ...  
    // do file writev  
}
```

Solution I: Userfaultfd & FUSE

- Pause at `generic_perform_write`
 - *prefaults* user pages
 - Pauses kernel execution at the page fault

```
ssize_t generic_perform_write(struct file *file,
                               struct iov_iter *i, loff_t pos)
{
    /*
     * Bring in the user page that we will copy from _first_.
     * Otherwise there's a nasty deadlock on copying from the
     * same page as we're writing to, without it being marked
     * up-to-date.
     */
    if (unlikely(iov_iter_fault_in_readable(i, bytes))) {
        status = -EFAULT;
        break;
    }
    ...
    // call the write operation of the file system
    status = a_ops->write_begin(file, mapping, pos, bytes, flags,
                                 &page, &fsdata);
    ...
}
```

Challenge 3: Stabilizing File Exploitation

- **Solution I: Extend with Userfaultfd & FUSE**
 - Pause kernel execution when accessing userspace memory
 - Userfaultfd & FUSE might not be available
- **Solution II: Extend with file lock**
 - Pause kernel execution with lock

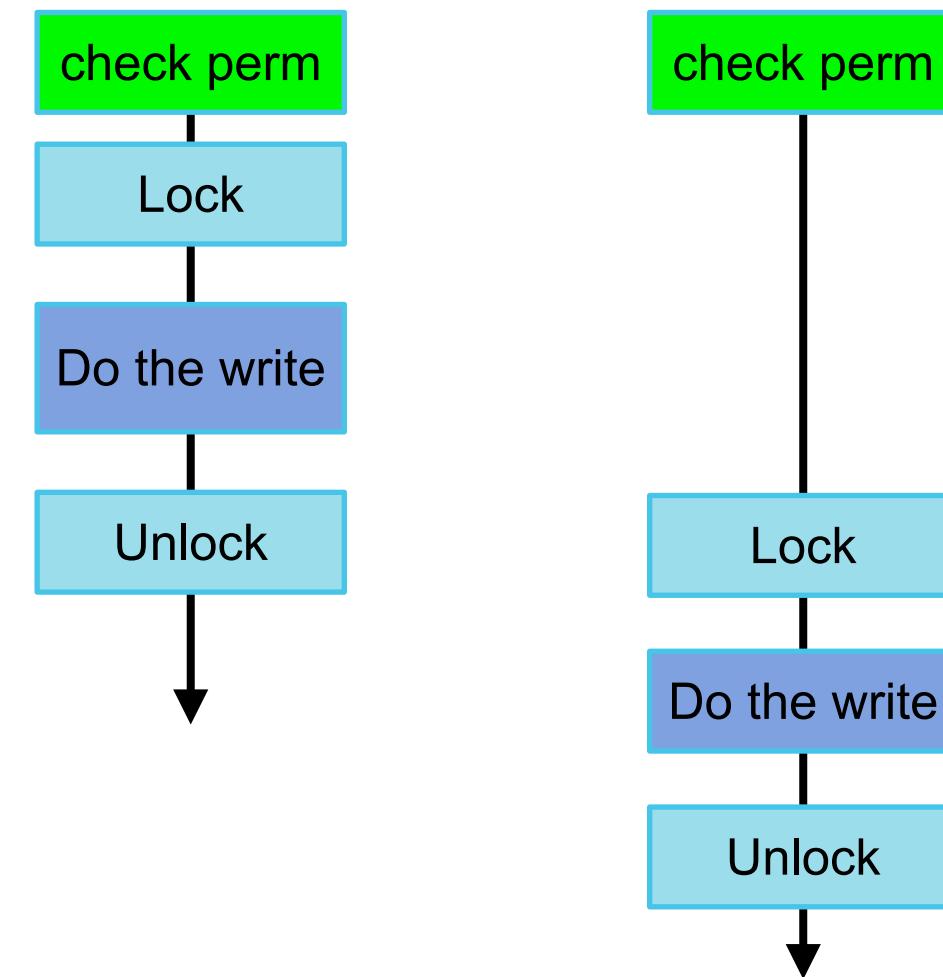
Solution II: File Lock

- A lock of the *inode* of the file
- Lock the file when it is being writing to

```
static ssize_t ext4_buffered_write_iter(struct kiocb *iocb,
                                      struct iov_iter *from)
{
    ssize_t ret;
    struct inode *inode = file_inode(iocb->ki_filp);
    inode_lock(inode);
    ...
    ret = generic_perform_write(iocb->ki_filp, from,
                                iocb->ki_pos);
    ...
    inode_unlock(inode);
    return ret;
}
```

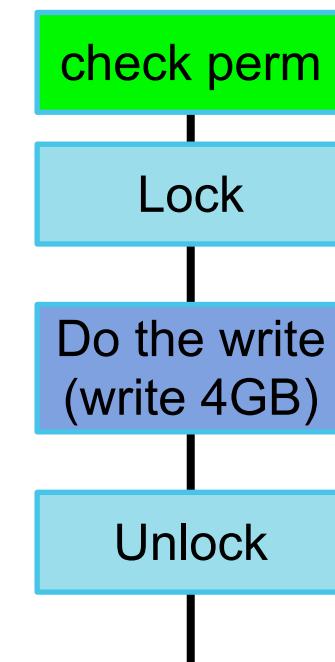
Solution II: File Lock

Thread A Thread B

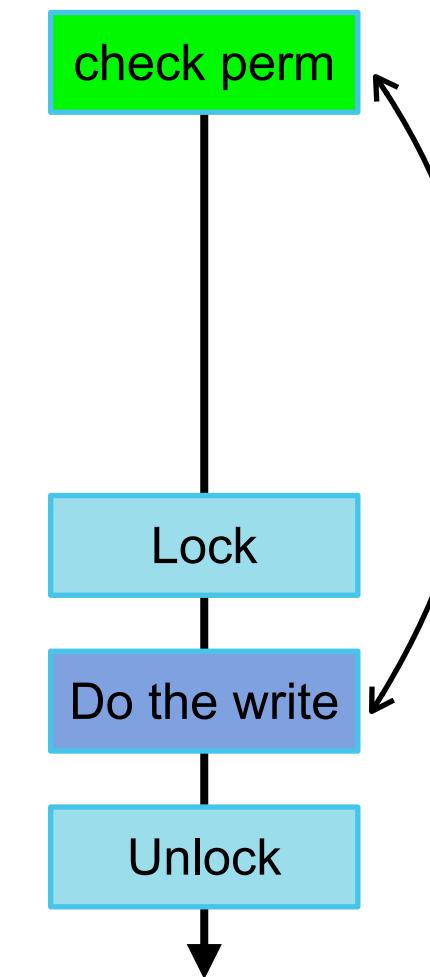


Solution II: File Lock

Thread A



Thread B

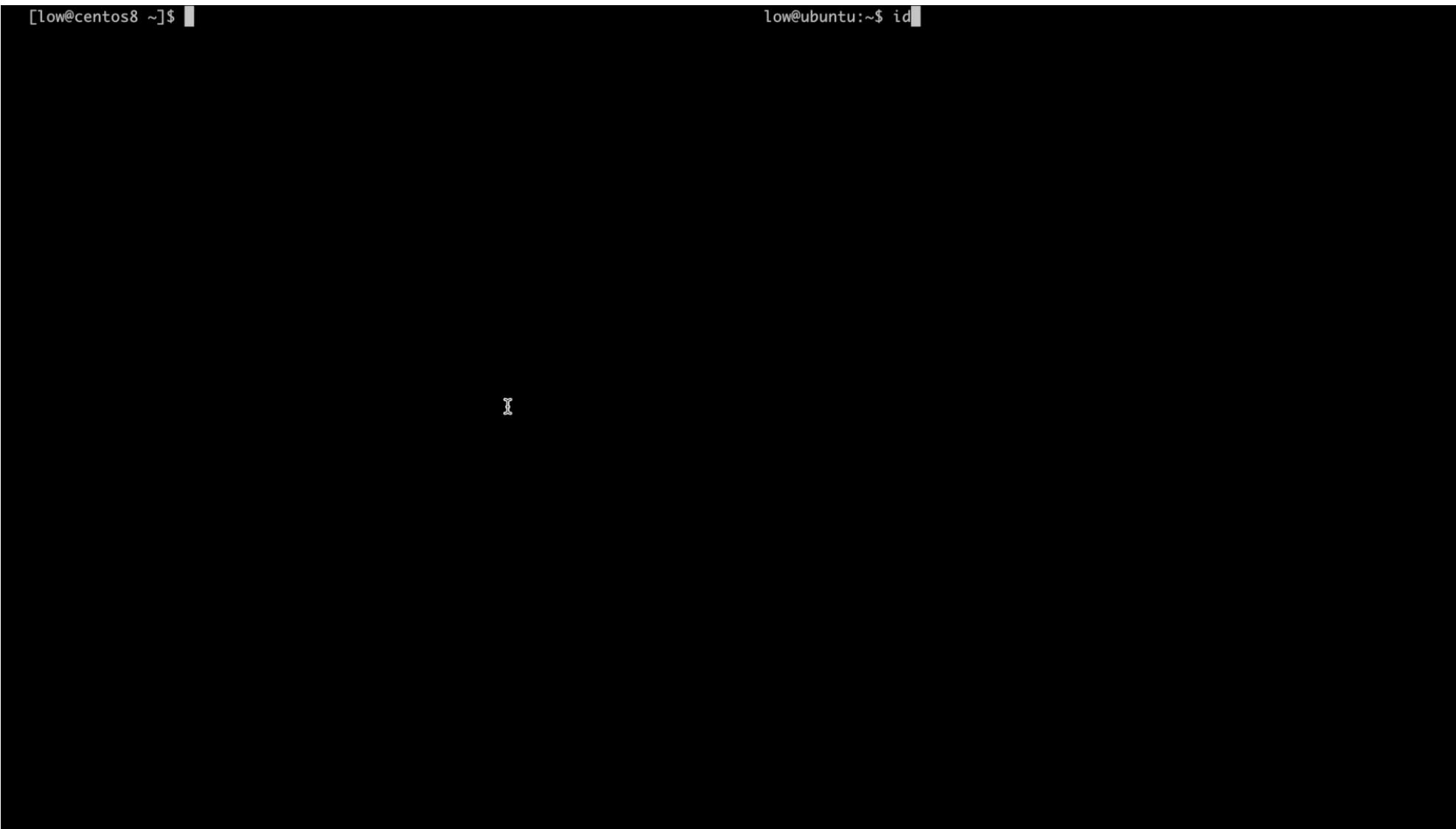


A large time window

Demo Time!

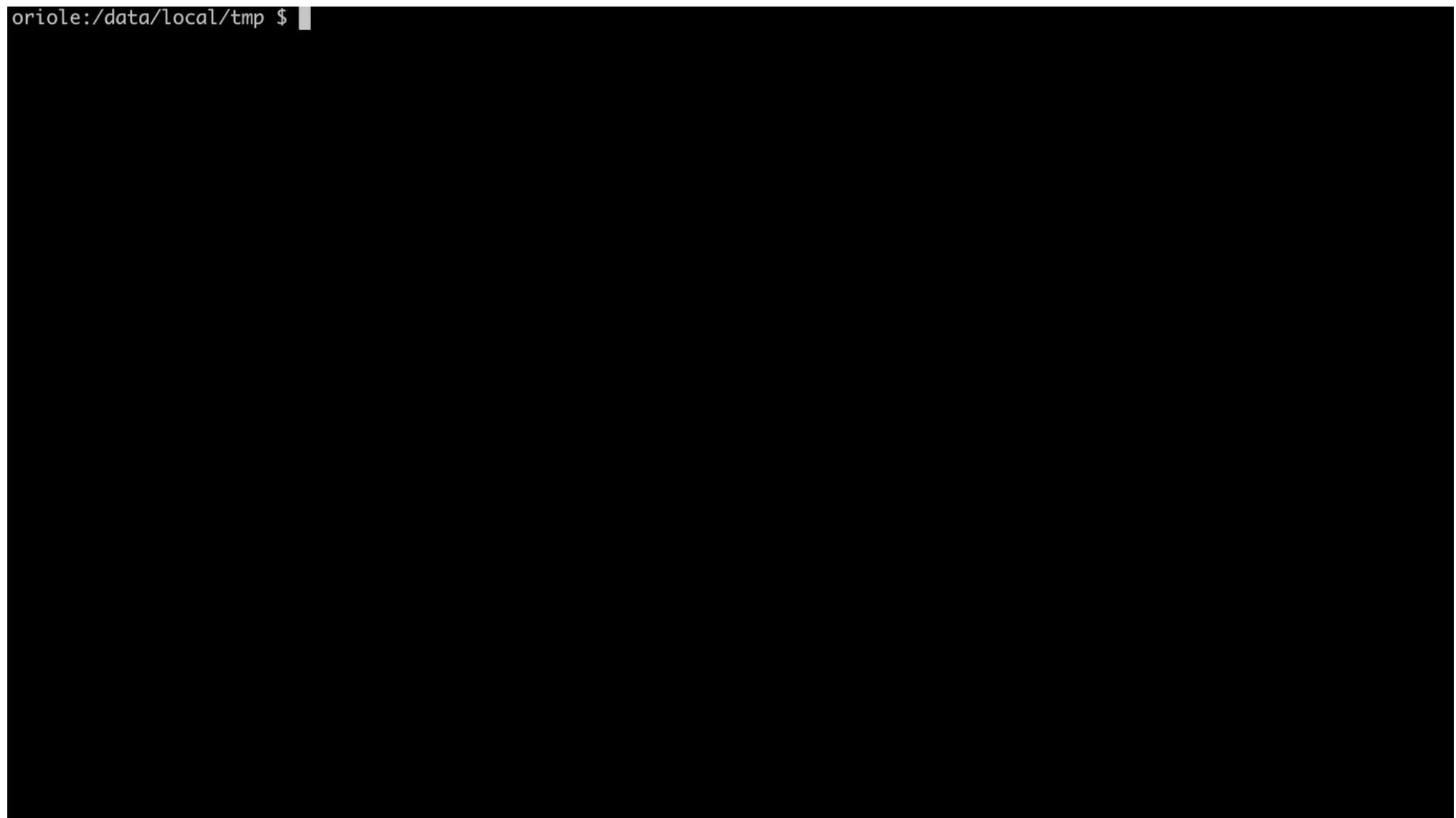
CVE-2021-4154

Centos 8 and Ubuntu 20



Android Kernel with CFI enabled*

```
oriole:/data/local/tmp $ █
```



Advantages of DirtyCred

- **A generic method**
 - The method applies to container and Android.
- **Simple but powerful**
 - No need to deal with KASLR, CFI.
 - Data-only method.
- **Exploitation friendly**
 - Make your exploit **universal!**
 - empowers different bugs to be Dirty-Pipe-like (sometimes even better).

Defense Against DirtyCred

- **Fundamental problem**
 - Object isolation is based on *type* not *privilege*
- **Solution**
 - *Isolate* privileged credentials from unprivileged ones
- **Where to isolate?**
 - Virtual memory (using `vmalloc`): No *cross cache attack* anymore!
- Code is available at <https://github.com/markakd/DirtyCred>

Takeaways

- New exploitation concept — DirtyCred: swapping credentials
- Principled approach to different challenges
- *Universal* exploits to different kernels
- Effective defense

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