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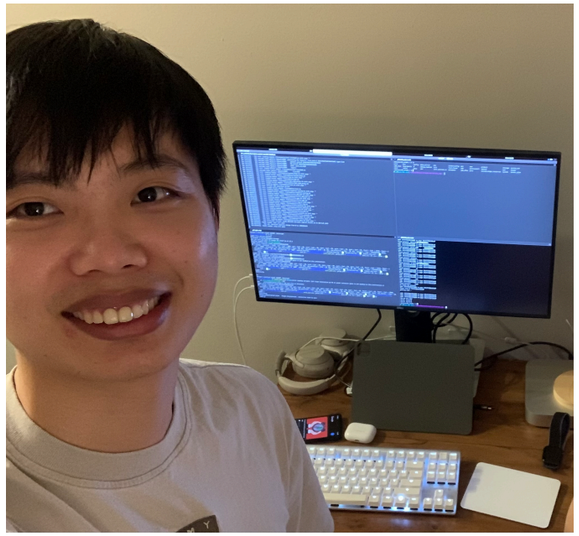
BRIEFINGS

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

Zhenpeng Lin, Yuhang Wu, Xinyu Xing
Northwestern University

Who Are We



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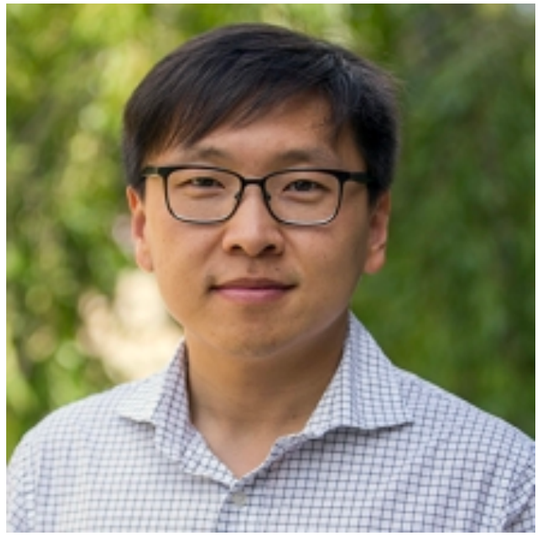

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Recap About Dirty Pipe

- 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?	✗	✓

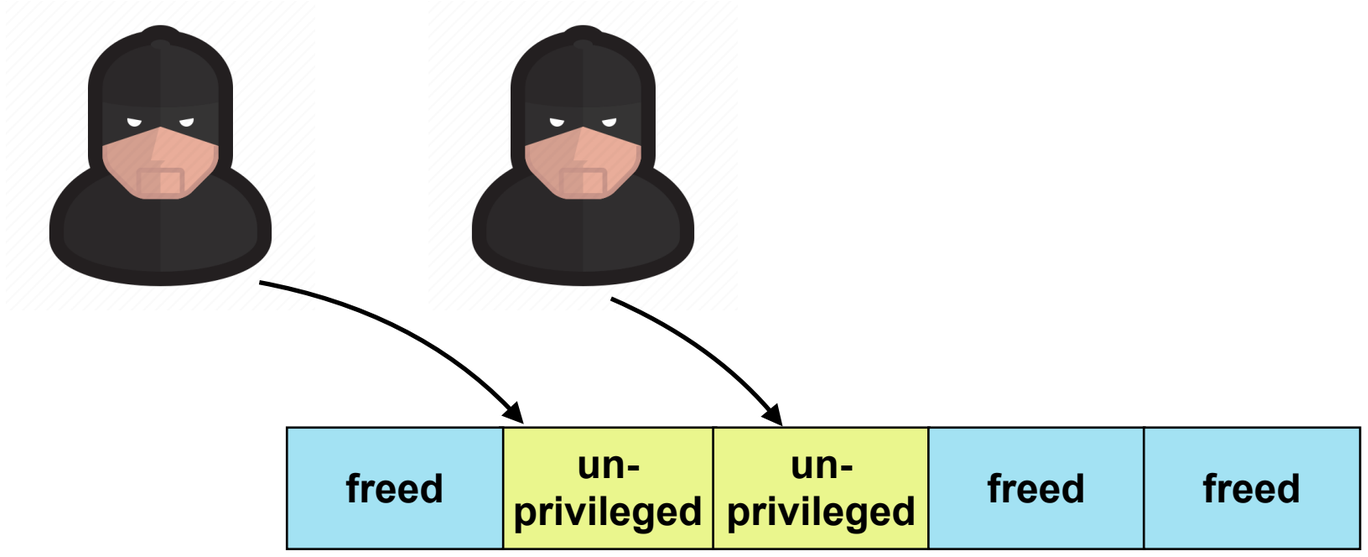
Kernel Credential

- **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

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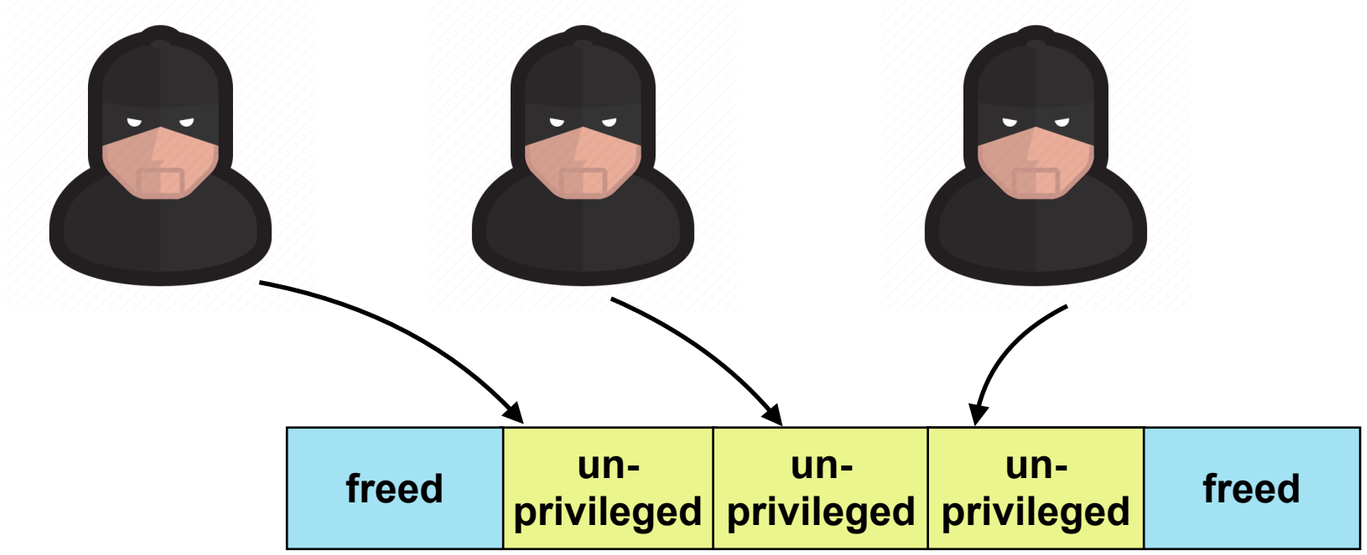
- `Struct cred` in kernel's implementation



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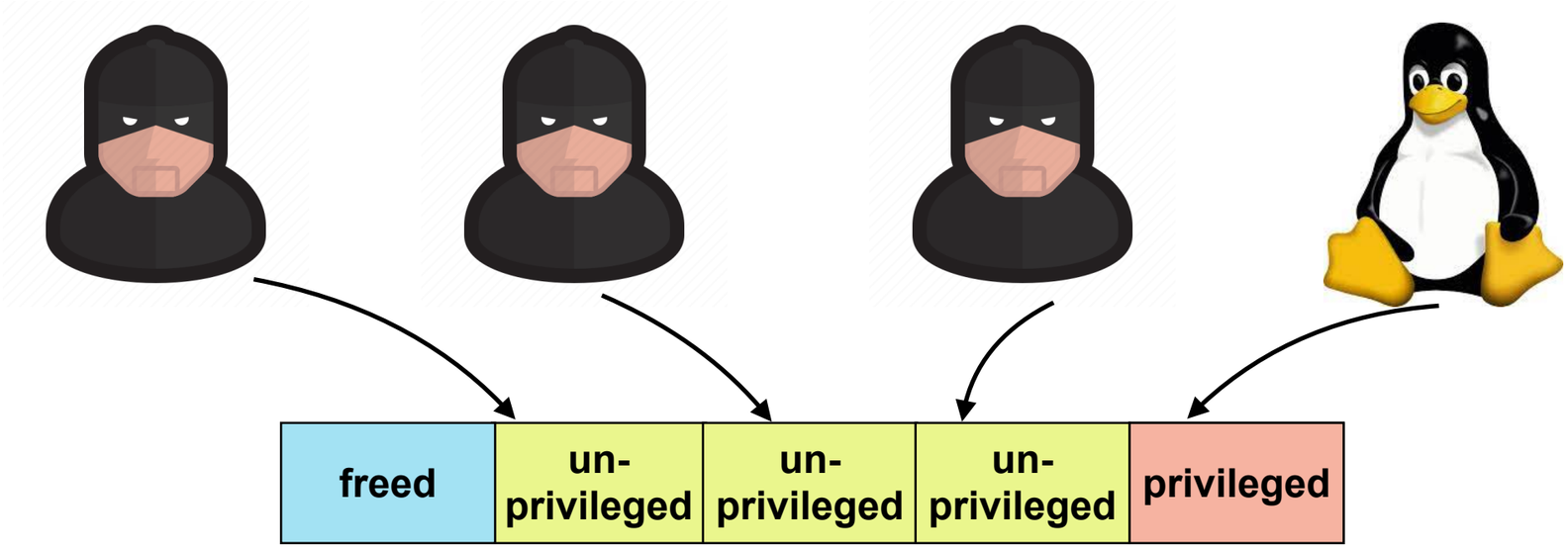
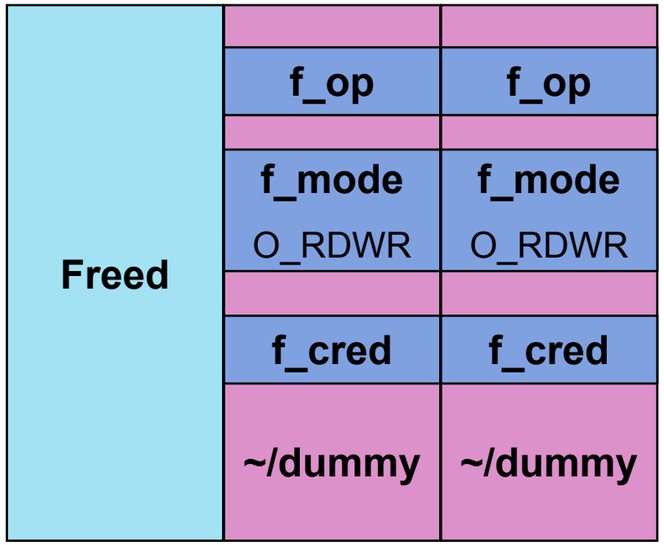


`struct cred` on kernel heap

Open File Credentials

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

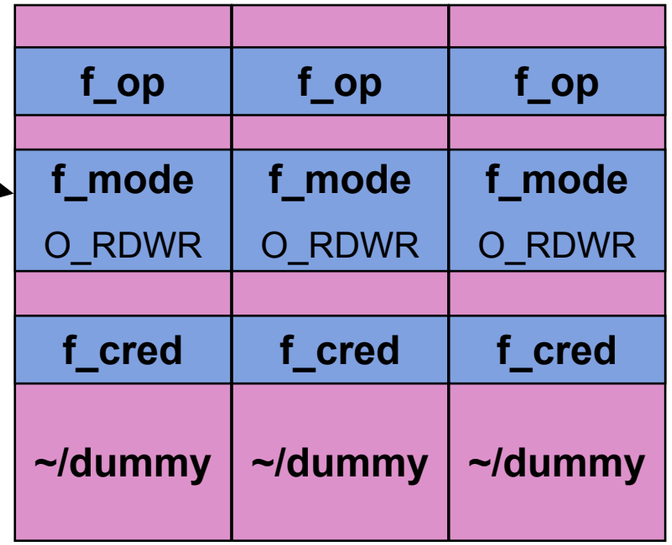


`struct file` on kernel heap

Open File Credentials

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

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



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Open File Credentials

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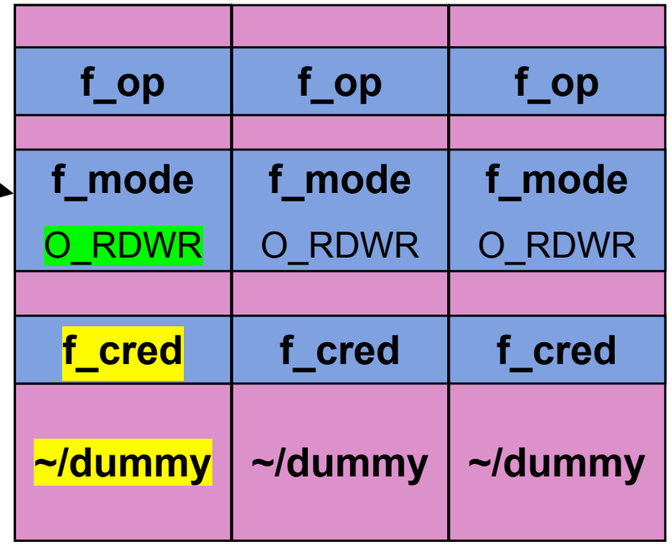
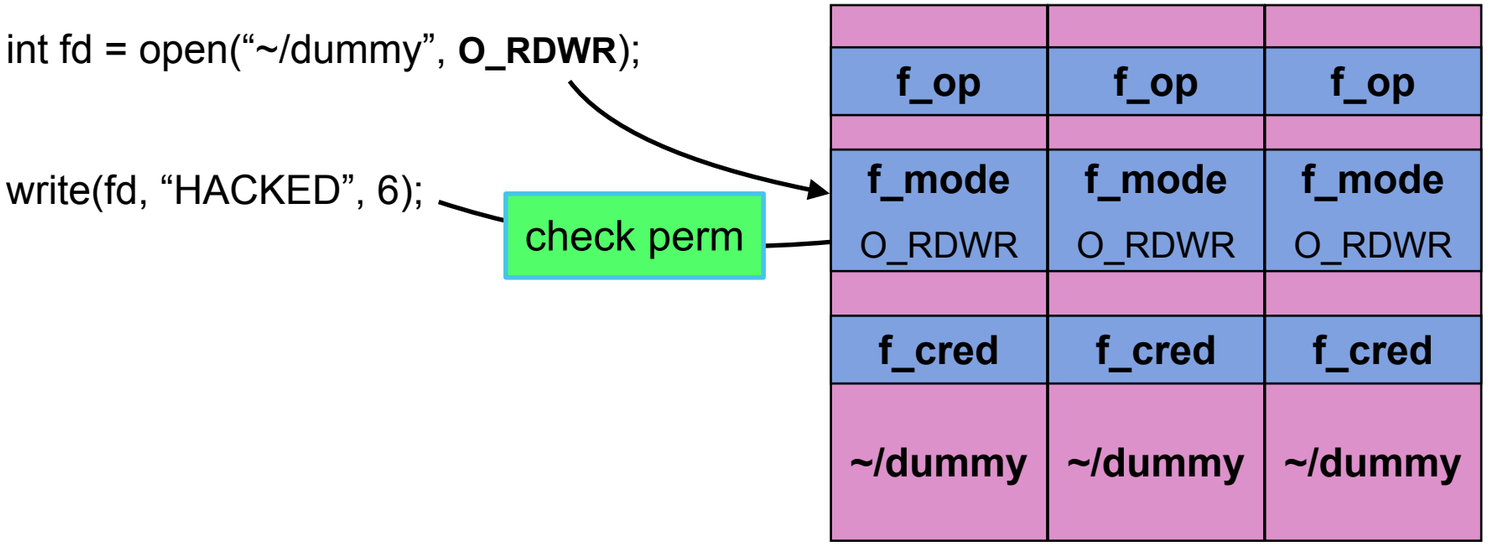


`struct file` on kernel heap

Open File Credentials

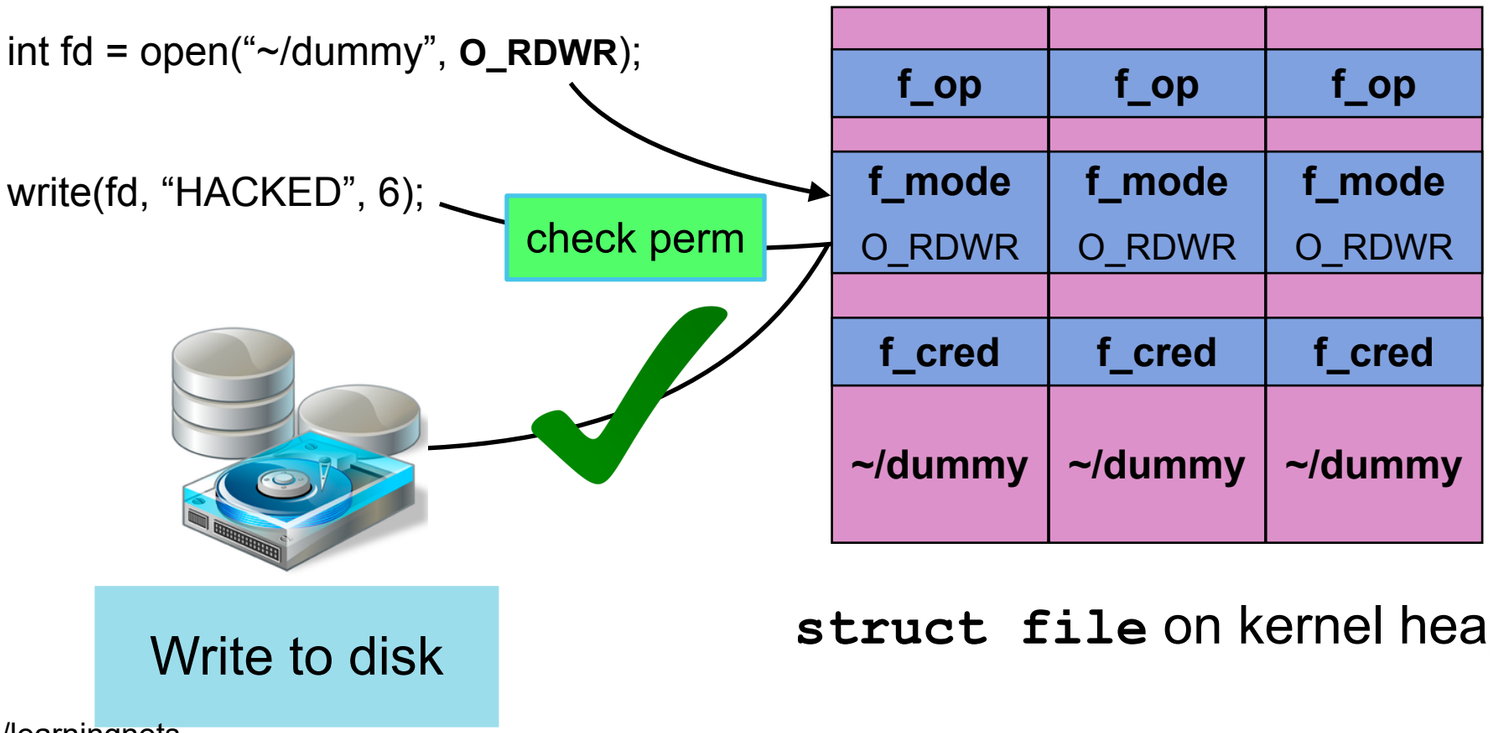
- Kernel checks permission on the **`file`** object when accessing



`struct file` on kernel heap

Open File Credentials

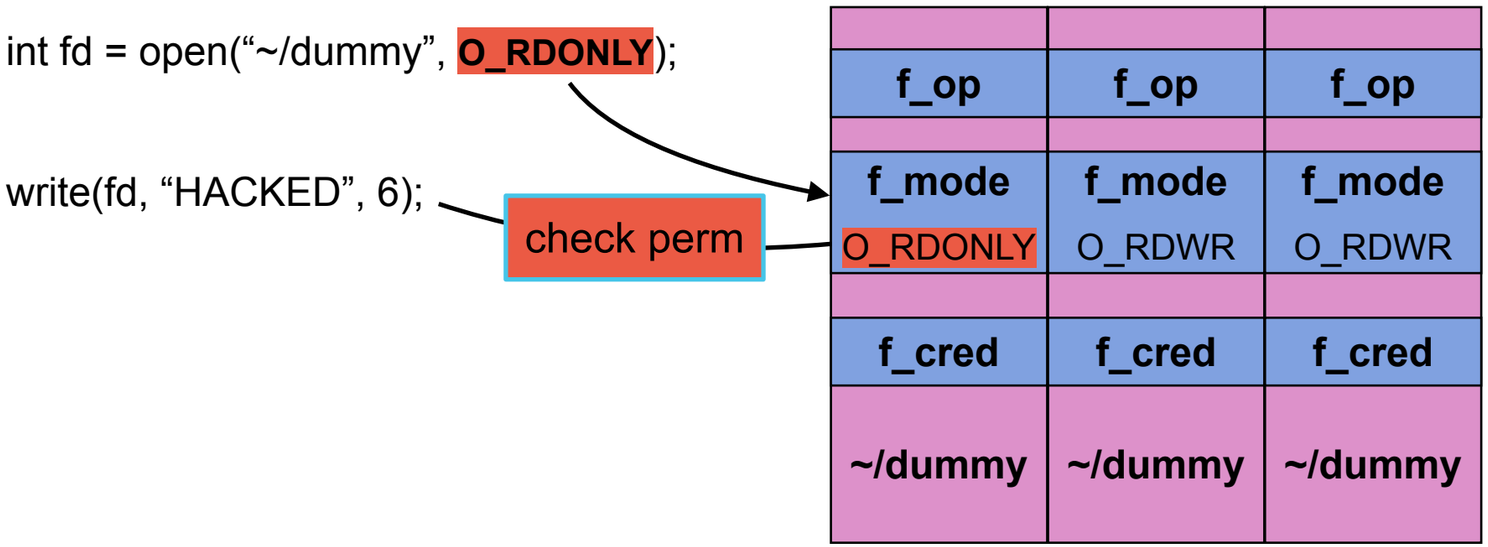
- Write content to file on disk if permission is granted



`struct file` on kernel heap

Open File Credentials

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



`struct file` on kernel heap

Open File Credentials

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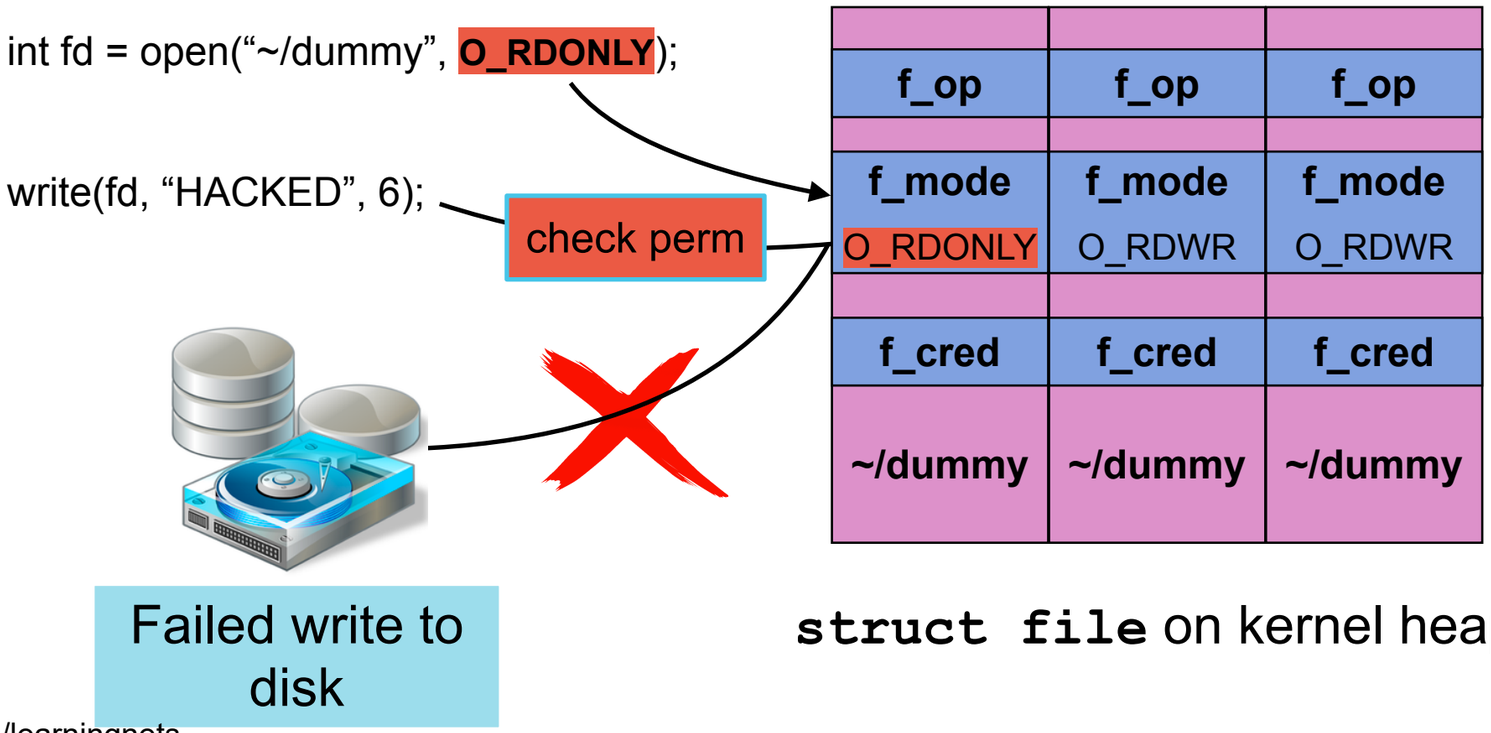


`struct file` on kernel heap

DirtyCred: Swapping Linux Kernel Credentials

High-level idea

- Swapping ***unprivileged*** credentials with ***privileged*** ones

Two-Path attacks

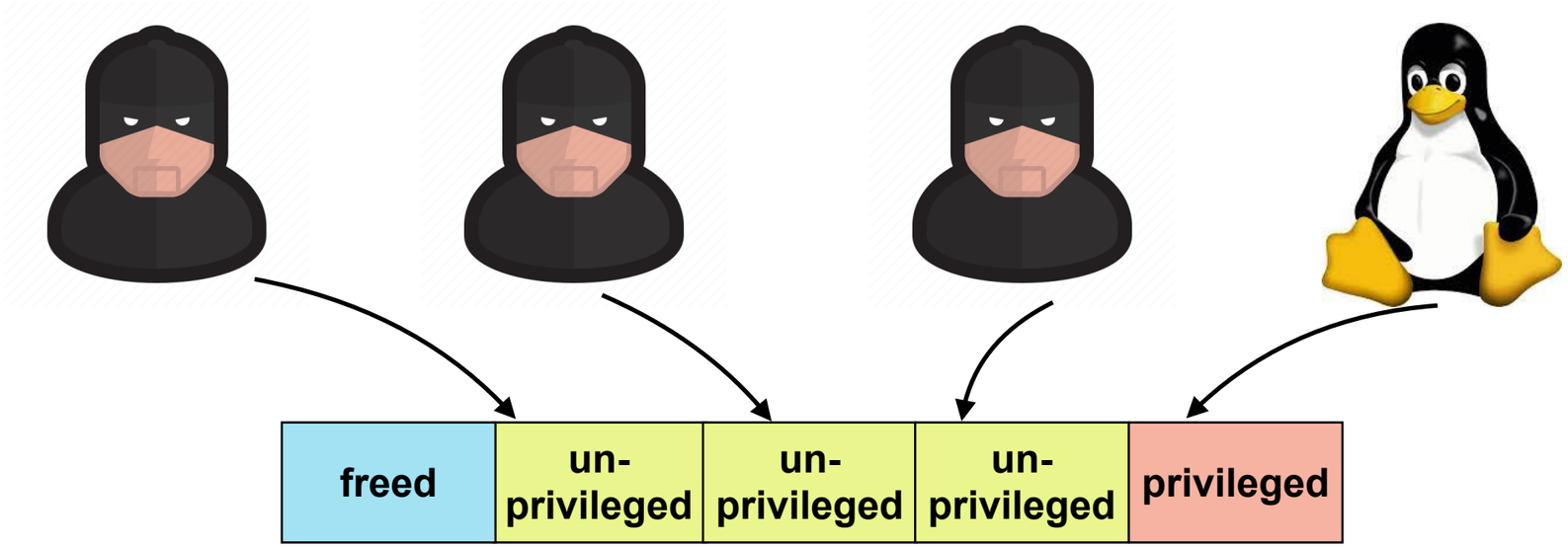
- Attacking *task credentials* (`struct cred`)
- Attacking *open file credentials* (`struct file`)

DirtyCred: Swapping Linux Kernel Credentials

Two-Path attacks

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

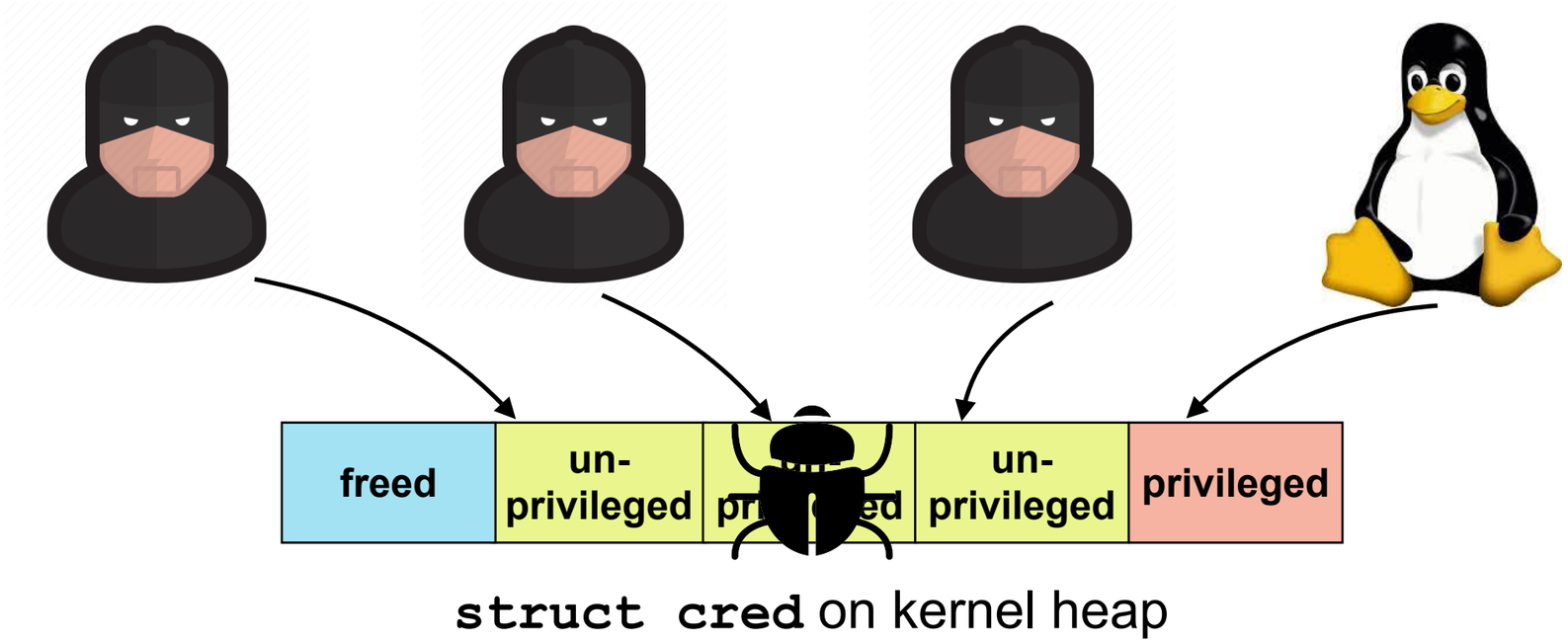
Attacking Task Credentials



`struct cred` on kernel heap

Attacking Task Credentials

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



`struct cred` on kernel heap

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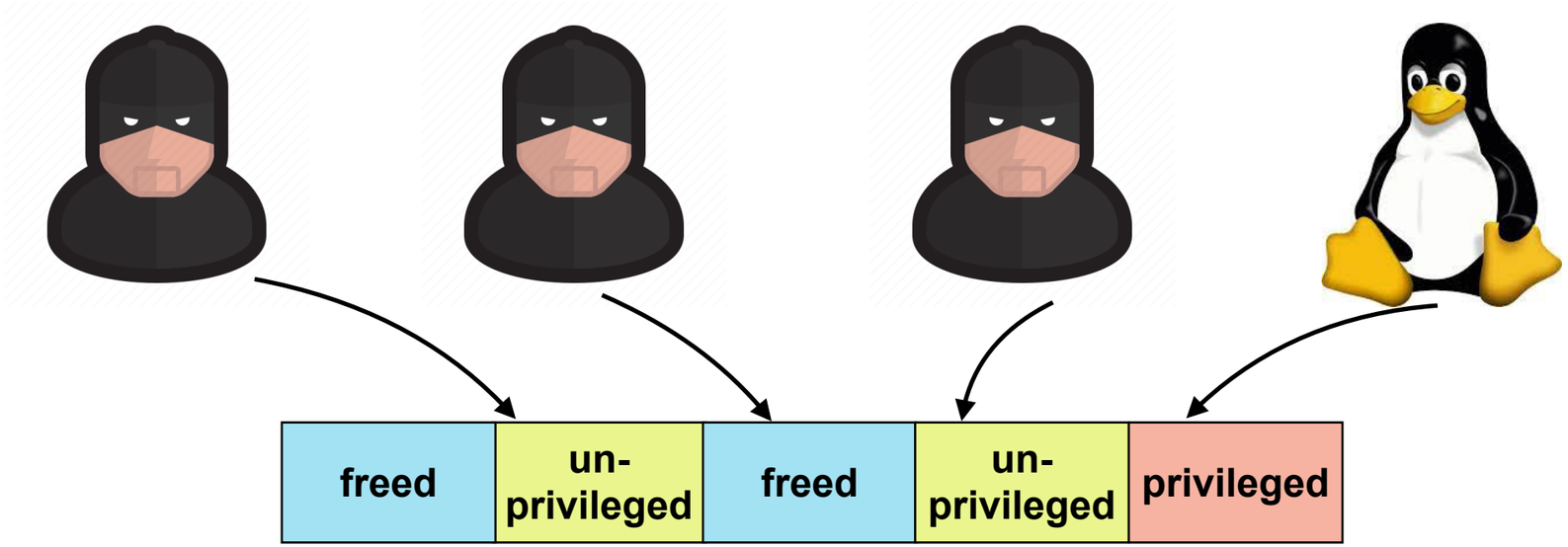
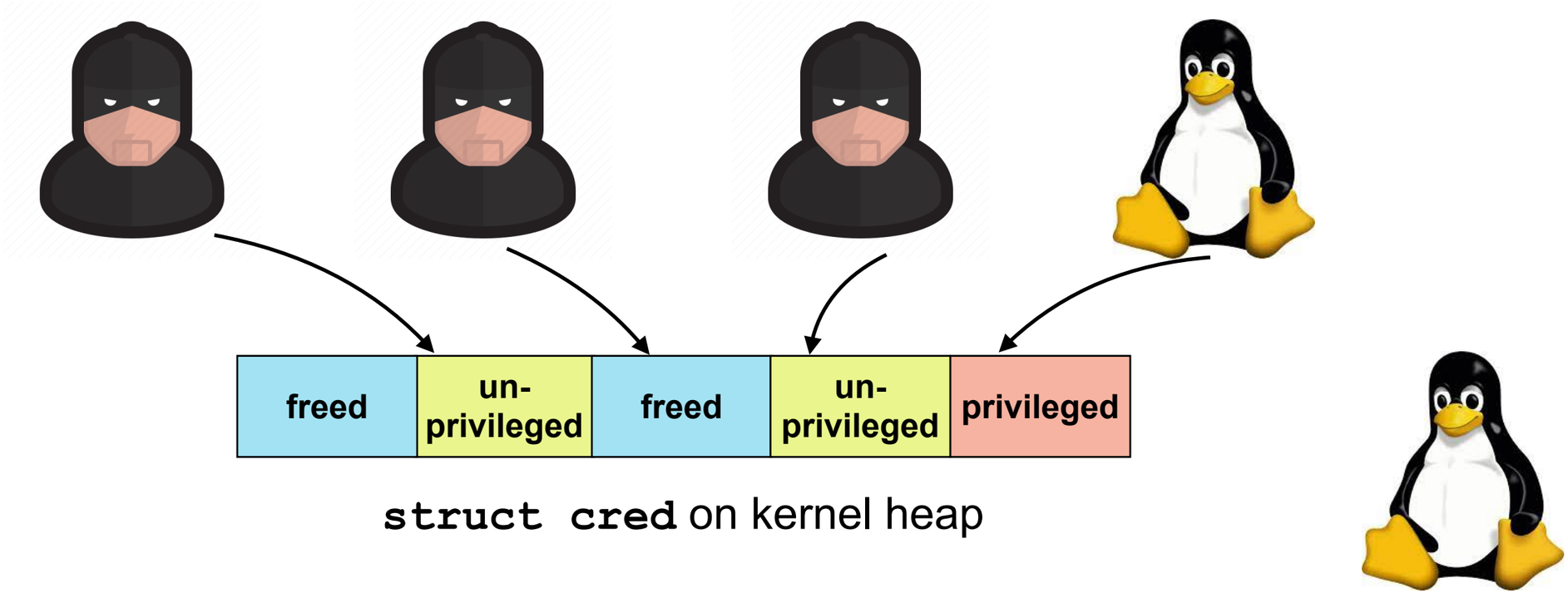


`struct cred` on kernel heap

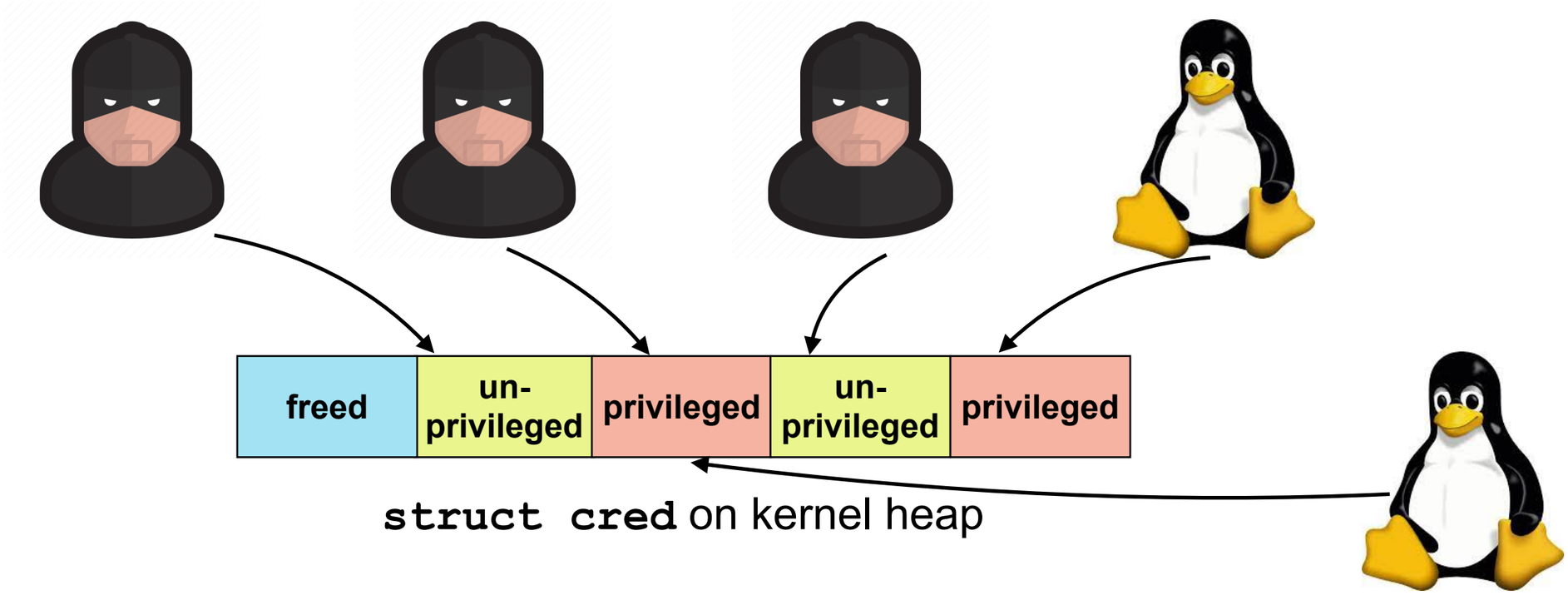
Attacking Task Credentials

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



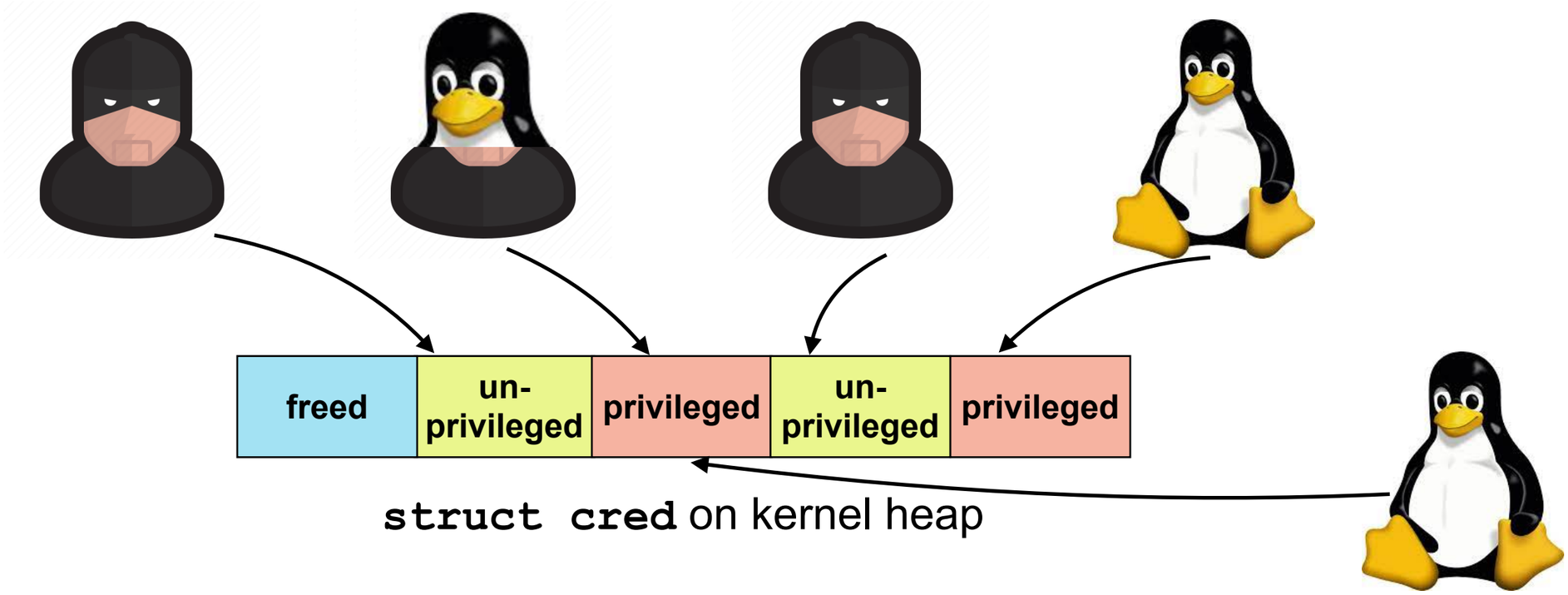
Attacking Task Credentials

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



Attacking Task Credentials

Step 3. **Operate** as *privileged* user



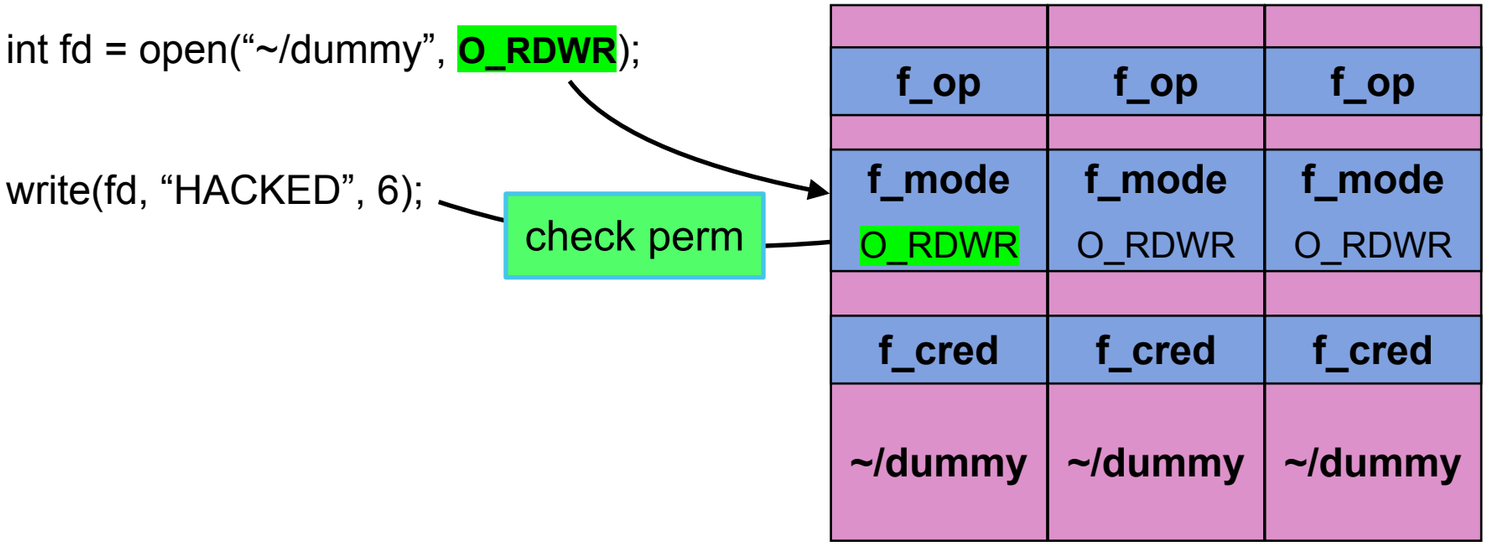
DirtyCred: Swapping Linux Kernel Credentials

Two-Path attacks

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

Attacking Open File Credentials

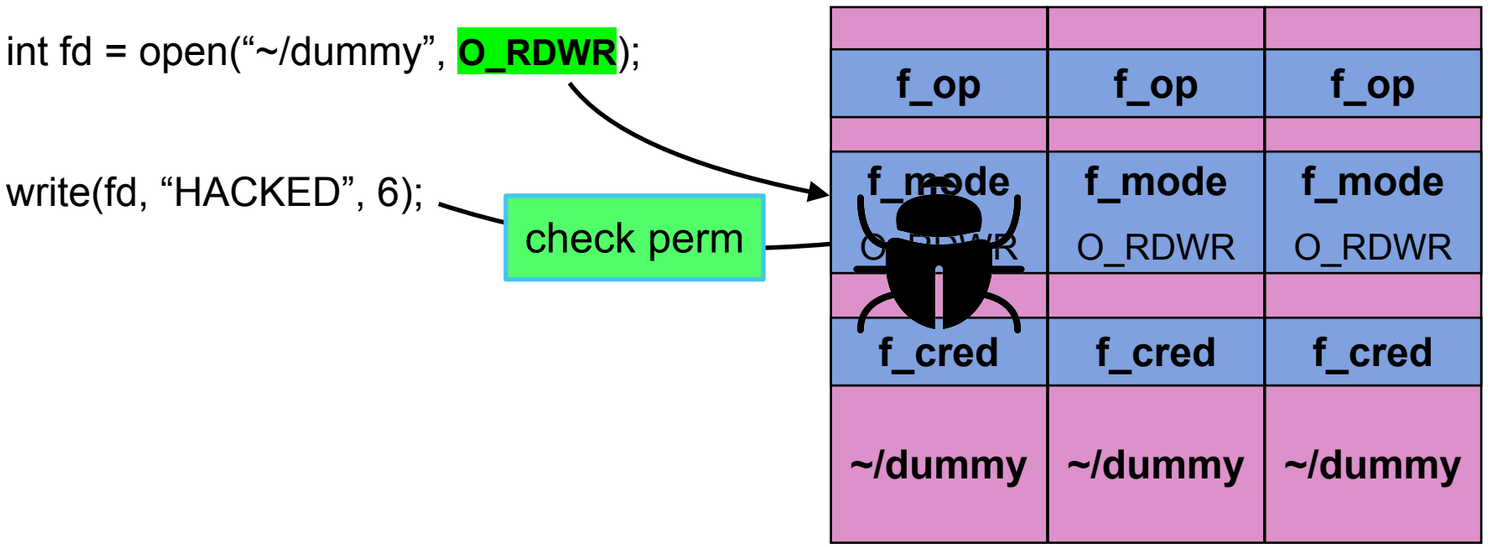
- Write content to file on disk if permission is granted



`struct file` on kernel heap

Attacking Open File Credentials

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



`struct file` on kernel heap

Attacking Open File Credentials

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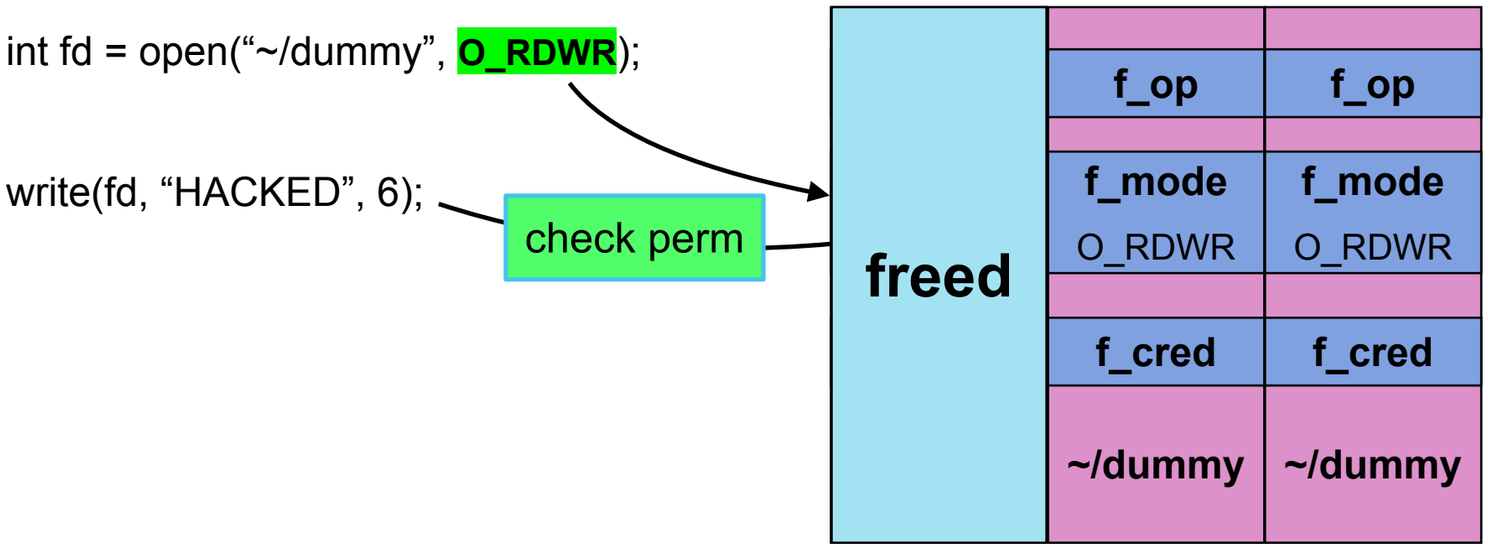
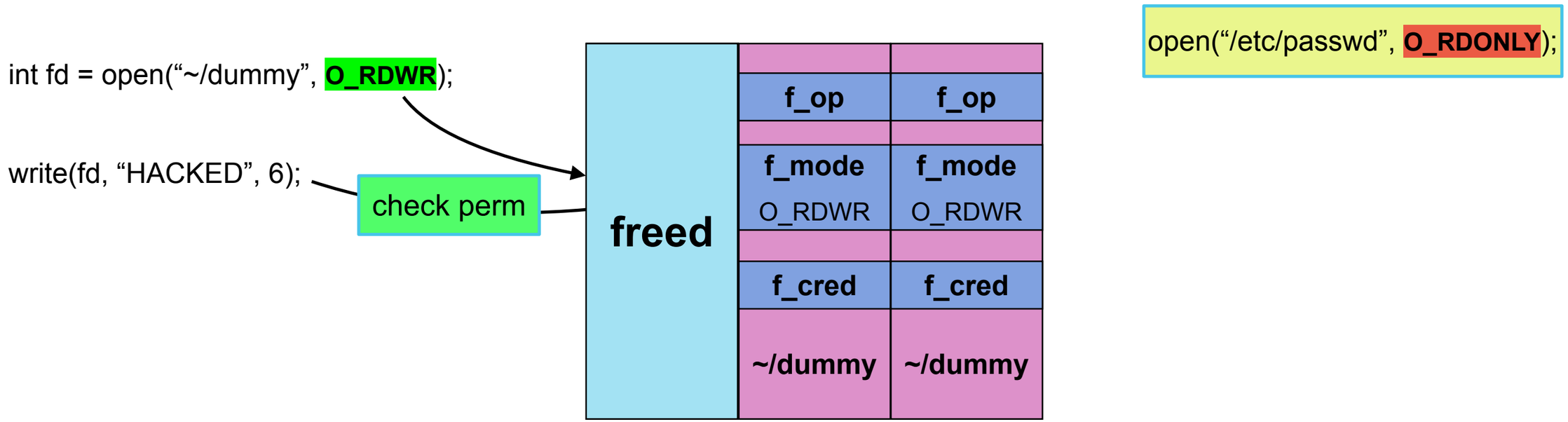


`struct file` on kernel heap

Attacking Open File Credentials

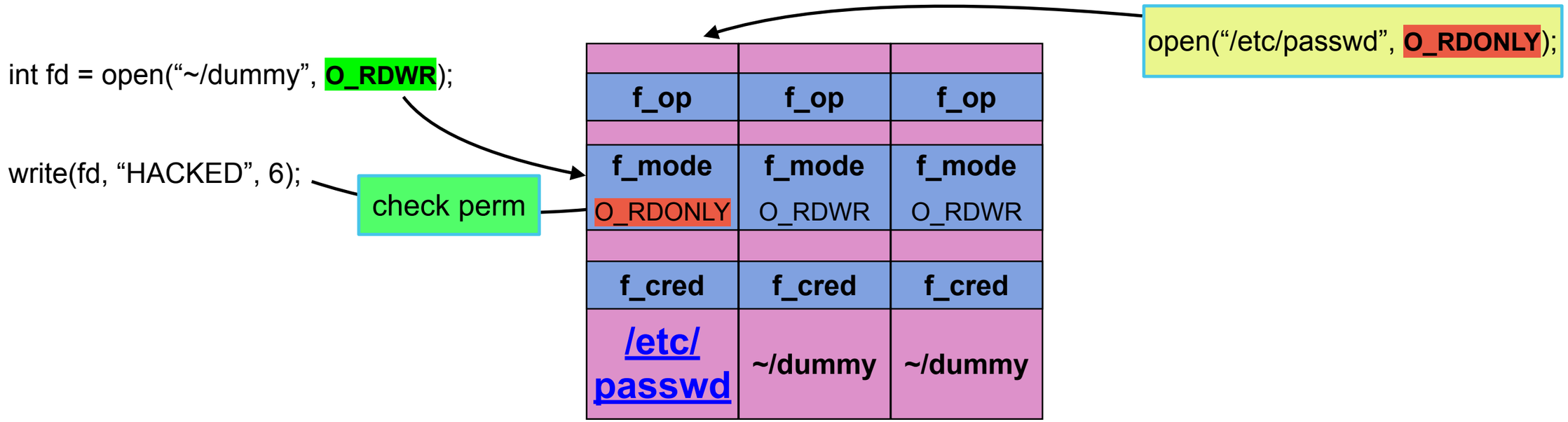
Step 2. **Allocate** a *read-only* file obj in the **freed** memory slot



`struct file` on kernel heap

Attacking Open File Credentials

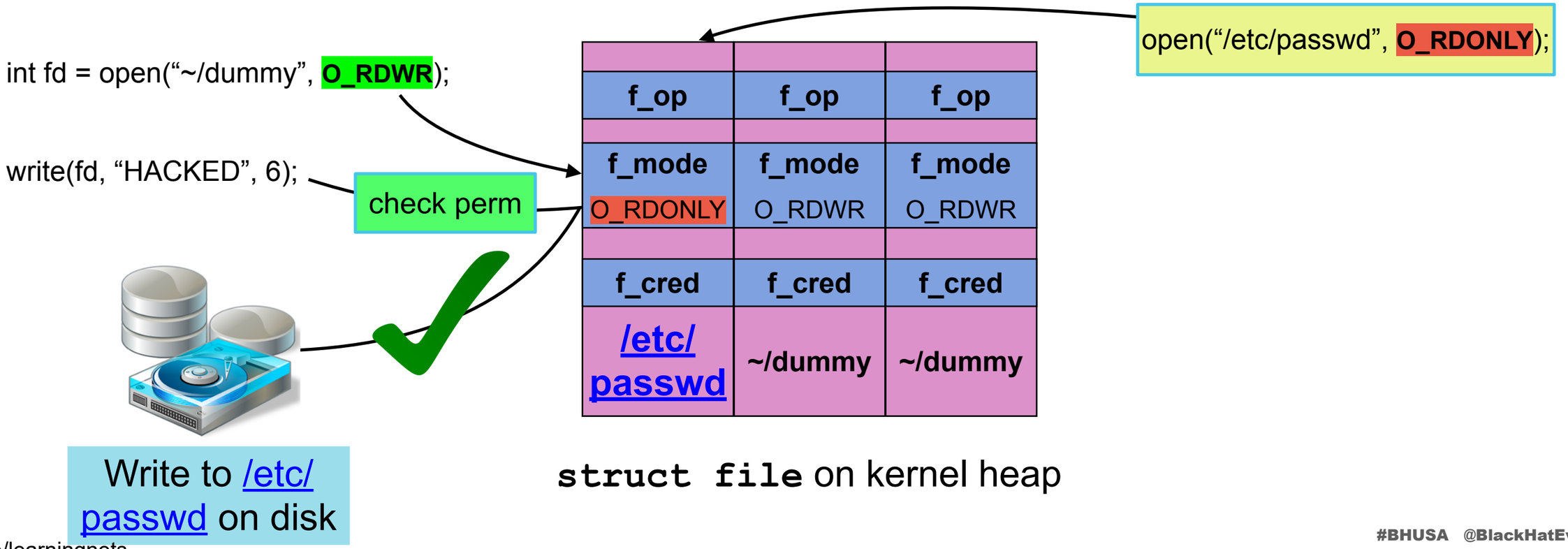
Step 2. **Allocate** a *read-only* file obj in the **freed** memory slot



`struct file` on kernel heap

Attacking Open File Credentials

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



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)

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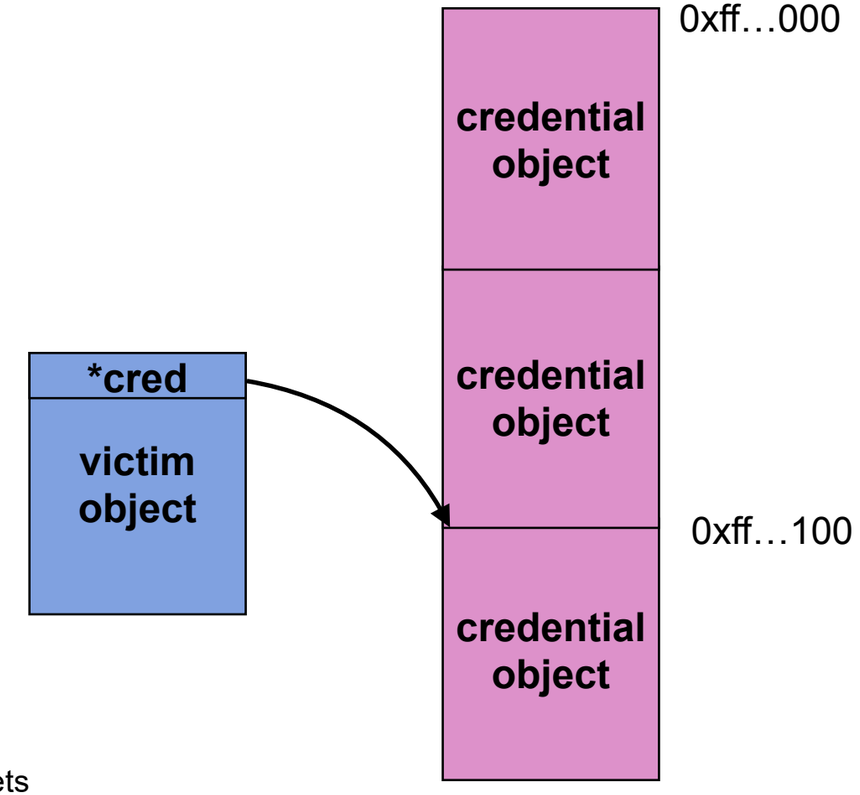
Pivoting Invalid-Write

Pivoting Invalid-Write

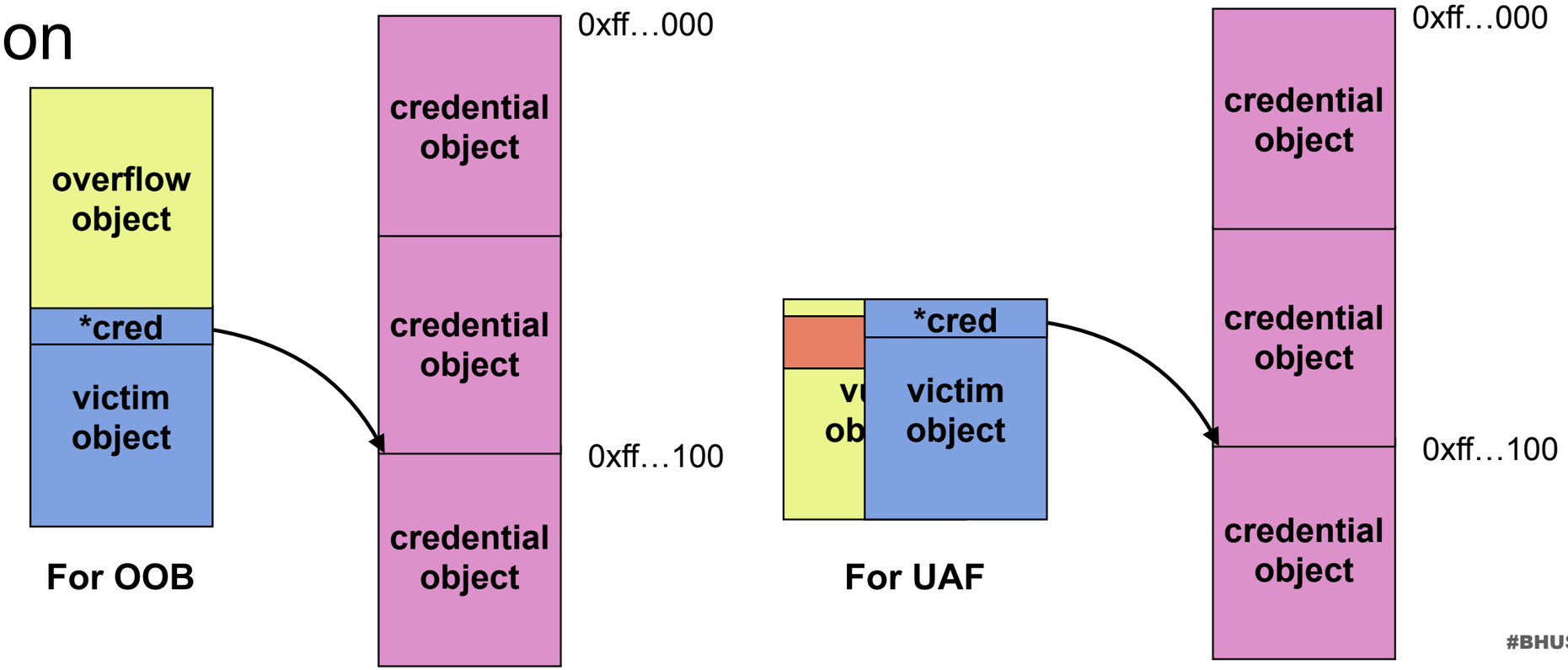
- Leverage victim objects with a reference to credentials




```
struct request_key_auth {
        struct rcu_head         rcu;
        struct key              *target_key;
        struct key              *dest_keyring;
        const struct cred       *cred;
        void                    *callout_info;
        size_t                  callout_len;
        pid_t                   pid;
        char                    op[8];
} __randomize_layout;
```

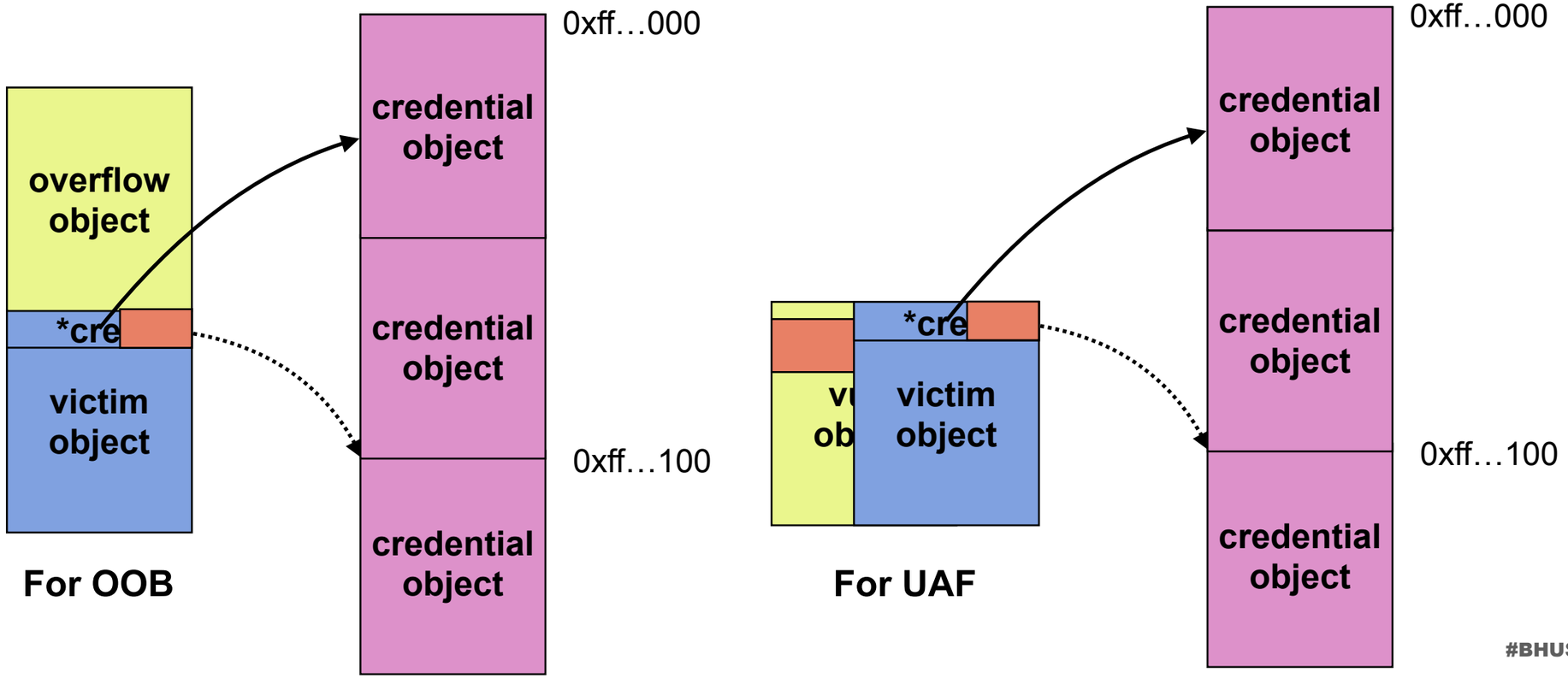
Pivoting Invalid-Write

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



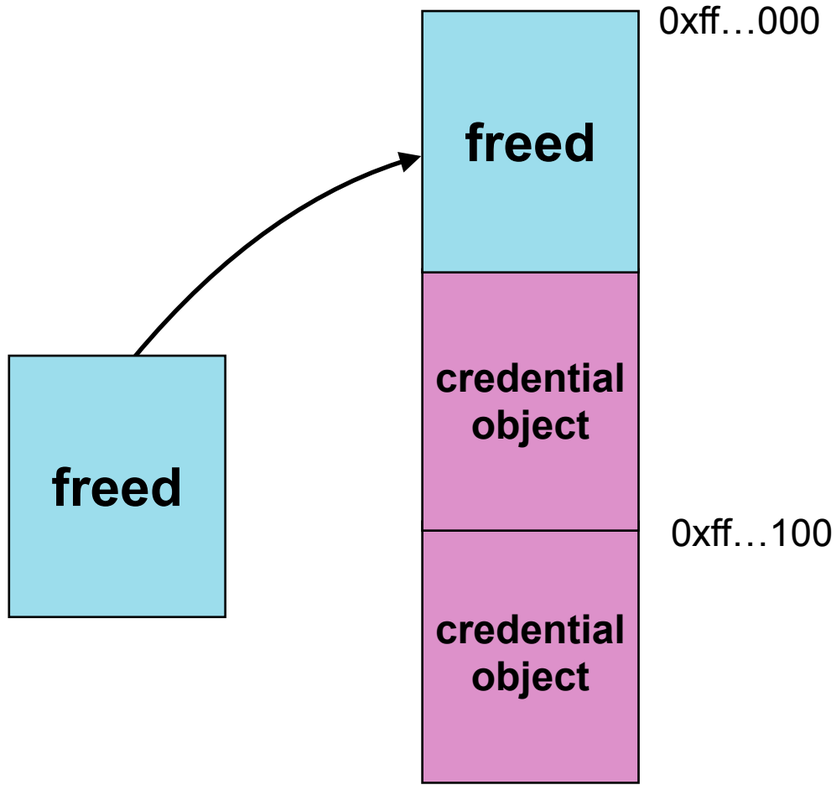
Pivoting Invalid-Write

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



Pivoting Invalid-Write

- Free the credential object when freeing the victim object



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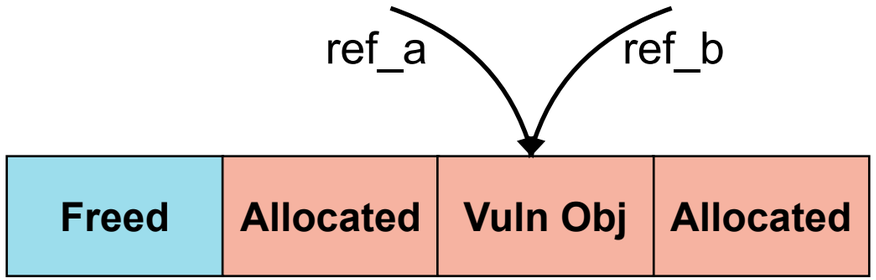
Pivoting Invalid-Free

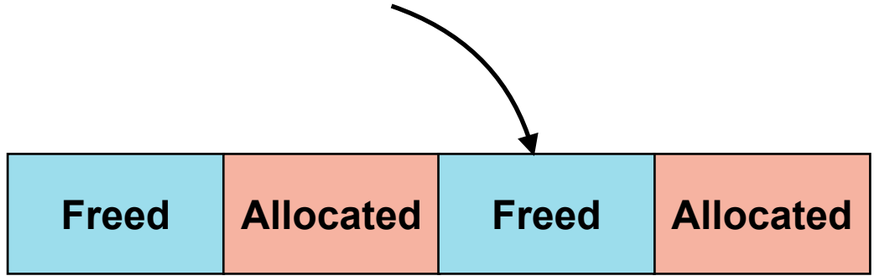
Pivoting Invalid-Free

- **Two** references to free the same object



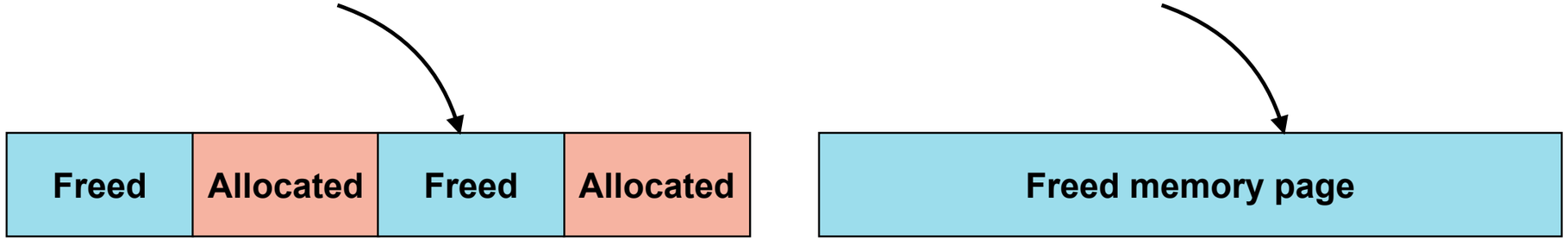
Vulnerable object in kernel memory

Pivoting Invalid-Free



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

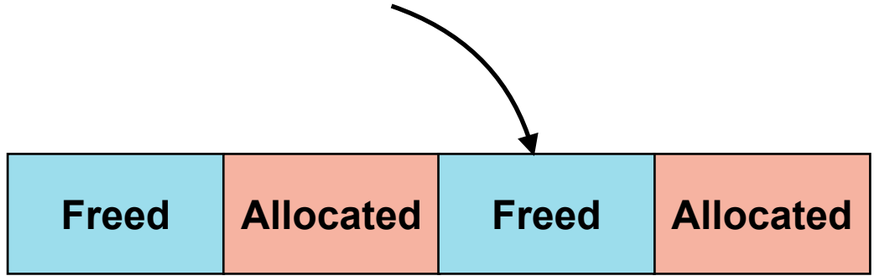
Pivoting Invalid-Free



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



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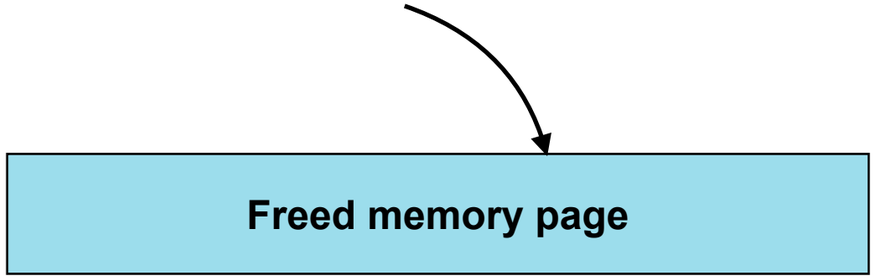

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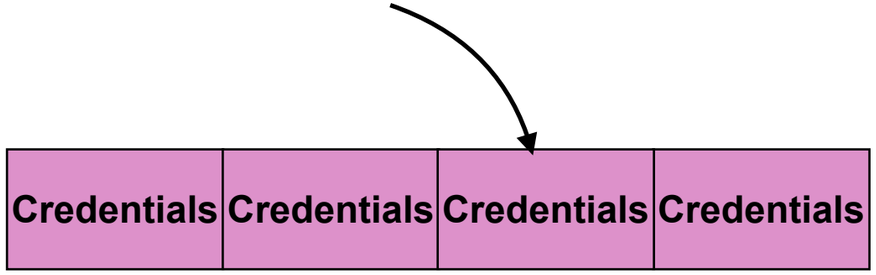
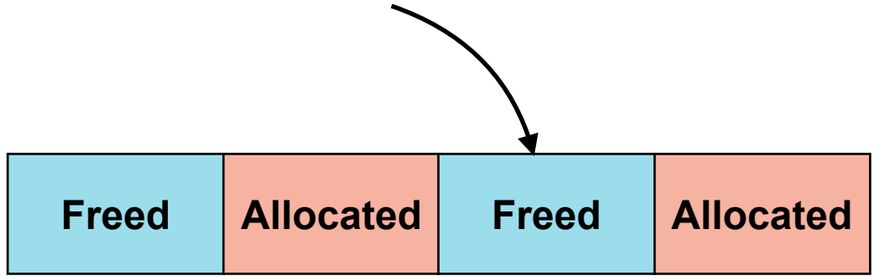


Step 3. *A*llocate credentials to reclaim the *freed* memory page (*Cross Cache Attack*)

Pivoting Invalid-Free



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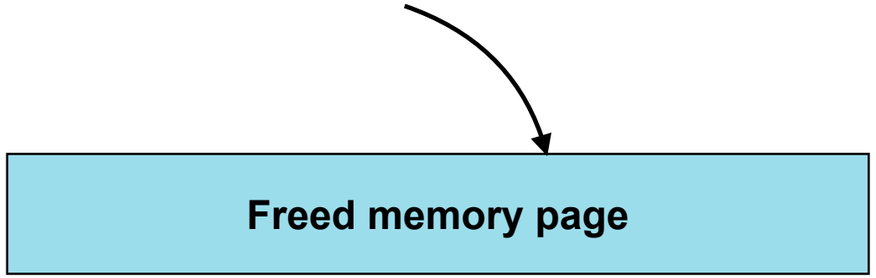

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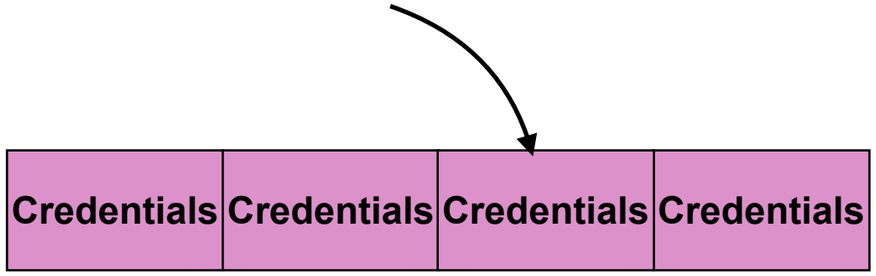
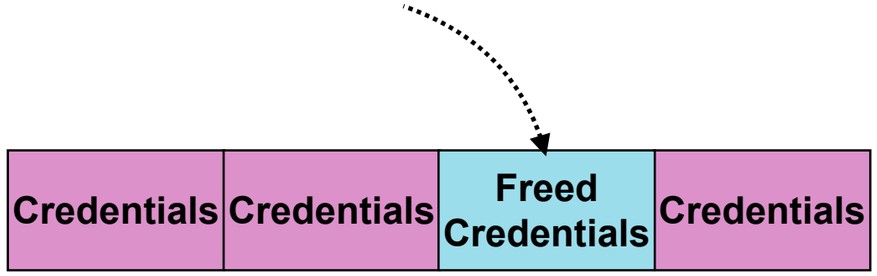


Step 3. *A*llocate credentials to reclaim the *freed* memory page (*Cross Cache Attack*)



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.
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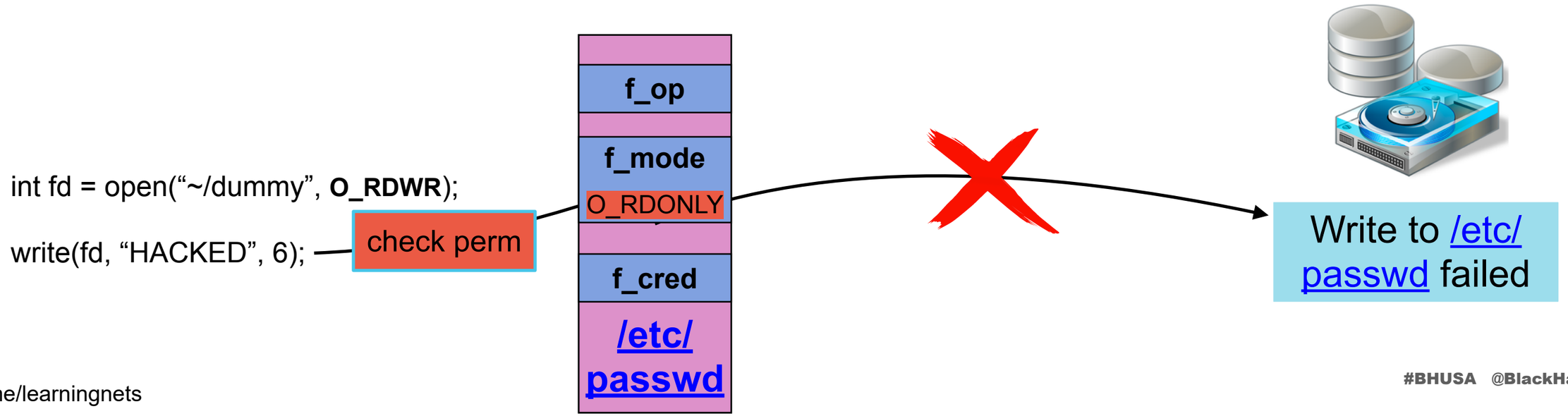
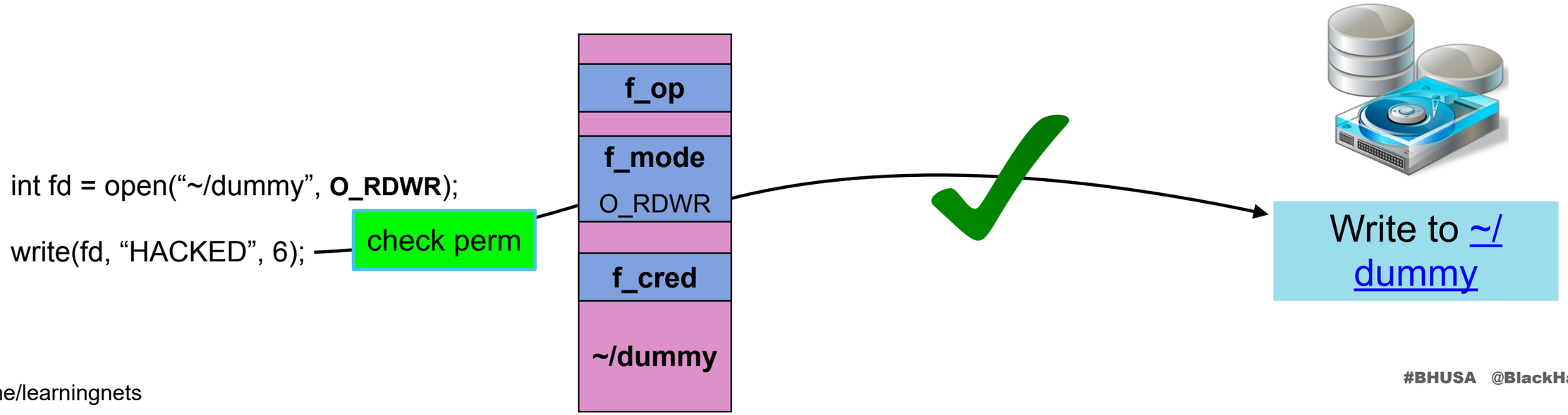
Challenge 3: Stabilizing File Exploitation

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



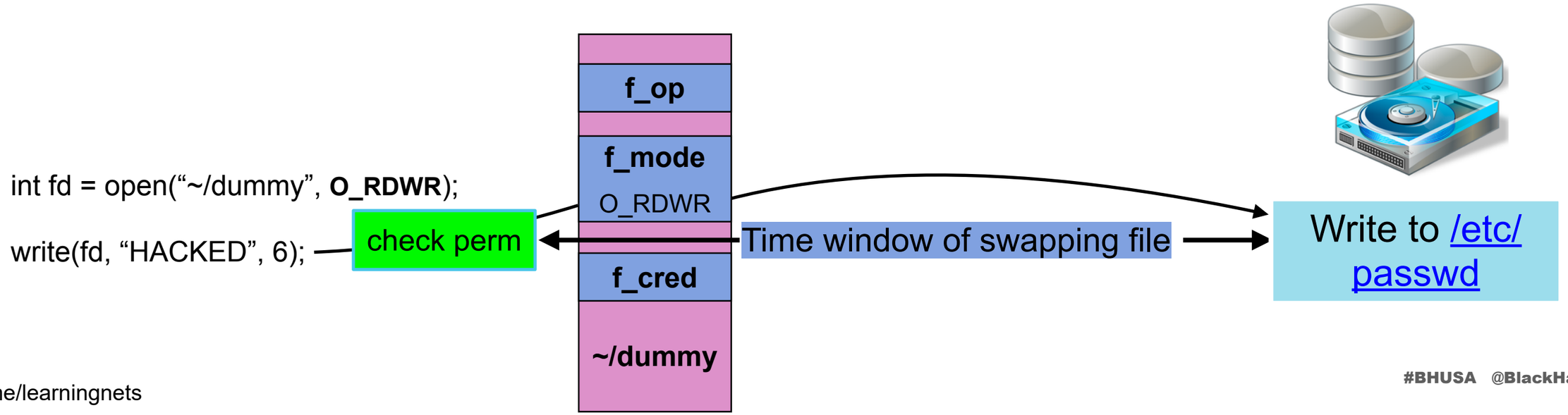
Challenge 3: Stabilizing File Exploitation

- 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 v*4.13***
  - *`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 v*4.13***
  - `import_iovec` copies userspace memory
  - Used in Jann Horn's exploitation for CVE-2016-4557
  - *Dead* after v*4.13*

Solution I: Userfaultfd & FUSE

- `vfs_writev` after v*4.13*

```
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

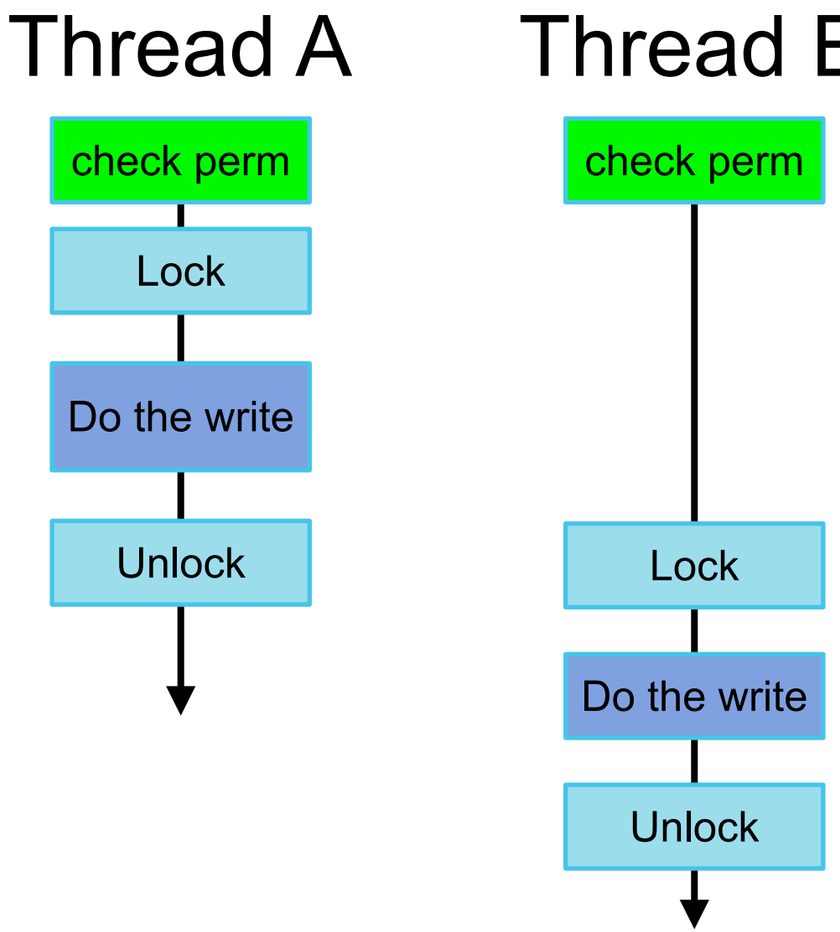
Solution II: File Lock

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

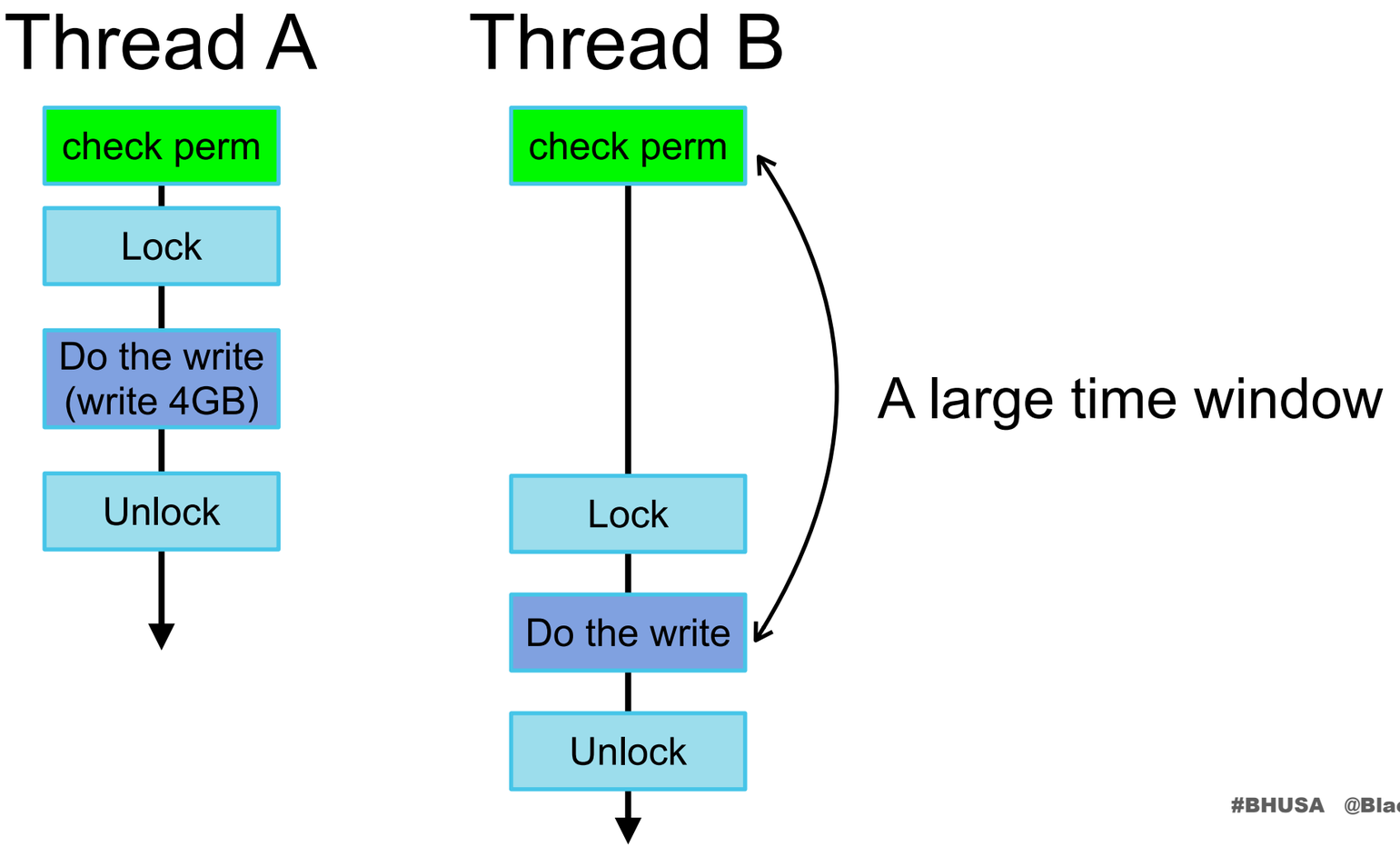
```
static ssize_t ext4_buffered_write_iter(struct kiocb *iocb,
                                        struct iov_iter *from)
{
    ssize_t ret;
    struct inode *inode = file_inode(iocb->ki_filp);
    inode_lock(inode);
    ...
    ret = generic_perform_write(iocb->ki_filp, from,
    ↪  iocb->ki_pos);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

#DirtyCred
Zhenpeng Lin
@Markak_

Solution II: File Lock



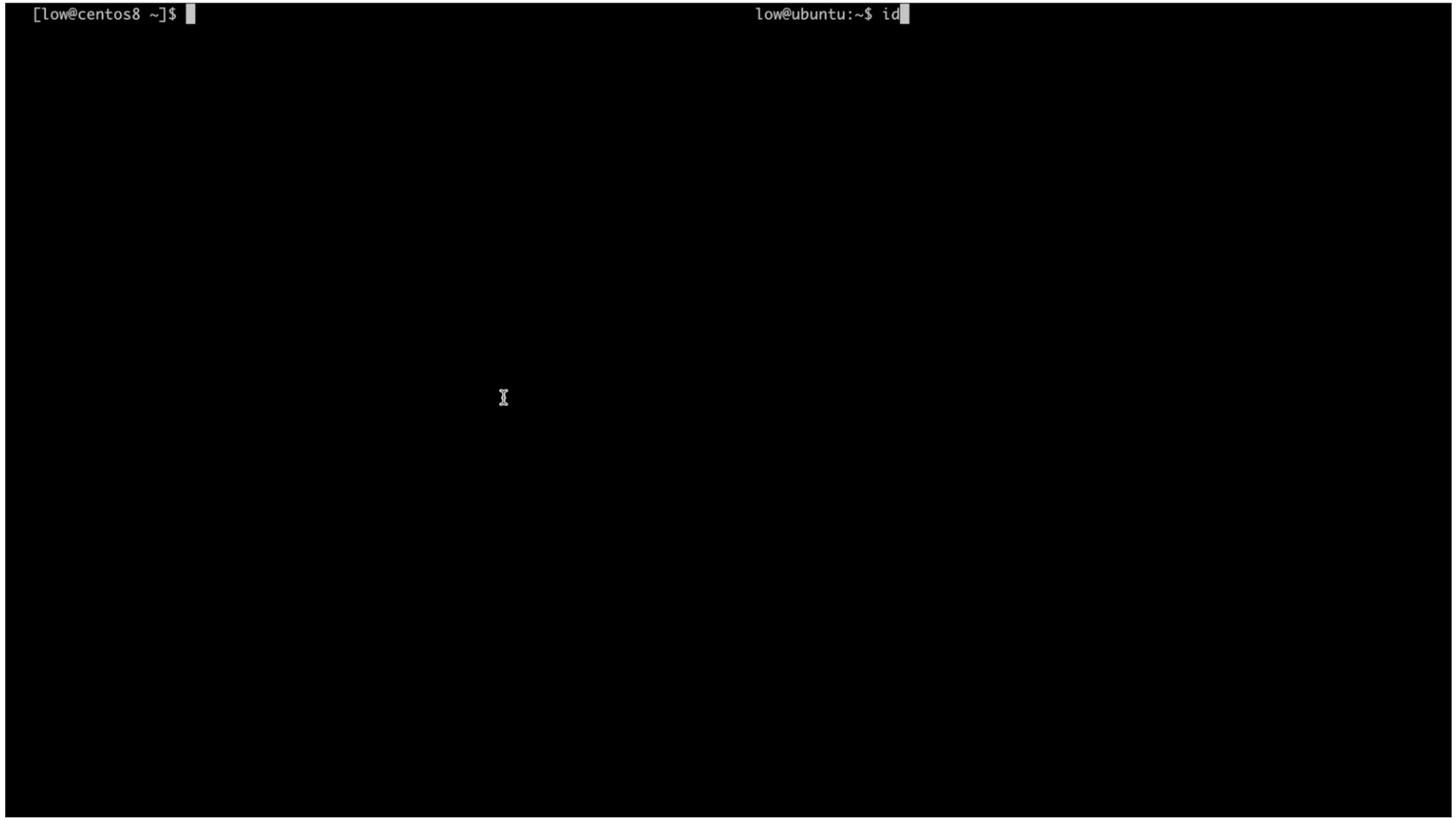
Solution II: File Lock



Demo Time!

CVE-2021-4154

Centos 8 and Ubuntu 20



Android Kernel with CFI enabled*

* access check removed for demonstration

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-liked (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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Pic comes from @sirdarckcat