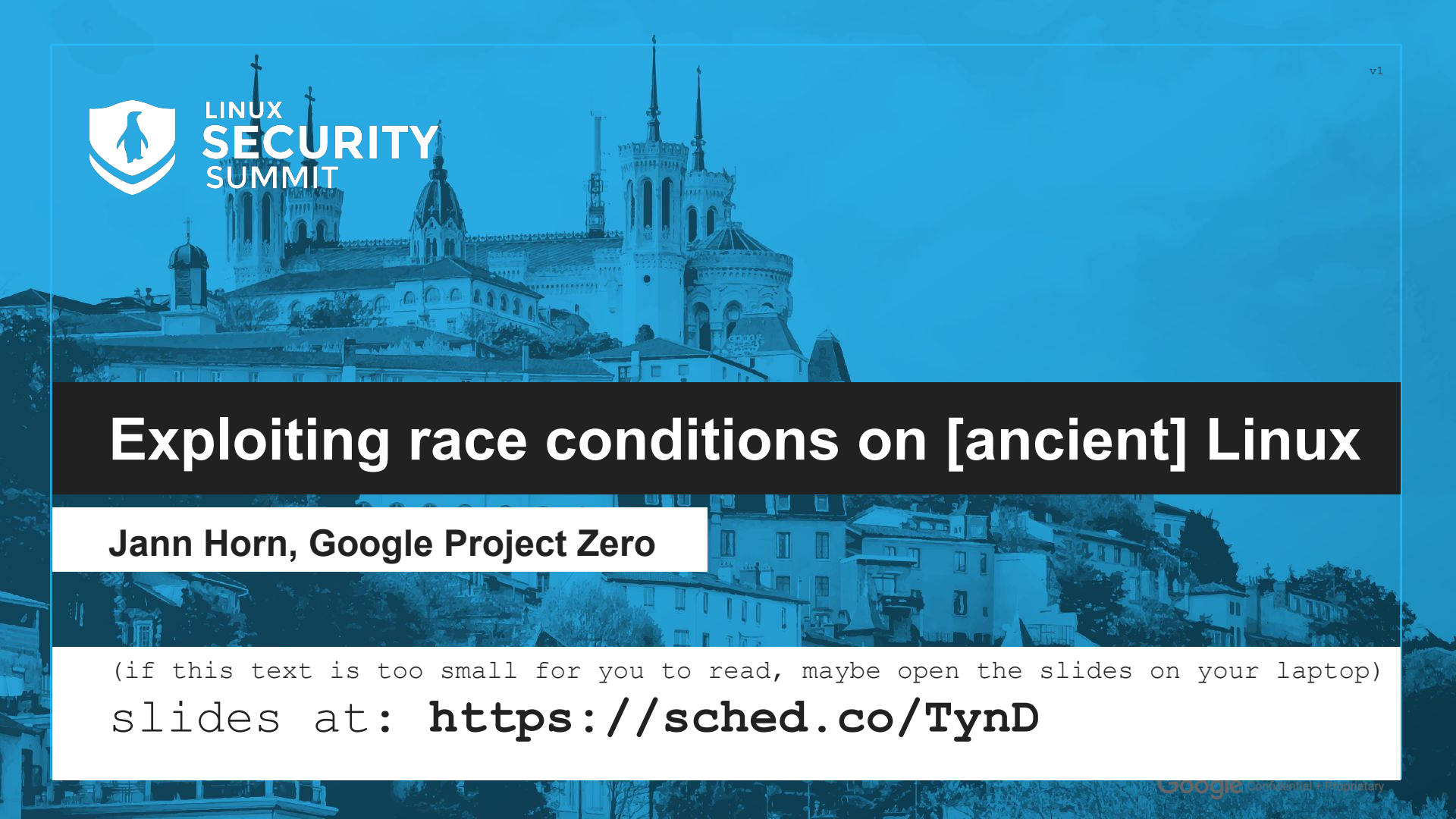


Exploiting race conditions on [ancient] Linux

Jann Horn, Google Project Zero

(if this text is too small for you to read, maybe open the slides on your laptop)

slides at: **https://sched.co/TynD**

Introduction

- bugs described here have been fixed for a long time
- all exploits against kernel 4.4
- focus on exploitation techniques, not impact of individual bugs

Agenda

- physical-page use-after-free via stale TLB [bug 1]
  - [kernel bug, PoC for Google Pixel 2]
  - buddy allocator
  - preemption and scheduler control
- refcount decrement on struct file [bug 2]
  - [kernel bug, PoC for Ubuntu 16.04]
  - userfaultfd() and FUSE
  - kcmp()
- a poor substitute for FUSE/userfaultfd [bug 3]
  - [userspace bug, PoC for Google Pixel 2]
  - i_mutex on kernel 4.4
  - priority inversion
  - repeated file mapping faults

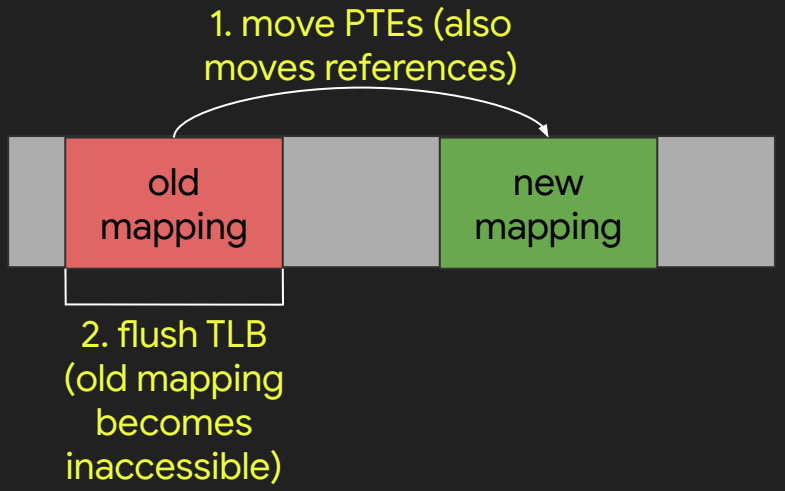
Bug 1: mremap()+fallocate() race

Translation Lookaside Buffer (TLB)

- in-CPU cache for page table entries (PTEs)
- PTEs are essentially refcounted page pointers
- TLB borrows references from PTEs
- kernel can invalidate TLB for virtual address ranges
  - x86: IPI for remote CPUs
  - arm64: magic system-wide TLBI instruction

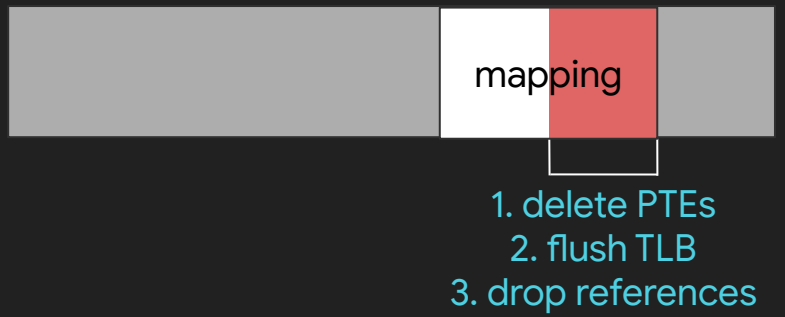
mremap(): moving a memory mapping

- moves associated page table entries (PTEs)
- has to flush the TLB for the old address range



fallocate(): (de)allocate space for a file

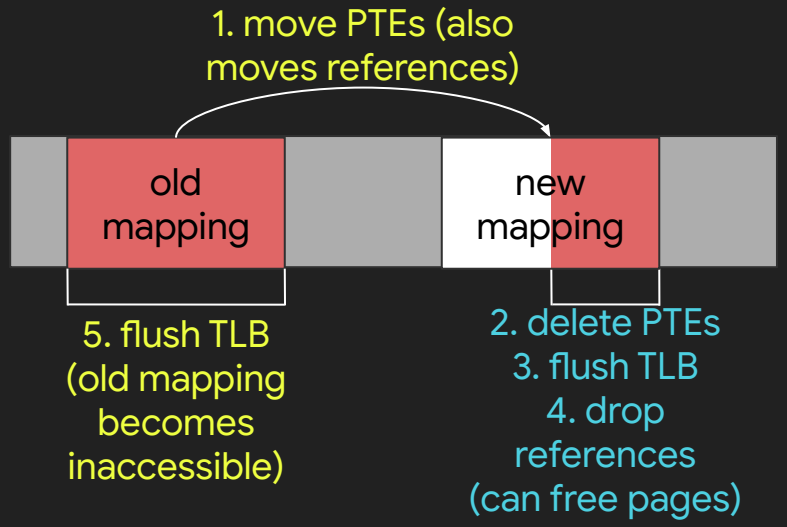
- interesting case: punch a hole in a file
- file pages in the hole are:
  - yanked out of all mappings (in all processes)
  - released once all references are gone



Bug 1: mremap()+fallocate() race

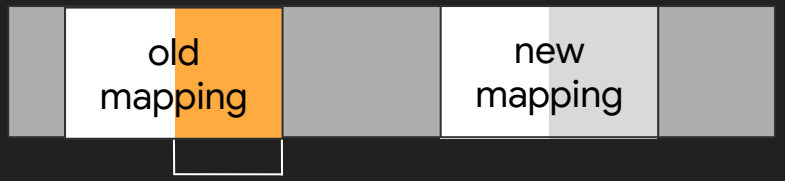
crbug.com/project-zero/1695

- mremap() holds no relevant lock between moving PTEs and TLB flush, fallocate() possible in between
- fallocate() drops page references after its TLB flush
- stale TLB entry for old mapping permits **physical-page use-after-free** between dropping page reference and flushing TLB for old mapping

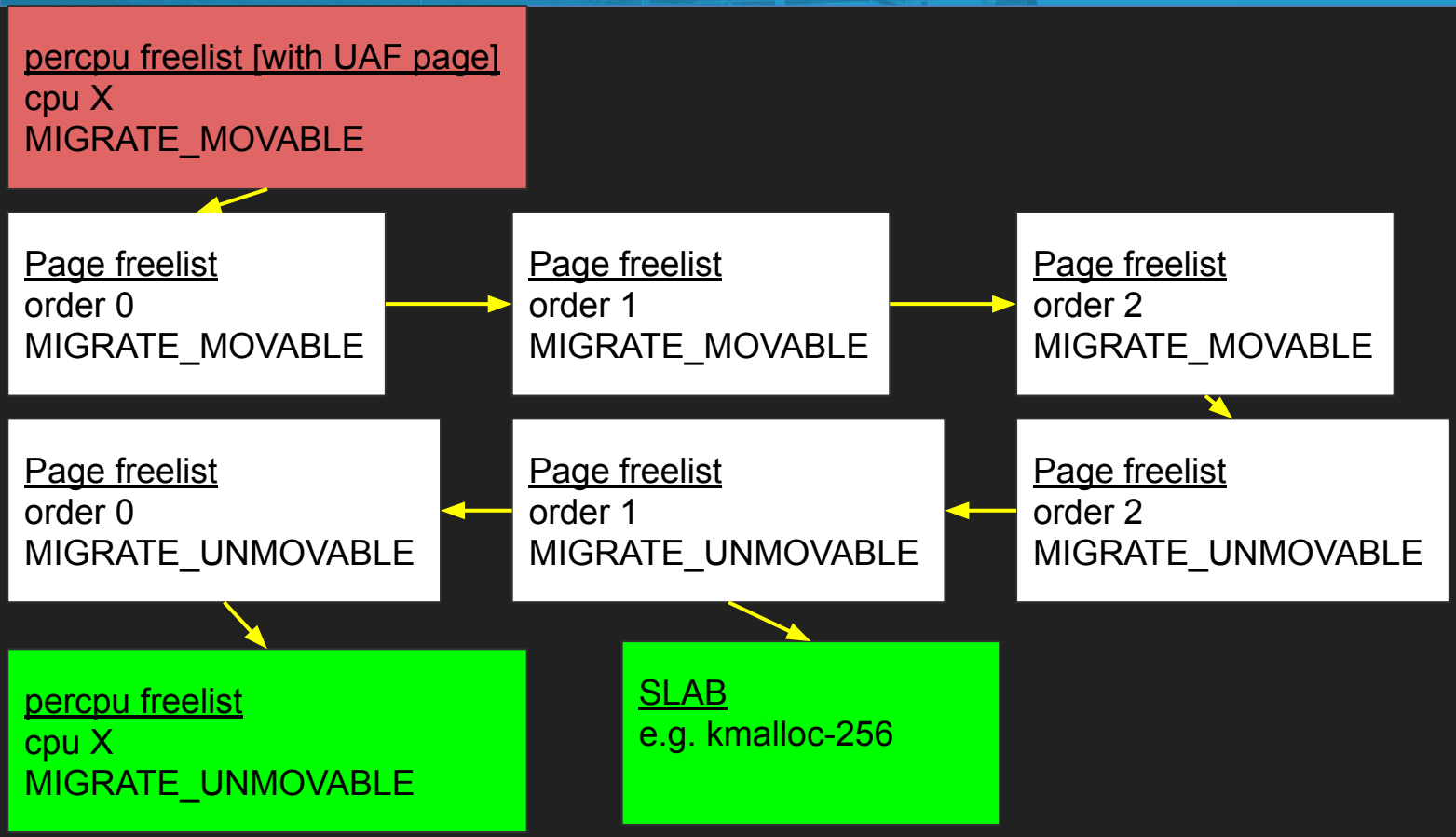


Exploit plan: Basics

- biggest impact on Linux <4.9; exploiting for *write* access is much harder on newer kernels
- goal: Pixel 2 (Linux 4.4) exploit
- exploit idea: reallocate freed page with kernel data



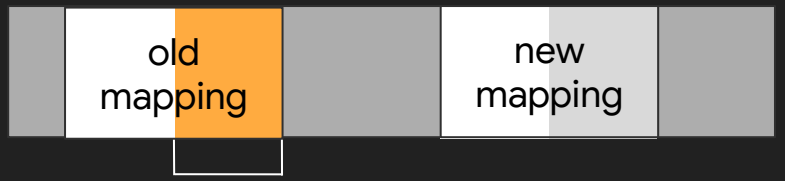
Buddy allocator



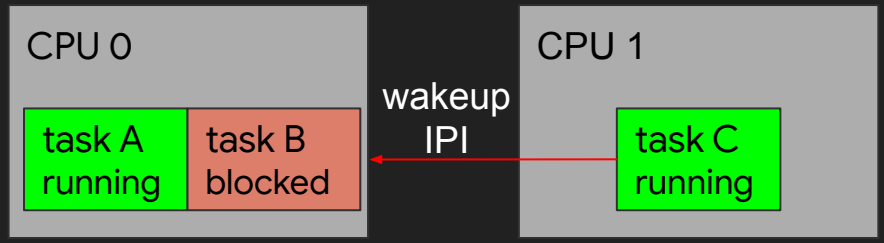
(highly simplified, not entirely correct)

Exploit plan

- biggest impact on Linux <4.9; exploiting for *write* access is much harder on newer kernels
- goal: Pixel 2 (Linux 4.4) exploit
- ~~exploit idea: reallocate freed page with kernel data~~ - ✘, looked too messy
- exploit idea: reallocate freed page as page cache for privileged code ✔
  - requires disk I/O within the race window
  - **need to make the mremap() race window wide enough for disk I/O**
- race window detectable through procfs

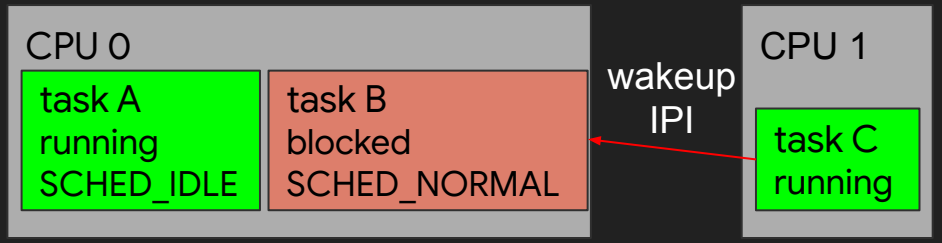


Preemption



- waking up a task can cause a scheduler Inter-Processor Interrupt (IPI)
  - depending on policy, priority and past CPU usage [see `check_preempt_wakeup()`]
- Linux supports three kernel preemption models:
  - "voluntary" preemption can yield the CPU at `cond_resched()` [called in ~1000 places]
    - used by many Linux distributions by default
  - full preemption
    - enabled on Android
    - syscall context interruptible directly via inter-processor interrupt (IPI) on task wakeup
    - no preemption in some code regions (holding a spinlock [/ preemption explicitly disabled / interrupts disabled])
    - [preemption requests in critical region are delivered on critical section exit]
    - mutexes don't block preemption!

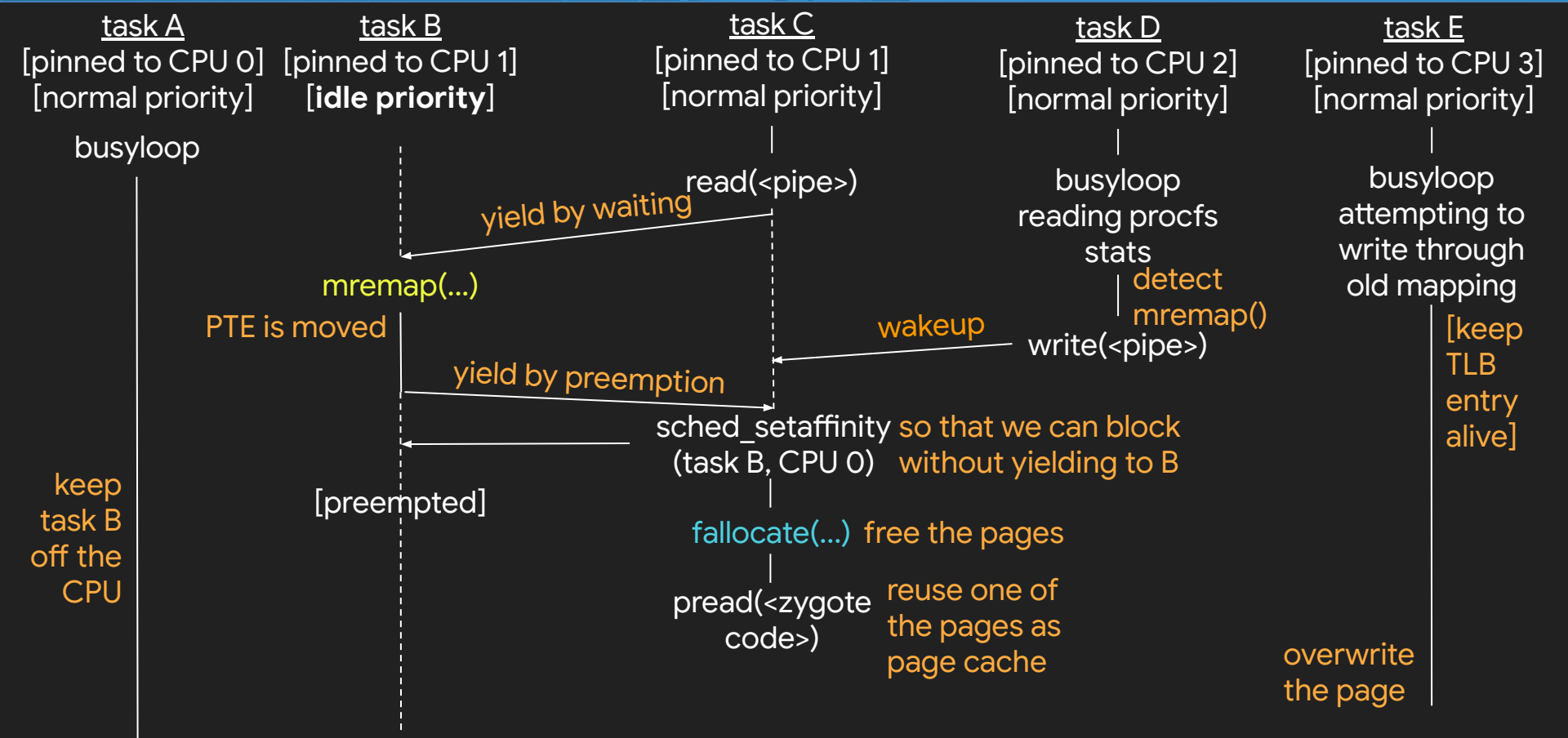
Scheduler control



- sched_setscheduler(): set SCHED_NORMAL / SCHED_IDLE
  - [realtime policies require CAP_SYS_NICE or RealtimeKit]
- on busy CPU, SCHED_IDLE has infrequent wakeups
- SCHED_IDLE never preempts
- sched_setaffinity(): pin task to CPU bitmask
- also affects execution in kernel mode!

➢ pin two own tasks to a single CPU
➢ set different scheduling classes
➢ interrupt kernel code execution

Android kernel exploit (app -> zygote)



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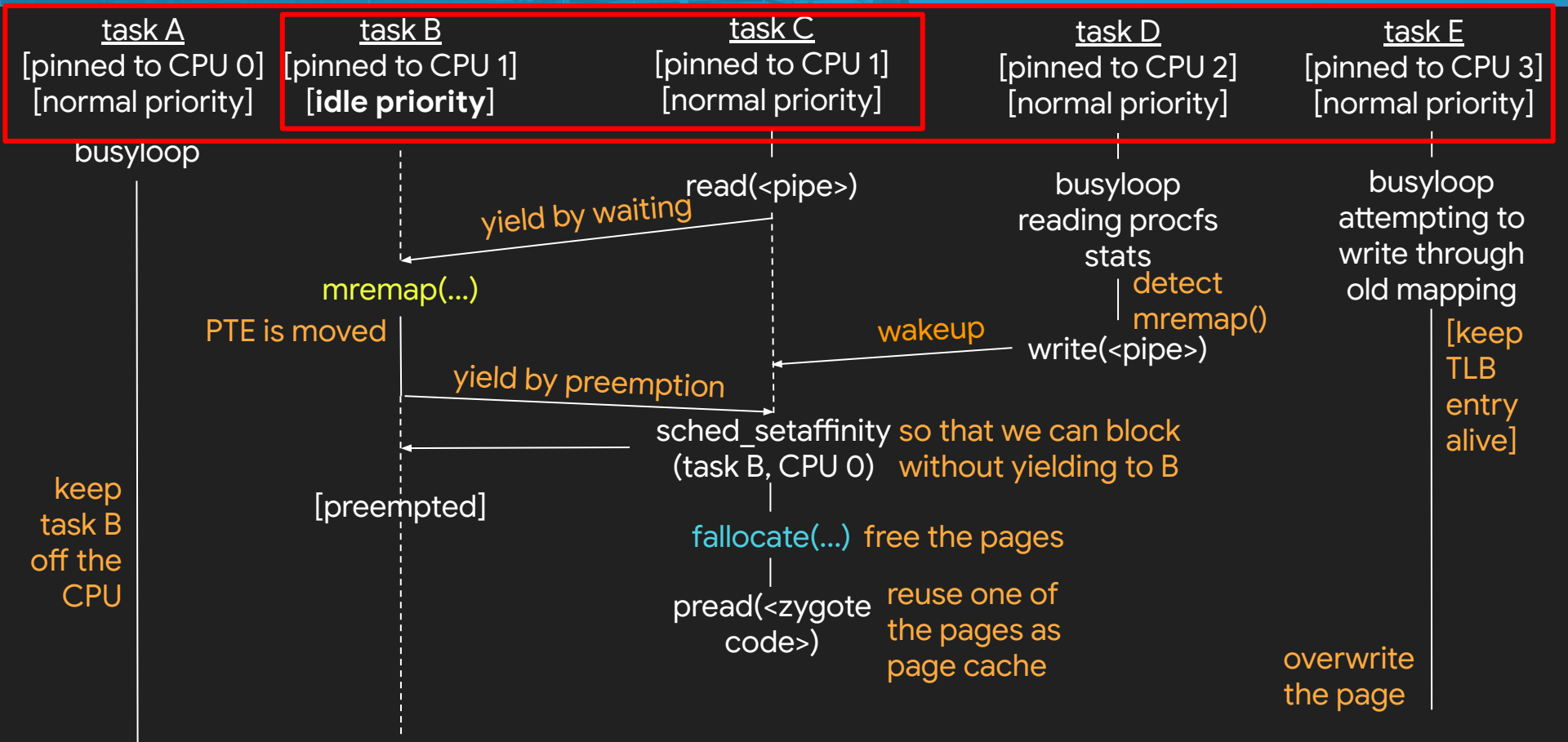

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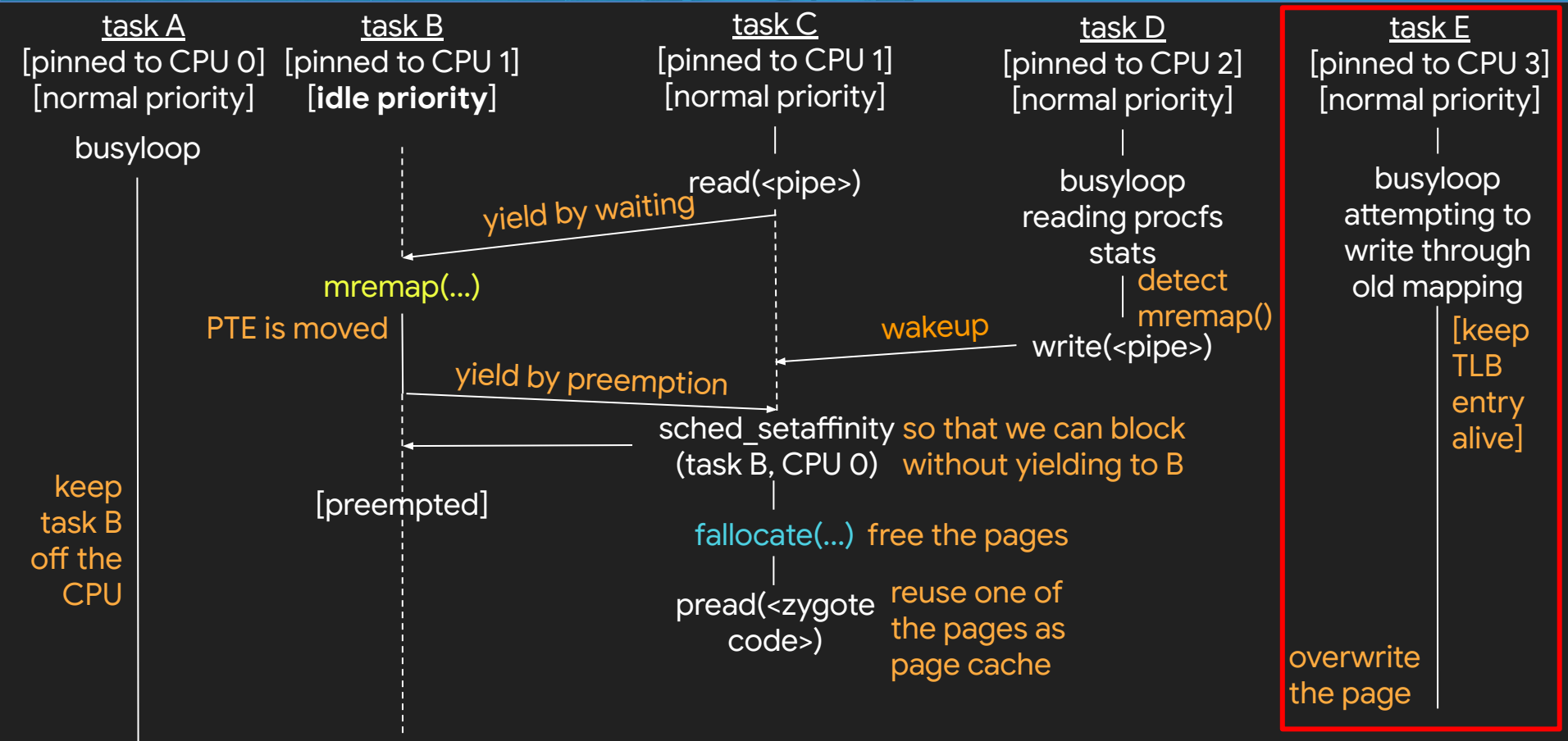

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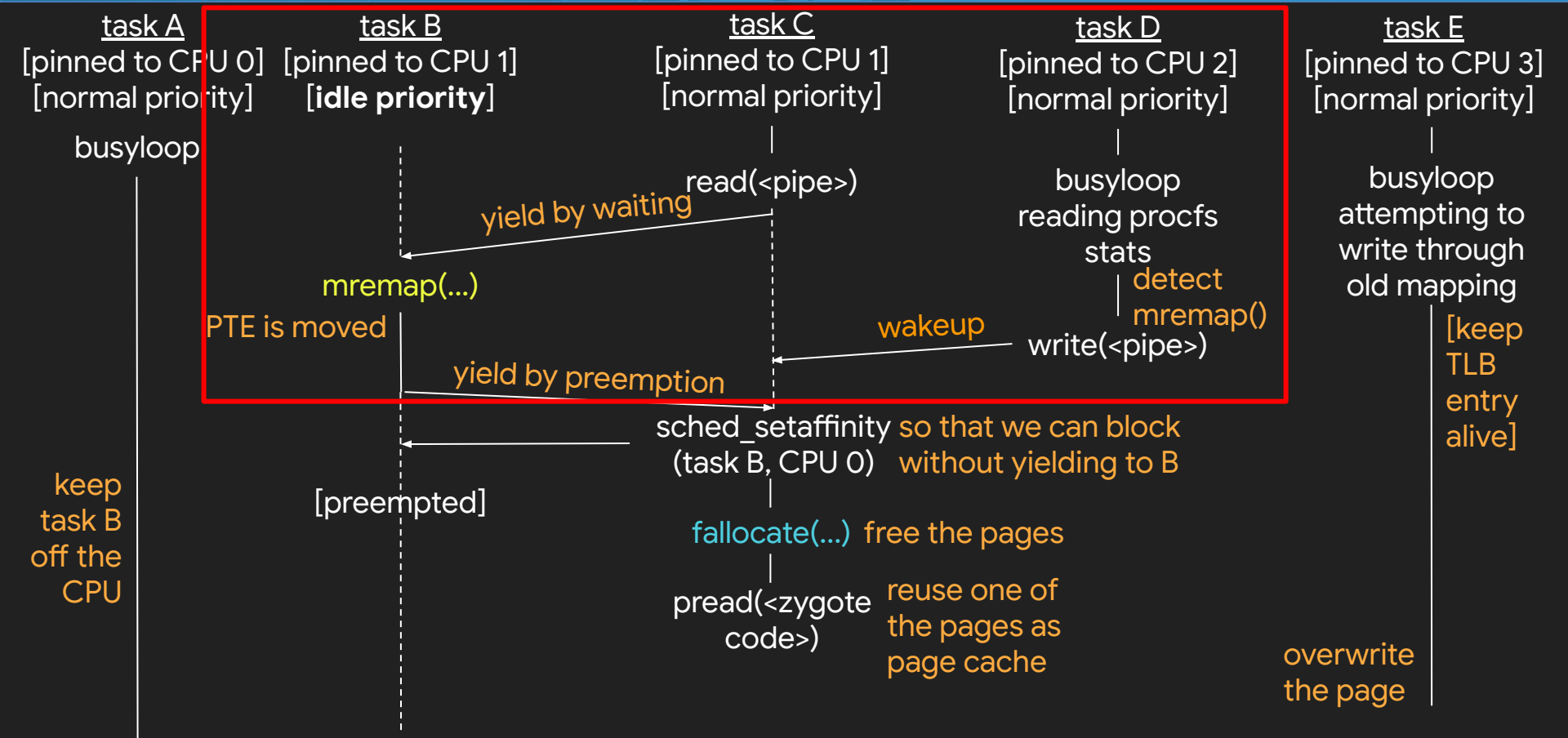

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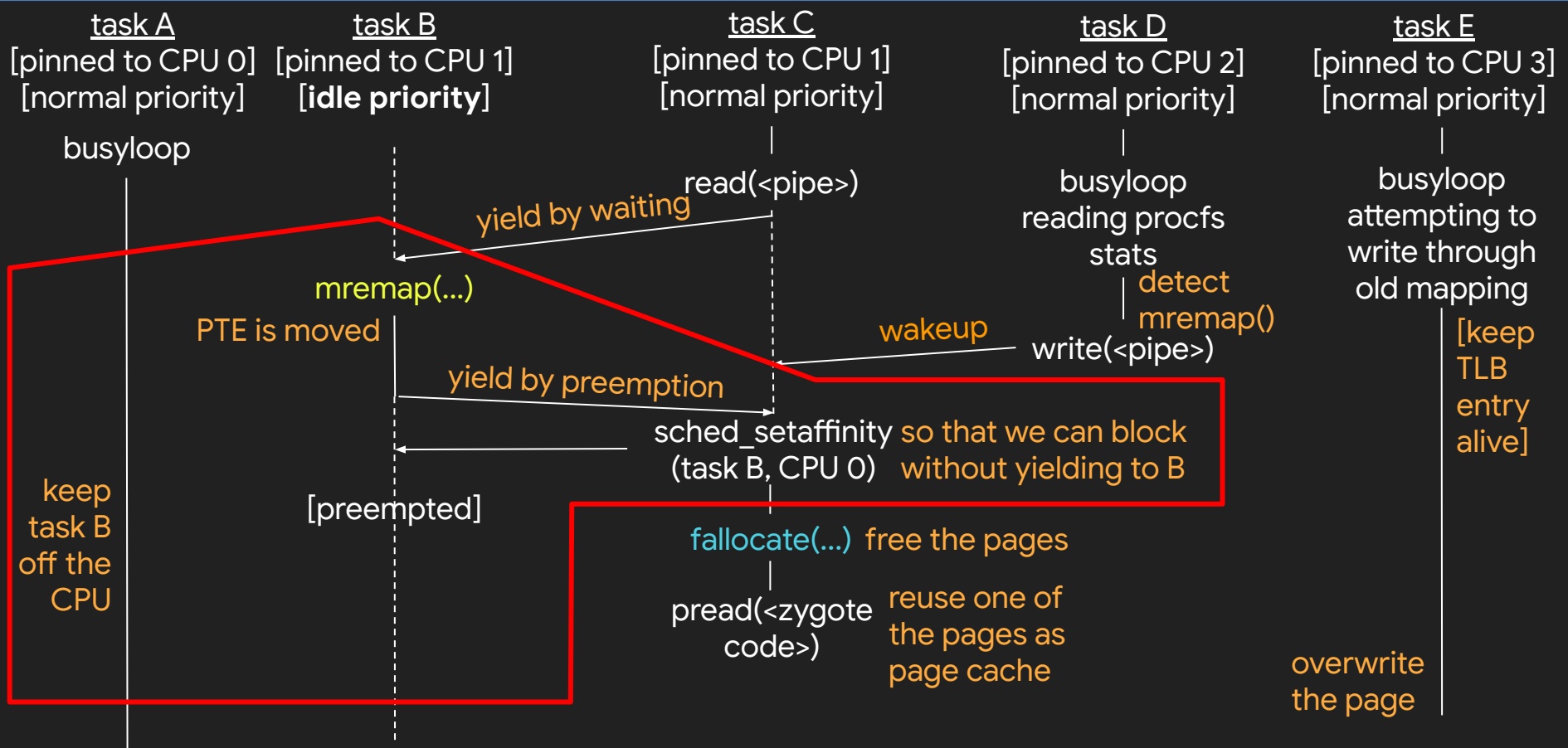

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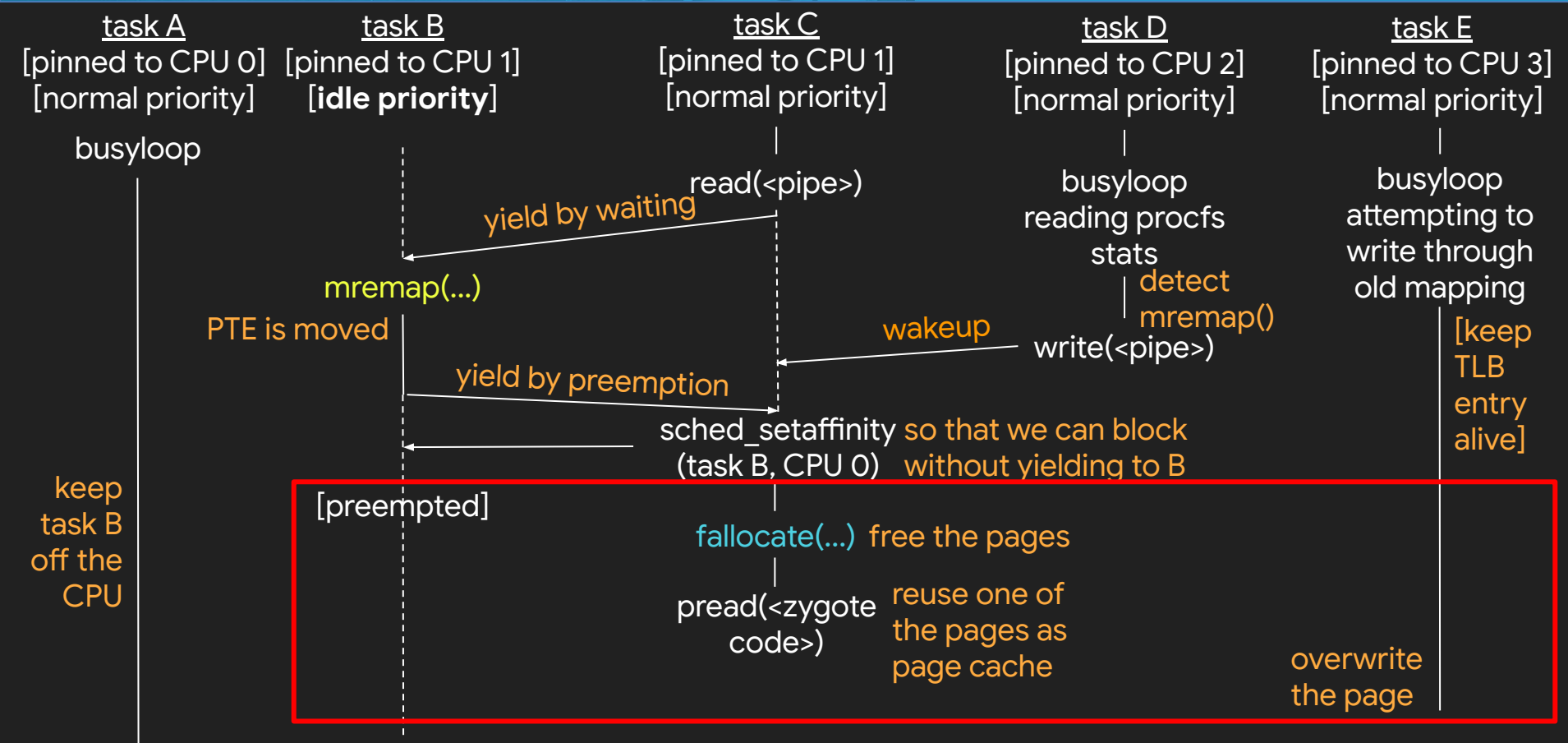


Bug 2: refcount decrement on `struct file`

(yes, the bug doesn't involve a race condition, but the exploit kinda does)

userfaultfd and FUSE

- userfaultfd() and FUSE allow userspace to synchronously handle page faults
- => userspace can block arbitrarily at copy_from_user()/copy_to_user()
- userfaultfd() and FUSE are not exposed to unprivileged Android code

=> not applicable on Android, but relevant on desktop Linux

FUSE for exploiting `struct file` refcount overdecrement in Linux 4.4

bug from 2016 to illustrate FUSE-based use-after-free exploitation

- file reference acquired with `fdget()`
- error path accidentally called `fdput()` twice
- `struct file` freed prematurely
- use-after-free
- exploited on Ubuntu 16.04

```
f = fdget(insn->imm);
map = __bpf_map_get(f);
if (IS_ERR(map)) {
  verbose("fd %d is not pointing to valid
bpf_map\n", insn->imm);
  fdput(f);
  return PTR_ERR(map);
}

struct bpf_map *__bpf_map_get(struct fd f)
{
  if (!f.file)
    return ERR_PTR(-EBADF);
  if (f.file->f_op != &bpf_map_fops) {
    fdput(f);
    return ERR_PTR(-EINVAL);
  }

  return f.file->private_data;
}
```

crbug.com/project-zero/808

kcmp() for reliable UAF

- CONFIG_CHECKPOINT_RESTORE
- smaller/equal/greater comparison between permuted kernel pointers
- intended for grouping same-object references in O(n log(n))
- works on:
  - **struct file**
  - struct mm_struct
  - struct files_struct
  - struct fs_struct
  - struct sighand_struct
  - struct io_context
  - struct sem_undo_list
- tag reuse oracle for Memory Tagging unless tag bits are ignored

```
static long kptr_obfuscate(long v, int type)
{
  return (v ^ cookies[type][0]) *
cookies[type][1];
}

static int kcmp_ptr(void *v1, void *v2, enum
kcmp_type type)
{
  long t1, t2;

  t1 = kptr_obfuscate((long)v1, type);
  t2 = kptr_obfuscate((long)v2, type);

  return (t1 < t2) | ((t1 > t2) << 1);
}
```

FUSE for exploiting `struct file` refcount overdecrement in Linux 4.4

- create FUSE mapping
- open writable file (/dev/null)
- start `writev()` with iov in FUSE mapping
- write mode check passes
- `import_iovec()` stalls on page fault
- trigger bug to free the file
- open */etc/crontab* as read-only
- verify that struct file was allocated at the same address with `kcmp()` (else re-open */etc/crontab*)
- resolve FUSE page fault
- `writev()` writes into */etc/crontab*

```
ssize_t vfs_writev(struct file *file, const
struct iovec __user *vec, [...]) {
  if (!(file->f_mode & FMODE_WRITE))
    return -EBADF;
[...]
  return do_readv_writev(WRITE, file, vec,
vlen, pos);
}

static ssize_t do_readv_writev(int type,
struct file *file, const struct iovec __user
* uvector, unsigned long nr_segs, loff_t
*pos) {
[...]
  ret = import_iovec(type, uvector, nr_segs,
        ARRAY_SIZE(iovstack), &iov, &iter);
[...]
  if (iter_fn)
    ret = do_iter_readv_writev(file, &iter,
pos, iter_fn);
[...]
}
```

Bug 3: use of getpidcon()

int getpidcon(pid_t pid, char **context)

- userspace daemons need to check peer SELinux contexts
- unix domain sockets: SO_PEERSEC
- Android binder: until recently no context name, only sender PID

```
fd = open("/proc/$pid/attr/current", O_RDONLY)
read(fd, buf, len)
```

Bug 3: race condition in hwservicemanager

crbug.com/project-zero/1741

- receive binder IPC call (with caller PID)
- `getpidcon(pid, &context)`
- ACL check for `context`

- exit and make privileged thread reuse the PID
- race window can be widened to ~15s

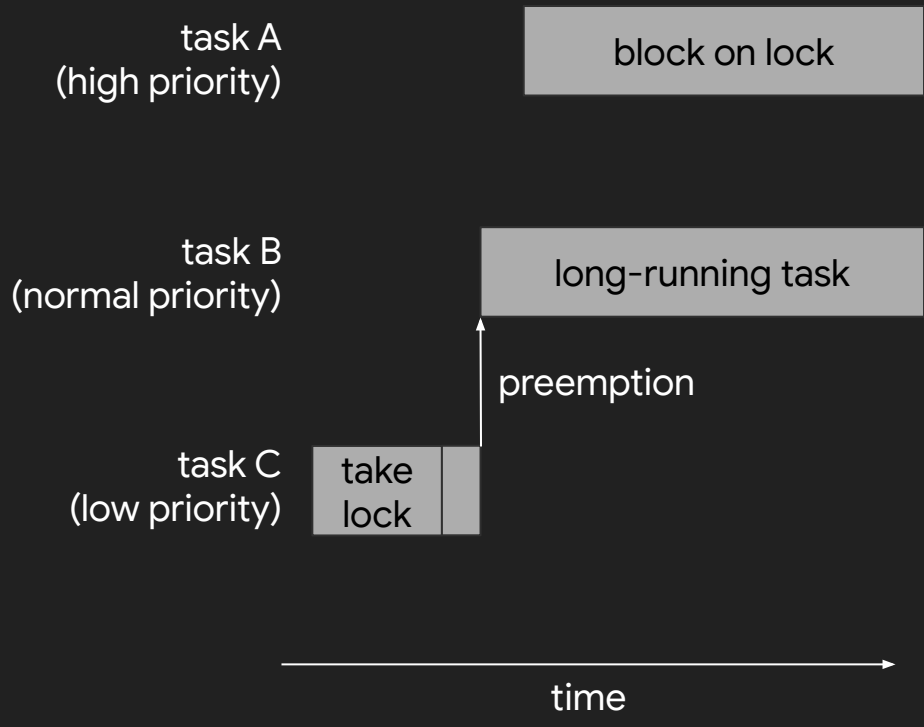
i_mutex on kernel 4.4

- `sys_getdents()` (for `readdir()`) iterates directory entries and copies to userspace under `inode->i_mutex`
  - potentially a large amount of data if the directory has many entries
- `lookup_slow()` (for looking up uncached directory entries) takes `parent->d_inode->i_mutex`
- => blocking userspace access in the middle of `sys_getdents()` blocks concurrent path traversal (e.g. `open()`) on the same inode

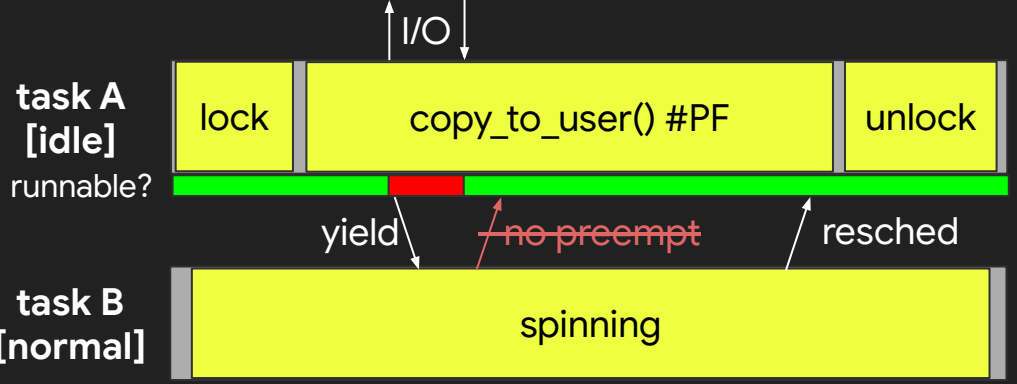
(Linux >=4.7 uses a semaphore `i_rwsem` in read mode instead of `i_mutex`)

Priority Inversion

- high-priority task blocks on mutex held by low-priority task
- low-priority task is preempted by medium-priority task (same CPU)
- also applies for violating fairness between two normal-priority tasks
- kernel mutexes are vulnerable to priority inversion!
  - (unless you're on PREEMPT_RT)
- => we can artificially create a priority inversion problem
- mitigated by infrequent idle-priority scheduling



Major faults



Instead of userfaultfd():

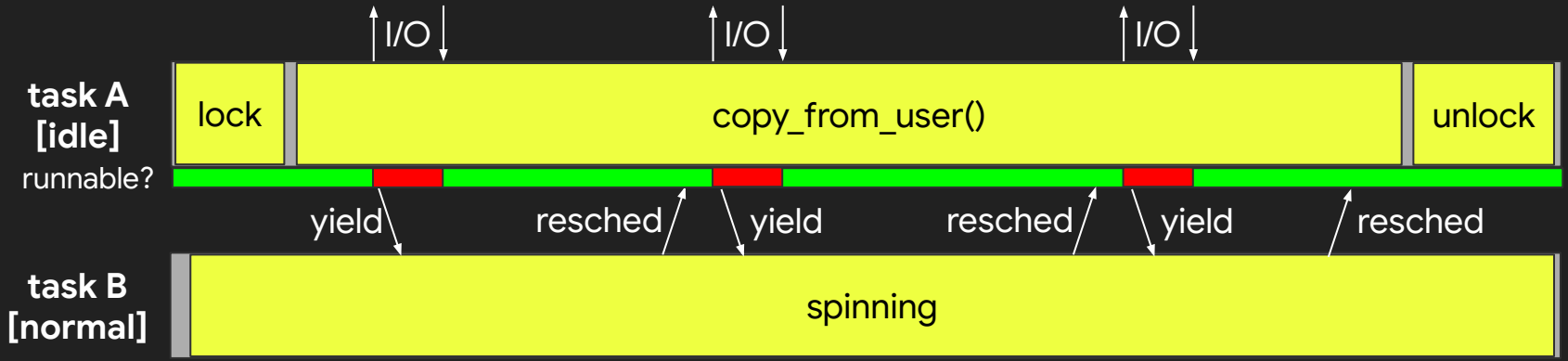
- create an uncached writable file mapping
  - [by filling up RAM with other data to force page cache eviction]
- let A trigger copy_to_user() on the file mapping while holding a lock
- let B spinloop at the same time

Consequences:

- copy_to_user() enters disk I/O path
- I/O path sleeps until disk responds, yielding the CPU
- scheduler won't preempt B when A is runnable again

Repeated file mapping faults

- [map pages such that readahead logic can't fire]
- 83560 bytes output from sys_getdents() = 21 pages [rounded up]
- >1s delay per disk read because of scheduler policy
- => >21s total delay



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Timing diagram