Unexpected, Unreasonable, Unfixable: Filesystem Attacks on macOS

Gergely Kalman

OBTS v6, 2023

Who am I

- my name is **Gergely** (

), but you can **call me Greg**
- lifetime computer nerd**:**
  - **hacking, linux, networks, coding (C, Python)**
- my job is:
  - ~~sysadmin~~
  - ~~programmer~~
  - ~~entrepreneur~~
  - ~~consultant~~
  - **independent bug hunter**
- my views are mine and mine alone

Intro

- we will attack **file operations** on **macOS**
- this is the **condensed** version
  - more info on my blog:
    - **https://gergelykalman.com**
    - or **bottom right corner**
  - two bugs (that were cut) are already up
  - the rest will follow
- my twitter: **@gergely_kalman**

Why attack file operations?

- they're **simple** (to find and exploit)
  - ubiquitous and often a result of **bad design** (→ hard to fix)
  - a **failed exploit has no downside**
- they're **dangerous**
  - a treasure trove of "classic" **LPE**s
  - **TCC + entitlements** made a lot of useless bugs bounty-eligible
    - by rugpulling **POSIX** and **30 years of legacy code**
- **Nobody is paying attention!**
  - and that's good, because I can't learn all the **CFI** / **PPL** / **PaC** BS

Terminology

- **LPE** is **user** → **root**
- **TCC bypass** is **user** → **user with FDA**
  - **FDA** → location, camera, contacts, etc...

How hard are file operations?

- well...

How hard are file operations?

no copy() syscall

“Everything is a file”

legacy filesystems

symlinks are hard to prevent

in-band signaling in file operations

. and .. are special

network filesystems

race conditions everywhere

POSIX permissions are incredibly complex

mountpoints can move

CWD is unintuitive

How hard are file operations?

no copy() syscall

case-insensitivity

reliance on extended attributes

“Everything is a file”

legacy filesystems

user sets fs options

user mounting

/.file, /.vol/

symlinks are hard to prevent

in-band signaling in file operations

firmlinks

sandbox_exec

union mounts

. and .. are special

user can change mount options at runtime

network filesystems

noowners

race conditions everywhere

applesingle/appledouble

in-band signaling: /..namedfork/rsrc

POSIX permissions are incredibly complex

(force) unmount

hardlinked directories

mountpoints can move

CWD is unintuitive

My bag of dirty tricks

- races: **TOCTOU**s, **rename()**s
- reshape the **fs** graph while in-use
- set **CWD** to a nonexistent directory
- hardlink a directory, hardlink a symlink
- use inheriting **ACL**s
- modify **xattr**s by editing applesingle / appledouble files
- rugpull programs
  - by force unmounting
  - by moving the mountpoint

My bag of dirty tricks

- mount (as a user):
  - a network volume with 5s latency
  - use mount options with **noowners**, **union**, **etc...**
  - update the mountpoint or remount in place
  - change filesystem e͆͜n̄c̬̃ỏ̱d̆͟i̡n̂g̊͆
  - use filesystems that don’t support **xattr**s
- corrupt the filesystem image:
  - create a directory loop
  - hardlink directories at the top level
  - make “..” point not to the parent
  - create structures that normally would not be possible

REALLY STUPID RS CONTENT RATED BY ESRB

File operations ARE hard

- an **unprivileged user** can do any/all of this
- So is this the end of the World?
  - No, but **Apple** is in a tough spot…
  - **without total FS isolation, TCC will always be problematic**
  - but to be fair: **TCC is better than nothing**
- **Apple** doesn’t isolate apps with **uid**s like **Android**
  - IDK why, but if you do → **DM** me :)

Our focus

- we will focus on **TCC bypass** and **LPE**
- lots of good syscalls, but the best are:
  - **open()** and **rename()**:
    - they're everywhere
    - they're easy to mess up
    - they're useful for **LPEs** and **TCC bypasses**
  - these are promising, but I don't have time:
    - **unlink()**, **rmdir()**, **mkdir()**: Ubiquitous, but tricky to exploit
  - honorable mentions:
    - chmod, chown, setxattrs, umask, chflags, clonefile, readlink, link, symlink, etc…
    - Rare and usually only good for **LPE**s

The obstacles

1) file **path control**
2) file **content control**

- **more control → higher severity**
  - partial control over each is only good for **LPE**s
  - for **TCC bypass** you need **full path and content** control
    - if I missed smth → **DM**s are open

The allies

- **lots of large entitled apps**
- **sudo**
- bad POSIX APIs: **O_NOFOLLOW**, no symlink prevention, etc...
- **atomic rename** → renamex_np() / renameatx_np() + RENAME_SWAP
- **user mounting**

The allies

- **string truncation bugs**
  - can help you get **full path control** → common and deadly
- **rename bugs:**
  - **rename()** always follows symlinks
  - **rename()** can be racy...

The allies

- **rename(“./tmp/a”, “./tmp/b”)** is a race-condition
  - “**./tmp/a**” and “**./tmp/b**” are looked up **separately**, and **CWD** is implicit
  - if I control any non-last path component in **CWD** I can turn this into
    - **rename(“anything/a”, “somethingelse/b”)**
  - **write a file called “b” anywhere**, with **fully controlled contents :)**
  - **CAVEAT: rename(“./a”, “./b”)** does not work, there has to be a real, attacker controlled subdirectory :(

Things I look for

- insecure **open():**
  - bad path, bad/missing flags
  - classic access() / open() races
  - file “copy”
  - file “recreation”
- insecure **rename():**
  - bad path
  - **dangerous renames**

The bugs

librarian (CVE-2023-38571) - **TCC bypass - check blog**

unnamed app sandbox escape (CVE-2023-32364) - **app sandbox escape - check blog**

1) **lateralus** (CVE-2023-32407) - **TCC bypass**
2) **sqlol** (CVE-2023-32422) - **TCC bypass**
3) **batsignal** (no CVE) - **LPE**
4) **alfred** (CVE-2023-40443) - **LPE**
5) **badmalloc** - (CVE-2023-32428) - **LPE**

Cut bugs

- **librarian** - TCC bypass
  - **fully controlled rename()** in **Music**
- **unnamed sbx escape** - app sbx escape
  - **sandbox escape** by preventing **quarantine xattr** placement using **devfs** and **symlinks**

The bugs

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Bugs: #1 Lateralus

- **lateralus** (CVE-2023-32407) - **TCC bypass**
- insecure file write in the **Metal** library
  - **MTL_DUMP_PIPELINES_TO_JSON_FILE=”path/name”**
- **Foundation**'s **NSFileManager createFileAtPath** is used:
  - **open()**s new tempfile: “**path/.dat.nosyncXXXX.XXXXXX**” (**X** is random)
  - writes the contents
  - calls **rename(“path/.dat.nosyncXXXX.XXXXXX”, “path/name”)**
- **dangerous rename** with **full control over the path**

Bugs: #1 Lateralus

- how do we get **content control?**
  - impossible if we use **“~/Library/Application Support/com.apple.TCC/”** directly
- but we can use **a controlled location**
  - wait for the temp file and **open()** it
  - race the **rename()**
    - in a loop: atomically swap the directory with a symlink
- **→ full control over path and contents**

Bugs: #1 Lateralus

https://www.youtube.com/watch?v=JPrCwUFYPkw

The bugs

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Bugs: #2 sqlol

- **sqlol** (CVE-2023-32422) - **TCC bypass**
- insecure file write in **libsqlite** (only on **macOS**)
  - debug functionality in production (compiled with SQLITE_ENABLE_SQLLOG)
  - **SQLITE_SQLLOG_DIR**="**whatever**" means:
    - copy the opened DBs to **whatever**
    - write a query log and index file as well
  - files are created with **open()**, which:
    - **follows symlinks**
    - **overwrites files**
- a trivial infoleak, but I **want to overwrite TCC.db**

Bugs: #2 sqlol

- **controlling the filename**: use a **symlink**
- **controlling content** is tricky
  - I can overwrite files, but only with debug files: the **DB**, the **statement log**, the **index**
  - this stumped me a bit...

Bugs: #2 sqlol

- until I realised:
  - a sqlite DB can have multiple tables in it
  - **TCC.db** is a sqlite DB
- we can “smuggle” the **TCC.db**’s tables into any other sqlite DB:
  - **Music** has **FDA**, and a writable DB (**Cache.db)**
  - I can add the **TCC** tables to it
  - **Cache.db** can now replace and function as **TCC.db** :)
  - we don’t even need to race

Bugs: #2 sqlol

https://www.youtube.com/watch?v=rfGcd0YrbTM

The bugs

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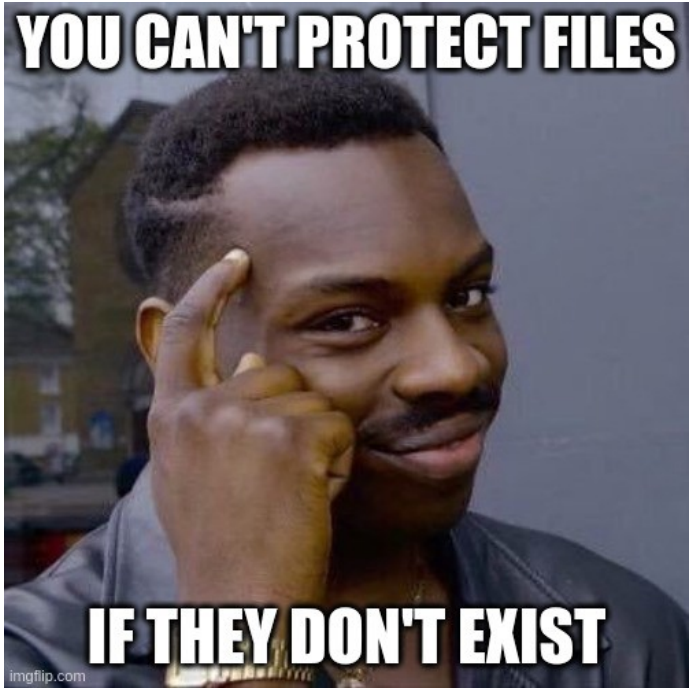
Bugs: #3 batsignal

- **batsignal** (no CVE) – **LPE**
- collision with **Joshua Mason**’s CVE-2022-32801
  - + a couple bypasses
  - no credit, just a small bounty…
- **Spotlight** performs file operations on **user-mounted volumes**
  - daemons **mds** and **mds_stores** run as **root** (mds even has FDA)
  - they use a **SIP-protected** directory on the volume:
    - **“/.Spotlight-V100”**

Bugs: #3 batsignal

- **v1: Exploiting Spotlight for the first time**



Bugs: #3 batsignal

- **umount** the disk and **edit it offline**
  - changing a directory name is easy in **HFS+** :)
    - buf.replace(b’**\x31**\x00\x30\x00\x30\x00’, b'**\x39**\x00\x30\x00\x30\x00’)
    - **.Spotlight-V100 → .Spotlight-V900**
- **HFS+** is fine with this
- **Spotlight** won’t care
- **SIP** won’t notice

Bugs: #3 batsignal

- (one of the) **bug**(s):
  - **Spotlight** writes cache files insecurely with **open()**
- to exploit:
  - **symlink** a file in the Caches directory
    - **Spotlight** will truncate and overwrite existing files
- the cache file has:
  - **attacker-controlled content**
  - a **known filename** → **X.txt**, where **X** is the inode number
- **the fix: Spotlight no longer likes symlinks :(**

Bugs: #3 batsignal

- v2: Exploiting Spotlight for the second time

Bugs: #3 batsignal

- the protection is **still** a regex engine
  - it’s not filesystem-aware
  - no idea about **mountpoints**, **symlinks**, etc…
- **hardlinks** are sort of like **symlinks**
  - if they’re on the same volume
- Can we **“merge”** volumes?
  - **macOS** does allow crazy things...

Bugs: #3 batsignal

- **Yes**, we can use **union**s
  - **these complicate EVERYTHING**
    - but not for us :)
- **union 101**:
  - two volumes mounted over each othe
  - **top** and **bottom**
  - lookups start in **top**
  - fall back to **bottom**
- they can also nest
  - nest
    - nest
      - nest

Bugs: #3 batsignal

- to exploit:
  - mirror Spotlight’s directory structure on the system disk (**bottom**)
  - mount the volume over it with union (**top**)
- delete the target file from **top**, so it’s used from **bottom**
  - where it’s hardlinked to **/etc/sudoers**
- **This is how you symlink without symlinks!**

Bugs: #3 batsignal

- **the fix: Apple now disallows union mounts using SIP :(**
- At least I got a bounty. After more than a year. Still no credit though
- **conclusion**:
  - allowing users to mount disk images is **crazy:**
    - **attacker has all the leverage**
  - **Apple does pay bounties**
    - but it’s complicated...

Bugs: #3 batsignal v1

https://www.youtube.com/watch?v=Xvb9peOSys0

The bugs

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Bugs: #4 alfred

- **alfred** (CVE-2023-40443) - **LPE**
- really it’s **batsignal v3**
- to recap:
  - **Spotlight** does insecure writes on user-provided volumes
  - now we can’t use **symlinks**, or **union-mounts** :(
- **What now?**

Bugs: #4 alfred

- **move the mountpoint :)**
  - by moving the parent
- rugpull **mds** → write to system volume
- **Apple did a good job** of restricting **mds**, with two exceptions:
  - (regex #"^/private/var/folders/[^/]+/[^/]+/C/**com.apple.metadata.mdworker**($|/)")
  - (regex #"^/private/var/folders/[^/]+/[^/]+/T/**com.apple.metadata.mdworker**($|/)")
  - “/var/folders/RANDOM/RANDOM/T/**com.apple.metadata.mdworker**/”
  - we’ll call this ^^^ **tmpdir**

Bugs: #4 alfred

- rinse and repeat...
  - prepare the directory structure like before in **tmpdir**
  - swap the mountpoint between **tmpdir** and the original mountpoint in a loop
- when the race is won **mds** will overwrite one of our files
  - that is a hardlink to **/etc/sudoers**
- **how do we control the content?**

Bugs: #4 alfred

- we need a file that:
  - we can smuggle our payload into
  - gets recreated
- the most obvious target is **VolumeConfiguration.plist**
  - we can smuggle our payload in as a bogus file exclusion path:
    - **“\n\nroot ALL=(ALL:ALL) ALL\n\n”**
- **Spotlight** will
  - remember this after a remount
  - recreate the file if it’s missing

Bugs: #4 alfred

https://www.youtube.com/watch?v=YfJdzqqqQFo

The bugs

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Bugs: #5 badmalloc

- **badmalloc** - (CVE-2023-32428) - **LPE**
- **MallocStackLogging**(.framework) on macOS / iOS performs **insecure file writes**
  - if **MallocStack*** env vars are set dyld force-loads **MallocStackLogging** into **any binary**
  - this is **in macOS since at least 2005 (!)** (phrack #63)
  - **MallocStackLogging** writes a file at an attacker-provided path
- we can make **any app (== “host”)** do this :)

Bugs: #5 badmalloc

- to trigger
  - **MallocStackLogging=1**
  - **MallocStackLoggingDirectory=“whatever”**
- **MallocStackLogging** writes debug files to **whatever**
- **Apple**’s not stupid though, so there are **defenses**

Bugs: #5 badmalloc

- **defenses:**
  - **whatever** is checked with **access()** first
  - **open()** will be used to create the file:
    - won’t overwrite files
    - and won’t follow a symlink
  - permissions are restricted (no umask() trickery)
  - the filename is randomized
- **Pretty secure, right?**

Bugs: #5 badmalloc

- **defenses:**
  - ~~**whatever** is checked with **access()** first~~
    - **access() / open()** is classic **TOCTOU**
      - we can race it
  - ~~**open()** will be used to create the file:~~
    - ~~won't overwrite files~~
    - ~~and **won't** follow a symlink~~
      - **O_NOFOLLOW** is used, not **O_NOFOLLOW_ANY (!)**
  - ~~permissions are restricted (no umask() trickery)~~
    - this actually helps us...
  - ~~the filename is randomized~~
    - **sudo** will gobble up any file from **/etc/sudoers.**
      - and the random generator was **hilariously broken...**

Bugs: #5 badmalloc

- only **minimal content control :(**
- this stumped me for quite a long time...

Bugs: #5 badmalloc

- until I realised that:
  - **every application** is affected
  - **“host” app has no idea** about the **open()**
  - **open()** does **not** set **O_CLOEXEC**
- Can we have a **suid** leak this **fd?**

Bugs: #5 badmalloc

- **Yes, crontab!**
- **crontab** is **suid** and **executes our editor**
  - it does not expect a **force-loaded library to open a file**
    - most programs wouldn’t...

Bugs: #5 badmalloc

- to exploit we can call **crontab** with
  - EDITOR=**ourscript.py**
  - MallocStackLogging=**1**
  - MallocStackLoggingDirectory=“**whatever**”
- we race the **access()/open()** by swapping **whatever** with a symlink to **/etc/sudoers.d/**

Bugs: #5 badmalloc

- the race is won in a couple tries
- our **EDITOR** gets executed:
  - with an open **fd** to a random file under **/etc/sudoers.d/**
  - writes payload: “**root ALL=(ALL:ALL) ALL**”
  - **sudo bash**

Bugs: #5 badmalloc

https://www.youtube.com/watch?v=iNfeo9vkhK0

We’re done :)

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Thank you friendly hackers!

- **Special thanks to these folks**
  - Csaba Fitzl (@theevilbit)
  - Wojciech Reguła (@_r3ggi)
  - Joshua Mason
  - Buherator
  - Zoltan Padanyi aka max
  - Tamas Kozak
  - Dora
- **among many others**

Thanks Apple!

Thank you!

Gergely Kalman
@gergely_kalman

Talk to me if you have questions

Find me in the hallways or Twitter

Gergely Kalman
@gergely_kalman