Race Conditions

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Linux Kernel "Dirty COW" Vulner. (Oct 2016)

"Linux users are being urged to patch servers to fix a vulnerability known as "**Dirty COW**." The **privilege elevation flaw** is caused by "**a race condition** ... in the way the Linux kernel's memory subsystem handles the copy-on-write (COW) breakage of private read-only memory mappings." Linux vendor Red Hat says that the flaw is being **actively exploited**. The flaw has been present in the **Linux kernel since 2007**, and is **trivial to exploit**. Linus Torvalds acknowledged that he **tried, unsuccessfully, to fix the problem more than 10 years ago**."

Race conditions (I)

- Violation of an assumption of atomicity
  - ☞ during a **window of vulnerability** or window of opportunity or window of inopportunity
  - ☞ 2 (or more) entities access concurrently the same object
- The vulnerability is always due to a problem of concurrency / lack of proper synchronization
  - ☞ between a target and malicious process(es), ***or***
  - ☞ between several processes/threads of the target

- To exploit this kind of vulnerability, the attacker races to break the assumption during the window of vulnerability

Race conditions (II)

- Example: a service that generates unique sequential numbers
  - ☞ called by several threads concurrently
  - ☞ vulnerability allows returning the same number twice

```
int count = 0;    // global and shared by 2 threads

// Two threads execute this code concurrently
int getticket() {
    count++;
    return count;
}
```

There is an assumption of atomicity, which creates a window of vulnerability!

To address this problem, the access to getticket() needs to be synchronized using locks, semaphores, … or some other mechanism offered by the language.

Race conditions (III)

- Sources of races
  - ☞shared data: files and memory
  - ☞preemptive routines (signal handlers)
  - ☞multi-threaded programs

- We are going to study them in three scenarios
  - ☞TOCTOU (*Time-Of-Check to Time-Of-Use*)
  - ☞Temporary files
  - ☞Internal concurrency and reentrant functions

TOCTOU:
TIME OF CHECK – TIME OF USE

TOCTOU Time-of-check to time-of-use

aka TOCTTOU
also **symlink attack**

- Typical case:
  - A program running *setuid* root is asked to write to a file owned by the user running the program
  - Root can write to any file so the program has to check if the actual user has the right to write to the file

access() checks if the *Real UID* has write access to the file

```
// 0 if the user has write privilege
if(!access(file, W_OK)) {
    f = fopen(file, "w+");
    write_to_file(f);
}
else {
    fprintf(stderr, "Permission denied\n");
}
```

window vulnerab

Run this until success:
$ touch dummy
$ ln -s dummy link
$ program link &
$ rm link;\
  ln -s /etc/passwd link

access()

- int access(const char *pathname, int mode);
  - ☞ checks whether the calling process can access the file <u>pathname</u> according with <u>mode</u>
  - ☞ designed for setuid programs, does privilege check using the process' **real UID** instead of the **effective UID**

- However it is usually vulnerable to race conditions / TOCTOU
  - ☞ the file it checks can be altered before it is used
  - ☞ why? because it is identified by a <u>path</u>, so the object in the end can change
- <u>Should never be used!</u>

A real example (I)

- Broken **passwd** command (SunOS, HP/UX)
  - ☞ it allows for instance to change the password

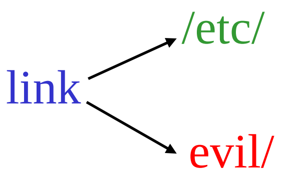
- passwd takes as parameter the password file to manipulate, then:

window vulnerab

1. Opens password file, retrieves user's entry, and closes file
2. Create and open temporary file (*ptmp*) in the same directory as password file
3. Open password file again, copy content to *ptmp* and update modified info
4. Close both files, rename *ptmp* to be the password file

A real example (II)

- Attack script (interleaved with desired passwd execution):



$ mkdir evil

$ cp /etc/passwd evil/passwd

$ echo “hacker::0:0:::/bin/bash” >> evil/passwd

$ ln -s /etc link

$ passwd link/passwd

passwd step 1: open link/passwd, get user entry, close file

passwd step 2: create *ptmp*

$ rm link ; ln -s evil link

passwd step 3: open and copy link/passwd to *ptmp*, update modified info

$ rm link ; ln -s /etc link

passwd step 4: close files; move *ptmp* to link/passwd (i.e. /etc/passwd)

- ***/etc/passwd*** *has a new user hacker with superuser privileges*

Putting it to work

- Running *passwd* and exploiting the window of vulnerability seems hard...
- Solutions:
  - ☞ make a script that tries as many times as needed until the attack works
  - ☞ delay the program someway
  - ☞ insert some random delays between operations

- Easier if the file system is distributed (e.g., NFS)

stat() function family

- Collect information about files and symbolic links
  - ☞ int stat(const char *pathname, struct stat *buf);
    - pathname – file to be checked
    - buf – structure to be filled with data about the file
  - ☞ lstat() – the same but data returned is about the link itself, if pathname is a link

- These calls give info about the file
  - ☞ Owner, owning group, number of hardlinks to the file
  - ☞ Type of file (regular, dir, char device, block device, named pipe, symbolic link, socket)

- Apparently, these functions could be helpful to distinguish real files from links …

Vulnerability with lstat()

- *setuid* program has to open a file but does not want to be tricked into opening a symbolic link
  - ☞ trick: use lstat() instead of access()

- Vulnerable code in Kerberos 4 lib used in login daemon

```
if (lstat(file, &statb) != 0) goto out;
if (!(statb.st_more & S_ISREG) || …) goto out;
if ((fd=open(file, O_RWDR|O_SYNC, 0)) < 0) goto out;
```

If it is **not** a regular file then exit.

- If file is not a link it is safe to open…

  but what if it changes after *lstat()* and before *open()* ?

Vulnerability with lstat (cont)

- Is it still vulnerable if done in the opposite order?

```
fd = open(fname, O_RDONLY);
if (fd == -1) perror("open");
if (lstat(fname, &statb) != 0) die("file not
  there");
if (!S_ISREG(statb.st_mode)) die("it's a symlink");
```

- Attacker creates link, then deletes it after the *open()* and before the *lstat()*

Preventing file race conditions (I)

- Most file races have to do with pathnames
- When a call with a *pathname* is done (open, access, stat, lstat,…), the pathname is resolved until the *inode* is found
- If two calls are made one after the other, the path can lead to different *inodes*

- *So the protection is to avoid the two sequential resolutions and use filenames only when strictly necessary inside the program*

Preventing file race conditions (II)

- Correct example – with *file descriptors*

```
fd=open("/tmp/bob", O_RDWR);
fstat(fd, &sb);
```

- If someone unlinks and re-links /tmp/bob between the two calls, fd would still point to the same *inode*

- Unsafe: access, stat, lstat, chmod, chown
- Safe: fstat, fchmod, fchown

Permission races

- Are we vulnerable in this case?

```
FILE *fp;  //stream
int fd;
if (!(fp = fopen("myfile.txt", "w+"))) die("fopen");
fd = fileno(fp);  // returns fd associated to stream
if (fchmod(fd, 0600)<0)  // fchmod() to prevent race
  die("fchmod");
```

- If file does not exist
  - *fopen()* creates it by calling *open()* with default permissions 0666
    - maybe lower as it is constrained by umask, but umask is inherited by the program
  - Program changes it to 0600 but it is too late, a race is possible
  - Attacker does not have to write in the file during the window, only open it for read/write (for instance)
  - *Solution: set umask*

Memory Races

- The following code is from a device driver in Windows 8.
- Are we vulnerable in this case?

```
PDWORD BufferSize = /* defined by a process in user mode */ ;
PUCHAR BufferPtr = /* defined by a process in user mode */ ;
PUCHAR LocalBuffer;
if (BufferSize > MAXSIZE) goto out;
LocalBuffer = ExAllocatePool(PagedPool, *BufferSize);
if (LocalBuffer != NULL) {
    RtlCopyMemory(LocalBuffer, BufferPtr, *BufferSize);
}
else goto out;
```

Copies an area of memory

- If the user changes the size of BufferSize between the check and its use, then he can write in areas of memory that were NOT supposed to (i.e., he can create a buffer overflow)

TEMPORARY FILES

Temporary files

- Have the same problems as others plus those derived from usually being in a shared dir
  - ☞ */tmp;* */var/tmp*
- Typical attack
  1. Privileged program checks that there is no file X in */tmp*
  2. Attacker races to create a link called X to some file, say */etc/passwd*
  3. Privileged program attempts to create X and opens the attacker's file doing something undesirable that its privileges allow …
- Two characteristics make the attack possible
  - ☞ the filename can be predicted by the attacker
  - ☞ the race condition between the check and the file creation

mktemp(), tmpnam(),…

- Trying to address the problem: *mktemp()* creates unique, currently unused, filename from a template

```
strcpy(temp, "/tmp/tmpXXXXXX");
if (!mktemp(temp))  die("mktemp");
fd = open(temp, O_CREAT | O_RDWR, 0700);
```

  ☞ after *mktemp()* and before *open()* an attacker can link filename to some file

  ☞ *open()* would then not create but open an existing file

- *tmpnam()* and *tempnam()* are similar

Possible solutions

- Non-solutions
  - ☞ Random file names: often the attacker can try the race many times, and if the name generator can be predicted …
  - ☞ Locks: many implementations are enforced by convention, not mandatory

- Acceptable solutions
  - ☞ Use long random number (e.g. 64 bits), set umask appropriately (e.g. 0066), and open the file
  - ☞ Use the safe calls → *see next slide*

mkstemp(), tmpfile(),…

- Possible solutions:

*int mkstemp(char *template)*

much safer than *mktemp()* since it checks for uniqueness, creates and opens with rw privileges only for the owner (0600)

*FILE *tmpfile(void)*

is similar, but in the past sometimes it was implemented on top of *mktemp(),* and therefore could be vulnerable to attacks

*char *mkdtemp(char *template)*

is similar but creates a directory with permissions 0700

CONCURRENCY AND REENTRANT FUNCTIONS

Concurrency

- In the previous cases, concurrency **is (mainly) created by the attacker**, with malicious intention
- In programs there is also the normal concurrency of operations that need to access shared objects
- Operations may have to be executed atomically, i.e., without interruption
- Mutual exclusion is a solution for <u>some</u> of the problems
  - ☞ mutexs, semaphores, transactions, etc.
- Difficulties with mutual exclusion
  - ☞ starvation: a thread is never scheduled for execution
  - ☞ deadlock: threads inter-block themselves

Reentrancy (I)

- A function is reentrant if several instances of the function can be executed in parallel in the same address space
  - ☞ for example, if it works correctly even if a thread is interrupted by another thread that calls the same function
  - ☞ Example:
    - – non-reentrant function supposed to give unique ticket

```
int count=0;    //global var
int getticket() {
  count++;
  return count;
}
```

atomic?

Reentrancy (II)

- Separating the reentrancy in two main sources of problems
  - ☞ Thread-safety – reentrancy in relation to several threads
  - ☞ Async-signal-safety – reentrancy in relation to signals

- Conditions for a function to be reentrant
  - ☞ <u>does not use</u>: static variables, global variables, other shared resources like libraries (i.e., uses only local non-static variables and function parameters)
  - ☞ <u>only calls</u> reentrant functions (namely libraries)

- Notice: conditions are **sufficient but not necessary**!
  - ☞ the use of global vars may ***not*** prevent the function from being reentrant

Signal handlers

- Signals are a Unix/POSIX mechanism to indicate asynchronous events to a process
  - ☞ often the semantics varies in different Unix flavors
- Can be treated by a signal handler (a function)
  - ☞ or ignored or blocked (except SIGKILL and SIGSTOP)
- Signal handlers have to be **asynchronous-safe** (or **async-safe** or **signal-safe**):
  - ☞ have to run correctly even if interrupted by other asynchronous events (i.e., by a signal) **and**
  - ☞ they should not corrupt the part of the program that was interrupted
- Otherwise they may be vulnerable (or create vulnerabilities) and often are!

Example of Signal Vulnerability

```
int size;
FILE *fd;
Char *bglobal;
int main(int argc, char **argv){
  signal(SIGTERM, complete);
  signal(SIGINT, complete);
  signal(SIGSEGV, complete);
  // open file for input
  fd = fopen("input.txt", "r");
  // now start two threads →
}
void thread_readData(){
  bglobal = malloc(MAX_BYTES);
  while (true) {
    wait_workDone(); // from thrd2
    size = fread(bglobal, 1,
                 MAX_BYTES, fd);
    more_work(); // warn thrd2
    printf("Read %d bytes.\n", size);
  }
}
```

```
void thread_workData(){
  char buffer[MAX_BYTES];
  while (true){
    wait_work(); //wait thread1
    memcpy(buffer, bglobal, size);
    done_work(); // warn thread1
    // does some processing
  }
}
int complete(int sig){
  printf("recv signal. Done!.\n");
  free(bglobal);
  fclose(fd);
  exit(1);
}
```

If the signal is executed :
What if complete is called two times?
What if signal occurs before memory is allocated or the file is open?
What if signal occurs when printf() was being executed?

Signals

- Some solutions
  - ☞ Read very carefully the man pages!!!
  - ☞ Make signal handler simple; ideally only set a flag
  - ☞ Use system calls safe for signal handlers
  - ☞ Block signals
    - (1) inside signal handlers and
    - (2) during non-atomic operations in the program

- Keep in mind that
  - ☞ mutual exclusion mechanisms typically cannot be used because they can lead to deadlocks (depending on how signals are configured)
  - ☞ alternatively, it is possible to use mechanisms that temporarily block the delivery of signals

Servlets

- Usually
  - ☞ Called by several threads concurrently
  - ☞ Each servlet is only one object in memory…

    … so class attributes are shared resources (like global vars in C)

- Servlet that can give two users the same count

```
public class Counter extends HttpServlet {
    int count = 0;    //shared!!
    public void doGet(…, HttpServletResponse out)
                       throws… {
        PrintWriter p = out.getWriter();
        count++;
        p.println(count + " hits so far!");
    }
}
```

There is an assumption of atomicity, which creates a window of vulnerability!

Solutions

```
public class Counter extends HttpServlet {
    int count = 0;    //shared!!
    public synchronized void doGet(…, HttpServletResponse out)
                                 throws… {
        PrintWriter p = out.getWriter();
        count++;
        p.println(count + " hits so far!");
    }
}
```

not efficient (if method longer…)

```
public class Counter extends HttpServlet {
    int count = 0;    //shared!!
    public void doGet(…, HttpServletResponse out) throws… {
        int my_count;  // NOT shared!!!
        PrintWriter p = out.getWriter();
        synchronized(this) {  my_count = ++count;  }
        p.println(my_count + " hits so far!");
    }
}
```

Bibliography

- M. Correia, P. Sousa, Segurança no Software, FCA Editora, 2017 (see chapter 6)

Other references: