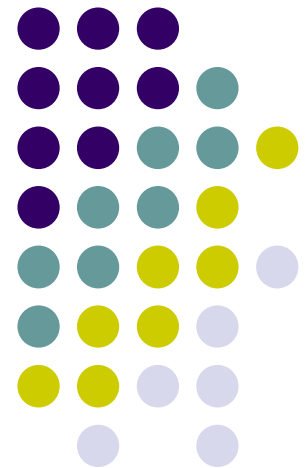
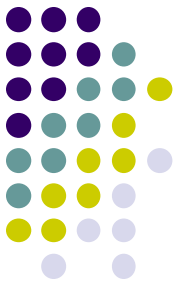

Secure Coding in C and C++
Race conditions



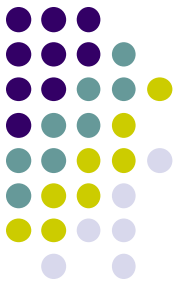
Lecture 6

Sept 27, 2017

Concurrency and Race condition

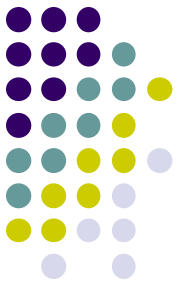


- Concurrency
 - Execution of Multiple flows (threads, processes, tasks, etc)
 - If not controlled can lead to nondeterministic behavior
- Race conditions
 - Software defect/vulnerability resulting from unanticipated execution ordering of concurrent flows
 - E.g., two people simultaneously try to modify the same account (withdrawing money)



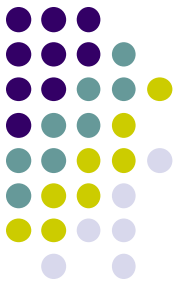
Race condition

- Necessary properties for a race condition
 - Concurrency property
 - At least two control flows executing concurrently
 - Shared object property
 - The concurrent flows must access a common shared *race object*
 - Change state property
 - At least one control flow must alter the state of the race object



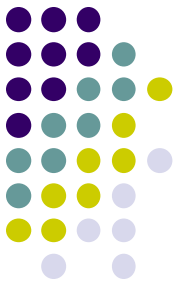
Race window

- A code segment that accesses the race object in a way that opens a window of opportunity for race condition
 - Sometimes referred to as critical section
- Traditional approach
 - Ensure race windows do not overlap
 - Make them mutually exclusive
 - Language facilities – *synchronization primitives (SP)*
 - *Deadlock* is a risk related to SP
 - Denial of service



Time of Check, Time of Use

- Source of race conditions
 - Trusted (tightly coupled threads of execution) or untrusted control flows (separate application or process)
- ToCToU race conditions
 - Can occur during file I/O
 - Forms a RW by first *checking* some race object and then *using* it

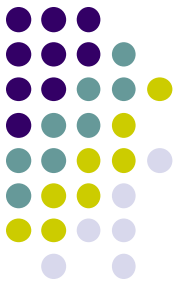


Example

```
int main(int argc, char *argv[]) {
    FILE *fd;
    if (access("/some_file", W_OK) == 0) {
        printf("access granted.\n");
        fd = fopen("/some_file", "wb+");
        /* write to the file */
        fclose(fd);
    } else {
        err(1, "ERROR");
    }
    return 0;
} Figure 7-1
```

- Assume the program is running with an effective UID of root

TOCTOU



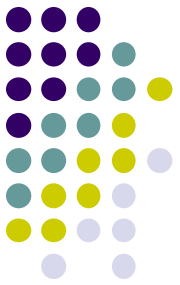
- Following shell commands during RW

```
rm /some_file
```

```
ln /myfile /some_file
```

- Mitigation

- Replace access() call by code that does the following
 - Drops the privilege to the real UID
 - Open with fopen() &
 - Check to ensure that the file was opened successfully

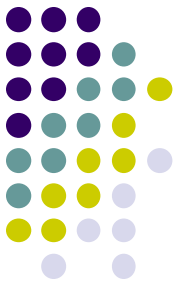


TOCTU

- Not all untrusted RCs are purely TOCTOU
 - E.g., GNU file utilities

```
chdir("/tmp/a");  
chdir("b");  
chdir("c");  
//race window  
chdir("../");  
chdir("c");  
unlink("*");
```

- Exploit is the following shell command
 - mv /tmp/a/b/c /tmp/c
 - Note there is no checking here - implicit



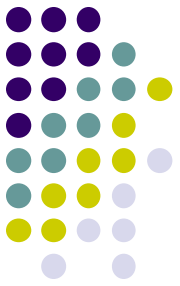
File locking

- Synchronization Primitives cannot be used to resolve RC from independent processes
 - Don't have shared access to global data
- File locks can be used to synchronize them

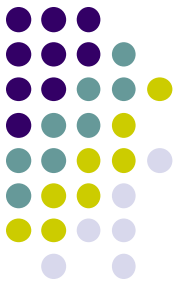
```
int lock(char *fn) {
    int fd;
    int sleep_time = 100;
    while (((fd=open(fn, O_WRONLY | O_EXCL | O_CREAT, 0)) == -1)
           && errno == EEXIST) {
        usleep(sleep_time);
        sleep_time *= 2;
        if (sleep_time > MAX_SLEEP)
            sleep_time = MAX_SLEEP;
    }
    return fd;
}

void unlock(char *fn) {
    if (unlink(fn) == -1) {
        err(1, "file unlock");
    }
}
} Figure 7-3
```

File locking

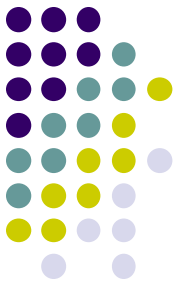


- Two disadvantages
 - Open() does not block
 - Use `sleep_time` that doubles at each attempt (also known as *spinlock* or *busy form of waiting*)
 - File lock can remain locked indefinitely (e.g., if the locking process crashes)
 - A common fix is to store the PID in the lock file, which is checked against the active PID.
 - Flaws with this fix
 - PID may have been reused
 - Fix itself may contain race conditions
 - Shared resource may also have been corrupted because of the crash



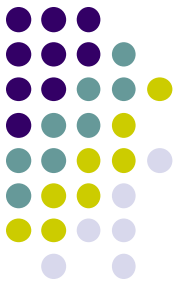
File System Exploits

- Files and directories are common race objects
- Open files are shared by peer threads
- File systems have exposure to other processes
 - As file permissions
 - File naming conventions
 - File systems mechanisms
- Most executing programs leave a file in a corrupted state when it crashes (backup is remedy)
- Exploits
 - Symbolic linking exploits
 - Temporary file open exploits
 - ulink() race exploit
 - Trusted filenames
 - Nonunique temp file names



Symbolic linking exploits

- Unix symbolic linking is most common
 - Symlink is a directory entry that references a target file or directory
 - Vulnerability involves programmatic reference to a filename that unexpectedly turns out to include a symbolic link
 - In the RW the attacker alters the meaning of the filename by creating a symlink



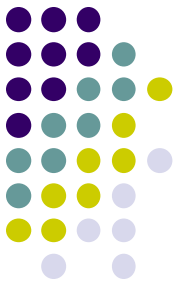
Symbolic linking exploits

```
if (stat("/some_dir/some_file", &statbuf) == -1) {
    err(1, "stat");
}
if (statbuf.st_size >= MAX_FILE_SIZE) {
    err(2, "file size");
}
if ((fd=open("/some_dir/some_file", O_RDONLY)) == -1) {
    err(3, "open - %s",argv[1]);
} Figure 7-4
```

Attacker does:

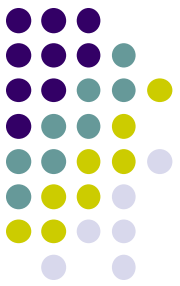
rm /some_dir/some_file

In -s attacker_file /some_dir/some_file



Symbolic linking exploits

- Reason for its wide spread use in exploits
 - Creation of symlink is not checked to ensure that the owner of the link has any permissions for the target file, nor
 - Nor Is it even necessary that the target file exists
 - The attacker only needs write permissions to the directory in which symlink is created
- Further complication introduced by the following
 - Symlink can reference a directory
 - E.g., in some passwd() function – required user to specify a password file as a parameter



Symbolic linking exploits

- **Vulnerable segment in passwd()**

- Open the password file, use it to authenticate the user, and then close the file

- Create and open a temporary file called ptmp in the directory of the password file

- Reopen the password file and copy an updated version into ptmp (which is still open)

- Close both files and rename ptmp as the new password file

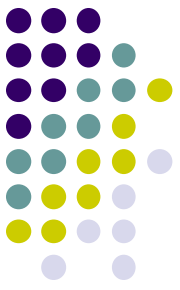
- **Exploit allows entry to an account**

- A creates a bogus attack_dir/.rhosts (A as a valid user)

- V has real password file in victim_dir

- A creates symlink to attack_dir called symdir

- A calls passwd() passing the password file as /symdir/.rhosts



Symbolic linking exploits

- Vulnerable segment in passwd()

Open the password file, use it to authenticate the user, and then close the file

- attacker changes /symdir to reference attack_dir

Create and open a temporary file called ptmp in the directory of the password file

- attacker changes /symdir to reference victim_dir

Reopen the password file and copy an updated version into ptmp (which is still open)

- attacker changes /symdir to reference attack_dir

Close both files and rename ptmp as the new password file

- attacker changes /symdir to reference victim_dir

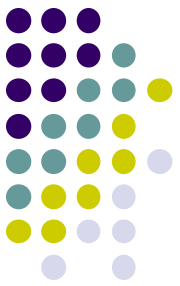
Result:

The password file in victim_dir is replaced by that from the attack_dir



Symbolic linking exploits

- Slightly different symlink vulnerability – when permissions of a file is elevated (StarOffice)
 - Permissions are threatened (elevated)
 - The attack works because of the following
 - When permissions are changed on a symbolic link, the change is applied to the target file rather than the link
- Windows “shortcut” is similar
 - But windows rarely have symlink problem because
 - The API includes primarily file functions that depend on file handles rather than the file names, and
 - Many programmatic windows functions do not recognize shortcuts as links



Temporary file open exploits

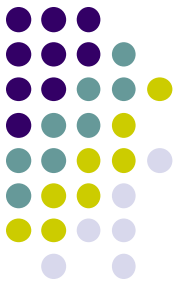
- Temporary files
 - Unique naming is difficult
 - Vulnerable when created in a directory where attacker has access
 - In unix /tmp is frequently used for temporary files
 - Simple vulnerability

```
int fd = open("/tmp/some_file",  
              O_WRONLY |  
              O_CREAT |  
              O_TRUNC,  
              0600)
```

Already exists or what if the /tmp/some_file is a symbolic link before the instruction is executed?

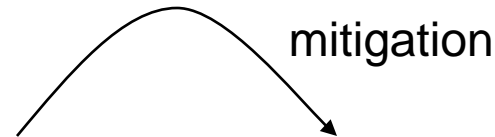
Solution:
add O_EXCL flag

File existence check and
creation -> atomic!



Temporary file open exploits

- Stream functions in C++ have no atomic equivalent

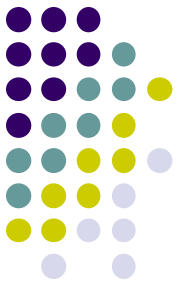


```
int main(int argc, _TCHAR* argv[])
{
    ofstream outStrm;
    ifstream chkStrm;
    chkStrm.open("/tmp/some_file",,
                ifstream::in);
    if (!chkStrm.fail())
        outStrm.open("/tmp/some_file",
                    ofstream::out);
    :
    :
}
```

Race window?

```
int main(int argc, char *argv[])
{ int fd;
  FILE *fp;
  if ((fd = open(argv[1],
                 O_EXCL|O_CREAT|O_TRUNC|O_RDWR,
                 0600)) == -1) {
    err(1, argv[1]);
  }
  fp = fdopen(fd, "w");
  :
  :
}
```

File descriptor + O_EXCL

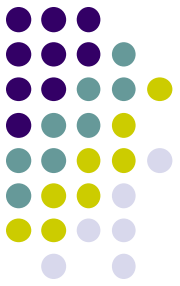


Temporary file open exploits

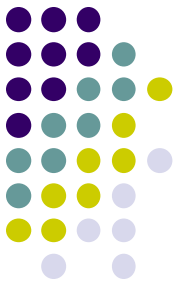
- Exploit would be possible if the filename can be guessed before a process creates it
- Random filename using mkstemp()
 - Each X is replaced by a random character

```
char template[] = "/tmp/fileXXXXXX";  
if (fd = mkstemp(template)) = -1) {  
    err(1, "random file");  
}
```

unlink Race exploits

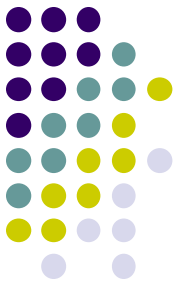


- RC is created when
 - A file is opened and later unlinked
 - Key reason, Linux does not support an equivalent to `unlink()` that uses a file descriptor
 - Replacing the named open file with another file or symbolic link, an attacker can cause `unlink()` to be applied to the wrong file
 - Mitigation: proper permissions on the directory



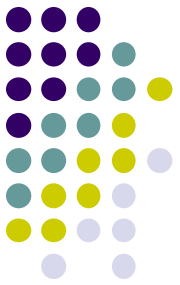
Trusted filenames

- Trusted filename vulnerability
 - Results as a result of unverified filenames
 - Filenames from user or untrusted source
- Goal of exploit
 - Cause a program to manipulate a file of attacker's choosing
 - Mitigation: verify the filename
- Some difficulties
 - Different length restrictions, remote file systems & shares, etc.
 - Device as a file (some OSs crash)
 - Inclusion of substring “..”
 - General mitigation: transform to canonical form
 - Generate an absolute path without “..”, “.” or symbolic links
 - Unix – realpath()
 - Care must be taken to avoid TOCTOU condition using realpath() to check a filename
 - Another mitigation is to validate ancestral directories.



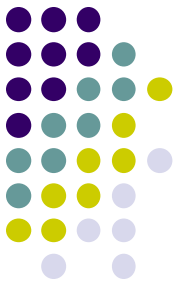
Nonunique Temp File Names

- Faulty implementation
 - Of `tempnam()` and `tempfile()` can produce non unique filenames (using a user ID)
 - `tmpnam_s()` generates a valid filename that is not the name of an existing file
 - RC is still possible if the name is guessed before use



Mitigation strategies

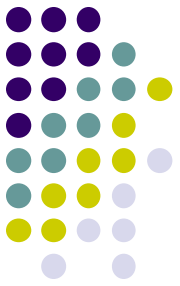
- Can be classified based on properties
 - Mitigations that remove concurrency property
 - Techniques that eliminate the shared object property
 - Ways to mitigate by controlling access to the shared object to eliminate the change state property
- Different strategies may/should be combined



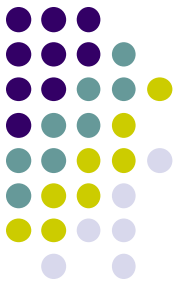
Mitigation strategies

- Closing the race window
 - Eliminate RW whenever possible
- Techniques
 - Mutual exclusion
 - Thread safe functions
 - Use of atomic operations
 - Checking file properties safely
 - Use file descriptors not filenames
 - Shared directories
 - Temporary files

Mitigation strategies

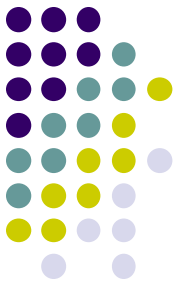


- Mutual exclusion
 - Implement mutually exclusive critical sections
 - Mutex/semaphores
 - Critical issue is to minimize CS size
 - Object-oriented alternative
 - Use decorator module to isolate access to shared resources
 - provides wrapper functions
 - Signal handling poses problems
 - Signals can interrupt normal execution flow at any time
 - Unhandled signals usually default to program termination
 - A signal handler can be invoked at any time, even in the midst of a mutually excluded section of code
 - If the attacker sends a signal to a process within a race window, it is possible to use signal handling to effectively lengthen the window
 - Mitigation:
 - Signal handling should not be used for normal functionality
 - Avoid sharing objects between signal handlers and other program code



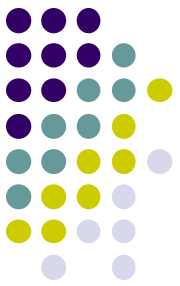
Thread safe function

- In Multithreaded applications
 - It is not enough to ensure code is RC free
 - It is possible that invoked functions could be responsible for race conditions
- Thread safe function
 - No RC when concurrent calls to this function
 - If non-thread safe function is called, treat it as a critical section



Use of atomic operations

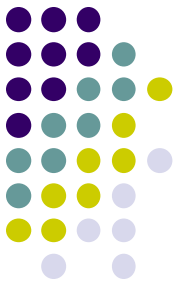
- Atomicity
 - Implemented by synchronization functions
- Entry to critical section
 - Should not be interrupted until completed
 - Concurrent executions of `EnterCriticalSection()` should not overlap
 - Concurrent execution of `EnterCriticalSection()` should not overlap with the execution of `LeaveCriticalSection()`
- `Open()` with `O_CREAT` and `O_EXCL`
 - Alternative is to call `stat()` or `access()` followed by `open()` – may introduce TOCTOU



Checking file properties securely

```
struct stat lstat_info;
int fd;
if (lstat("some_file", &lstat_info) == -1) {
    err(1, "lstat");
}
if (!S_ISLNK(lstat_info.st_mode)) {
    if ((fd = open("some_file", O_EXCL | O_RDWR, 0600)) == -1)
        err(2, argv[1]);
}
```

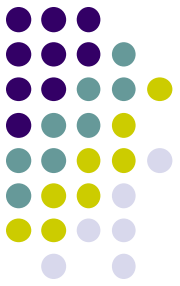
- `lpstat()` is a difficult problem
 - Stats a symbolic link
 - No file descriptor alternative
- Mitigation – follow the four steps
 - `lpstat()` the filename
 - `open()` the file
 - `fstat()` the file descriptor from step 2
 - Compare the results from steps 1 and 3



Checking file properties securely

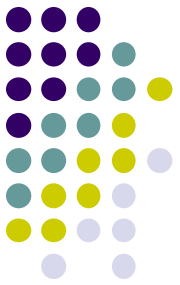
- The four steps are used in the following

```
struct stat lstat_info, fstat_info;
int fd;
if (lstat("some_file", &lstat_info) == -1) {
    err(1, "lstat");
}
if ((fd = open("some_file", O_EXCL | O_RDWR, 0600)) == -1) {
    err(2, "some_file");
}
if (fstat(fd, &fstat_info) == -1)
{
    err(3, "fstat");
}
if (lstat_info.st_mode == fstat_info.st_mode &&
    lstat_info.st_ino == fstat_info.st_ino)
    //process the file
```



Eliminating the race object

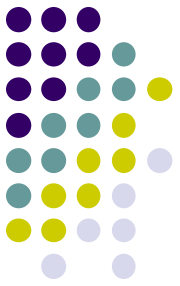
- RC exists because of
 - Concurrent execution flows share some object
- Hence, RC can be eliminated by
 - Eliminating shared objects, or
 - Removing shared access to it
- Mitigation
 - Identify the shared object (file system is key)
 - Use file descriptors, not file name
 - File's directory is key element
 - Once a file is opened, it is not vulnerable to symlink attack if the file descriptor is used instead of file/directory
 - Shared directories – avoid it
 - Temporary files: /tmp is key source (commonly shared)



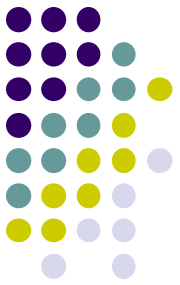
Eliminating the race object

- Temporary files: some good practices
 - Never reuse filenames, especially temporary files
 - Use random file names for temporary file – avoids conflict and guessing
 - Use cryptographically strong random number generator and seeds
 - Use `mkstemp()` instead of `mktemp()`, `tempnam()`, etc.
 - Unlink temporary files as early as possible
 - Reduces the RW
 - Log temporary file events

Controlling access to the race object

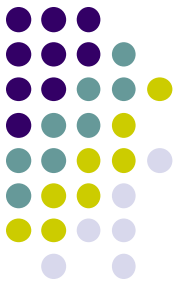


- Some techniques
 - Principle of least privilege
 - Eliminates RC or reduce exposure
 - If possible, avoid running processes with elevated permissions
 - When a process must use elevated permissions, these should be normally dropped (using `setuid()`)
 - When a file is created, the permissions should be restricted exclusively to the owner
 - Trustworthy directories
 - Chroot jail
 - Creates an isolated directory with its own root/tree
 - Avoids symlink, “..” exploits



Race detection tools

- Static analysis
 - Parses software to identify race conditions
 - Warlock for C (need annotation)
 - ITS4 uses (database of vulnerabilities)
 - RacerX for control-flow sensitive interprocedural analysis
 - Flawfinder and RATS – best public domain
- Extended Static checking
 - Use theorem proving technology
- Race condition detection is NP complete
 - Hence approximate detection
 - C/C++ are difficult to analyze statically –
 - pointers and pointer arithmetic
 - Dynamic dispatch and templates in C++



Race detection tools

- Dynamic analysis
 - Detect during execution
 - Disadvantages
 - Fails to consider execution path not taken
 - Runtime overhead
 - Some tools
 - Eraser, MultiRace
 - ThreadChecker (intel) – finds races and deadlocks
 - RaceGaurd for unix – secure use of temp files