

Secure Programming Lecture 16: Race Conditions

David Aspinall

18th March 2016

Outline

Overview

Race Conditions

- Race conditions with Unix file handling

Data Races

Preventing Races

- Preventing race conditions

- Preventing data races

- Tools to detect races

Summary

Recap

We have looked at:

- ▶ examples of vulnerabilities and exploits
- ▶ particular programming failure patterns
- ▶ security engineering
- ▶ tools, esp static analysis for code review

In the last two lectures we're examining some:

- ▶ **language-based security** principles

for (ensuring) secure programs.

This final lecture considers mechanisms for handling vulnerabilities due to multi-process or multi-threaded systems.

Outline

Overview

Race Conditions

Race conditions with Unix file handling

Data Races

Preventing Races

Preventing race conditions

Preventing data races

Tools to detect races

Summary

Outline

Overview

Race Conditions

Race conditions with Unix file handling

Data Races

Preventing Races

Preventing race conditions

Preventing data races

Tools to detect races

Summary

Race conditions with check before use

```
res = access("/tmp/userfile", R_OK);
if (res!=0)
    die("access");

/* ok, we can read from /tmp/userfile */
fd = open("/tmp/userfile", O_RDONLY);
```

API docs (GNU C library)

```
int access(const char *filename, int how)
```

The access function checks to see whether the file named by filename can be accessed in the way specified by the how argument. The how argument either can be the bitwise OR of the flags R_OK, W_OK, X_OK, or the existence test F_OK.

This function uses the real user and group IDs of the calling process, rather than the effective IDs, to check for access permission. As a result, if you use the function from a setuid or setgid program (see How Change Persona), it gives information relative to the user who actually ran the program.

The return value is 0 if the access is permitted, and -1 otherwise. (In other words, treated as a predicate function, access returns true if the requested access is denied.)

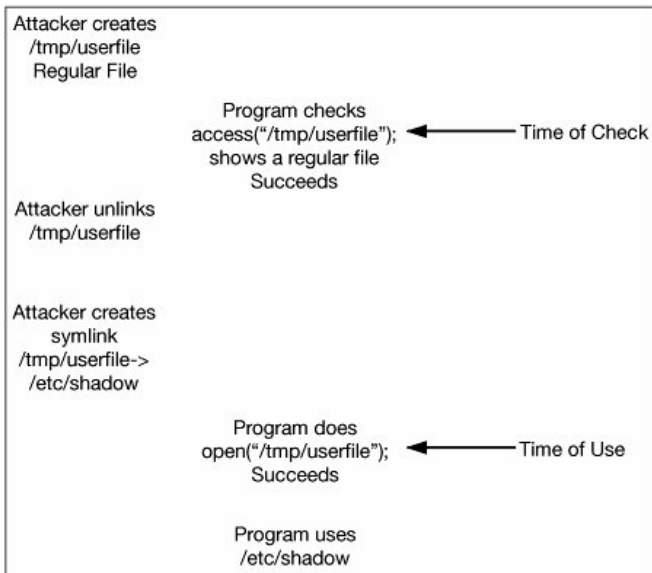
Race conditions with check before use

```
res = access("/tmp/userfile", R_OK);
if (res!=0)
    die("access");

/* ok, we can read from /tmp/userfile */
fd = open("/tmp/userfile", O_RDONLY);
```

- ▶ `access()` is designed for `setuid` programs
- ▶ privilege check on real user id (user running prog)
- ▶ `open()` returns a **file descriptor**
- ▶ f.d. is data type that refers to specific file

Time of Check to Time of Use (TOCTOU)



How can this be exploited?

- ▶ Unix runs multiple processes at once
 - ▶ Attacker runs a process alongside suid program
 - ▶ Must attack at exactly right moment
- ▶ Processes are scheduled by the OS
 - ▶ maybe on multiple CPUs
- ▶ Attacker may be able to influence scheduling
 - ▶ slow down system, send job control signals
- ▶ Attacker may be able to *automatically* schedule attack
 - ▶ e.g. Linux **inotify** API for monitoring file system

General problem: repeatedly looking up pathnames

Kernel resolves pathnames to *inodes* using file system.

Looking up file status twice repeats this:

```
stat("/tmp/bob", &sb);  
...  
stat("/tmp/bob", &sb);
```

If `/tmp/bob` (or `/tmp/`) change between the two calls, different files are examined by the two calls.

Fix: using file descriptors instead

File descriptors contain the resolved inode.

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

This always examines the same (actual) file on disk twice, whatever /tmp/bob points to by the second call.

Even if the file has been deleted from the filesystem the inode is not deallocated until the reference count becomes zero.

Risky patterns: using same filename twice

1. A status check like

- ▶ `stat()`
- ▶ `lstat()`
- ▶ `access()`

2. An access to the file like

- ▶ `open()`, `fopen()`,
- ▶ `chmod()`, `chgrp()`, `chown()`,
- ▶ `unlink()`, `rename()`,
- ▶ `link()`, `symlink()`

Better to use the file descriptor based calls instead:

- ▶ `fstat()`, `fchmod()`, and `fchown()`

Windows APIs a bit better here (but still tricky areas like the following).

Permission Races

```
FILE *fp;
int fd;

if (!(fp=fopen(myfile, "w+")))
    die("fopen");

/* we'll use fchmod() to prevent a race condition */
fd=fileno(fp);
/* lets modify the permissions */
if (fchmod(fd, 0600)==-1)
    die("fchmod");
```

- ▶ `fopen()` creates a file with default perms 0666

Exercise. (Recall Lab 1): review the codes for file permissions and masks on Linux.

Ownership races

```
drop_privs();

if ((fd=open(myfile, O_RDWR | O_CREAT | O_EXCL, 0600))<0)
    die("open");

regain_privs();

/* take ownership of the file */
if (fchown(fd, geteuid(), getegid())==-1)
    die("fchown");
```

Directory position race

GNU file utils had a race vulnerability in recursive deletion. Example strace for `rm -fr /tmp/a` removing `/tmp/a/b/c` tree:

```
chdir("/tmp/a")
chdir("b")
chdir("c")
chdir("../")
rmdir("c")
chdir("../")
rmdir("b")
fchdir(3)
rmdir("/tmp/a")
```

Question. Can you see an attack here?

Directory position race

GNU file utils had a race vulnerability in recursive deletion. Example strace for `rm -fr /tmp/a` removing `/tmp/a/b/c` tree:

```
chdir("/tmp/a")
chdir("b")
chdir("c")
chdir("../")
rmdir("c")
chdir("../")
rmdir("b")
fchdir(3)
rmdir("/tmp/a")
```

Question. Can you see an attack here?

- ▶ let `rm` work until it gets into `/tmp/a/b/c`

Directory position race

GNU file utils had a race vulnerability in recursive deletion. Example strace for `rm -fr /tmp/a` removing `/tmp/a/b/c` tree:

```
chdir("/tmp/a")
chdir("b")
chdir("c")
chdir("../")
rmdir("c")
chdir("../")
rmdir("b")
fchdir(3)
rmdir("/tmp/a")
```

Question. Can you see an attack here?

- ▶ let `rm` work until it gets into `/tmp/a/b/c`
- ▶ move `c` directory to `/tmp/c`

Directory position race

GNU file utils had a race vulnerability in recursive deletion. Example strace for `rm -fr /tmp/a` removing `/tmp/a/b/c` tree:

```
chdir("/tmp/a")
chdir("b")
chdir("c")
chdir("../")
rmdir("c")
chdir("../")
rmdir("b")
fchdir(3)
rmdir("/tmp/a")
```

Question. Can you see an attack here?

- ▶ let `rm` work until it gets into `/tmp/a/b/c`
- ▶ move `c` directory to `/tmp/c`
- ▶ then two `chdir("../")`s navigate to `/`

Races with temporary files

```
char temp[1024];
int fd;
strcpy(temp, "/tmp/tmpXXXX");
if (!mktemp(temp))
    die("mktemp");
fd=open(temp, O_CREAT | O_RDWR, 0700);
if (fd<0)
{
    perror("open");
    exit(1);
}
```

Question. Can you see two security issues here?

Races with temporary files

```
char temp[1024];
int fd;
strcpy(temp, "/tmp/tmpXXXX");
if (!mktemp(temp))
    die("mktemp");
fd=open(temp, O_CREAT | O_RDWR, 0700);
if (fd<0)
{
    perror("open");
    exit(1);
}
```

Question. Can you see two security issues here?

- ▶ `mktemp()` uses replaces XXX with random data

Races with temporary files

```
char temp[1024];
int fd;
strcpy(temp, "/tmp/tmpXXXX");
if (!mktemp(temp))
    die("mktemp");
fd=open(temp, O_CREAT | O_RDWR, 0700);
if (fd<0)
{
    perror("open");
    exit(1);
}
```

Question. Can you see two security issues here?

- ▶ `mktemp()` uses replaces XXX with random data
- ▶ unique so *not* completely unpredictable

Races with temporary files

```
char temp[1024];
int fd;
strcpy(temp, "/tmp/tmpXXXX");
if (!mktemp(temp))
    die("mktemp");
fd=open(temp, O_CREAT | O_RDWR, 0700);
if (fd<0)
{
    perror("open");
    exit(1);
}
```

Question. Can you see two security issues here?

- ▶ `mktemp()` uses replaces XXX with random data
- ▶ unique so *not* completely unpredictable
- ▶ moreover, has race condition

Races with temporary files

```
char temp[1024];
int fd;
strcpy(temp, "/tmp/tmpXXXX");
if (!mktemp(temp))
    die("mktemp");
fd=open(temp, O_CREAT | O_RDWR, 0700);
if (fd<0)
{
    perror("open");
    exit(1);
}
```

Question. Can you see two security issues here?

- ▶ `mktemp()` uses replaces XXX with random data
- ▶ unique so *not* completely unpredictable
- ▶ moreover, has race condition
- ▶ (although better than old `foobar.PID` scheme)

Races with temporary files

```
char temp[1024];
int fd;
strcpy(temp, "/tmp/tmpXXXX");
if (!mktemp(temp))
    die("mktemp");
fd=open(temp, O_CREAT | O_RDWR, 0700);
if (fd<0)
{
    perror("open");
    exit(1);
}
```

Question. Can you see two security issues here?

- ▶ `mktemp()` uses replaces XXX with random data
- ▶ unique so *not* completely unpredictable
- ▶ moreover, has race condition
- ▶ (although better than old `foobar.PID` scheme)

Races with temporary files

```
char temp[1024];
int fd;
strcpy(temp, "/tmp/tmpXXXX");
if (!mktemp(temp))
    die("mktemp");
fd=open(temp, O_CREAT | O_RDWR, 0700);
if (fd<0)
{
    perror("open");
    exit(1);
}
```

Question. Can you see two security issues here?

- ▶ `mktemp()` uses replaces XXX with random data
- ▶ unique so *not* completely unpredictable
- ▶ moreover, has race condition
- ▶ (although better than old `foobar.PID` scheme)

Recommended replacement: `fd = mkstemp(temp)`.

Outline

Overview

Race Conditions

Race conditions with Unix file handling

Data Races

Preventing Races

Preventing race conditions

Preventing data races

Tools to detect races

Summary

Risky Banking

```
public class BankAccount {  
    private int balance;  
  
    public BankAccount(int initialBalance) {  
        if (initialBalance < 0)  
            throw new  
                IllegalArgumentException("initial balance must be >= 0");  
  
        balance = initialBalance;  
    }  
}
```

Risky Banking

```
public class BankAccount {  
    public void adjustBalance(int adjustment) {  
        balance = balance + adjustment;  
    }  
}
```

Q: What's wrong with this code?

Risky Banking

```
public class BankAccount {  
    public void adjustBalance(int adjustment) {  
        balance = balance + adjustment;  
    }  
}
```

A: it goes wrong in a multi-threaded context.

Under the bonnet: Java bytecode

```
[dice]da: javac BankAccount.java
```

```
[dice]da: javap -c BankAccount
```

```
Compiled from "BankAccount.java"
```

```
public BankAccount1(int);
```

```
Code:
```

```
  0: aload_0                // push address of this object
  1: invokespecial #1        // Method java/lang/Object."<init>":()V
  4: iload_1                 // push first argument integer
  5: ifge                    18
  8: new                     #2        // class java/lang/IllegalArgumentException
 11: dup
 12: ldc                     #3        // String initial balance must be >= 0
 14: invokespecial #4        // Method java/lang/IllegalArgumentException.<init>:(Ljava/lang/String;)V
 17: athrow
 18: aload_0                // push address of this object
 19: iload_1                 // push first argument integer
 20: putfield               #5        // store in field balance
 23: return
```

```
public void adjustBalance(int);
```

Code:

```
0: aload_0           // push address of this object
1: aload_0           // and again
2: getfield          #5 // fetch field balance
5: iload_1           // first argument: adjustment
6: iadd              // top of stack = this.balance + adjustment
7: putfield          #5 // store in field balance
10: return
```

Observe that:

```
balance = balance + adjustment
```

is implemented in these steps:

```
temp = balance
temp = temp + adjustment
balance = temp
```

where temp is a location in the (thread local) stack.

Racy interleaving: missed update 1

Thread 1

=====

temp1 = balance

temp1 = temp1+adj1

balance = temp1

Thread 2

=====

temp2 = balance

temp2 = temp2+adj2

balance = temp2

- ▶ Final balance loses the adjustment adj 1.

Racy interleaving: missed update 2

Thread 1

=====

temp1 = balance

temp1 = temp1+adj1

balance = temp1

Thread 2

=====

temp2 = balance

temp2 = temp2+adj2

balance = temp2

- ▶ Final balance loses the adjustment adj2.

Data races defined

A data race is a race condition at the level of atomic memory accesses. It is the root cause of many subtle programming errors involving multi-threaded programs.

Data Race

A *data race* occurs when two or more threads access a shared variable:

1. (potentially) at the same time, and
2. at least one of the accesses is a write

Bugs from data races

Data races are usually accidental bugs.

- ▶ Lead to non-determinism
- ▶ Buggy behaviour may be very rare
- ▶ Hence difficult to reproduce: a “heisenbug”

Occasionally data races are *intentional* and safe:

- ▶ E.g., write-write races which write the same value
- ▶ Used knowingly e.g., in *lock-free* algorithms

This kind of thing is usually just for expert library code or O/S kernel developers.

Normal application developers should aim to write **data race free** programs.

Why can data races lead to security flaws?

Just as with race conditions:

- ▶ attacker may be able to influence thread scheduling
- ▶ or execute many, many times
- ▶ ... to cause an erroneous calculation/inconsistent value

Additionally, racy programs may have a strange issue:

- ▶ circular *causality* loops: undefined behaviour
- ▶ which allows registers to have any values..
- ▶ prevented by making **no out-of-thin-air** requirement

Java Memory Model: No Out-of-Thin-Air

Requirement: *A program should not be able to read values that couldn't be written by that program.*

Thread 1	Thread 2
-----	-----
r1 := x	r2 := y
y := r1	x := r2
print r1	print r2

- ▶ x, y are shared memory locations, initially both 0
- ▶ r1 and r2 are thread-local memory locations

The only possible result should be printing two zeros because no other value appears in or can be created by the program.

However, certain compiler/CPU optimisations would *any* value to be output here! (Q. Why is that bad?)

Write speculation breaks no out-of-thin-air

Thread 1	Thread 2
-----	-----
r1 := x	r2 := y
y := r1	x := r2
print r1	print r2

using **write speculation** this can be executed as

Thread 1	Thread 2
-----	-----
y := 42	
r1 := x	r2 := y
if (r1 != 42)	x := r2
y := r1	
print r1	print r2

Now the example program could output 42!

Exercise. Give an interleaved execution showing this.

Outline

Overview

Race Conditions

Race conditions with Unix file handling

Data Races

Preventing Races

Preventing race conditions

Preventing data races

Tools to detect races

Summary

Outline

Overview

Race Conditions

Race conditions with Unix file handling

Data Races

Preventing Races

Preventing race conditions

Preventing data races

Tools to detect races

Summary

Ensuring atomicity

In general, race conditions are prevented by ensuring that compound operations occur *atomically*.

- ▶ Examples previously with APIs for file systems
- ▶ If we are getting a value (file, variable, etc):
 - ▶ broken: **test**, then **get** (TOCTOU)
 - ▶ fix: combined API function **test-and-get**

Question. How can we write API functions that ensure atomicity?

Ensuring atomicity

In general, race conditions are prevented by ensuring that compound operations occur *atomically*.

- ▶ Examples previously with APIs for file systems
- ▶ If we are getting a value (file, variable, etc):
 - ▶ broken: **test**, then **get** (TOCTOU)
 - ▶ fix: combined API function **test-and-get**

Question. How can we write API functions that ensure atomicity?

- ▶ usually: enforce *mutual exclusion*
- ▶ or: use a *transaction* mechanism (has rollback)

Databases and file systems allow high throughput concurrency with transactions. *Transactional memory* is still a research topic.

Outline

Overview

Race Conditions

Race conditions with Unix file handling

Data Races

Preventing Races

Preventing race conditions

Preventing data races

Tools to detect races

Summary

Using locks

For multi-threaded application programs, e.g., in Java

- ▶ **locks** to ensure mutual exclusion for shared resources

Sometimes programmers are *forgetful* about doing this

- ▶ path through code possible without locking
- ▶ or use complicated, implicit conventions
- ▶ e.g., lock objects stored/removed in memory

It's better to be carefully explicit about locking conventions.

Safer online banking

Returning to the banking example:

```
protected final Object lock = new Object();  
  
@GuardedBy("lock")  
private int balance;
```

- ▶ Whenever we access `balance`, `lock` should be held
- ▶ `@GuardedBy` annotation is a hint from the developer
 - ▶ readable by other developers
 - ▶ but also by a tool, so it can be checked
- ▶ Several fields might be protected by the same lock

We can split the API into internal and external methods:

```
protected int readBalance() {
    return balance;
}

protected void adjustBalance(int adjustment) {
    balance = balance + adjustment;
}

public void credit(int amount) {
    if (amount < 0)
        throw new IllegalArgumentException("credit amount must be >= 0");

    synchronized (lock) {
        adjustBalance(amount);
    }
}
```

But we need to be careful that the locking strategy is followed in all subclasses.

For more, see [Contemplate's technical briefing](#)

Outline

Overview

Race Conditions

Race conditions with Unix file handling

Data Races

Preventing Races

Preventing race conditions

Preventing data races

Tools to detect races

Summary

Dynamic analysis

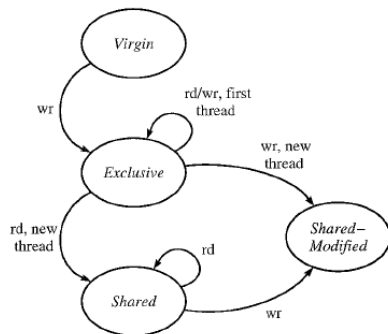
Dynamic analysis is in principle very expensive: monitor every access to every memory location, and see whether the access *might have raced* with a previous access from a different thread.

The **Lockset algorithm** simplifies this using the heuristic/expectation that every shared variable is protected by at least one lock.

- ▶ For each location x , initialise $C(x)$ be all locks
- ▶ For each thread t , let $\text{locks}(t)$ be locks held by t
- ▶ On each access to x from thread t
 - ▶ refine $C(x)$ by removing locks not in $\text{locks}(t)$
 - ▶ if $C(x) = \{\}$ then give a warning

The *Eraser* tool operates a tuned version of this algorithm that distinguishes the kinds of access.

Eraser state model for shared locations



- ▶ Calculate locksets for *Shared* and *Shared-Modified*
- ▶ Only report errors in the *Shared-Modified* state

Eraser implemented this using binary modification to instrument a program dynamically.

Static analysis for race detection

Can use a static version of the Lockset algorithm.

Advantages:

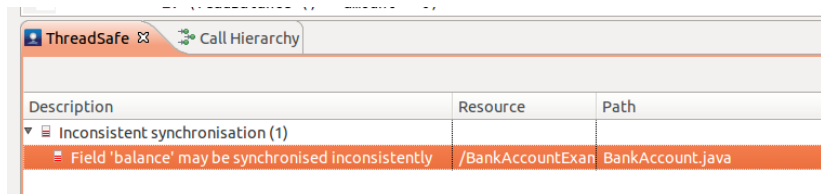
- ▶ Spot data races that are missed by dynamic tool
 - ▶ dynamic: may not explore paths “near enough”
- ▶ Doesn't impact code execution speed
 - ▶ dynamic: instrumentation gives significant slow-down

Disadvantages:

- ▶ Difficult to track locks held in data structures, etc.

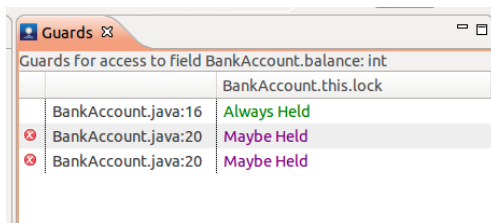
The analysis can be made precise if programmers use `@GuardedBy` annotations to describe the locking policy. Otherwise a tool has to guess the relevant locks and use heuristics to report discrepancies.

Contemplate's ThreadSafe tool



The screenshot shows the ThreadSafe tool interface. At the top, there are two tabs: "ThreadSafe" (selected) and "Call Hierarchy". Below the tabs is a table with three columns: "Description", "Resource", and "Path". The table contains one main entry, "Inconsistent synchronisation (1)", which is expanded to show a sub-entry: "Field 'balance' may be synchronised inconsistently". This sub-entry has a resource of "/BankAccountExam" and a path of "BankAccount.java".

Description	Resource	Path
▼ Inconsistent synchronisation (1)		
Field 'balance' may be synchronised inconsistently	/BankAccountExam	BankAccount.java



The screenshot shows the Guards tool interface. At the top, there is a tab labeled "Guards". Below the tab is a table with the title "Guards for access to field BankAccount.balance: int". The table has two columns: the first column lists the location of the guard (e.g., "BankAccount.java:16"), and the second column lists the guard type (e.g., "Always Held", "Maybe Held"). The first row shows "BankAccount.java:16" with "Always Held". The second and third rows show "BankAccount.java:20" with "Maybe Held", and each of these rows has a red 'x' icon in the first column.

Guards for access to field BankAccount.balance: int	
	BankAccount.this.lock
BankAccount.java:16	Always Held
✗ BankAccount.java:20	Maybe Held
✗ BankAccount.java:20	Maybe Held

Outline

Overview

Race Conditions

Race conditions with Unix file handling

Data Races

Preventing Races

Preventing race conditions

Preventing data races

Tools to detect races

Summary

Review Questions

Race Conditions

- ▶ Using an example based on Unix file handling, describe what a *race condition* is, and explain how an attacker can exploit it.

Data races

- ▶ Describe the two necessary conditions for a program to contain a data race.
- ▶ Discuss whether it is possible for a racy program to compute a completely arbitrary value.

Program securely

- ▶ Describe two programming techniques that can be used to avoid security issues with race conditions.

References and credits

This lecture included examples from:

- ▶ M. Dowd, J. McDonald and J. Schuh. *The Art of Software Security Assessment*, Addison-Wesley 2007. The Unix file samples and TOCTOU picture are from Chapter 9.
- ▶ Contemplate Ltd's technical briefing on its *ThreadSafe* tool.
- ▶ Savage et al. *Eraser: A Dynamic Data Race Detector for Multithreaded Programs*, ACM TOCS, **15**(4), 1997.