Secure Programming Lecture 8: Race Conditions

David Aspinall

Informatics @ Edinburgh

Outline

Overview

Race Conditions

- Race conditions with Unix file handling

Data Races

Races in Hardware

Preventing Races

- Preventing race conditions
- Preventing data races
- Tools to detect races

Summary

Recap

We have look at:

- examples of vulnerabilities and exploits
- particular programming failure patterns
- software based mitigations

In this lecture we consider a new vulnerability category and also a new defence strategy

- **language-based security** principles

for (ensuring) secure programs.

We introduce security vulnerabilities that can arise in concurrent systems, due to multi-processes or multi-threading.

Outline

Overview

Race Conditions

- Race conditions with Unix file handling

Data Races

Races in Hardware

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

Races in Hardware

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: `man access`)

```
int access(const char *pathname, int mode)

DESCRIPTION
  access() checks whether the calling process can access the file
  pathname.  If pathname is a symbolic link, it is dereferenced.

  The mode specifies the accessibility check(s) to be performed, and
  is either the value F_OK, or a mask consisting of the bitwise OR
  of one or more of R_OK, W_OK, and X_OK.  [...]

  The check is done using the calling process's real UID and GID,
  rather than the effective IDs as is done when actually attempting
  an operation (e.g., open(2)) on the file. [...]

RETURN VALUE
  On success (all requested permissions granted, or mode is F_OK
  and the file exists), zero is returned.  On error (at least one
  bit in mode asked for a permission that is denied, or mode is
  F_OK and the file does not exist, or some other error occurred),
  -1 is returned [...]
```

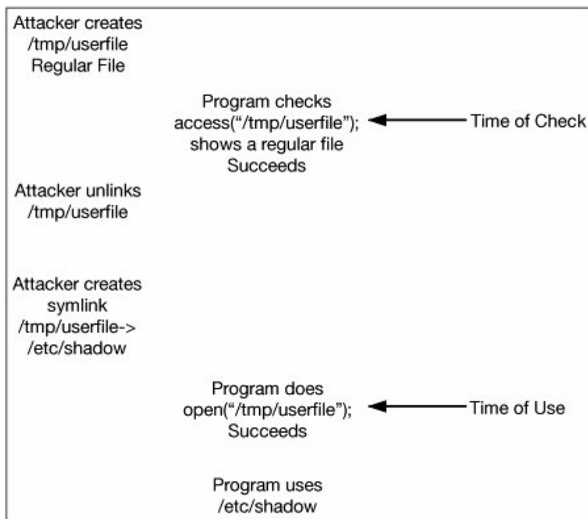
Race conditions with check before use

```
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);
/* let's modify the permissions */
if (fchmod(fd, 0600)==-1)
    die("fchmod");
```

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

Exercise. (Recall labs): 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");
```

A broken attempt in a setuid program: creates a file as calling user, then sets ownership as `root`. Unprivileged users may get file descriptor between steps.

Note: O_EXCL suggests “exclusivity” but really means file should not already exist, it has no effect on ability to access the file!

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()` replaces XXXX 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()` replaces XXXX with random data
- unique so *not* completely unpredictable

Races with temporary files

```c
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()` replaces XXXX with random data
- unique so *not* completely unpredictable
- moreover, has race condition

Races with temporary files

```c
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()` replaces XXXX 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()` replaces XXXX 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()` replaces XXXX 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
- Races in Hardware
- Preventing Races
  - Preventing race conditions
  - Preventing data races
  - Tools to detect races
- Summary

Risky Banking

```java
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

```java
public class BankAccount {

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

Q: What’s wrong with this code?

Risky Banking

```java
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/l
  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                            Thread 2
     ========                            ========

temp1 = balance
                                     temp2 = balance

temp1 = temp1+adj1
                                     temp2 = temp2+adj2

balance = temp1
                                     balance = temp2
```

- Final balance loses the adjustment `adj1`.

Racy interleaving: missed update 2

```
     Thread 1                   Thread 2
     ========                   ========

temp1 = balance
                             temp2 = balance

temp1 = temp1+adj1
                             temp2 = temp2+adj2

                             balance = temp2
balance = temp1
```

- Final balance loses the adjustment `adj2`.

Data races defined

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

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.

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 OS 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 allow *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
- Races in Hardware
- Preventing Races
  - Preventing race conditions
  - Preventing data races
  - Tools to detect races
- Summary

Hardware security

2018: *Meltdown* and *Spectre* were made public.

CPU architecture bugs affecting many recent CPUs.

- Combine a *race condition* with *side-channel attack*
  - result: process A steals data from process B
  - attacks are generally undetectable
- Complex CPUs use software *microcode* to implement ISAs
  - bugs/vulns also possible in microcode
  - but workarounds/repairs may be possible

Since 2018 then a variety of other CPU vulnerabilities have been published related to speculative execution, including the class of *Microarchitectural Data Sampling* vulnerabilities. Microarcitectural states reveal information about paths not taken.

Emerging areas: hardware security cost-risk trade-off assessments for security mitigations.

Outline

Overview

Race Conditions

- Race conditions with Unix file handling

Data Races

Races in Hardware

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

Races in Hardware

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* has been an active research topic for a while (for both software and hardware).

Outline

Overview

Race Conditions

- Race conditions with Unix file handling

Data Races

Races in Hardware

Preventing Races

- Preventing race conditions
- Preventing data races
- Tools to detect races

Summary

Using locks

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

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

Sometimes programmers are *forgetful* about doing this

- paths through code possible without locking
- 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

Races in Hardware

Preventing Races

- Preventing race conditions
- Preventing data races
- Tools to detect races

Summary

Dynamic analysis

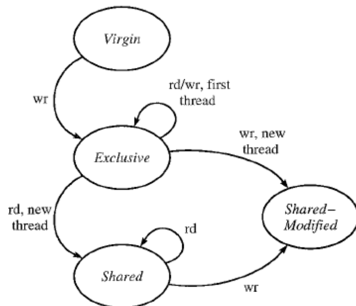
Dynamic analysis is in principle very expensive: monitor every access to every memory location, and see whether the access *might have raced* with a previous access from a different thread.

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 `locks(t)` be locks held by `t`
- On each access to `x` from thread `t`
  - refine `C(x)` by removing locks not in `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:

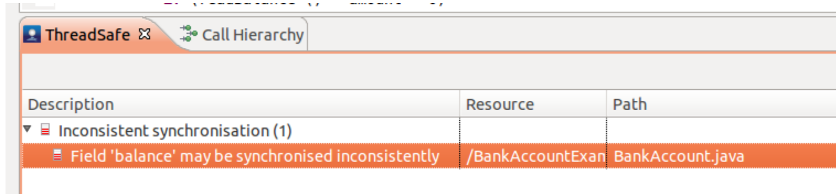
- Spot data races that are missed by dynamic tool
  - dynamic: may not explore paths “near enough”
- Doesn’t impact code execution speed
  - dynamic: instrumentation gives significant slow-down

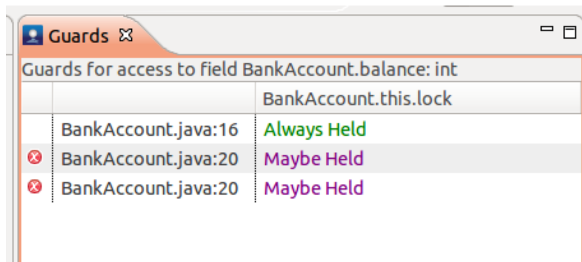
Disadvantages:

- 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.

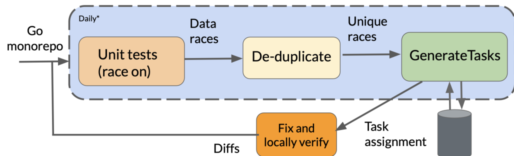
Contemplate’s ThreadSafe tool

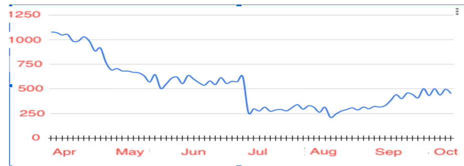




Race conditions at Uber

Feature	Subfeature	Java	Go
LoC	-	19 Million	46 Million
services	-	857	2100
concurrency creation	-	4162	11515
	total/MLoC	**219.1**	**250.3**





“Since higher concurrency can introduce more concurrency bugs, it is only natural to expect more data races in Go, especially when the language does not have a built-in mechanism to avoid data races, unlike languages such as Rust.” See *A Study of Real-World Data Races in Golang*, M. Chabbi and M. K. Ramanathan, PLDI 2022.

Outline

Overview

Race Conditions

- Race conditions with Unix file handling

Data Races

Races in Hardware

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.