# Concurrency vs Security

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## Overview

- Part 1: Concurrent Programs
- Part 2: Race Conditions
- Part 3: Security Implications

- Part 4: Valgrind

# Part 1: Concurrent Programs

# What is Concurrency?

- events that can happen at the same time
- it is not important if it does, only that it can
- events can be given a happens-before partial order
- they are concurrent if unordered by happens-before

## Why Concurrency?

- higher throughput on multicore computers
- serving multiple clients at once
- multiple tasks that are largely independent

## How?

- multiprocessing vs multithreading
- different resource vs isolation trade-offs

## What is a Process?

- an isolated address space
- executing a single program
- owns OS-level resources
  - (virtual) memory
  - access to the CPU
  - open file descriptors
  - including network connections
- created by `fork()` on UNIX

# Multiprocessing

- example: `httpd`
- each client connection gets a new process
- expensive: slow `fork`, needs more memory
- safe: no interference from other processes
- less safe but faster: process pools

# What is a Thread?

- a sequence of instructions
- each CPU core can run 1 thread at a time
  - more with SMT-capable cores (2–8)
  - one process can contain many threads
- instructions within a thread run in a sequence
- no guarantees on operation ordering between threads
- also applies to threads from different processes

# Multithreading

- think about `httpd` again
- each client connection gets a single thread
- threads are lightweight
- less context switching overhead
- further optimisation: thread pools

## Multithreading in HPC

- HPC = high-performance computing
- threads can share data much more easily
- easier to write fast algorithms
- usually not security-relevant

# The OS Kernel

- also runs concurrently with itself
- many processes can be doing system calls at once
- possibly preemptible
- “big kernel lock”: slows everything down
- preemptible kernels: fast but dangerous

# Processes and Communication

- IPC = inter-process communication
- message passing: (relatively) safe but slow
- stdio, sockets or networks: even slower
- shared memory: fast but dangerous

```c
void *thread( void *state )
{
    puts( "thread running" );
}

int main()
{
    pthread_t tid;
    pthread_create( &tid, NULL, thread, &x );
    puts( "main running" );
    pthread_join( tid, NULL );
}
```

# Example: C++

```
int main()
{
    auto f = [] { puts( "thread running" ); };
    std::thread t( f );
    puts( "main running" );
    t.join();
}
```

# Part 2: Race Conditions

## Shared Resources

- memory can be shared by multiple threads
- or even processes, through IPC mechanisms
- when is it safe to access/use a shared resource?

## Critical Section

- any section of code that must not be interrupted
- the statement `x = x + 1` could be a critical section
- what is a critical section is domain-dependent
  - another example could be a bank transaction
  - or an insertion of an element into a linked list

# Race Condition: Example

- consider a shared counter, `i`
- and the following two threads

```
int i = 0;
void thread1() { i = i + 1; }
void thread2() { i = i - 1; }
```

What is the value of `i` after both finish?

# Race Condition: Definition

- (anomalous) behaviour that depends on timing
- typically among multiple threads or processes
- an unexpected sequence of events happens
- recall that ordering is not guaranteed

# Mutual Exclusion

- only one process (thread) can access a resource at once
- ensured by a mutual exclusion device (a.k.a mutex)
- a mutex has 2 operations: lock and unlock
- those must be correctly paired up
- lock may need to wait until another thread unlocks

# Mutual Exclusion: Deadlocks

- happens if 2 or more threads cannot proceed
- each is waiting for a mutex locked by the other thread
- many other scenarios (not specific to mutexes)

# Example

- 2 mutexes: A, B
- first thread locks A first, then B
- second thread locks B first, then A
- race condition on mutexes

## Semaphore

- somewhat more general than a mutex
- allows multiple interchangeable instances of a resource
- and equal number of threads in the critical section
- basically an atomic counter

# Monitors

- a programming language device (not OS-provided)
- internally uses standard mutual exclusion
- data of the monitor is only accessible to its methods
- only one thread can enter the monitor at any given time

## Condition Variables

- what if the monitor needs to wait for something?
- imagine a bounded queue implemented as a monitor
  - what happens if it becomes full?
  - the writer must be suspended
- condition variables have `wait` and `signal` operations

## Spinlocks

- a spinlock is the simplest form of a mutex
- the `lock` method repeatedly tries to acquire the lock
  - this means it is taking up processor time
  - also known as busy waiting
- spinlocks between threads on the same CPU are very bad
  - but can be very efficient between CPUs

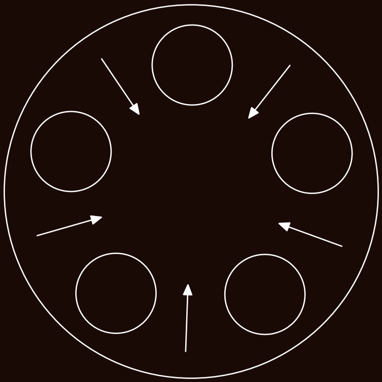
## Suspending Mutexes

- these need cooperation from the OS scheduler
- when lock acquisition fails, the thread sleeps
  - it is put on a waiting queue in the scheduler
- unlocking the mutex will wake up the waiting thread
- needs a system call → slow compared to a spinlock

# Condition Variables Revisited

- same principle as a suspending mutex
- the waiting thread goes into a wait queue
- the `signal` method moves the thread back to a run queue
- the busy-wait version is known as polling

# Dining Philosophers



# Readers and Writers

- imagine a shared database
- many threads can read the database at once
- but if one is writing, no other can read nor write
- what if there are always some readers?

## Shared Resources Revisited

- the file system is also a shared resource
- shared even between processes
- race conditions with other programs
  - possibly under the control of the attacker
- same with network resources &c.

# Part 3: Security Implications

# Two Types of Races

- within a single application (program)
  - bugs, not necessarily security-relevant
  - unexpected behaviour due to sequencing
  - eg. deadlocks/livelocks, memory corruption, etc.
  - races on file descriptors (`write` vs `close`)
- on resources shared with third parties
  - file system, network, etc.
  - almost always a security problem

## Single-Program Races

- not always, but sometimes security problems
- CVE-2017-2636: race condition in the Linux kernel
- unprivileged user can cause a timing-related double free
- and possibly gain `root` privileges

`https://a13xp0p0v.github.io/2017/03/24/CVE-2017-2636.html`

# The Systrace Race

- systrace was a BSD syscall restriction tool (sandbox)
- works by interposing every system call
- inspected at runtime by a user-space program
- syscall performed by the kernel if OK'd by the helper
- typical check–perform (TOC-TOU) race condition

# Denial of Service: Deadlocks

- denial of service is a type of security problem
- the attacker can cause the system to malfunction
- deadlocks often lead to denial of service
- a deadlocked program cannot proceed executing

# Non-Resource Deadlocks

- not all deadlocks are due to resource contention
- imagine a message-passing system
- process A is waiting for a message
- process B sends a message to A and waits for reply
- the message is lost in transit

# File System: Permission Checks

- imagine a program is executing as `root`
- it can send files to users
- subject to standard permission checks
- what happens if it does `stat()` to check access
- then open the file and send content?

# Exploiting FS Races: Symlink Attacks

- the attacker creates, say, `/tmp/innocent`
- it requests access to that file via the above app
- replaces the file after the app does its `stat()`
- by a symlink pointing to, say, `/etc/shadow`

# File System: Changing Ownership

- a program creates a file or a directory
- then calls `chown` to change the owner
- also vulnerable to symlink attacks
- CVE-2012-6095 (ProFTPd)

## File System: Changing Permissions

- a file is written (with sensitive content)
- it's immediately `chmod`-ed
- but the attacker can read it in a narrow time window
- CVE-2013-2162
- solution:
  - set `umask` (for shell scripts)
  - pass restrictive `mode` to `open()`

# File System: Closing the Window

- file names are sensitive to symlink attacks
- but file descriptors are not
- `fchown`, `fstat`, `fchmod` and so on
- open first, check using the file descriptor
- if the file is deleted, the fd still points to original

# File System: Temporary Files

- race between picking a free name and creating a file
  - always use `O_CREAT | O_EXCL` for creation
  - never use `mktemp`, use `mkstemp` instead
- also applies to creating directories
  - never create with `mkdir -p`
  - either `mkdtemp` or `mkdir` with error checking
- should be created in a safe location
  - either owned by the same user as the process
  - or with the sticky permission bit set

## Symlink Attacks: Not Just Races

- GDM did `chmod("/tmp/.X11-unix", 1777)`
- the attacker can symlink anything to `/tmp/.X11-unix`
- they get write access to that file
- instant `root` privileges
- CVE-2013-4169

# SMT (Hyper-Threading)

- allows multiple threads to run on a single core
- this means such threads share certain resources
- this opens a window for side-channel attacks
- threads from different processes should not SMT
  - but in practice, this is often allowed

# Part 4: Valgrind

# Why Valgrind: Memory Safety

- we have seen many memory bugs so far
  - buffer overflows
  - use-after-free
  - double free
- C (and C++) are memory unsafe

## Buffer Overflow

- out-of-bounds write to a buffer
- does not matter if heap or stack
- both are usually (and fatally) exploitable

## Examples

- `gets` … never use this function
- `scanf( "%s", buffer )` likewise
- `sprintf`, `strcpy`, etc. are often used wrong

# Use After Free

- allocate some memory
- call `free` later, but retain the pointer
- read or (worse) write through the pointer
- usually exploitable

```
char *mem = malloc( 1024 );
if ( error )
    free( mem );
strncpy( mem, 1024, some_input );
```

# Double Free

- call `free` on memory that was already freed
- usually causes heap corruption
- may very well be exploitable

```
char *mem = malloc( 1024 );
if ( error )
    free( mem );
// ...
free( mem )
```

## Finding Memory Bugs

- memory bugs are notoriously hard to debug
- `valgrind` (specifically its `memcheck` tool)
- only finds bugs that were actually triggered by a test
- clean report does not mean your program is secure
- works by instrumenting/interpreting binary code

# Helgrind

- races are even harder to find & fix than memory bugs
- use `valgrind` to detect concurrency issues
- data races, locking problems and so on
- you will learn more in the seminar

# Some Other Tools

- static: LockLint (Sun)
  - fast but false positives
- runtime
  - Visual Threads (HP)
  - Thread Checker (Intel)
  - DRDT (Data Race Detection Tool; Sun)
- verification: DIVINE
  - slow but exact