

## Lecture 08—Race Conditions; Mutexes

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# Roadmap

Past: Non-blocking I/O;

Now: Race Conditions, Locking.

# Part I

## Race Conditions

# Race Conditions

- A race occurs when you have two concurrent accesses to the same memory location, at least one of which is a **write**.

When there's a race, the final state may not be the same as running one access to completion and then the other.

Race conditions arise between variables which are shared between threads.

## Example Data Race (Part 1)

```
#include <stdlib.h>
#include <stdio.h>
#include <pthread.h>

void* run1(void* arg)
{
    int* x = (int*) arg;
    *x += 1;
}

void* run2(void* arg)
{
    int* x = (int*) arg;
    *x += 2;
}
```

## Example Data Race (Part 2)

```
int main(int argc, char *argv[])
{
    int* x = malloc(sizeof(int));
    *x = 1;
    pthread_t t1, t2;
    pthread_create(&t1, NULL, &run1, x);
    pthread_join(t1, NULL);
    pthread_create(&t2, NULL, &run2, x);
    pthread_join(t2, NULL);
    printf("%d\n", *x);
    free(x);
    return EXIT_SUCCESS;
}
```

Do we have a data race? Why or why not?

## Example Data Race (Part 2)

```
int main(int argc, char *argv[])
{
    int* x = malloc(sizeof(int));
    *x = 1;
    pthread_t t1, t2;
    pthread_create(&t1, NULL, &run1, x);
    pthread_join(t1, NULL);
    pthread_create(&t2, NULL, &run2, x);
    pthread_join(t2, NULL);
    printf("%d\n", *x);
    free(x);
    return EXIT_SUCCESS;
}
```

Do we have a data race? Why or why not?

- No, we don't. Only one thread is active at a time.

## Example Data Race (Part 2B)

```
int main(int argc, char *argv[])
{
    int* x = malloc(sizeof(int));
    *x = 1;
    pthread_t t1, t2;
    pthread_create(&t1, NULL, &run1, x);
    pthread_create(&t2, NULL, &run2, x);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    printf("%d\n", *x);
    free(x);
    return EXIT_SUCCESS;
}
```

Do we have a data race now? Why or why not?



## Example Data Race (Part 2B)

```
int main(int argc, char *argv[])
{
    int* x = malloc(sizeof(int));
    *x = 1;
    pthread_t t1, t2;
    pthread_create(&t1, NULL, &run1, x);
    pthread_create(&t2, NULL, &run2, x);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    printf("%d\n", *x);
    free(x);
    return EXIT_SUCCESS;
}
```

Do we have a data race now? Why or why not?

- Yes, we do. We have 2 threads concurrently accessing the same data.

# Tracing our Example Data Race

What are the possible outputs? (initially `*x` is 1).

1	<code>run1</code>	<code>run2</code>
2	<code>D.1 = *x;</code>	<code>D.1 = *x;</code>
3	<code>D.2 = D.1 + 1;</code>	<code>D.2 = D.1 + 2</code>
4	<code>*x = D.2;</code>	<code>*x = D.2;</code>

- Memory reads and writes are key in data races.

## Outcome of Example Data Race

- Let's call the read and write from run1 R1 and W1; R2 and W2 from run2.
- Assuming a sane<sup>1</sup> memory model,  $R_n$  must precede  $W_n$ . C/C++ don't guarantee that model.

All possible orderings:

Order				*x
R1	W1	R2	W2	4
R1	R2	W1	W2	3
R1	R2	W2	W1	2
R2	W2	R1	W1	4
R2	R1	W2	W1	2
R2	R1	W1	W2	3

WARNING: see the provisos in the written notes!

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<sup>1</sup>sequentially consistent

# Detecting Data Races Automatically

Dynamic and static tools can help find data races in your program.

- `helgrind` is one such tool. It runs your program and analyzes it (and causes a large slowdown).

Run with `valgrind --tool=helgrind <prog>`.

It will warn you of possible data races along with locations.

For useful debugging information, compile with debugging information (`-g` flag for `gcc`).

## Helgrind Output for Example

```
==5036== Possible data race during read of size 4 at
           0x53F2040 by thread #3
==5036== Locks held: none
==5036==    at 0x400710: run2 (in datarace.c:14)
...
==5036==
==5036== This conflicts with a previous write of size 4 by
           thread #2
==5036== Locks held: none
==5036==    at 0x400700: run1 (in datarace.c:8)
...
==5036==
==5036== Address 0x53F2040 is 0 bytes inside a block of size
           4 alloc'd
...
==5036==    by 0x4005AE: main (in datarace.c:19)
```

# Mutual Exclusion

Mutexes are the most basic type of synchronization.

- Only one thread can execute code protected by a mutex at a time.
- All other threads must wait until the mutex is free before they can execute protected code.

## Live Coding Example: Mutual Exclusion

## Creating Mutexes—Pthreads Example

```
pthread_mutex_t m1 = PTHREAD_MUTEX_INITIALIZER;  
pthread_mutex_t m2;  
  
pthread_mutex_init(&m2, NULL);  
...  
pthread_mutex_destroy(&m1);  
pthread_mutex_destroy(&m2);
```

- Two ways to initialize mutexes: statically and dynamically
- If you want to include attributes, you need to use the dynamic version



## Creating Mutexes—C++ Example

```
mutex m1;  
mutex *m2;  
  
m2 = new mutex();  
// ...  
  
delete(m2);
```

# Mutex Attributes

- **Protocol**: specifies the protocol used to prevent priority inversions for a mutex
- **Prioceiling**: specifies the priority ceiling of a mutex
- **Process-shared**: specifies the process sharing of a mutex

You can specify a mutex as *process shared* so that you can access it between processes. In that case, you need to use shared memory and `mmap`, which we won't get into.

## Using Mutexes: Pthreads Example

```
// code  
pthread_mutex_lock(&m1);  
// protected code  
pthread_mutex_unlock(&m1);  
// more code
```

- Everything within the lock and unlock is protected.
- Be careful to avoid deadlocks if you are using multiple mutexes.
- Also you can use `pthread_mutex_trylock`, if needed.

## Using Mutexes: C++11 Threads Example

```
// code  
m1.lock();  
// protected code  
m1.unlock();  
// more code
```

# Data Race Example

Recall that **dataraces** occur when two concurrent actions access the same variable and at least one of them is a **write**.

```
...
static int counter = 0;

void* run(void* arg) {
    for (int i = 0; i < 100; ++i) {
        ++counter;
    }
}

int main(int argc, char *argv[])
{
    // Create 8 threads
    // Join 8 threads
    printf("counter = %i\n", counter);
}
```

Is there a datarace in this example? If so, how would we fix it?

# Example Problem Solution

```
...
static pthread_mutex_t mutex = PTHREAD_MUTEX_INITIALIZER;
static int counter = 0;

void* run(void* arg) {
    for (int i = 0; i < 100; ++i) {
        pthread_mutex_lock(&mutex);
        ++counter;
        pthread_mutex_unlock(&mutex);
    }
}

int main(int argc, char *argv[])
{
    // Create 8 threads
    // Join 8 threads
    pthread_mutex_destroy(&mutex);
    printf("counter = %i\n", counter);
}
```