CS3.301 Operating Systems and Networks

Concurrency - Locks

Karthik Vaidhyanathan

https://karthikvaidhyanathan.com

INTERNATIONAL INSTITUTE OF INFORMATION TECHNOLOGY
HYDERABAD

Software Engineering Research Centre

Acknowledgement

The materials used in this presentation have been gathered/adapted/generate from various sources as well as based on my own experiences and knowledge -- Karthik Vaidhyanathan

Sources:

- Operating Systems in three easy pieces by Remzi et al.

Creating a Thread

- POSIX provides interface for management of threads - pthread.h

int pthread_create(pthread_t *thread, const pthread_attr_t *attr,

void *(*start_routine)(void *), void *arg)

- ***thread:** Pointer to pthread_t variable
- ***attr:** holds the attributes for new thread, stack size, scheduling policy, etc. NULL points to default
- ***start_routine:** Pointer to the function that will be executed by the thread upon execution
    - Takes a single void parameters and returns void value
- ***arg:** Argument that will be passed to the start_routine function
- Returns 0 if thread successfully created

Some Interesting things to be considered

```
void *worker_thread(void *arg)
{
    printf("%s\n", (char *) arg);
}
```

```
Starting the threading demo
thread 1
thread 2
end
```

```
Starting the threading demo
thread 2
thread 1
end
```

- Order of execution can be non deterministic
- Its hard to predict which thread executes first
- Two executions have two different sequence here!!
- So what could have happened?

An Ideal Trace

main	Thread 1	Thread 2
Running prints “Starting the threading demo” Creates T1 Creates T2 Waits for T1		
	Runs Prints “thread 1” Returns	
Waits for T2		Runs Prints “thread 2” Returns
print “end”		

This can also happen!

main	Thread 1	Thread 2
Running prints “Starting the threading demo” Creates T1		
	Runs Prints “thread 1” Returns	
Creates T2		Runs Prints “thread 2” Returns
Waits for T1 Waits for T2 prints “end”		

Shared Data - More Tricky

```c
void *worker_thread(void *arg)
{
    int index;
    for (index =0; index<max_index; index++)
    {
        counter++;
    }
}
```

```
Inital value of the counter 0
Final value of the counter 4000
```

```
Inital value of the counter 0
Final value of the counter 3790
```

- Max size: 2000, assume global variable counter initialised to 0
- Desired final result: **4000!, even on a single processor system there is no guarantee**
- **Why does this happen?**

Lets break the code down in assembly

counter = counter + 1

```
mov 0x8049a1c, %eax
add &0x1, %eax
mov %eax, 0x8049a1
```

1. Load memory value to register eax
2. Increment the value in the register by 1
3. Move the value from register back to memory

What can happen?

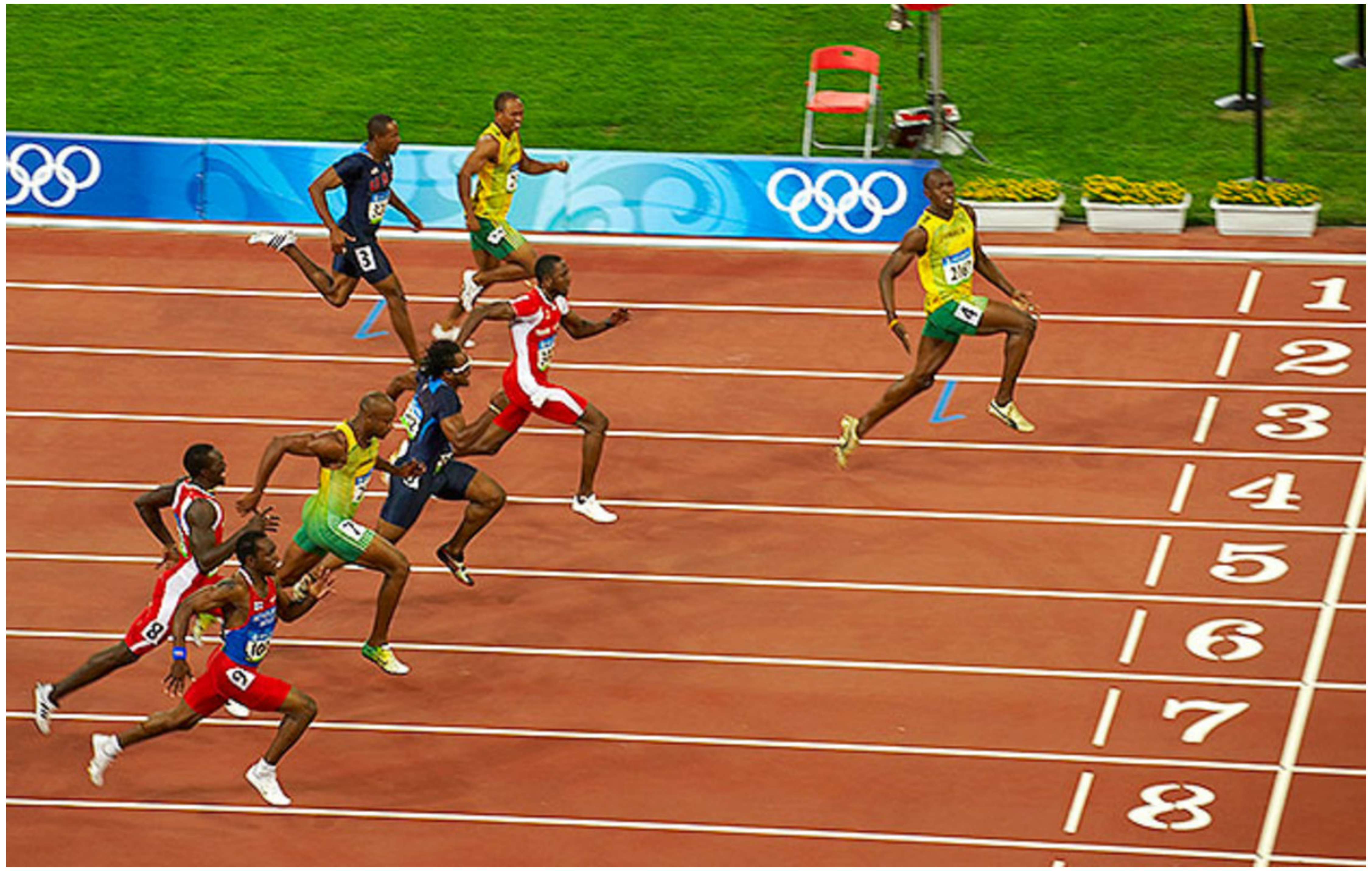
OS	Thread 1	Thread 2	Counter and Register (Initial value of counter = 50
	mov 0x8049a1c, %eax add $0x1, %eax		eax = 51 **counter = 50**
interrupt **Save T1' state** **Restore T2's state**			

		mov 0x8049a1c, %eax
		add $0x1, %eax
		Mov %eax, 0x8049a1c
			eax = 51
			counter = 51

interrupt **Save T2' state** **Restore T1's state**			

Race Condition and Critical Section

- **Race Condition: Condition where**
  - Multiple threads executing concurrently and
  - results depend on order of execution (time)
  - Scheduler can swap threads, also interrupts
  - Non-deterministic results
- **Critical Section:**
  - The section of code that is shared between the threads (leads to race conditions)
  - Shared variables or data



Source: https://www.si.com/olympics/2016/07/14/usain-bolt-2016-rio-olympics

Concurrency is tricky!

Race conditions can result in fatal issues

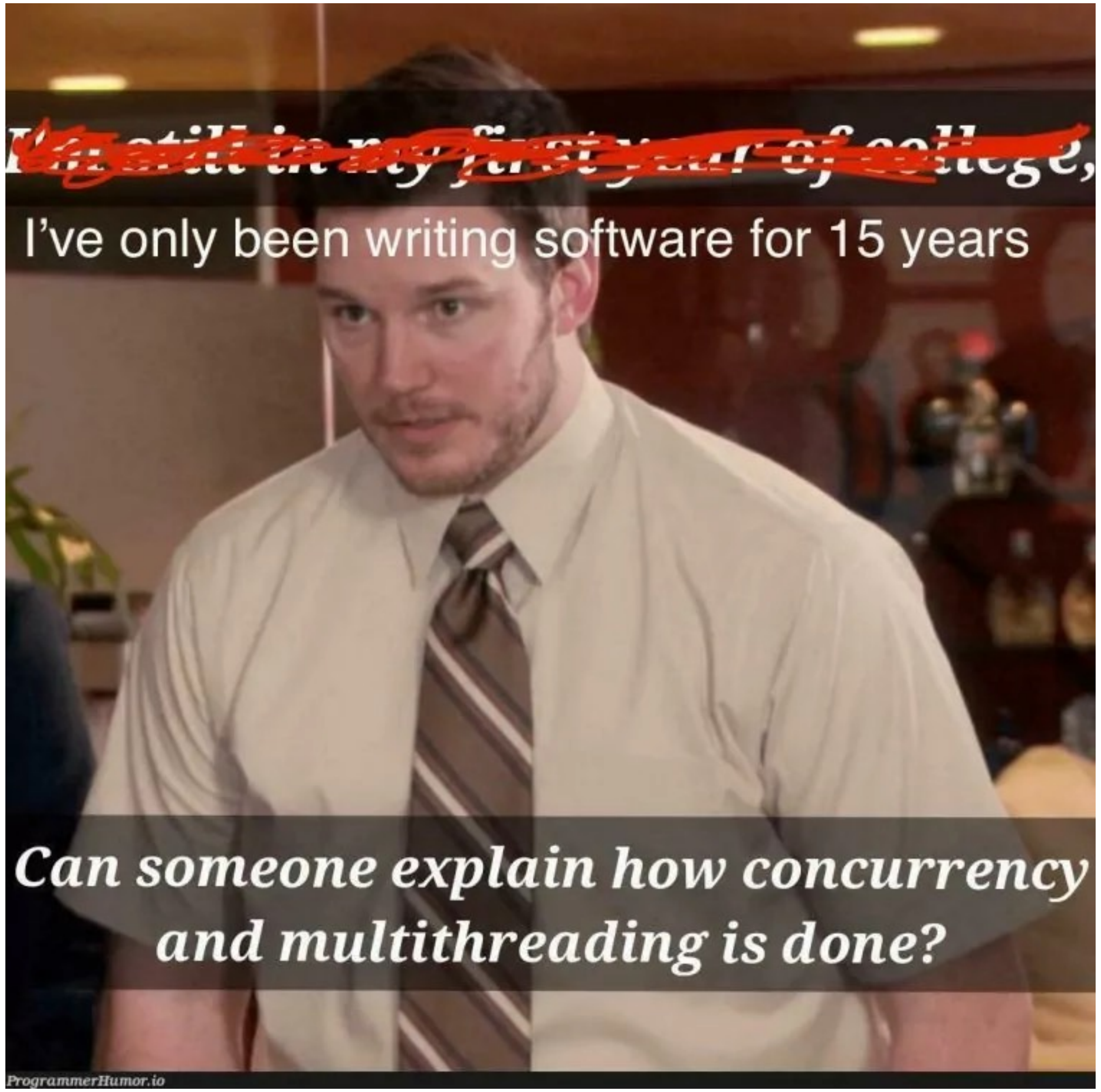
Therac 25

Northeast Blackout of 2003, US

https://www.everydayshouldbesaturday.com/2018/8/14/17687734/flashback-the-blackout-of-2003

Source: https://hackaday.com/2015/10/26/killed-by-a-machine-the-therac-25/

Concurrency can be tricky!



Source: programmerhumor.io

What can be done?

Bring in Atomicity

- What we want here is mutual exclusion!
  - When one thread is accessing critical section, others should wait
  - No two threads should access critical section at the same time
- In other words, **atomicity** needs to be provided
  - What if there was one instruction in assembly:
    - memory-add 0x8049a1c, &0x1 - Reality is not this!!

```
mov 0x8049a1c, %eax
add &0x1, %eax
mov %eax, 0x8049a1
```

This should execute atomically!!

What we need?

- Need to build synchronization primitives
  - Hardware + software support
  - Ensure that critical section is accessed in synchronised and controlled manner
- **One part:** Build some primitives for synchronisation
  - This will ensure atomicity (avoid race conditions)
- **Second part:** Ensure every thread gets access!
  - No one should starve

Some Issues needs to be addressed

- What support do we need from hardware?
- What support is needed from software?
- How to build primitives correctly and effectively?
- How can programs use these primitives?

Locks: A Basic Idea

- Lets go back to the shared variable code in **Critical Section (CS):**

$$counter = counter + 1$$

- What if we can have a lock surrounding the statement

```
lock_t mutex; //a global lock
....
lock (&mutex);   // lock the crticial section
counter = counter + 1;
unlock (&mutex); // release the lock
```

What are locks?

- Lock here is just a variable
- The lock variable holds the state of lock at any instant of time
- It is either available (free) or acquired:
  - **Available:** No threads hold the lock
  - **Acquired:** Lock not available, one thread is holding it and in CS
- We can also enrich with more information - which thread holds the lock, create a queue for threads to get locks, etc.

Lock and Unlock

- The thread that holds the lock - **Owner**
- Owner needs to call unlock to free the lock
  - The lock becomes free
  - There may be threads waiting for the lock, one of them will acquire it
  - The next thread with lock enters CS
  - When no thread is waiting for the lock, the lock stays as free
- **How to go about building a lock?**

How to go about building a lock?

- Think about classrooms and locks
- In the physical locks itself there are many options
- Many hardware primitives have been added to instruction set architecture to support locks
- The way in which the primitives are used + OS support forms the key

Image generated using stable diffusion

Criteria to evaluate

- **Mutual Exclusion**
    - Does the lock prevent multiple threads from entering CS at same time?
- **Fairness**
    - Does each thread get a fair chance to enter into the CS? - Avoid starvation!!
- **Performance**
    - When there is only one thread what is the overhead?
    - Multiple threads on single CPU - What about overhead?
    - Multiple threads on multiple CPU - What's are overhead?

Why threading is challenging?

- Two threads running at the same time
  - Interrupts - Can we disable interrupt inside a lock?

```
void lock()
{
  DisableInterrupts();
  //disables interrupts
}

void unlock()
{
  EnableInterrupt();
}
```

Main positive approach is simplicity

Are there any issues?

There are Negatives

- Thread gets a **very high privilege**
  - Thread can switch on and off the interrupts
  - Arbitrary thread can monopolize the processor
  - Errant program could call lock() and get into endless loop
- The approach does not work on multiple processor systems
  - Even if interrupts are disabled, other threads can run on different processor
- **Inefficiency:** Code that masks or unmasks interrupts are executed slowly
- Interrupt control is used in limited context as mutual exclusion primitive **(inside OS)**

Can we try with a software lock?

Software based lock

```
typedef struct __lock_t
{
    int flag;
} lock_t;

void init (lock_t *mutex)
{
  mutex -> flag = 0;
}

void lock(lock_t *mutex)
{
  while(mutex->flag==1)
    //do nothing
  mutex -> flag = 1;

}

void unlock (lock_t *mutex)
{
  mutex->flag = 0;
}
```

- Use software based locking mechanism
- Create a lock which has a flag value
- Every time a thread wants to enter CS
  - Invoke lock function, if flag = 1, wait for the lock to be available
  - Else acquire the lock and enter CS
- **Do you foresee some problem here?**

Simple Trace

Thread 1	Thread 2
Call lock() while (flag== 1) Interrupt to Thread 2	

	Call lock()
	While (flag==1)
	flag = 1;
	Interrupt to thread 1

flag = 1	

- No mutual exclusion - Both threads have flag set to 1
- Performance overhead due to spin-waiting

Working Spin Lock with Test-And-Set

Test and Set Instruction

Test and Set Lock

```
int TestAndSet(int *ptr, int new)
{
  int old = *ptr;
  *ptr = new;
  return old;
}
```

C Pseudocode

- Simplest hardware primitive - test-and-set or atomic exchange instruction
- Sequence of instructions executed atomically
- Enables testing of old values while setting the main to a new value
- Think about implementing a CS code with this lock!

Implementing using Test and Set Lock

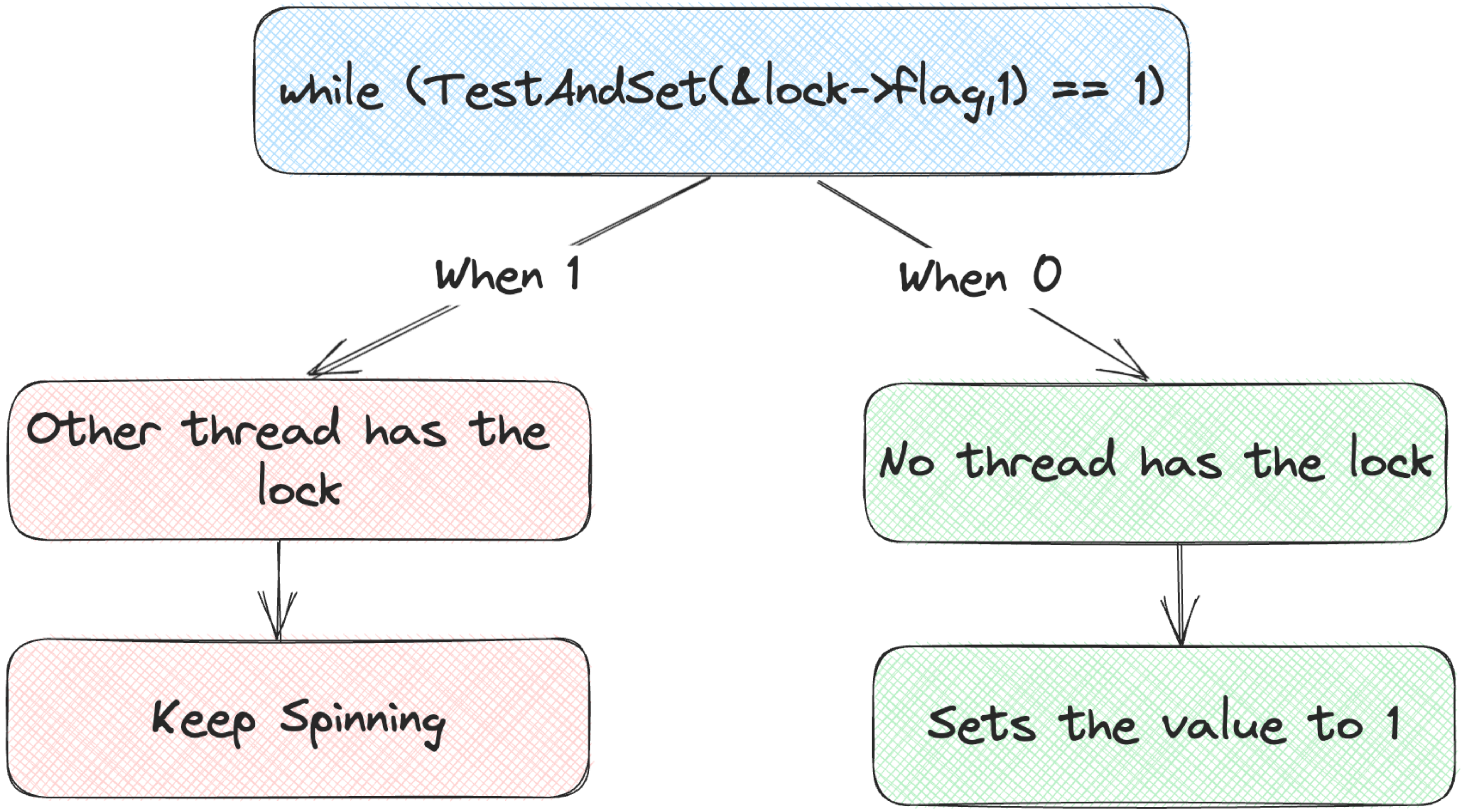
Using TestAndSet Lock

```
typedef struct __lock_t
{
    int flag
} lock_t;


void init (lock_t *lock)
{
  lock -> flag = 0;
}

void lock (lock_t *lock)
{
  while (TestAndSet(&lock-> flag, 1)==1)
   // Keep spinning
}

void unlock (lock_t *lock)
{
  lock -> flag = 0;
}
```



Only one thread can acquire the lock

Evaluating Spin Locks

- **Correctness perspective** Provides mutual exclusion, so correct!
- **Fairness perspective**
  - They don't provide fairness guarantee
  - Threads can keep spinning forever leading to starvation
- **Performance perspective**
  - In single CPU - significant overhead, What if thread holding the lock is preempted in critical section? - Run all N-1 threads to waste CPU
  - On multiple CPUs these locks work reasonably well (esp if n. Threads ~ n. CPUs)

Compare-And-Swap

Another Hardware Primitive

C Pseudocode

Compare-And-Swap

```
int CompareAndSwap(int *ptr, int expected, int new)
{
  int actual = *ptr;
  if (actual == expected)
  {
    *ptr = new;
  }
  return actual;
}
```

Inside the lock function the call will be:

```
while(CompareAndSwap(&lock->flag, 0,1) ==1)
```

- **Basic idea:** Test whether the value at address specified by ptr is equal to expected
  - If yes, update the memory location pointed to ptr by new value
  - If not, do nothing!
- In either case, return actual value at the memory location

Load-Linked and Store-Conditional (LL SC)

- In MIPS architecture, they can be used in tandem to build locks and concurrent structures

Load Linked

```c
int LoadLinked (int *ptr)
{
  return *ptr;
}
```

Store Conditional

```c
int StoreConditional(int *ptr, int value)
{
  if (no one has updated ptr since load linked)
  {
    *ptr = value;
     return 1;
  }
  else
  {
    return 0;
  }
}
```

C Pseudocode

LL/SC for building locks

- Load linked is like a typical load operation
  - Simply fetches a value from memory and places it in a register
- Store conditional succeeds if no intermittent store to address has taken place
  - In case of success, it updates ptr to value and returns 1 else returns 0

When does failure condition of store conditional arise?

LL/SC for building locks

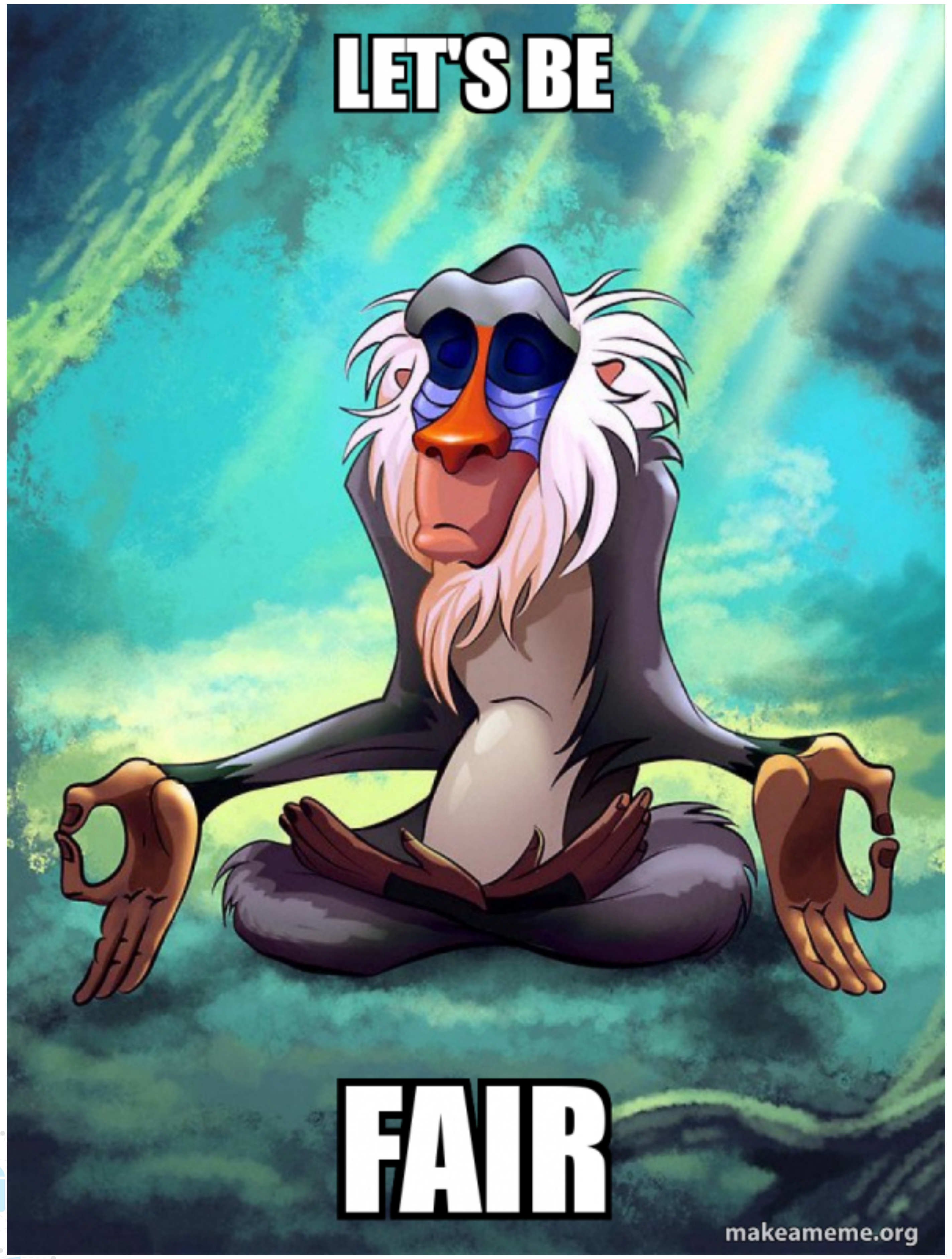
```
void lock(lock_t *lock)
{
  while (1)
  {
    while (LoadLinked(&lock->flag)==1)
    ; //Keep spinning

    if (StoreConditional(&lock->flag,1)==1)
    {
     //store is successful, retrun else repeat all
     again
      return;
    }
  }
}

void unlock(lock_t *lock)
{
  lock->flag = 0;
}
```

What about Fairness?

Can we incorporate fairness through locks?



- Lock only has a flag variable
- Every time a thread acquires, it checks for flag
- However, which threads are checking is not recorded
- The threads that are looking for locks may have to be stored somewhere
- Can we store more information within each lock?

What if we leverage Turns and Tickets

Think about going to some crowded office space

Source: juvale.com

SCAN ME

Thank you

Course site: karthikv1392.github.io/cs3301_osn

Email: karthik.vaidhyanathan@iiit.ac.in

Twitter: @karthi_ishere