CS3.301 Operating Systems and Networks

Concurrency - Locks

Karthik Vaidhyanathan

https://karthikvaidhyanathan.com

INTERNATIONAL INSTITUTE OF INFORMATION TECHNOLOGY
HYDERABAD

SERC
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.

Shared Data - More Tricky

```
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?

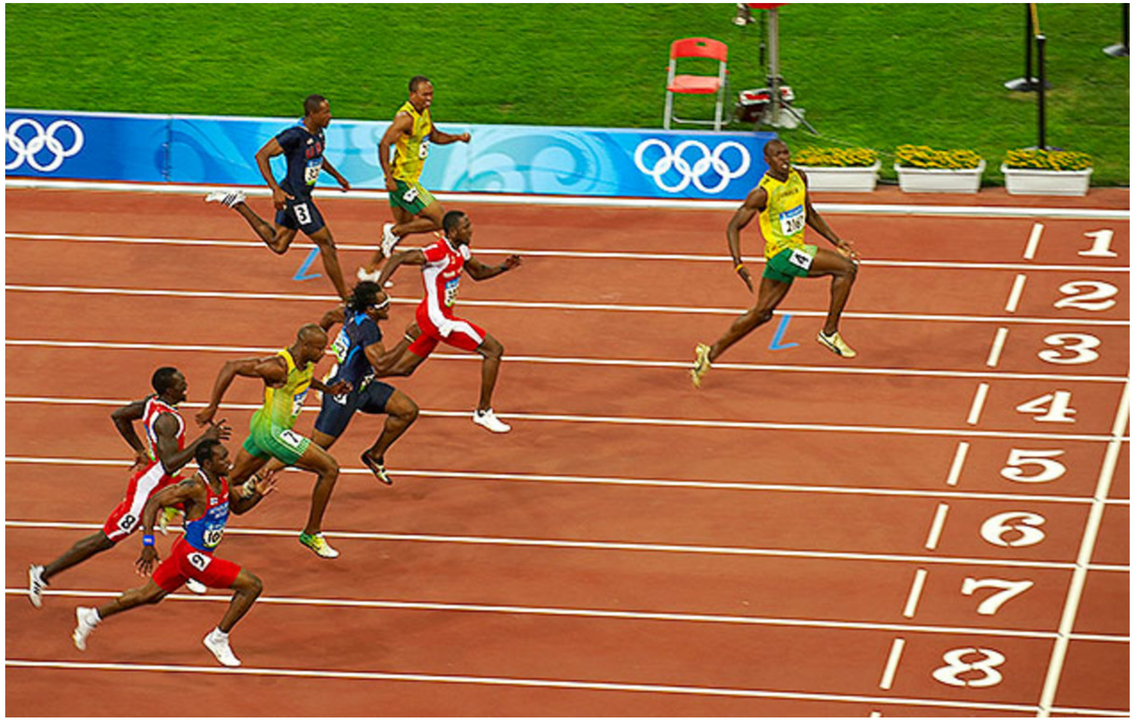
OS	Thread 1	Thread 2	Counter and Register (Initial value of counter = 50
	mov 0x8049a1c, %eax add $0x1, %eax		eax = 51 **counter = 50**
interrupt **Save T1' state** **Restore T2's state**			

		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

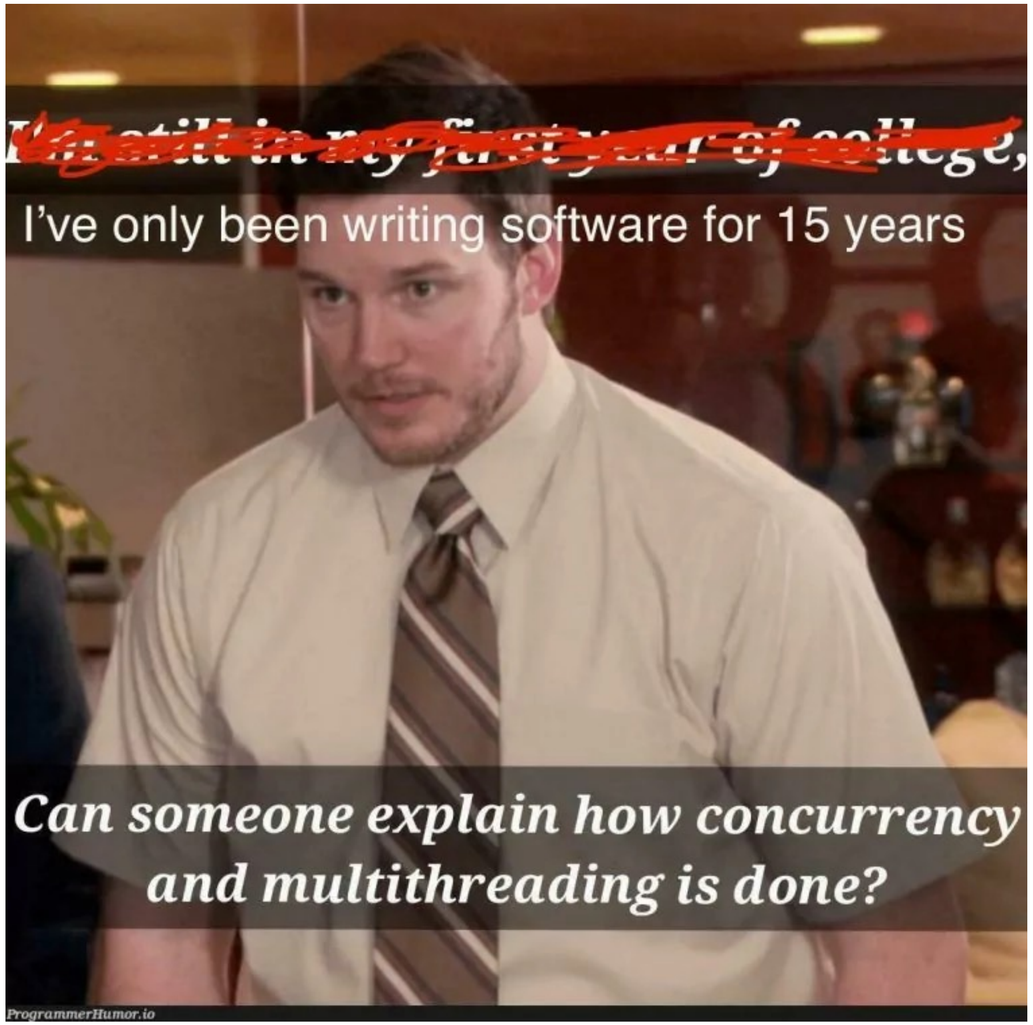
Therac 25

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

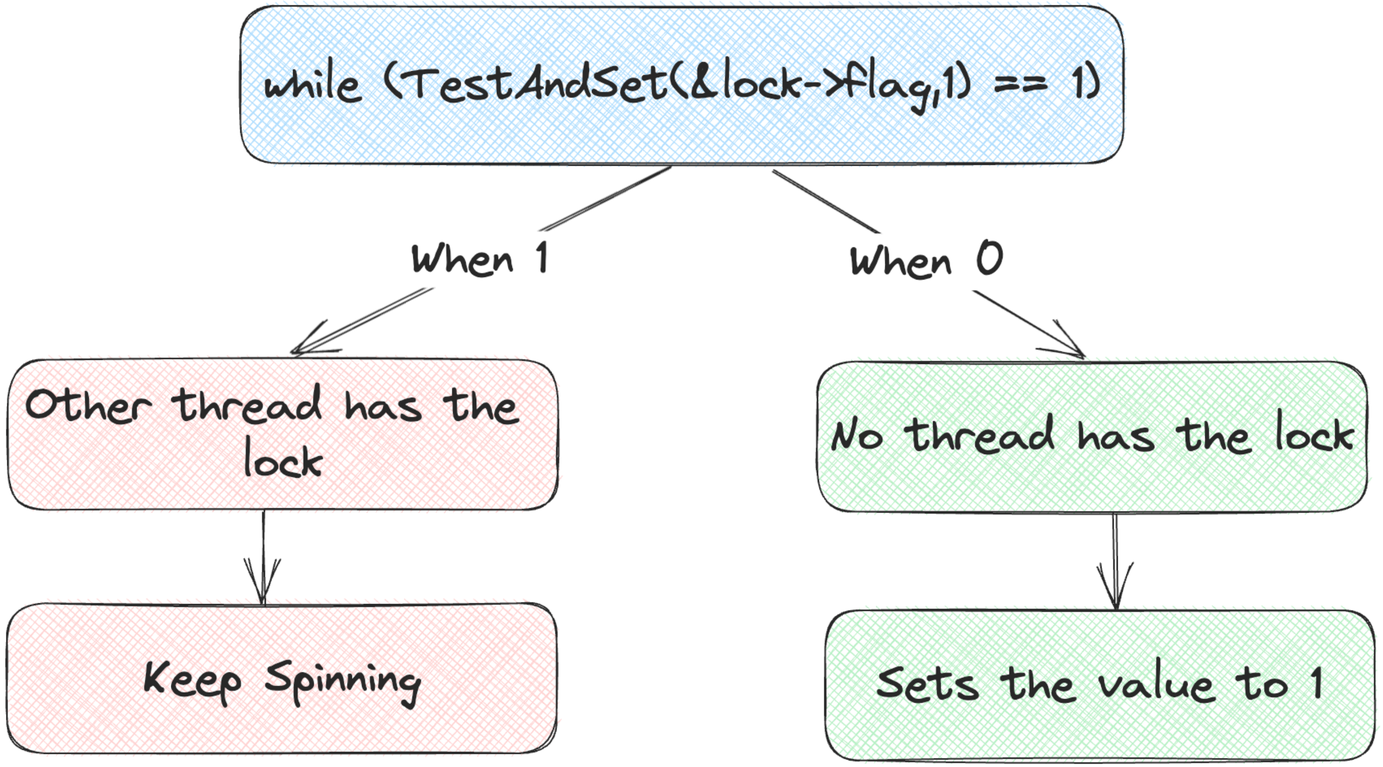
Using TestAndSet Lock

```
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

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

Store Conditional

```
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

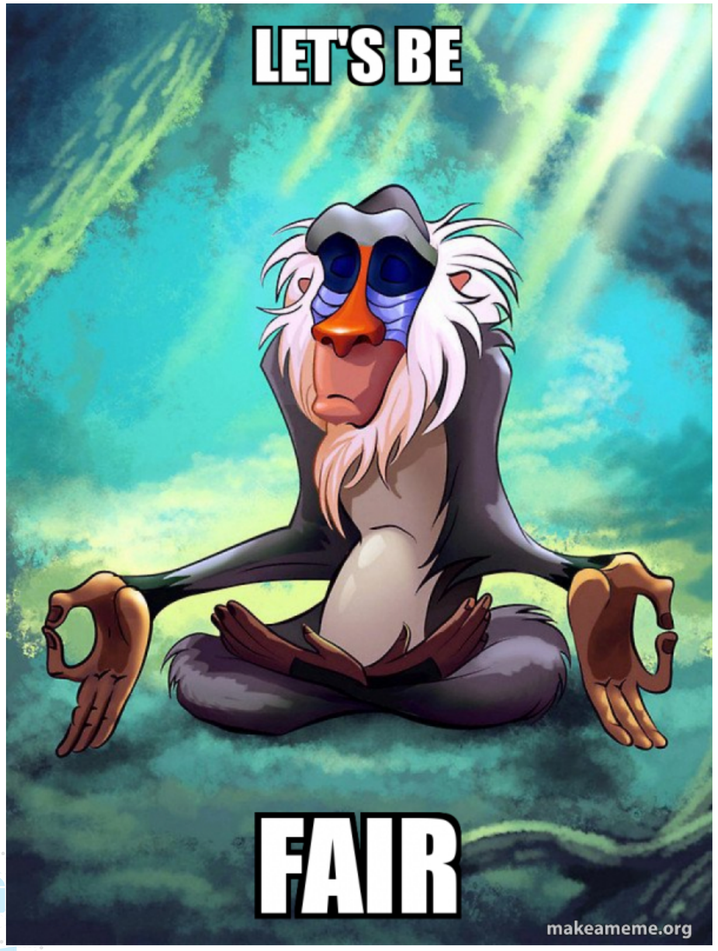
```
void lock(lock_t *lock)
{
  while (1)
  {
    while (LoadLinked(&lock->flag)==1)
    ; //Keep spinning

    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?

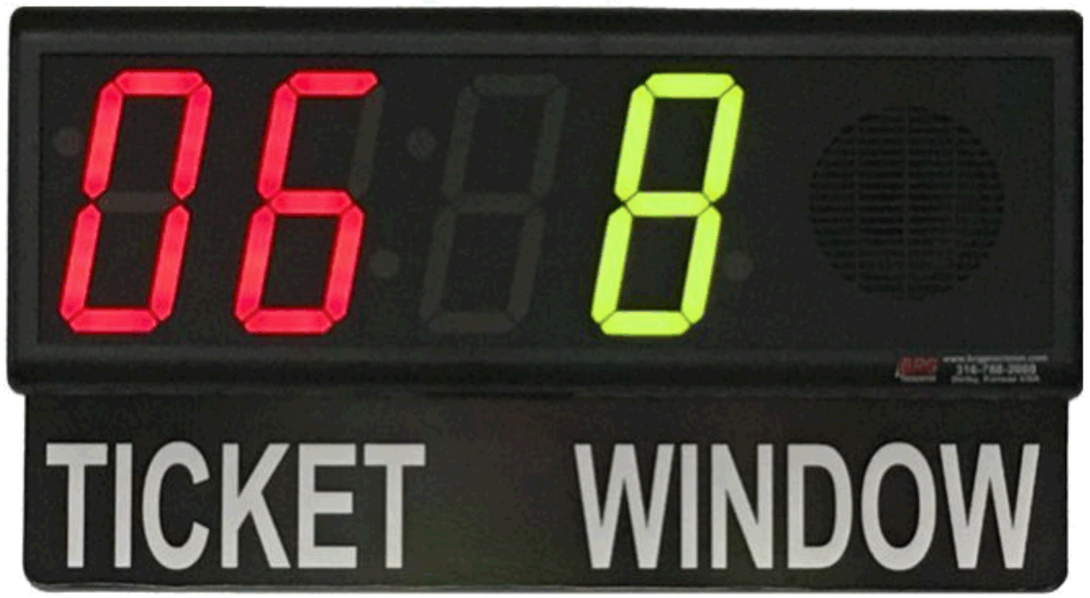
Can we incorporate fairness through locks?



- 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



Current Number and Window

Source: juvale.com

Fetch and Add

Yet another hardware primitive but very powerful

Fetch And Add

```
int FetchAndAdd(int *ptr)
{
  int old = *ptr;
  *ptr = old + 1;
  return old;    //returns old value
}
```

- Atomically increment a value while returning the old value at a particular address
- Used to build interesting type of lock - **The ticket lock**
- Instead of single variable a combination of ticket and turn variable is used
- Not just flag: ticket and turn

Ticket Lock

Ticket Lock

```
typedef struct __lock_t
{
    int ticket;
    int turn;
} lock_t;

void lock_init (lock_t *lock)
{
  lock_t -> ticket = 0;
  lock_t -> turn = 0;
}
```

Ticket Lock

```
void lock (lock_t *lock)
{
  int myturn = FetchAndAdd(&lock->ticket);
  //when ticket value = my turn, thread goes into CS
  while (lock->turn != myturn)
  {
    // keep spinning
  }
}

void unlock (lock_t *lock)
{
  // next waiting thread can enter CS
  FetchAndAdd(&lock->turn);
}
```

An Illustration of Ticket Lock

Four Processor Ticket Lock Example

Row	Action	next_ticket	now_serving	P1 my_ticket	P2 my_ticket	P3 my_ticket	P4 my_ticket
1	Initialized to 0	0	0	-	-	-	-
2	P1 tries to acquire lock (succeed)	1	0	0	-	-	-
3	P3 tries to acquire lock (fail + wait)	2	0	0	-	1	-
4	P2 tries to acquire lock (fail + wait)	3	0	0	2	1	-
5	P1 releases lock, P3 acquires lock	3	1	0	2	1	-
6	P3 releases lock, P2 acquires lock	3	2	0	2	1	-
7	P4 tries to acquire lock (fail + wait)	4	2	0	2	1	3
8	P2 releases lock, P4 acquires lock	4	3	0	2	1	3
9	P4 releases lock	4	4	0	2	1	3
10	...	4	4	0	2	1	3

Source: wikipedia article on ticket lock

How good is the spin based locks?

- Simple hardware based locks are simple to implement and powerful
- They are also quite inefficient especially when it comes to performance
  - Consider that there are two threads and one thread has the lock
  - When thread has lock, it may get interrupted, the other thread spins for a time slice, waste CPU cycle
  - Think about N threads, N-1 threads might waste CPU cycles in spinning (especially if round robin)
- **Can we come up with something better instead of wasting cycles with spinning?**

Thank you

Course site: karthikv1392.github.io/cs3301_osn
Email: karthik.vaidhyanathan@iiit.ac.in
Twitter: @karthi_ishere