Concurrency: Locks

CS 537: Introduction to Operating Systems

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Administrivia

- Project 4 out, due Tue Mar 12th @ 11:59pm
- Exam 1 graded, check `~cs537-1/handin/$USER/exam1_results.txt` for feedback
  - Piazza post has more details (eg, solutions are posted to Canvas)
  - If you need a regrade, see Piazza for form to fill out

Review: Threads

A **thread** is similar to a process in that it is a unit of execution and can be scheduled.

The main difference is threads **share virtual address space** (code and heap data) but have different **registers and stack**.

Understand the **race condition** between threads accessing shared data.

Remember how to:

- Create a thread
- Wait for a thread to finish executing
- Pass arguments to a thread
- Get return values after a thread has finished

Review Threads: looping-race-nolock.s

```
# assumes %bx has loop count in it
.main
.top
# critical section
mov 2000, %ax  # get 'value' at address 2000
add $1, %ax    # increment it
mov %ax, 2000  # store it back

# see if we're still looping
sub  $1, %bx
test $0, %bx
jgt .top

halt
```

Review: x86.py

```
./x86.py -p looping-race-nolock.s --argv='bx=2' --threads=1 --memtrace=2000 -c

 2000          Thread 0
    0
    0   1000 mov 2000, %ax
    0   1001 add $1, %ax
    1   1002 mov %ax, 2000
    1   1003 sub  $1, %bx
    1   1004 test $0, %bx
    1   1005 jgt .top
    1   1000 mov 2000, %ax
    1   1001 add $1, %ax
    2   1002 mov %ax, 2000
    2   1003 sub  $1, %bx
    2   1004 test $0, %bx
    2   1005 jgt .top
    2   1006 halt
```

```
./x86.py -p looping-race-nolock.s --argv='bx=2' --threads=2 --memtrace=2000 -c

 2000          Thread 0                Thread 1
    0
    0   1000 mov 2000, %ax
    0   1001 add $1, %ax
    1   1002 mov %ax, 2000
    1   1003 sub  $1, %bx
    1   1004 test $0, %bx
    1   1005 jgt .top
    1   1000 mov 2000, %ax
    1   1001 add $1, %ax
    2   1002 mov %ax, 2000
    2   1003 sub  $1, %bx
    2   1004 test $0, %bx
    2   1005 jgt .top
    2   1006 halt
    2   ----- Halt;Switch -----  ----- Halt;Switch -----
    2                            1000 mov 2000, %ax
    2                            1001 add $1, %ax
    3                            1002 mov %ax, 2000
    3                            1003 sub  $1, %bx
    3                            1004 test $0, %bx
    3                            1005 jgt .top
    3                            1000 mov 2000, %ax
    3                            1001 add $1, %ax
    4                            1002 mov %ax, 2000
    4                            1003 sub  $1, %bx
    4                            1004 test $0, %bx
    4                            1005 jgt .top
    4                            1006 halt
```

```
./x86.py -p looping-race-nolock.s -a 'bx=2' -t 2 -M 2000 --regtrace=ax --interrupt=6 --randints -s 3 -c
```

```
 2000  ax          Thread 0                Thread 1
    0   0
    0   0   1000 mov 2000, %ax
    0   1   1001 add $1, %ax
    0   0   --- Interrupt ----  ---- Interrupt ----
    0   0                            1000 mov 2000, %ax
    0   1                            1001 add $1, %ax
    1   1                            1002 mov %ax, 2000
    1   1                            1003 sub  $1, %bx
    1   1   --- Interrupt ----  ---- Interrupt ----
    1   1   1002 mov %ax, 2000
    1   1   1003 sub  $1, %bx
    1   1   1004 test $0, %bx
    1   1   --- Interrupt ----  ---- Interrupt ----
    1   1                            1004 test $0, %bx
    1   1                            1005 jgt .top
    1   1                            1000 mov 2000, %ax
    1   2                            1001 add $1, %ax
    1   1   --- Interrupt ----  ---- Interrupt ----
    1   1   1005 jgt .top
    1   1   1000 mov 2000, %ax
    1   2   1001 add $1, %ax
    2   2   1002 mov %ax, 2000
    2   2   --- Interrupt ----  ---- Interrupt ----
```

```
 2000  ax          Thread 0                Thread 1
    2   2                            1002 mov %ax, 2000
    2   2   --- Interrupt ----  ---- Interrupt ----
    2   2   1003 sub  $1, %bx
    2   2   --- Interrupt ----  ---- Interrupt ----
    2   2                            1003 sub  $1, %bx
    2   2                            1004 test $0, %bx
    2   2                            1005 jgt .top
    2   2                            1006 halt
    2   2   -- Halt;Switch ---  --- Halt;Switch ---
    2   2   1004 test $0, %bx
    2   2   1005 jgt .top
    2   2   --- Interrupt ----  ---- Interrupt ----
    2   2   1006 halt
```

Quiz 9: Intro to Threads

https://tinyurl.com/cs537-sp24-q9

Locks (Programmer's Perspective)

```c
#include <pthread.h>

pthread_mutex_t lock;
pthread_mutex_lock(&lock);
x=x+1; //or whatever your critical section is
pthread_mutex_unlock(&lock);
```

Use different locks to protect different variables / data structures

Rest of lecture is to understand how locks are built (hardware and OS support)
Next lecture on using locks with different data structures

Lock Implementation Goals

1. **Safety:** *mutual exclusion*, only one thread in critical section at a time
2. **Liveness:**
   - *deadlock free*: if two simultaneous requests, must allow one to proceed
   - *starvation free*: must eventually allow each waiting thread to enter
   - *fairness*: each thread waits for same amount of time
3. **Performance** – minimize CPU usage for lock/unlock
   - case 1 – no contention
   - case 2 – multiple threads contending, single CPU
   - case 3 – multiple threads contending, multiple CPUs

Earliest Solution: Disable Interrupts

```
void lock() {
   DisableInterrupts();
}

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

On single CPU, thread assured no other thread will interfere (including OS)

This approach used sparingly by OS itself

Disadvantages

- User program has control of CPU, could `lock()` and run forever
- Doesn't work on multiprocessor systems
- Can lead to lost interrupts (imagine OS not being notified of I/O completion)
- Very inefficient

Failed Attempt: Using Loads/Stores

Why doesn't this work?

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

void init(lock_t *mutex) {
   //0 -> lock is available, 1 -> held
   mutex->flag = 0;
}

void lock(lock_t *mutex) {
   while (mutex->flag == 1) { // TEST the flag
   }
   mutex->flag = 1;
}

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

Failed Attempt: Reason

Thread 1	Thread 2
call `lock()`	
while (flag == 1)	
interrupt: switch to Thread 2	
	call `lock()`
	while (flag == 1)
	flag = 1;
	interrupt: switch to Thread 1
flag = 1; // set flag to 1 (too!)	

No Mutual Exclusion!

Wasteful **Spin-waiting**

Hardware Support: Atomic Exchange

On x86 `xchg (dst), src` atomically swaps the contents of memory at dst with register src

Happens Atomically:

```
int xchg(int *addr, int new) {
  int old = *addr;
  *addr = new;
  return old;
}
```

```
int Xchg(int *addr, int newval)
{
  int result;
  __asm__("xchgl %0, %1" :
          "+m" (*addr), "=a" (result) :
          "1" (newval) :
          "cc");
  return result;
}
```

Lock Implementation with Xchg

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

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

void lock(lock_t *lock) {
  while(Xchg(&lock->flag, 1) == 1) {
    // spin-wait (do nothing)
  }
}

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

Other Atomic HW Instructions

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

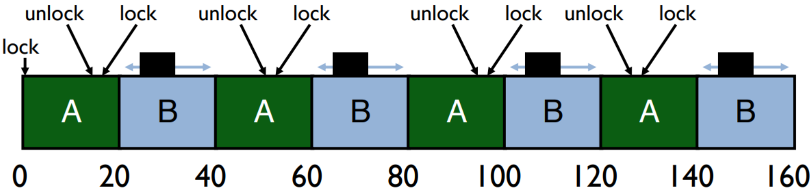
```
void lock(lock_t *lock) {
  while (CompareAndSwap(&lock->flag, 0, 1) != 0) {
    //spin
  }
}
```

A Pair of Atomic HW Instructions

```
int LoadLinked(int *ptr) {
   return *ptr;
}
int StoreConditional(int *ptr, int value) {
   if (no one has updated *ptr since the LoadLinked to this address) {
      *ptr = value;
      return 1; //success
   } else {
      return 0; //failed to update
   }
}
```

```c
void lock(lock_t *lock) {
  while (1) {
    while (LoadLinked(&lock->flag) == 1) {
      // spin until it's zero
    }
    if (StoreConditional(&lock->flag, 1) == 1) {
       return; //if set-it-to-1 was a success: all done
               //otherwise: try it all over again
    }
  }
}
void unlock(lock_t *lock) {
  lock->flag = 0;
}
```

Basic Spinlocks Are Unfair



Scheduler is unaware of locks/unlocks!

Fairness: Ticket Locks – Based on Atomic HW Instruction

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

```
typedef struct __lock_t {
    int ticket; //thread's ticket number
    int turn; //whose turn it is
} lock;
void lock_init(lock_t *lock) {
    lock->ticket = 0;
    lock->turn = 0;
}

void lock(lock_it *lock) {
    //first, reserve this thread's turn
    int myturn = FetchAndAdd(&lock->ticket);
    while (lock->turn != myturn)
        ; //spin until thread's turn
}

void unlock(lock_t *lock) {
    lock->turn = lock->turn+1;
}
```

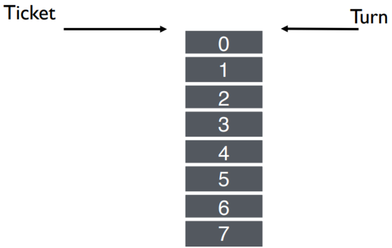
Ticket Lock Example

```
A lock():
B lock():
C lock():

A unlock():

A lock():
B unlock():

C unlock():
A unlock():
```



Spinlock Performance

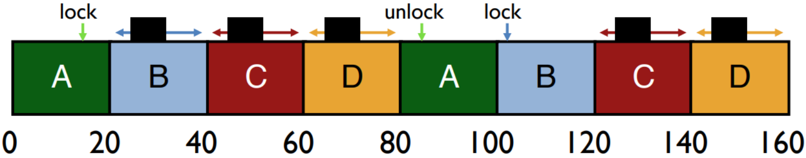
Fast when...

- many CPUs
- locks held a short time
- advantage: avoid context switch

Slow when...

- one CPU
- locks held a long time
- disadvantage: spinning is wasteful

CPU Scheduler is Ignorant of Spinlocks



CPU scheduler may run **B,C,D** instead of **A**
even though **B,C,D** are waiting for **A**

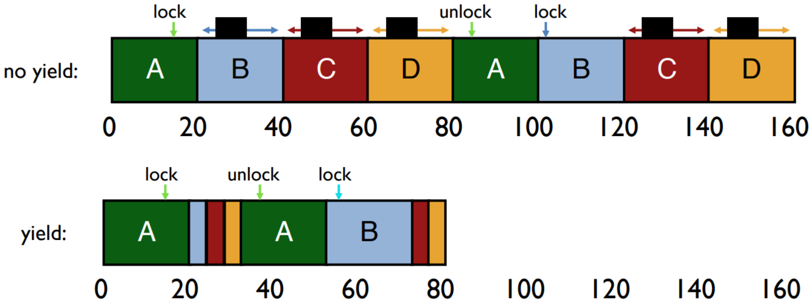
Ticket Lock With Yield (OS Call)

Instead of spinning, give up CPU with special yield() instruction

```
typedef struct __lock_t {
   int ticket; //thread's ticket number
   int turn; //whose turn it is
}
void lock_init(lock_t *lock) {
   lock->ticket = 0;
   lock->turn = 0;
}
void lock(lock_it *lock) {
   int myturn = FetchAndAdd(&lock->ticket); // Reserve turn
   while (lock->turn != myturn)
      yield(); //give up rest of time-slice
}

void unlock(lock_t *lock) {
   lock->turn = lock->turn+1;
}
```

Yield Instead of Spin



Spinlock Performance

Waste of CPU cycles?

- Without yield: threads * **time_slice**
- With yield: threads * **context_switch_time**

Even with yield, spinning is slow with high thread contention

Next improvement: put thread on waiting queue and block instead of spinning

New OS call:

- `park()` – put calling thread to sleep
- `unpark()` – wake a particular thread

Lock Implementation

```
typedef struct __lock_t {
   int guard; // guards flag and q
   int flag; // 1 if lock is acquired
   queue_t *q;
}

void lock_init(lock_t *m) {
   m->flag = 0;
   m->guard = 0;
   queue_init(m->q);
}

void lock(lock_t *m) {
   while (Xchg(&m->guard, 1) == 1)
      ; //acquire guard lock by spinning
   if (m->flag == 0) {
      m->flag = 1; //lock is acquired
      m->guard = 0;
   } else {
      queue_add(m->q, gettid());
      m->guard = 0;
      park();
   }
}
```

```
void unlock(lock_t *m) {
   while (Xchg(&m->guard, 1) == 1)
      ; //acquire guard lock by spinning
   if (queue_empty(m->q))
      m->flag = 0; //let go of lock, no one wants it
   else
      unpark(queue_remove(m->q)); //hold for next
   m->guard = 0;
}
```

What would happen if release of guard came *after* the `park()`?

Think about possible **wakeup/waiting race condition** just before the call to `park()`

Add `setpark()` OS call to indicate *about* to park(). Add call to setpark() just before releasing guard:

```
queue_add(m->q, gettid());
setpark();
m->guard = 0;
park();
```

Lock Implementation: fixing race with setpark

```
void lock(lock_t *m) {
   while (Xchg(&m->guard, 1) == 1)
      ; //acquire guard lock by spinning
   if (m->flag == 0) {
      m->flag = 1; //lock is acquired
      m->guard = 0;
   } else {
      queue_add(m->q, gettid());
      m->guard = 0;
      park();
   }
}
```

```
void unlock(lock_t *m) {
   while (Xchg(&m->guard, 1) == 1)
      ; //acquire guard lock by spinning
   if (queue_empty(m->q))
      m->flag = 0; //let go of lock, no one wants it
   else
      unpark(queue_remove(m->q)); //hold for next
   m->guard = 0;
}
```

Just before `park()`, this code has a **wakeup/waiting race condition**

Add `setpark()` OS call to indicate *about* to park():

```
queue_add(m->q, gettid());
setpark();
m->guard = 0;
park();
```

After `setpark()`, if `unpark()` is called first then subsequent `park()` returns immediately.

Spin-Waiting vs. Blocking

Each approach is better under different circumstances:

- Uniprocessor
  - Waiting process is scheduled $\rightarrow$ Process holding lock is not
  - Waiting process should always relinquish processor
  - Associate queue of waiters with each lock (as in previous implementation)
- Multiprocessor
  - Waiting process is scheduled $\rightarrow$ process holding lock might be
  - spin or block depends on t time before lock released vs context-switch cost C:
    - Lock released quickly ($t \ll C$) $\rightarrow$ **Spin-wait**
    - Lock released slowly ($t \geq C$) $\rightarrow$ **Block**