Operating System Principles: Mutual Exclusion and Asynchronous Completion

CS 111
Operating Systems

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Outline

- Mutual Exclusion
- Asynchronous Completions

Mutual Exclusion

- Critical sections can cause trouble when more than one thread executes them at a time
  - Each thread doing part of the critical section before any of them do all of it
- Preventable if we ensure that only one thread can execute a critical section at a time
- We need to achieve *mutual exclusion* of the critical section

Critical Sections in Operating System

- Operating systems are loaded with internal critical sections
- Shared data used by concurrent threads
  - Process state variables
  - Resource pools
  - Device driver state
- Logical parallelism
  - Created by preemptive scheduling and asynchronous interrupts
- Physical parallelism
  - Shared memory, symmetric multi-processors
- OSes extensively use locks to avoid these problems
  - Without any user-visible effects

Critical Sections in Applications

- Most common for multithreaded applications
  - Which frequently share data structures
- Can also happen with processes
  - Which share operating system resources
  - Like files
- Avoidable if you don’t share resources of any kind
  - But that’s not always feasible

Recognizing Critical Sections

- Generally involves updates to object state
  - May be updates to a single object
  - May be related updates to multiple objects
- Generally involves multi-step operations
  - Object state inconsistent until operation finishes
  - Pre-emption compromises object or operation
- Correct operation requires mutual exclusion
  - Only one thread at a time has access to object(s)
  - Client 1 completes before client 2 starts

Critical Sections and Atomicity

- Using mutual exclusion allows us to achieve *atomicity* of a critical section
- Atomicity has two aspects:

1. <u>Before or After</u> atomicity
   - A enters critical section before B starts
   - B enters critical section after A completes
   - There is no overlap
2. <u>All or None</u> atomicity
   - An update that starts will complete
   - An uncompleted update has no effect

- Correctness generally requires both

Options for Protecting Critical Sections

- Turn off interrupts
  - We covered that in the last class
  - Prevents concurrency
- Avoid shared data whenever possible
- Protect critical sections using hardware mutual exclusion
  - In particular, atomic CPU instructions

Avoiding Shared Data

- A good design choice when feasible
- Don’t share things you don’t need to share
- But not always an option
- Even if possible, may lead to inefficient resource use
- Sharing read only data also avoids problems
  - If no writes, the order of reads doesn’t matter
  - But a single write can blow everything out of the water

Atomic Instructions

- CPU instructions are uninterruptable
- What can they do?
  - Read/modify/write operations
  - Can be applied to 1-8 contiguous bytes
  - Simple: increment/decrement, and/or/xor
  - Complex: test-and-set, exchange, compare-and-swap
- Either do entire critical section in one atomic instruction
- Or use atomic instructions to implement locks
  - Use the lock operations to protect critical sections

Atomic Instructions – Test and Set

A C description of a machine language instruction

```
bool TS( char *p) {
    bool rc;
    rc = *p;                /* note the current value          */
    *p = TRUE;          /* set the value to be TRUE          */
    return rc;              /* return the value before we set it   */
}

if !TS(flag) {
        /* We have control of the critical section! */
}
```

Atomic Instructions – Compare and Swap

Again, a C description of machine instruction

```
bool compare_and_swap( int *p, int old, int new ) {
  if (*p == old) {    /* see if value has been changed     */
      *p = new;        /* if not, set it to new value        */
      return( TRUE);   /* tell caller he succeeded           */
  } else               /* value has been changed      */
    return( FALSE);    /* tell caller he failed              */
}

if (compare_and_swap(flag,UNUSED,IN_USE) {
      /* I got the critical section! */
} else {
      /* I didn't get it.  */
}
```

Preventimg Concurrency Via Atomic Instructions

- CPU instructions are hardware-atomic
  - So if you can squeeze a critical section into one instruction, no concurrency problems
- What can you do in one instruction?
  - Simple operations like read/write
  - Some slightly more complex operations
  - With careful design, some data structures can be implemented this way
- Limitations
  - Unusable for complex critical sections
  - Unusable as a waiting mechanism

Lock-Free Operations

- Multi-thread safe data structures and operations
  – An alternative to locking or disabling interrupts
- How do they work?
  – Carefully program data structure to perform critical operations with one instruction
- Allows:
  – Single reader/writer with ordinary instructions
  – Multi-reader/writer with atomic instructions
  – All-or-none and before-or-after semantics
- Limitations
  – Unusable for complex critical sections
  – Unusable as a waiting mechanism

An Example

```
// push an element on to a singly linked LIFO list
void SLL_push(SLL *head, SLL *element) {
    do {
        SLL *prev = head->next;
        element->next = prev;
    } while ( CompareAndSwap(&head->next, prev, element) != prev);
}
```

Evaluating Lock-Free Operations

- Effectiveness/Correctness
  - Effective against all conflicting updates
  - Cannot be used for complex critical sections
- Progress
  - No possibility of deadlock or convoy
- Fairness
  - Small possibility of brief spins
  - Like the compare-and-swap while loop in example
- Performance
  - Expensive instructions, but cheaper than syscalls

Locking

- Protect critical sections with a data structure
  - Use atomic instructions to implement that structure
- Locks
  - The party holding a lock can access the critical section
  - Parties not holding the lock cannot access it
- A party needing to use the critical section tries to acquire the lock
  - If it succeeds, it goes ahead
  - If not . . .?
- When finished with critical section, release the lock
  - Which someone else can then acquire

Using Locks

- Remember this example?

thread #1 counter = counter + 1;

thread #2 counter = counter + 1;

What looks like one instruction in C gets compiled to:

```
mov counter, %eax
add $0x1, %eax
mov %eax, counter
```

Three instructions . . .

- How can we solve this with locks?

Using Locks For Mutual Exclusion

```
pthread_mutex_t lock;
pthread_mutex_init(&lock, NULL);
…
if (pthread_mutex_lock(&lock) == 0) {
    counter = counter + 1;
    pthread_mutex_unlock(&lock);
}
```

Now the three assembly instructions are mutually exclusive

What Happens When You Don't Get the Lock?

- You could just give up
  - But then you'll never execute your critical section
- You could try to get it again
- But it still might not be available
- So you could try to get it again . . .

Locks and Interrupts: A Dangerous Combination

Synchronous Code

Interrupt Handler

Infinite Loop!

```
while( TS(lockp) );
/* critical section */
…
*lockp = 0;
```

!

```
while( TS(lockp) );
/* critical section */
...
```

Interrupt handler will loop

Interrupts disabled when handler entered

Interrupt handler can't get the lock

Interrupts will remain disabled

Synchronous code will never complete

So lock will never be released

Spin Waiting

- The computer science equivalent
- Check if the event occurred
- If not, check again
- And again
- And again
- . . .

Spin Locks: Pluses and Minuses

- Good points
  - Properly enforces access to critical sections
    - Assuming properly implemented locks
  - Simple to program
- Dangers
  - Wasteful
    - Spinning uses processor cycles
  - Likely to delay freeing of desired resource
    - Spinning uses processor cycles
  - Bug may lead to infinite spin-waits

How Do We Build Locks?

- The very operation of locking and unlocking a lock is itself a critical section
  - If we don't protect it, two threads might acquire the same lock
- Sounds like a chicken-and-egg problem
- But we can solve it with hardware assistance
- Individual CPU instructions are atomic
  - So if we can implement a lock with one instruction . . .

Single Instruction Locks

- Sounds tricky
- The core operation of acquiring a lock (when it's free) requires:
  1. Check that no one else has it
  2. Change something so others know we have it
- Sounds like we need to do two things in one instruction
- No problem – hardware designers have provided for that

Building Locks From Single Instructions

- Requires a complex atomic instruction
  - Test and set
  - Compare and swap
- Instruction must atomically:
  - Determine if someone already has the lock
  - Grant it if no one has it
  - Return something that lets the caller know what happened
- Caller must honor the lock . . .

Using Atomic Instructions to Implement a Lock

- Assuming C implementation of test and set

```
bool getlock( lock *lockp) {
 if (TS(lockp) == 0 )
    return( TRUE);
 else
    return( FALSE);
}
void freelock( lock *lockp ) {
 *lockp = 0;
}
```

Locks Come in Many Flavors

- Lock and wait
  - Block until resource becomes available
- Non-blocking
  - Return an error if resource is unavailable
- Timed wait
  - Block a specified maximum time, then fail
- Spin and wait (futex)
  - Spin briefly, and then join a waiting list
- Strict FIFO
  - Join a FIFO queue of those waiting on the lock
  - Other wait options might not guarantee FIFO

The Asynchronous Completion Problem

- Parallel activities move at different speeds
- One activity may need to wait for another to complete
- The *asynchronous completion problem* is how to perform such waits without killing performance
- Examples of asynchronous completions
  - Waiting for an I/O operation to complete
  - Waiting for a response to a network request
  - Delaying execution for a fixed period of real time

How Can We Wait?

- Spin locking/busy waiting
- Yield and spin …
- Either spin option may still require mutual exclusion
- Completion events

Spin Waiting For Asynchronous Completions

- Wastes CPU, memory, bus bandwidth
  - Each path through the loop costs instructions
- May actually delay the desired event
  - One of your cores is busy spinning
  - Maybe it could be doing the work required to complete the event instead
  - But it’s spinning . . .

Spinning Sometimes Makes Sense

1. When awaited operation proceeds in parallel
   – A hardware device accepts a command
   – Another CPU releases a briefly held spin-lock
2. When awaited operation is guaranteed to be soon
   – Spinning is less expensive than sleep/wakeup
3. When spinning does not delay awaited operation
   – Burning CPU delays running another process
   – Burning memory bandwidth slows I/O
4. When contention is expected to be rare
   – Multiple waiters greatly increase the cost

A Classic "spin-wait"

```
/* set a specified register in the ZZ controller to a specified value   */

zzSetReg( struct zzcontrol *dp, short reg, long value ) {
        while( (dp->zz_status & ZZ_CMD_READY) == 0)
                ;
        dp->zz_value = value;
        dp->zz_reg = reg;
        dp->zz_cmd = ZZ_SET_REG;
}
```

No guarantee that hardware is ready when this routine returns.

```
/* program the ZZ for a specified DMA read or write operation            */

zzStartIO( struct zzcontrol *dp, struct ioreq *bp ) {

        zzSetReg(dp, ZZ_R_ADDR, bp->buffer_start);

        zzSetReg(dp, ZZ_R_LEN, bp->buffer_length);

        zzSetReg(dp, ZZ_R_CMD, bp->write ? ZZ_C_WRITE : ZZ_C_READ );

        zzSetReg(dp, ZZ_R_CTRL, ZZ_INTR + ZZ_GO);

}
```

Yield and Spin

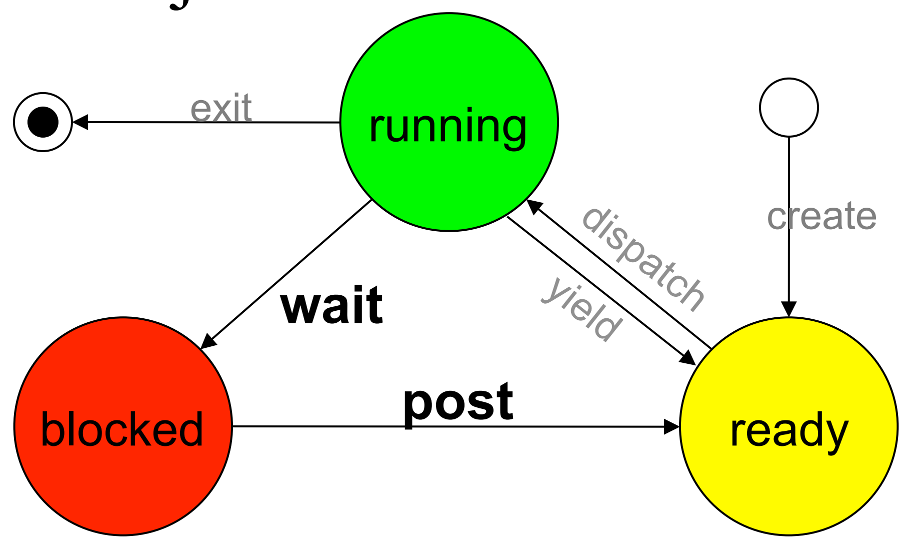
- Check if your event occurred
- Maybe check a few more times
- But then yield
- Sooner or later you get rescheduled
- And then you check again
- Repeat checking and yielding until your event is ready

Problems With Yield and Spin

- Extra context switches
  - Which are expensive
- Still wastes cycles if you spin each time you're scheduled
- You might not get scheduled to check until long after event occurs
- Works very poorly with multiple waiters

Another Approach: Condition Variables

- Create a synchronization object associated with a resource or request
  - Requester blocks awaiting event on that object
  - Upon completion, the event is "posted"
  - Posting event to object unblocks the waiter



Condition Variables and the OS

- Generally the OS provides condition variables
  - Or library code that implements threads does
- It blocks a process or thread when condition variable is used
  - Moving it out of the ready queue
- It observes when the desired event occurs
- It then unblocks the blocked process or thread
  - Putting it back in the ready queue
  - Possibly preempting the running process

Waiting Lists

- Likely to have threads waiting on several different things
- Pointless to wake up everyone on every event
  - Each should wake up when his event happens
- Suggests all events need a waiting list
  - When posting an event, look up who to awaken
    - Wake up everyone on the list?
    - One-at-a-time in FIFO order?
    - One-at-a-time in priority order (possible starvation)?
  - Choice depends on event and application

Who To Wake Up?

- Who wakes up when a condition variable is signaled?
  - pthread_cond_wait … at least one blocked thread
  - pthread_cond_broadcast … all blocked threads
- The broadcast approach may be wasteful
  - If the event can only be consumed once
  - Potentially unbounded waiting times
- A waiting queue would solve these problems
  - Each post wakes up the first client on the queue

Evaluating Waiting List Options

- Effectiveness/Correctness
  - Should be very good
- Progress
  - There is a trade-off involving *cutting* in line
- Fairness
  - Should be very good
- Performance
  - Should be very efficient
  - Depends on frequency of spurious wakeups

Locking and Waiting Lists

- Spinning for a lock is usually a bad thing
  - Locks should probably have waiting lists
- A waiting list is a (shared) data structure
  - Implementation will likely have critical sections
  - Which may need to be protected by a lock
- This seems to be a circular dependency
  - Locks have waiting lists
  - Which must be protected by locks
  - What if we must wait for the waiting list lock?

A Possible Problem

- The sleep/wakeup race condition

Consider this sleep code:

```
void sleep( eventp *e ) {
  while(e->posted == FALSE) {
      add_to_queue( &e->queue,
      myproc );
      myproc->runstate |= BLOCKED;
      yield();
  }
}
```

And this wakeup code:

```
void wakeup( eventp *e) {
      struct proce *p;

      e->posted = TRUE;
      p = get_from_queue(&e->
queue);
      if (p) {
         p->runstate &= ~BLOCKED;
         resched();
      }  /* if !p, nobody’s
waiting */
}
```

What’s the problem with this?

A Sleep/Wakeup Race

- Let's say thread B is using a resource and thread A needs to get it
- So thread A will call `sleep()`
- Meanwhile, thread B finishes using the resource
  - So thread B will call `wakeup()`
- No other threads are waiting for the resource

The Race At Work

Thread A

```
void sleep( eventp *e ) {

 while(e->posted == FALSE) {
```

CONTEXT SWITCH!

Nope, nobody's in the queue!

CONTEXT SWITCH!

```
   add_to_queue( &e->queue, myproc );
   myproc->runsate |= BLOCKED;
   yield();
  }
}
```

Thread B

Yep, somebody's locked it!

```
void wakeup( eventp *e) {
 struct proce *p;

 e->posted = TRUE;
 p = get_from_queue(&e-> queue);
 if (p) {

  }  /* if !p, nobody's waiting */
 }
```

The effect?

Thread A is sleeping

But there's no one to wake him up

Solving the Problem

- There is clearly a critical section in `sleep()`
  - Starting before we test the posted flag
  - Ending after we put ourselves on the notify list
- During this section, we need to prevent
  - Wakeups of the event
  - Other people waiting on the event
- This is a mutual-exclusion problem
  - Fortunately, we already know how to solve those

Progress vs. Fairness

- Consider …
  - P1: lock(), park()
  - P2: unlock(), unpark()
  - P3: lock()
- Progress says:
  - It is available, so P3 gets it
  - Spurious wakeup of P1
- Fairness says:
  - FIFO, P3 gets in line
  - And a convoy forms

```
void lock(lock_t *m) {
    while(true) {
        while (TestAndSet(&m->guard, 1) == 1);
        if (!m->locked) {
            m->locked = 1;
            m->guard = 0;
            return;
        }
        queue_add(m->q, me);
        m->guard = 0;
        park();
    }
}

void unlock(lock_t *m) {
    while (TestAndSet(&m->guard, 1) == 1);
    m->locked = 0;
    if (!queue_empty(m->q))
        unpark(queue_remove(m->q);
    m->guard = 0;
}
```

Spin-Waits Revisited

- Spin-waits await asynchronous completions
  - But they do so by busy-waiting

    while (event_not_ready) ;
- Sleep/wake-up is almost always better
  - Fewer wasted cycles and faster response
  - But these are software completion mechanisms
    - There are hardware-related situations where they don't work (or don't make sense)
- There are cases where it makes sense to spin
  - Very briefly for events originating outside our CPU

Spin-waits: when to use them

- When the event does not come from our CPU
  - So spinning will not delay the completion
- And waiting time guaranteed to be very brief
  - Fewer cycles than would be required to go to sleep
- Examples:
  - Waiting a few μ-seconds for hardware to come ready
    - **IF** it is <u>guaranteed</u> to be come back promptly
  - Waiting for another CPU to release a lock
    - **IF** critical section is very short (e.g. 1 digit # of instructions)
    - **IF** interrupts are disabled so preemption is impossible
- Almost <u>never</u> appropriate in user-mode code