Mutual Exclusion and Asynchronous Completion
CS 111
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Operating System Principles
Peter Reiher

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
  - If one thread is running the critical section, the other definitely isn’t

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
  - Or multiple related data structures
- 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. Before or After atomicity
   - A enters critical section before B starts
   - B enters critical section after A completes
   - There is no overlap

Vice versa is OK.

2. All or None atomicity
   - An update that starts will complete or will be undone
   - An uncompleted update has no effect

- Correctness generally requires both

Options for Protecting Critical Sections

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

Not available for applications, limits all concurrency

Often impossible

Also often impossible

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
- Can we do entire critical section in one instruction?
  - With careful design, some data structures can be implemented this way

Usually not feasible

- Doesn’t help with waiting synchronization

Locking

- Protect critical sections with a data 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

Software Locks

- ISAs usually do not include instructions for completely building locks
  - Individual instructions are properly serialized
  - But multiple instructions are not

Usually . . .

- So we need to build locks in software
  - Leading to issues of enforcing their mutual exclusion
  - Which have different solutions in different cases

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

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 . . .

Using Single Instructions To Build 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

Atomic Instructions – Test and Set

A C description of a machine language instruction **REAL Instructions are silicon, not C!!!**

```
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! */
}
```

If rc was false, nobody else ran TS. We got the lock!

If rc was true, someone else already ran TS. They got the lock!

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              /* someone else changed *p           */
    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.  */
}
```

Using Atomic Instructions to Implement a Lock

- Assuming silicon implementation of test and set

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

Note that building the lock requires more than the TS instruction.

So more than one thread might run this code concurrently.

Lock Enforcement

- Locking resources only works if either:
  - It's not possible to use a locked resource without the lock
  - Or everyone who might use the resource carefully follows the rules
- Otherwise, a thread might use the resource when it doesn't hold the lock
- We'll return to practical options for enforcement later

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 yet again . . .

Spin Waiting

- Spin waiting for a lock is called *spin locking*

- 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
    - The cycles burned could be used by the locking party to finish its work
  - Bug may lead to infinite spin-waits

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
- Can we use spin locks for this synchronization?

Spinning Sometimes Makes Sense

1. When awaited operation proceeds in parallel
   – A hardware device accepts a command
   – Another core releases a briefly held spin lock
2. When awaited operation is guaranteed to happen 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

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
  - Potential unfairness

Fairness and Mutual Exclusion

- What if multiple processes/threads/machines need mutually exclusive access to a resource?
- Locking can provide that
- But can we make guarantees about fairness?
- Such as:
  – Anyone who wants the resource gets it sooner or later (no starvation)
  – Perhaps ensuring FIFO treatment
  – Or enforcing some other scheduling discipline

How Can We Wait?

- Spin locking/busy waiting
- Yield and spin …
- Either spin option may still require mutual exclusion
  - And any time spent spinning is wasted
- And fairness may be an issue
- *Completion events*

Completion Events

- If you can't get the lock, block
- Ask the OS to wake you when the lock is available
- Similarly for anything else you need to wait for
  - Such as I/O completion
  - Or another process to finish its work
- Implemented with *condition variables*

Condition Variables

- Create a synchronization object associated with a resource or request
- Initially set to “event hasn’t happened”
- Requester blocks and is queued awaiting event completion on that object
- Upon completion, the event is “posted”
  - Posting event to object unblocks one or more waiters for that event
- Return condition variable to “event hasn’t happened” (if others might wait on it)

I.e., “Event has happened”

Depending . . .

Condition Variables and the OS

- Generally the OS provides condition variables
  - Or library code that implements threads does
- Block a process or thread when a 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

Handling Multiple Waits

- Threads will wait on several different events
- Pointless to wake up everyone on every event
  - Each should wake up only when <u>his</u> event happens
- So OS (or thread package) should allow easy selection of "the right one"
  - When some particular event occurs
- But what if several threads are waiting for the same thing?

Waiting Lists

- Suggests each completion event needs an associated waiting list
  - When posting an event, consult this list to determine who's waiting for that event
  - Then what?
    - Wake up everyone on that event's waiting list?
    - One-at-a-time in FIFO order?
    - One-at-a-time in priority order (possible starvation)?
  - Choice depends on event and application

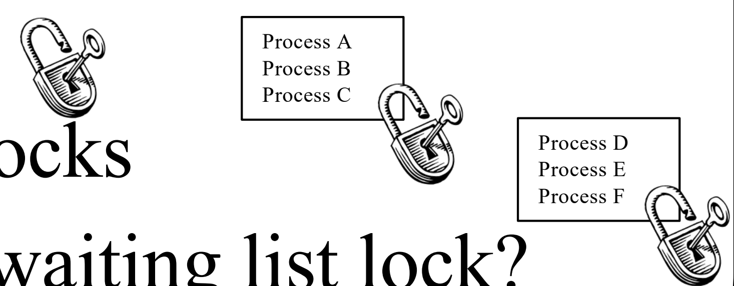
This isn't the ready queue!

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

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?
  - Where does it end?



?????

A Real Problem For Waiting Lists

- 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();
  }
}
```

This queue is a waiting list.

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 has locked a resource and thread A needs to get that lock
- So thread A will call `sleep()` to wait for the lock to be free
- Meanwhile, thread B finishes using the resource
  - So thread B will call `wakeup()` to release the lock
- 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->runstate |= BLOCKED;
   yield();
 }
}
```

Thread B

The event hasn't happened yet!

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

Now it happens!

```
 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 and blocked

Think about why these actions are part of the critical section.

- During this section, we need to prevent:
  - Wakeups of the event
  - Other people waiting on the event

SEE IF YOU CAN FIGURE THAT OUT FOR YOURSELF!

- This is a mutual-exclusion problem
  - Fortunately, we already know how to solve those
  - We just need a lock

But how will we handle contention for <u>that</u> lock?

Conclusion

- Two classes of synchronization problems:

1. Mutual exclusion
   – Only allow one of several activities to happen at once
2. Asynchronous completion
   – Properly synchronize cooperating events

- Locks are one way to assure mutual exclusion
- Spinning and completion events are ways to handle asynchronous completions