15-410
“...Arguably less wrong...”

Synchronization #3
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Synchronization

Project 1 due tonight

- Again, try not to use a late day
  • But if you do, please carefully read and follow the instructions

Project 2 out Wednesday
Outline

Synch 1
- Two building blocks
- Three requirements for critical-section algorithms
- Algorithms people *don't* use for critical sections

Synch 2
- How critical sections are really implemented

Synch 3
- Condition variables
  - Under the hood
  - The atomic-sleep problem
- Semaphores, monitors – overview
Road Map

Two Fundamental operations

✓ Atomic instruction sequence
▷ Voluntary de-scheduling
Voluntary de-scheduling

The Situation

- You hold lock on shared resource
- But it's not in “the right mode”

Action sequence

- Unlock shared resource
- Write down “wake me up when...”
- Block until resource changes state
What **Not** To Do

```c
while (!reckoning) {
    mutex_lock(&scenario_lk);
    if ((date >= 1906-04-18) &&
        (hour >= 5))
        reckoning = true;
    else
        mutex_unlock(&scenario_lk);
}
wreak_general_havoc();
mutex_unlock(&scenario_lk);
```
What **Not** To Do

```c
while (!reckoning) {
    mutex_lock(&scenario_lk);
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        (hour >= 5))
        reckoning = true;
    else
        mutex_unlock(&scenario_lk);
}
wreak_general_havoc();
mutex_unlock(&scenario_lk);
```

Is this code correct?
What **Not** To Do

```c
while (!reckoning) {
    mutex_lock(&scenario_lk);
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        reckoning = true;
    else
        mutex_unlock(&scenario_lk);
}
wreak_general_havoc();
mutex_unlock(&scenario_lk);
```
What **Not** To Do

**Why is this wrong?**

- Make sure you understand!
- See previous two lectures
- Do *not* do this in P2 or P3
  - Not even if it is *really tempting* in P3
“Arguably Less Wrong”

while (!reckoning) {
    mutex_lock(&scenario_lk);
    if ((date >= 1906-04-18) &&
        (hour >= 5))
        reckoning = true;
    else {
        mutex_unlock(&scenario_lk);
        sleep(1);
    }
}

wreak_general_havoc();
mutex_unlock(&scenario_lk);
“Arguably Less Wrong”

Don't do this either

- How wrong is “sleep(1)”?
“Arguably Less Wrong”

Don't do this either

- How wrong is “sleep(1)”?
  - N-1 times it's much too short
  - Nth time it's much too long
“Arguably Less Wrong”

Don't do this either

- How wrong is “sleep(1)”?
  - N-1 times it's much too short
  - Nth time it's much too long
  - It's wrong every time
“Arguably Less Wrong”

Don't do this either

- How wrong is “sleep(1)”?
  - N-1 times it's much too short
  - Nth time it's much too long
  - It's wrong *every time*

- What's the problem?
“Arguably Less Wrong”

Don't do this either

− How wrong is “sleep(1)”?
  • N-1 times it's much too short
  • Nth time it's much too long
  • It's wrong every time

− What's the problem?
  • We don't really want to wait for some duration!
  • We want to wait for a condition change
“Honorable Mention”?

```c
while (!reckoning) {
    mutex_lock(&scenario_lk);
    if ((date >= 1906-04-18) &&
        (hour >= 5))
        reckoning = true;
    else {
        mutex_unlock(&scenario_lk);
        yield(); // Better than sleep()???
    }
}
wreak_general_havoc();
mutex_unlock(&scenario_lk);
```
Something Is Missing...

✔ “Protect shared state” is solved
  – We use a “mutex object”
  – Also encapsulates “Which code interferes with this?”
  – Good

❖ How to solve “block for the right duration”? 
Something Is Missing

✔ "Protect shared state" is solved
  - We use a “mutex object”
  - Also encapsulates “Which code interferes with this?”
  - Good

➜ How to solve “block for the right duration”??
  - Get an expert to tell us!
  - Encapsulate “the right duration”...
  - ...into a condition variable object
Once More, With Feeling!

```c
mutex_lock(&scenario_lk);
while (cvarp = wait_on()) {
    cond_wait(cvarp, &scenario_lk);
}
wreak_general_havoc(); /* locked! */
mutex_unlock(&scenario_lk);
```
wait_on()?

```c
if (y < 1906)
    return (&new_year);
else if (m < 4)
    return (&new_month);
else if (d < 18)
    return (&new_day);
else if (h < 5)
    return (&new_hour);
else
    return (0); // done!

// Code is “conceptual example”, not 100% correct
```
What Awakens Us?

for (y = 1900; y < 2000; y++)
    for (m = 1; m <= 12; m++)
        for (d = 1; d <= days(m); d++)
            for (h = 0; h < 24; h++)
                ...
                cond_broadcast(&new_hour);
                cond_broadcast(&new_day);
                cond_broadcast(&new_month);
                cond_broadcast(&new_year);

// Code is "conceptual example", not 100% correct
Condition Variable Requirements

Keep track of threads blocked “for a while”
Allow notifier thread(s) to unblock blocked thread(s)
Must be “thread-safe”
  - Many threads may call condition_wait() at same time
  - Many threads may call condition_signal() at same time
  - Say, those look like “interfering sequences”...
Why *Two* Parameters?

```c
condition_wait(&cvar, &mutex);
```

Mutex required to examine/modify the “world” state
- If you examine unlocked state, it's changing.

Whoever awakens you will need to hold that mutex
- So you'd better give it up.

When you wake up, you will need to hold it again
- “Convenient” for condition_wait() to un-lock/re-lock

But there's something more subtle
- Try to recall this issue when working on P2...
Inside a Condition Variable

**cvar->queue**
- of blocked threads
- FIFO, or more exotic

**cvar->mutex**
- Protects queue against interfering `wait()`/`signal()` calls
- This isn't the caller's mutex (locking caller's world state)
- This is our secret invisible mutex
Inside a Condition Variable

```c
cond_wait(cvar, world_mutex)
{
    lock(cvar->mutex);
    enq(cvar->queue, my_thread_id());
    unlock(world_mutex);
    ATOMICALLY { 
        unlock(cvar->mutex);
        kernel_please_pause_this_thread();
    }
    lock(world_mutex);
}
```

**What is this “ATOMICALLY” stuff?**
### What We Hope For

<table>
<thead>
<tr>
<th>cond_wait(m,c)</th>
<th>cond_signal(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>enq(c-&gt;que,me);</td>
<td></td>
</tr>
<tr>
<td>unlock(m);</td>
<td></td>
</tr>
<tr>
<td>unlock(c-&gt;m);</td>
<td></td>
</tr>
<tr>
<td>kern_thr_pause();</td>
<td></td>
</tr>
<tr>
<td>lock(c-&gt;m);</td>
<td></td>
</tr>
<tr>
<td>id = deq(c-&gt;que);</td>
<td></td>
</tr>
<tr>
<td>kern_thr_wake(id);</td>
<td></td>
</tr>
<tr>
<td>unlock(c-&gt;m);</td>
<td></td>
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</table>
## Pathological Execution Sequence

<table>
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<th>$\text{cond_wait}(m,c)$</th>
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<tr>
<td>enq$(c-&gt;\text{que},\text{me});$</td>
<td>\emptyset</td>
</tr>
<tr>
<td>unlock$(m);$</td>
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$kern\_thr\_wake(id) \Rightarrow \text{ERR\_NOT\_ASLEEP}$
Achieving “wait() Atomicity”

Rules of the game
- There isn't an underlying unlock_and_block() primitive
- We have unlock(), and block(), and maybe “other stuff”
- From outside cond_wait()/cond_signal(), we must achieve *apparent* (as-if) “atomicity of unlock and block”.

Approaches
- Disable interrupts (if you are a kernel)
- Rely on OS to implement condition variables
  - *(Why is this not the best idea?)*
- Have a better kernel thread-block interface
- Hmm....
Achieving “wait() Atomicity”

P2 challenges

- Understand the issues!
  - mutex, cvar
- Understand the host kernel we give you
- Put the parts together
  - Don't use “wrong” or “arguably less wrong” approaches!
  - Seek solid, clear solutions
    - There's more than one way to do it
    - Make sure to pick a correct way...
    - Try to pick a *good* way.
Outline

Last time
  - How mutual exclusion is really implemented
Condition variables
  - Under the hood
  - The atomic-sleep problem

⇒ Semaphores

Monitors
Semaphore Concept

Semaphore is a different encapsulation object
- Can produce mutual exclusion
- Can produce block-until-it's-time

Intuition: counted resource
- Integer represents “number available”
  - Number of buffers, number of pairs of scissors, ...
  - Semaphore object initialized to a particular count
- Thread blocks until it is allocated an instance
Semaphore Concept

wait(), aka P(), Dutch probeer te verlagen (“try to decrease”)
  - wait until value > 0
  - then decrement value (“taking” one instance)

signal(), aka V(), Dutch verhogen (“increase”)
  - increment value (“releasing” one instance)

Just one small issue...
  - wait() and signal() must be atomic
“Mutex-style” Semaphore

semaphore m = 1;

do {
    wait(m); /* mutex_lock() */
    ..critical section...
    signal(m); /* mutex_unlock() */

    ...remainder section...
} while (1);
“Condition-style” Semaphore

<table>
<thead>
<tr>
<th>Thread 0</th>
<th>Thread 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><code>wait(c);</code></td>
</tr>
<tr>
<td><code>result = 42;</code></td>
<td></td>
</tr>
<tr>
<td><code>signal(c);</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>use(result);</code></td>
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“Condition with Memory”

Semaphores *retain memory* of signal() events
  - “full/empty bit” - *unlike* condition variables

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Semaphore vs. Mutex/Condition

Good news

- Semaphore is a higher-level construct
- Integrates mutual exclusion, waiting
- Avoids mistakes common in mutex/condition API
  - `signal()` too early is “lost”
  - ...

Semaphore vs. Mutex/Condition

Bad news

- Semaphore is a higher-level construct
- Integrates mutual exclusion, waiting
  - Some semaphores are “mutex-like”
  - Some semaphores are “condition-like”
  - How's a poor library to know?
    - Spin-wait or not???
Semaphores - 31 Flavors

Binary semaphore
  - It counts, but only from 0 to 1!
    • “Available” / “Not available”
  - Consider this a hint to the implementor...
    • “Think mutex!”

Non-blocking semaphore
  - wait(semaphore, timeout);

Deadlock-avoidance semaphore
  - #include <deadlock.lecture>
My Personal Opinion

One “simple, intuitive” synchronization object
- In 31 performance-enhancing flavors!!!

“The nice thing about standards is that you have so many to choose from.”
- Andrew S. Tanenbaum

Conceptually simpler to have two objects
- One for mutual exclusion
- One for waiting
- ...after you've understood what's actually happening
Semaphore Wait: Inside Story

```c
wait(semaphore s)

ACQUIRE EXCLUSIVE ACCESS
--s->count;
if (s->count < 0) {
enqueue(s->queue, my_id());
ATOMICALLY {
    RELEASE EXCLUSIVE ACCESS
    thread_block()
}
} else {
    RELEASE EXCLUSIVE ACCESS
}
```
Semaphore Signal: Inside Story

```c
signal(semaphore s)
    ACQUIRE EXCLUSIVE ACCESS
    ++s->count;
    if (s->count <= 0) {
        tid = dequeue(s->queue);
        thread_unblock(tid);
    }
    RELEASE EXCLUSIVE ACCESS
```

What's all the shouting?

- An exclusion algorithm much like a mutex, or
- OS-assisted atomic de-scheduling / awakening
Monitor

Basic concept
- Semaphores eliminate some mutex/condition mistakes
- Still some common errors
  - Swapping “signal()” & “wait()”
  - Accidentally omitting one

Monitor: higher-level abstraction
- Module of high-level language procedures
  - All access some shared state
- Compiler adds synchronization code
  - Thread running in any procedure blocks all thread entries
Monitor “commerce”

int cash_in_till[NSTORES] = { 0 };
int wallet[NCUSTOMERS] = { 0 };

boolean buy(int cust, store, price) {
    if (wallet[cust] >= price) {
        cash_in_till[store] += price;
        wallet[cust] -= price;
        return (true);
    } else
        return (false);
}
Monitors – What about waiting?

Automatic mutual exclusion is nice...
  - ...but it is too strong

Sometimes one thread needs to wait for another
  - Automatic mutual exclusion forbids this
  - Must leave monitor, re-enter - when?

Have we heard this “when” question before?
Monitor Waiting – The Problem

```c
void stubbornly_cash_check(acct a, check c) {
    while (account[a].bal < check.val) {
        ...Sigh, must wait for a while...
        ...What goes here?  I forget...
    }
    account[a].bal -= check.val;
}
```
Monitor Waiting – Wrong Solution

boolean
try_cash_check(acct a, check c)
{
    if (account[a].bal < check.val)
        return (false); /* pass the buck */
    account[a].bal -= check.val;
    return (true);
}
Monitor condition variables

Similar to condition variables we've seen

condition_wait(cvar)

- Only one parameter
- Mutex-to-drop is implicit
  - (the “monitor mutex”)
- Operation
  - “Temporarily exit monitor” -- drop the mutex
  - Wait until signalled
  - “Re-enter monitor” - re-acquire the mutex
Monitor Waiting

void
stubbornly_cash_check(acct a, check c)
{
    while (account[a].bal < check.val) {
        cond_wait(account[a].activity);
    }
    account[a].bal -= check.val;
}

Q: Who would signal() this cvar?
Monitor condition variables

signal() policy question - which thread to run?
  - Signalling thread? Signalled thread?
    • Can argue either way
  - Or: signal() exits monitor as side effect!
  - Different signal() policies mean different monitor flavors
Summary

**Two fundamental operations**
- Mutual exclusion for must-be-atomic sequences
- Atomic de-scheduling (and then wakeup)

**Mutex/condition-variable ("pthreads") style**
- Two objects for two core operations

**Semaphores, Monitors**
- Semaphore: one object
- Monitor: invisible compiler-generated object
  - *Same core ideas inside*
Summary

What you should know
- Issues/goals
- Underlying techniques
- How environment/application design matters

All done with synchronization?
- Only one minor issue left
  - Deadlock