CSE 451: Operating Systems
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Module 8
Semaphores, Condition Variables, and Monitors

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Semaphores

• Semaphore = a synchronization primitive
  – higher level of abstraction than locks
  – invented by Dijkstra in 1968, as part of the THE operating system

• A semaphore is:
  – a variable that is manipulated through two operations, P and V (Dutch for “wait” and “signal”)
    • P(sem) (wait)
      – block until sem > 0, then subtract 1 from sem and proceed
    • V(sem) (signal)
      – add 1 to sem

• Do these operations atomically
Blocking in semaphores

- Each semaphore has an associated queue of threads
  - when P (sem) is called by a thread,
    - if sem was “available” (>0), decrement sem and let thread continue
    - if sem was “unavailable” (0), place thread on associated queue; run some other thread
  - when V (sem) is called by a thread
    - if thread(s) are waiting on the associated queue, unblock one
      - place it on the ready queue
      - might as well let the “V-ing” thread continue execution
    - otherwise (when no threads are waiting on the sem), increment sem
      - the signal is “remembered” for next time P(sem) is called
Two types of semaphores

• **Binary** semaphore (aka mutex semaphore)
  – sem is initialized to 1
  – guarantees mutually exclusive access to resource (e.g., a critical section of code)
  – only one thread/process allowed entry at a time
  – Logically equivalent to a lock with *blocking* rather than *spinning*

• **Counting** semaphore
  – Allow up to $N$ threads continue (we’ll see why in a bit …)
  – sem is initialized to $N$
    • $N =$ number of units available
  – represents resources with many (identical) units available
  – allows threads to enter as long as more units are available
Binary semaphore usage

• From the programmer’s perspective, P and V on a binary semaphore are just like Acquire and Release on a lock
  
  \[
  \begin{align*}
  &P(\text{sem}) \\
  &\quad \vdots \\
  &\quad \vdots \\
  &\quad \text{do whatever stuff requires mutual exclusion; could conceivably be a lot of code} \\
  &\quad \vdots \\
  &\quad \vdots \\
  &V(\text{sem})
  \end{align*}
  \]

  – same lack of programming language support for correct usage

• Important differences in the underlying implementation, however
Example: Bounded buffer problem

• **AKA “producer/consumer” problem**
  – there is a circular buffer in memory with N entries (slots)
  – producer threads insert entries into it (one at a time)
  – consumer threads remove entries from it (one at a time)

• **Threads are concurrent**
  – so, we must use synchronization constructs to control access to shared variables describing buffer state
Bounded buffer using semaphores
(both binary and counting)

<table>
<thead>
<tr>
<th>var mutex: semaphore = 1 ; mutual exclusion to shared data</th>
</tr>
</thead>
<tbody>
<tr>
<td>empty: semaphore = n ; count of empty slots (all empty to start)</td>
</tr>
<tr>
<td>full: semaphore = 0 ; count of full slots (none full to start)</td>
</tr>
</tbody>
</table>

**producer:**

<table>
<thead>
<tr>
<th>P(empty) ; block if no slots available</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(mutex) ; get access to pointers</td>
</tr>
<tr>
<td>&lt;add item to slot, adjust pointers&gt;</td>
</tr>
<tr>
<td>V(mutex) ; done with pointers</td>
</tr>
<tr>
<td>V(full) ; note one more full slot</td>
</tr>
</tbody>
</table>

**consumer:**

<table>
<thead>
<tr>
<th>P(full) ; wait until there’s a full slot</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(mutex) ; get access to pointers</td>
</tr>
<tr>
<td>&lt;remove item from slot, adjust pointers&gt;</td>
</tr>
<tr>
<td>V(mutex) ; done with pointers</td>
</tr>
<tr>
<td>V(empty) ; note there’s an empty slot</td>
</tr>
<tr>
<td>&lt;use the item&gt;</td>
</tr>
</tbody>
</table>

**Note:**
I have elided all the code concerning which is the first full slot, which is the last full slot, etc.
Example: Readers/Writers

• Description:
  – A single object is shared among several threads/processes
  – Sometimes a thread just reads the object
  – Sometimes a thread updates (writes) the object

  – **We can allow multiple readers at a time**
    • why?

  – **We can only allow one writer at a time**
    • why?
Readers/Writers using semaphores

```
var mutex: semaphore = 1 ; controls access to readcount
wrt: semaphore = 1 ; control entry for a writer or first reader
readcount: integer = 0 ; number of active readers

writer:
P(wrt) ; any writers or readers?
<perform write operation>
V(wrt) ; allow others

reader:
P(mutex) ; ensure exclusion
readcount++ ; one more reader
if readcount == 1 then P(wrt) ; if we’re the first, synch with writers
V(mutex)
<perform read operation>
P(mutex) ; ensure exclusion
readcount-- ; one fewer reader
if readcount == 0 then V(wrt) ; no more readers, allow a writer
V(mutex)
```
Readers/Writers notes

- Notes:
  - the first reader blocks on P(wrt) if there is a writer
    - any other readers will then block on P(mutex)
  - if a waiting writer exists, the last reader to exit signals the waiting writer
    - can new readers get in while a writer is waiting?
    - so?
  - when writer exits, if there is both a reader and writer waiting, which one goes next?
Semaphores vs. Spinlocks

• Threads that are blocked at the level of program logic (that is, by the semaphore P operation) are placed on queues, rather than busy-waiting.

• Busy-waiting may be used for the “real” mutual exclusion required to implement P and V.
  – but these are very short critical sections – totally independent of program logic.
  – and they are not implemented by the application programmer.
Abstract implementation

- P/wait(sem)
  - acquire “real” mutual exclusion
    - if sem is “available” (>0), decrement sem; release “real” mutual exclusion; let thread continue
    - otherwise, place thread on associated queue; release “real” mutual exclusion; run some other thread

- V/signal(sem)
  - acquire “real” mutual exclusion
    - if thread(s) are waiting on the associated queue, unblock one (place it on the ready queue)
    - if no threads are on the queue, sem is incremented
      » the signal is “remembered” for next time P(sem) is called
  - release “real” mutual exclusion
  - [the “V-ing” thread continues execution, or may be preempted]
Pressing questions

• How do you acquire “real” mutual exclusion?

• Why is this any better than using a spinlock (test-and-set) or disabling interrupts (assuming you’re in the kernel) in lieu of a semaphore?

• What if some bozo issues an extra V?

• What if some bozo forgets to P before manipulating shared state?

• Could locks be implemented in exactly the same way? That is, “software locks” that you acquire and release, where the underlying implementation involves moving descriptors to/from a wait queue?
Condition Variables

• Basic operations
  – Wait()
    • Wait until some thread does a signal and release the associated lock, as an atomic operation
  – Signal()
    • If any threads are waiting, wake up one
    • Cannot proceed until lock re-acquired

• Signal() is not remembered
  – A signal to a condition variable that has no threads waiting is a no-op

• Qualitative use guideline
  – You wait() when you can’t proceed until some shared state changes
  – You signal() when shared state changes from “bad” to “good”
Bounded buffers with condition variables

```plaintext
var mutex: lock ; mutual exclusion to shared data
freeslot: condition ; there's a free slot
fullslot: condition ; there's a full slot
```

**producer:**
- lock(mutex) ; get access to pointers
  - if [no slots available] wait(freeslot);
    - <add item to slot, adjust pointers>
- signal(fullslot);
- unlock(mutex)

**consumer:**
- lock(mutex) ; get access to pointers
  - if [no slots have data] wait(fullslot);
    - <remove item from slot, adjust pointers>
- signal(freeslot);
- unlock(mutex);
- <use the item>

Note 1:
Do you see why wait() must release the associated lock?

Note 2:
How is the associated lock re-acquired?

[Let's think about the implementation of this inside the threads package]
The possible bug

• Depending on the implementation …
  – Between the time a thread is woken up by signal() and the time it re-acquires the lock, the condition it is waiting for may be false again
    • Waiting for a thread to put something in the buffer
    • A thread does, and signals
    • Now another thread comes along and consumes it
    • Then the “signalled” thread forges ahead …
  – Solution
    • Not
      – if [no slots available] wait(fullslot)
    • Instead
      – While [no slots available] wait(fullslot)
  – Could the scheduler also solve this problem?
Problems with semaphores, locks, and condition variables

- They can be used to solve any of the traditional synchronization problems, but it’s easy to make mistakes
  - they are essentially shared global variables
    - can be accessed from anywhere (bad software engineering)
  - there is no connection between the synchronization variable and the data being controlled by it
  - No control over their use, no guarantee of proper usage
    - Condition variables: will there ever be a signal?
    - Semaphores: will there ever be a V()? 
    - Locks: did you lock when necessary? Unlock at the right time? At all?
- Thus, they are prone to bugs
  - We can reduce the chance of bugs by “stylizing” the use of synchronization
  - Language help is useful for this
One More Approach: Monitors

• A *monitor* is a programming language construct that supports controlled access to shared data
  – synchronization code is added by the compiler
  • why does this help?

• A monitor is (essentially) a class in which every method automatically acquires a lock on entry, and releases it on exit – it combines:
  – shared data structures (object)
  – procedures that operate on the shared data (object methods)
  – synchronization between concurrent threads that invoke those procedures

• Data can only be accessed from within the monitor, using the provided procedures
  – protects the data from unstructured access
  – Prevents ambiguity about what the synchronization variable protects

• Addresses the key usability issues that arise with semaphores
A monitor

waiting queue of threads trying to enter the monitor

at most one thread in monitor at a time

Don’t confuse this box with the box we have used to denote a process!

shared data

Proc A

Proc B

Proc C

operations (methods)
Monitor facilities

• “Automatic” mutual exclusion
  – only one thread can be executing inside at any time
    • thus, synchronization is implicitly associated with the monitor – it “comes for free”
  – if a second thread tries to execute a monitor procedure, it blocks until the first has left the monitor
    • more restrictive than semaphores
    • but easier to use (most of the time)

• But, there’s a problem…
Problem: Bounded Buffer Scenario

- Buffer is empty
- Now what?
Problem: Bounded Buffer Scenario

- Buffer is full
- Now what?
Solution?

- Monitors require condition variables
- Operations on condition variables (just as before!)
  - wait(c)
    - release monitor lock, so somebody else can get in
    - wait for somebody else to signal condition
    - thus, condition variables have associated wait queues
  - signal(c)
    - wake up at most one waiting thread
      - “Hoare” monitor: wakeup immediately, signaller steps outside
    - if no waiting threads, signal is lost
      - this is different than semaphores: no history!
  - broadcast(c)
    - wake up all waiting threads
Bounded buffer using (Hoare) monitors

Monitor bounded_buffer {
    buffer resources[N];
    condition not_full, not_empty;

produce(resource x) {
    if (array "resources" is full, determined maybe by a count)
        wait(not_full);
    insert "x" in array "resources"
    signal(not_empty);
}

consume(resource *x) {
    if (array "resources" is empty, determined maybe by a count)
        wait(not_empty);
    *x = get resource from array "resources"
    signal(not_full);
}
Problem: Bounded Buffer Scenario

- Buffer is full
- Now what?
Bounded Buffer Scenario with CV’s

- Buffer is full
- Now what?

Queue of threads waiting for condition “not full” to be signaled
Runtime system calls for (Hoare) monitors

- EnterMonitor(m) \{guarantee mutual exclusion\}
- ExitMonitor(m) \{hit the road, letting someone else run\}
- Wait(c) \{step out until condition satisfied\}
- Signal(c) \{if someone’s waiting, step out and let him run\}

- EnterMonitor and ExitMonitor are inserted automatically by the compiler.
- This guarantees mutual exclusion for code inside of the monitor.
Bounded buffer using (Hoare) monitors

Monitor bounded_buffer {
    buffer resources[N];
    condition not_full, not_empty;

    procedure add_entry(resource x) {
        if (array "resources" is full, determined maybe by a count)
            wait(not_full);
        insert "x" in array "resources"
        signal(not_empty);
    }

    procedure get_entry(resource *x) {
        if (array "resources" is empty, determined maybe by a count)
            wait(not_empty);
        *x = get resource from array "resources"
        signal(not_full);
    }
}

EnterMonitor(m)

ExitMonitor(m)
There is a subtle issue with that code…

- Who runs when the signal() is done and there is a thread waiting on the condition variable?

- **Hoare monitors**: signal(c) means
  - run waiter immediately
  - signaller blocks immediately
    - condition guaranteed to hold when waiter runs
    - but, signaller must **restore monitor invariants** before signalling!
      - cannot leave a mess for the waiter, who will run immediately!

- **Mesa monitors**: signal(c) means
  - waiter is made ready, but the signaller continues
    - waiter runs when signaller leaves monitor (or waits)
  - signaller need not restore invariant until it leaves the monitor
  - being woken up is only a hint that something has changed
    - signalled condition may no longer hold
    - must recheck conditional case
Hoare vs. Mesa Monitors

• Hoare monitors: \[
\text{if} \ (\text{notReady}) \ \text{wait}(c)
\]

• Mesa monitors: \[
\text{while} \ (\text{notReady}) \ \text{wait}(c)
\]

• Mesa monitors easier to use
  – more efficient
  – fewer context switches
  – directly supports broadcast

• Hoare monitors leave less to chance
  – when wake up, condition guaranteed to be what you expect
Runtime system calls for Hoare monitors

• **EnterMonitor(m)** \{guarantee mutual exclusion\}
  – if m occupied, insert caller into queue m
  – else mark as occupied, insert caller into ready queue
  – choose somebody to run

• **ExitMonitor(m)** \{hit the road, letting someone else run\}
  – if queue m is empty, then mark m as unoccupied
  – else move a thread from queue m to the ready queue
  – insert caller in ready queue
  – choose someone to run
• \textbf{Wait(c) \{step out until condition satisfied\}}
  – if queue m is empty, then mark m as unoccupied
  – else move a thread from queue m to the ready queue
  – put the caller on queue c
  – choose someone to run
• \textbf{Signal(c) \{if someone’s waiting, step out and let him run\}}
  – if queue c is empty then put the caller on the ready queue
  – else move a thread from queue c to the ready queue, and put the caller into queue m
  – choose someone to run
Runtime system calls for Mesa monitors

- **EnterMonitor(m)** \{**guarantee mutual exclusion**\}
  - ...

- **ExitMonitor(m)** \{**hit the road, letting someone else run**\}
  - ...

- **Wait(c)** \{**step out until condition satisfied**\}
  - ...

- **Signal(c)** \{**if someone’s waiting, give him a shot after I’m done**\}
  - if queue c is occupied, move one thread from queue c to queue m
  - return to caller
• **Broadcast(c) \{food fight!\}\n  – move all threads on queue c onto queue m
  – return to caller
Monitor ReadersNWriter { 
  int WaitingWriters, WaitingReaders, NReaders, N Writers;
  Condition CanRead, CanWrite;

  Void BeginWrite()
  {
      if(NWriters == 1 || NReaders > 0)
      {
          ++WaitingWriters;
          wait(CanWrite);
          --WaitingWriters;
      }
      NWriters = 1;
  }

  Void EndWrite()
  {
      NWriters = 0;
      if(WaitingReaders)
          Signal(CanRead);
      else
          Signal(CanWrite);
  }

  Void BeginRead()
  {
      if(NWriters == 1 || WaitingWriters > 0)
      {
          ++WaitingReaders;
          Wait(CanRead);
          --WaitingReaders;
      }
      ++NReaders;
      Signal(CanRead);
  }

  Void EndRead()
  {
      if(--NReaders == 0)
          Signal(CanWrite);
  }
}
Monitors and Java

- Java offers something a bit like monitors
  - It should be clear that they’re not monitors in the full sense!
- Every Java object contains an intrinsic lock
- The `synchronized` keyword locks that lock
- Can be applied to methods, or blocks of statements
Synchronized methods

• Atomic integer is a commonly provided (or built) package

• public class atomicInt {
  int value;
  public atomicInt(int initVal) {
    value = initVal;
  }
  public synchronized postIncrement() {
    return value++;
  }
  public synchronized postDecrement() {
    return value--;    
  }
  ...
}
Monitor Summary

• Language supports monitors
• Compiler understands them
  – Compiler inserts calls to runtime routines for
    • monitor entry
    • monitor exit
  – Programmer inserts calls to runtime routines for
    • signal
    • wait
  – Language/object encapsulation ensures correctness
    • Sometimes! With conditions, you still need to think about synchronization
• Runtime system implements these routines
  – moves threads on and off queues
  – ensures mutual exclusion!