CSE 451: Operating Systems
Autumn 2013

Module 8
Semaphores, Condition Variables, and Monitors

Ed Lazowska
lazowska@cs.washington.edu
Allen Center 570

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

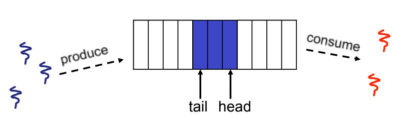
```
P(sem)
   :
   do whatever stuff requires mutual exclusion; could conceivably
   be a lot of code
   :
V(sem)
```

  - 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)

```
var mutex: semaphore = 1    ; mutual exclusion to shared data
    empty: semaphore = n    ; count of empty slots (all empty to start)
    full: semaphore = 0     ; count of full slots (none full to start)
```

```
producer:
    P(empty)                ; block if no slots available
    P(mutex)                ; get access to pointers
      <add item to slot, adjust pointers>
    V(mutex)                ; done with pointers
    V(full)                 ; note one more full slot
```

```
consumer:
    P(full)                 ; wait until there's a full slot
    P(mutex)                ; get access to pointers
      <remove item from slot, adjust pointers>
    V(mutex)                ; done with pointers
    V(empty)                ; note there's an empty slot
      <use the item>
```

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

```
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?

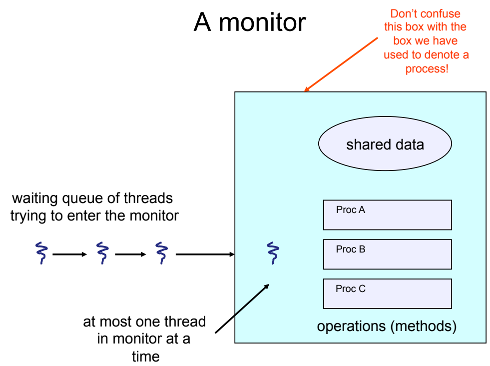
Problems with semaphores, locks, and condition variables

- 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 metnods)
  - 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

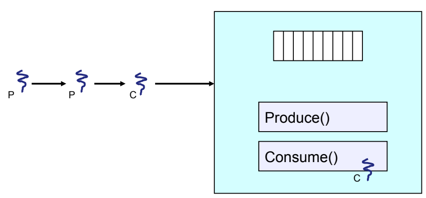
A monitor



Monitor facilities

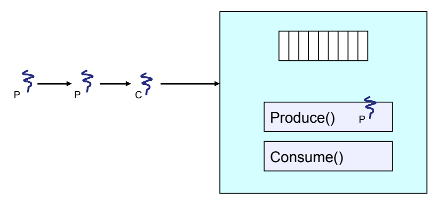
- "Automatic" mutual exclusion
  - only one thread can be executing inside at any time
    - thus, synchronization is implicitly associated with the monitor – it "comes for free"
  - if a second thread tries to execute a monitor procedure, it blocks until the first has left the monitor
    - more restrictive 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?

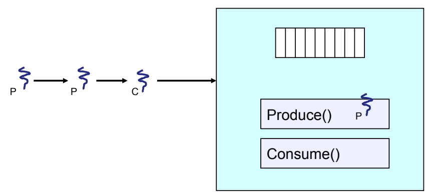
Solution?

- 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

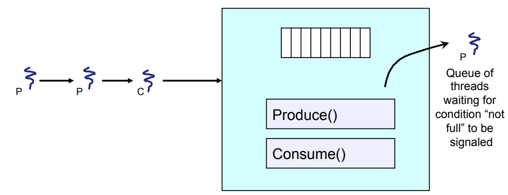
```
Monitor bounded_buffer {
  buffer resources[N];
  condition not_full, not_empty;

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?

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) {                        EnterMonitor(m)
    if (array "resources" is full, determined maybe by a count)
      wait(not_full);
    insert "x" in array "resources"
    signal(not_empty);                                     ExitMonitor(m)
  }
  procedure get_entry(resource *x) {                       EnterMonitor(m)
    if (array "resources" is empty, determined maybe by a count)
      wait(not_empty);
    *x = get resource from array "resources"
    signal(not_full);                                      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: `if (notReady) wait(c)`
- Mesa monitors: `while (notReady) 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

- 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
- 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!}
  - move all threads on queue c onto queue m
  - return to caller

Readers and Writers
(stolen from Cornell ☺)

```
Monitor ReadersNWriters {
 int WaitingWriters, WaitingReaders, NReaders, NWriters;
 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!*