CSE 451: Operating Systems
Winter 2006

Module 7
Semaphores and Monitors

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Semaphores

- Semaphore = a synchronization primitive
  - higher level than locks
  - invented by Dijkstra in 1968, as part of the THE operating system
- A semaphore is:
  - a variable that is manipulated *atomically* through two operations, **P(sem)** (wait) and **V(sem)** (signal)
    - P and V are Dutch for "wait" and "signal"
    - Plus, you get to say stuff like "the thread p's on the semaphore"
  - P/wait/down(sem): block until sem > 0, then subtract 1 from sem and proceed
  - V/signal/up(sem): add 1 to sem

Blocking in semaphores

- Each semaphore has an associated queue of threads
  - when P/wait/down(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/signal/up(sem) is called by a thread
    - if thread(s) are waiting on the associated queue, unblock one (place it on the ready queue)
    - if no threads are waiting on the associated queue, increment sem
      - the signal is "remembered" for next time P(sem) is called
    - might as well let the "V-ing" thread continue execution
- Semaphores thus have history

Abstract implementation

- P/wait/down(sem)
  - acquire "real" mutual exclusion
  - if sem was "available" (>0), decrement sem
  - release "real" mutual exclusion; let thread continue
  - if sem was "unavailable" (<=0), place thread on associated queue and release "real" mutual exclusion; run some other thread
- When V/signal/up(sem) is called by a thread
  - 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
  - might as well let the "V-ing" thread continue execution

Two types of semaphores

- Binary semaphore (aka mutex semaphore)
  - guarantees mutually exclusive access to resource (e.g., a critical section of code)
  - only one thread/process allowed entry at a time
  - sem is initialized to 1
- Counting semaphore
  - represents resources with many units available
  - allows threads to enter as long as more units are available
  - sem is initialized to N
    - N = number of units available
- We'll mostly focus on binary semaphores

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

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?

Example: Bounded buffer problem

- AKA producer/consumer problem
  - there is a buffer in memory
    - with finite size N entries
  - a producer thread inserts an entry into it
  - a consumer thread removes an entry from it
- 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 buffers (all empty to start)
    full: semaphore = 0    ;count of full buffers (none full to start)

producer:
    P(empty)        ; one fewer buffer, block if none available
    P(mutex)        ; get access to pointers
        <add item to buffer>
    V(mutex)        ; done with pointers
    V(full)         ; note one more full buffer

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

Note 1: I have spared you a repeat of the clip-art!

Note 2: I have elided all the code concerning which is the first full buffer, which is the last full buffer, etc.

Note 3: Try to figure out how to do this without using counting semaphores!

Example: Readers/Writers

- Basic problem:
  - object is shared among several processes
  - some read from it
  - others write to it
- 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          ; controls access to readcount
    clear: semaphore          ; control entry for a writer or first reader
    readcount: integer        ; number of active readers

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

reader:
    P(mutex)                  ; ensure exclusion
        readcount = readcount + 1     ; one more reader
        if readcount = 1 then P(clear)  ; if we're the first, synch with writers
    V(mutex)
        <perform read operation>
    P(mutex)                  ; ensure exclusion
        readcount = readcount – 1     ; one fewer reader
        if readcount = 0 then V(clear) ; no more readers, allow a writer
    V(mutex)
```


Readers/Writers notes

- Note:
  - the first reader blocks if there is a writer
    - any other readers will then block on 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?
  - when writer exits, if there is both a reader and writer waiting, which one goes next is up to scheduler

Semaphores vs. locks

- Threads that are blocked at the level of program logic are placed on queues, rather than busy-waiting
- Busy-waiting is used for the "real" mutual exclusion required to implement P and V, but these are very short critical sections – totally independent of program logic
- In the not-very-interesting case of a thread package implemented in an address space "powered by" only a single kernel thread, it's even easier that this

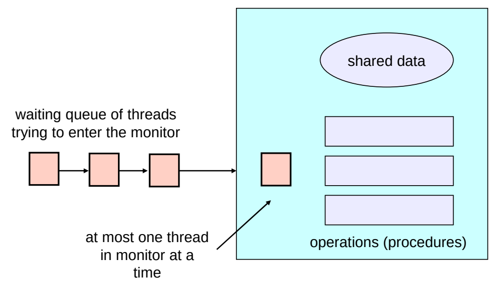
Problems with semaphores

- They can be used to solve any of the traditional synchronization problems, but:
  - semaphores are essentially shared global variables
    - can be accessed from anywhere (bad software engineering)
  - there is no connection between the semaphore and the data being controlled by it
  - used for both critical sections (mutual exclusion) and for coordination (scheduling)
  - no control over their use, no guarantee of proper usage
- Thus, they are prone to bugs
  - another (better?) approach: use programming language support

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 encapsulates:
  - shared data structures
  - procedures that operate on the shared data
  - 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
- 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)

- Once inside a monitor, a thread may discover it can't continue, and may wish to wait, or inform another thread that some condition has been satisfied (e.g., an empty buffer now exists)
  - a thread can wait on a condition variable, or signal others to continue
    - condition variables can only be accessed from within the monitor
    - a thread that waits "steps outside" the monitor (onto a wait queue associated with that condition variable)
    - precisely what happens to a thread that signals depends on the precise monitor semantics that are used – "Hoare" vs. "Mesa" – more later

Condition variables

- A place to wait; sometimes called a rendezvous point
- Three operations on condition variables
  - 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
    - 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;

  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);
  }
```


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}

Bounded buffer using Hoare monitors

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

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


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

Two kinds of monitors: Hoare and Mesa

- 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 monitors
  - if (notReady)
    - wait(c)
- Mesa monitors
  - while(notReady)
    - wait(c)
- Mesa monitors easier to use
  - more efficient
  - fewer switches
  - directly supports broadcast
- Hoare monitors leave less to chance
  - when wake up, condition guaranteed to be what you expect

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

Summary

- Language supports monitors
- Compiler understands them
  - compiler inserts calls to runtime routines for
    - monitor entry
    - monitor exit
    - signal
    - wait
- Runtime system implements these routines
  - moves threads on and off queues
  - *ensures mutual exclusion!*

