CSE 451: Operating Systems
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Module 8
Semaphores 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 "test" and "increment")
    - **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; dispatch some other runnable 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
      - or not, depending on priority
    - otherwise (when no threads are waiting on the sem), increment sem
      - the signal is "remembered" for next time P(sem) is called
- Semaphores thus have history

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 is preempted]

Hypothetical Implementation

```
type semaphore = record
    value: integer:
    L: list of processes;
end

wait(S):
    S.value = S.value - 1;
    if S.value < 0
    then begin
        add this process to S.L;
        block;
        end;

signal(S):
    S.value = S.value + 1;
    if S.value <= 0
    then begin
        remove a process P from S.L;
        wakeup P
        end;
```

wait()/signal() are critical sections! Hence, they must be executed atomically with respect to each other.

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
- Counting semaphore
  - 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

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)
```

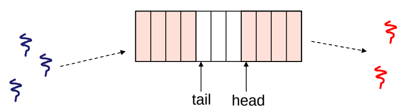
  - same lack of programming language support for correct usage
- Important differences in the underlying implementation, however

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 do a P before manipulating shared state?

Example: Bounded buffer problem

- *AKA* “producer/consumer” problem
  - there is a buffer in memory with N entries
  - 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 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 elided all the code concerning which is the first full buffer, which is the last full buffer, etc.

Note 2:
Try to figure out how to do this without using counting semaphores!

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?
    - does this cause any problems?
  - when writer exits, if there is both a reader and writer waiting, which one goes next?

Semaphores vs. Locks

- Threads that are blocked 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
- 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 than this

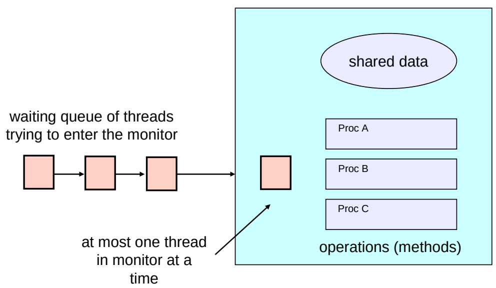
Problems with semaphores (and locks)

- 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

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 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

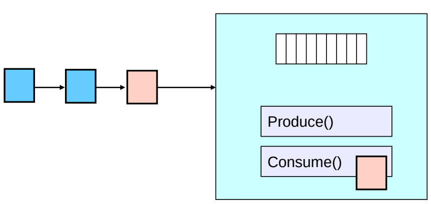
A monitor



Monitor facilities

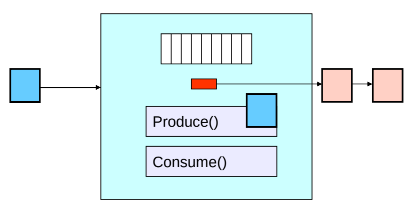
- "Automatic" mutual exclusion
  - only one thread can be executing inside at any time
    - thus, synchronization is implicitly associated with the monitor – it "comes for free"
  - if a second thread tries to execute a monitor procedure, it blocks until the first has left the monitor
    - more restrictive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

Example: Bounded Buffer Scenario



- Buffer is empty
- Now what?

Example: Bounded Buffer Scenario

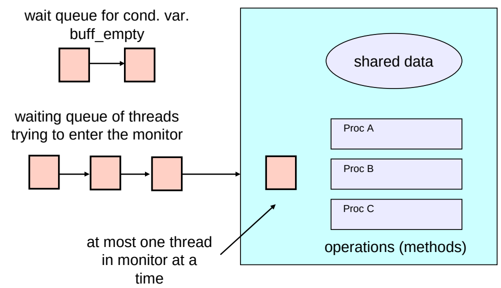


- Buffer is full
- Now what?

Condition variables

- A place to wait; sometimes called a rendezvous point
- "Required" for monitors
  - So useful they're often provided even when monitors aren't available
- 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

A monitor (including CVs)



Bounded buffer using (Hoare) monitors

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

produce(resource x) {
    if (array "resources" is full)
          wait(not_full);
    insert "x" in array "resources"
    signal(not_empty);
  }

 consume(resource *x) {
    if (array "resources" is empty)
          wait(not_empty);
    *x = get resource from array "resources"
    signal(not_full);
  }
```


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);
 }
```

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
    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
  }
```


There are two kinds of Monitors

- Question: who runs when the signal() is executed 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

Runtime system calls for Hoare monitors (cont'd)

- 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

Monitor Summary

- Language supports monitors
- Compiler understands them
  - compiler inserts calls to runtime routines for
    - monitor entry
    - monitor exit
    - 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!*

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