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”)
    • \textbf{P(sem)} (wait)
      – block until \(\text{sem} > 0\), then subtract 1 from \text{sem} and proceed
    • \textbf{V(sem)} (signal)
      – add 1 to \text{sem}

• Do these operations \textit{atomically}
Blocking in semaphores

• Each semaphore has an associated queue of blocked threads

  – when P (sem) is called by a thread,
    • if sem is “available” (>0), decrement sem and let thread continue
    • if sem is “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

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

• **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
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
    • (C++ RAII)

• 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)
  – the first reader’s P(wrt) blocks subsequent writers, once acquire

    – the last current reader enables writers by V(wrt)

• Questions:
  – 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 (spinlocks) may be used for the 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 someone issues an extra V?

• What if someone 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”
    - Secret: You can signal any time at all and the code should still be correct!
(Buggy) 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)

c 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>

Q1: Do you see why wait() must release the associated lock?
Q2: 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?
Correct Bounded buffers with condition variables

Q1:
Do you see why wait() must release the associated lock?

Q2:
How is the associated lock re-acquired?

[Let's think about the implementation of this inside the threads package]
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?
  – What if an exception occurs while holding one?
• Thus, they are prone to bugs
One More Approach: Monitors

• We can reduce the chance of bugs by “stylizing” the use of synchronization: monitors

• Language help is useful for this, but we can come close without language support for monitors
  – Java: synchronized
  – C++: RAII
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 an instance-specific 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

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

shared data

waiting queue of threads trying to enter the monitor

Proc A

Proc B

Proc C

operations (methods)

at most one thread in monitor at a time
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.
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);
    }
}
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:**
  ```java
  if (notReady) wait(c)
  ```

- **Mesa monitors:**
  ```java
  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)** \(\{\text{guarantee mutual exclusion}\}\)
  - if \(m\) occupied, insert caller into queue \(m\)
  - else mark as occupied, insert caller into ready queue
  - choose somebody to run

- **ExitMonitor(m)** \(\{\text{hit the road, letting someone else run}\}\)
  - 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 $\textbf{ReadersNWriters}$ {
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
Monitors and C++

- Look at `lock_guard`, `unique_lock`, `scoped_lock`
Other synchronized methods

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

```java
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!