Project 1 Due Thursday 10/20


# Lecture 6 (cont.): Semaphores and Monitors

CSE 120: Principles of Operating Systems
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# Higher-Level Synchronization

- We looked at using locks to provide mutual exclusion
- Locks work, but they have some drawbacks when critical sections are long
  - Spinlocks – inefficient
  - Disabling interrupts – can miss or delay important events
- Instead, we want synchronization mechanisms that
  - Block waiters
  - Leave interrupts enabled inside the critical section
- Look at two common high-level mechanisms
  - Semaphores: binary (mutex) and counting
  - Monitors: mutexes and condition variables
- Use them to solve common synchronization problems

# Semaphores

- Semaphores are another data structure that provides mutual exclusion to critical sections
  - Block waiters, interrupts enabled within CS
  - Described by Dijkstra in THE system in 1968
- Semaphores can also be used as atomic counters
  - More later
- Semaphores support two operations:
  - wait(semaphore): decrement, block until semaphore is open
    - Also P(), after the Dutch word for test, or down()
  - signal(semaphore): increment, allow another thread to enter
    - Also V() after the Dutch word for increment, or up()

# Blocking in Semaphores

- Associated with each semaphore is a queue of waiting processes
- When wait() is called by a thread:
  - If semaphore is open, thread continues
  - If semaphore is closed, thread blocks on queue
- Then signal() opens the semaphore:
  - If a thread is waiting on the queue, the thread is unblocked
  - If no threads are waiting on the queue, the signal is remembered for the next thread
    - » In other words, signal() has "history" (c.f. condition vars later)
    - » This "history" is a counter

# Semaphore Types

- Semaphores come in two types
- Mutex semaphore
  - Represents single access to a resource
  - Guarantees mutual exclusion to a critical section
- Counting semaphore
  - Represents a resource with many units available, or a resource that allows certain kinds of unsynchronized concurrent access (e.g., reading)
  - Multiple threads can pass the semaphore
  - Number of threads determined by the semaphore "count"
    - » mutex has count = 1, counting has count = N

# Using Semaphores

- Use is similar to our locks, but semantics are different

```
struct Semaphore {
    int value;
    Queue q;
} S;
withdraw (account, amount) {
    wait(S);
    balance = get_balance(account);
    balance = balance – amount;
    put_balance(account, balance);
    signal(S);
    return balance;
}
```

```
wait(S);
balance = get_balance(account);
balance = balance – amount;
```

```
wait(S);
```

```
wait(S);
```

```
put_balance(account, balance);
signal(S);
```

```
…
signal(S);
```

```
…
signal(S);
```

**Threads block**

**It is undefined which thread runs after a signal**

# Semaphores in Nachos

```
wait (S) {
  Disable interrupts;
  while (S->value == 0) {
    enqueue(S->q, current_thread);
    thread_sleep(current_thread);
  }
  S->value = S->value – 1;
  Enable interrupts;
}
```

```
signal (S) {
  Disable interrupts;
  thread = dequeue(S->q);
  thread_start(thread);
  S->value = S->value + 1;
  Enable interrupts;
}
```

- thread_sleep() assumes interrupts are disabled
  - Note that interrupts are disabled only to enter/leave critical section
  - How can it sleep with interrupts disabled?
- Need to be able to reference current thread

# Using Semaphores

- We’ve looked at a simple example for using synchronization
  - Mutual exclusion while accessing a bank account
- Now we’re going to use semaphores to look at more interesting examples
  - Readers/Writers
  - Bounded Buffers

# Readers/Writers Problem

- Readers/Writers Problem:
  - An object is shared among several threads
  - Some threads only read the object, others only write it
  - We can allow multiple readers
  - But only one writer
- How can we use semaphores to control access to the object to implement this protocol?
- Use three variables
  - int readcount – number of threads reading object
  - Semaphore mutex – control access to readcount
  - Semaphore w_or_r – exclusive writing or reading

# Readers/Writers

```
// number of readers
int readcount = 0;
// mutual exclusion to readcount
Semaphore mutex = 1;
// exclusive writer or reader
Semaphore w_or_r = 1;

writer {
    wait(w_or_r); // lock out readers
    Write;
    signal(w_or_r); // up for grabs
}
```

```
reader {
    wait(mutex);       // lock readcount
    readcount += 1; // one more reader
    if (readcount == 1)
        wait(w_or_r); // synch w/ writers
    signal(mutex);    // unlock readcount
    Read;
    wait(mutex);       // lock readcount
    readcount -= 1; // one less reader
    if (readcount == 0)
        signal(w_or_r); // up for grabs
    signal(mutex);    // unlock readcount}
}
```

# Readers/Writers Notes

- If there is a writer
  - First reader blocks on w_or_r
  - All other readers block on mutex
- Once a writer exits, all readers can fall through
  - Which reader gets to go first?
- The last reader to exit signals a waiting writer
  - If no writer, then readers can continue
- If readers and writers are waiting on w_or_r, and a writer exits, who goes first?
- Why doesn't a writer need to use mutex?

# Bounded Buffer

- Problem: There is a set of resource buffers shared by producer and consumer threads
- Producer inserts resources into the buffer set
  - Output, disk blocks, memory pages, processes, etc.
- Consumer removes resources from the buffer set
  - Whatever is generated by the producer
- Producer and consumer execute at different rates
  - No serialization of one behind the other
  - Tasks are independent (easier to think about)
  - The buffer set allows each to run without explicit handoff

# Bounded Buffer (2)

- Use three semaphores:
  - mutex – mutual exclusion to shared set of buffers
    - » Binary semaphore
  - empty – count of empty buffers
    - » Counting semaphore
  - full – count of full buffers
    - » Counting semaphore

# Bounded Buffer (3)

```
Semaphore mutex = 1;   // mutual exclusion to shared set of buffers
Semaphore empty = N;  // count of empty buffers (all empty to start)
Semaphore full = 0;     // count of full buffers (none full to start)
```

```
producer {
  while (1) {
    Produce new resource;
    wait(empty); // wait for empty buffer
    wait(mutex); // lock buffer list
    Add resource to an empty buffer;
    signal(mutex); // unlock buffer list
    signal(full);     // note a full buffer
  }
}
```

```
consumer {
  while (1) {
    wait(full);        // wait for a full buffer
    wait(mutex);     // lock buffer list
    Remove resource from a full buffer;
    signal(mutex); // unlock buffer list
    signal(empty); // note an empty buffer
    Consume resource;
  }
}
```

# Bounded Buffer (4)

- Why need the mutex at all?
- Where are the critical sections?
- What happens if operations on mutex and full/empty are switched around?
  - The pattern of signal/wait on full/empty is a common construct often called an interlock
- Producer-Consumer and Bounded Buffer are classic examples of synchronization problems
  - The Mating Whale problem in Project 1 is another
  - You can use semaphores to solve the problem
  - Use readers/writers and bounded buffer as examples for hw

# Semaphore Summary

- Semaphores can be used to solve any of the traditional synchronization problems
- However, they have some drawbacks
  - They are essentially shared global variables
    - » Can potentially be accessed anywhere in program
  - No connection between the semaphore and the data being controlled by the semaphore
  - Used both for critical sections (mutual exclusion) and coordination (scheduling)
  - No control or guarantee of proper usage
- Sometimes hard to use and prone to bugs
  - Another approach: Use programming language support

# Monitors

- A monitor is a programming language construct that controls access to shared data
  - Synchronization code added by compiler, enforced at runtime
  - Why is this an advantage?
- A monitor is a module that encapsulates
  - Shared data structures
  - Procedures that operate on the shared data structures
  - Synchronization between concurrent threads that invoke the procedures
- A monitor protects its data from unstructured access
- It guarantees that threads accessing its data through its procedures interact only in legitimate ways

# Monitor Semantics

- A monitor guarantees mutual exclusion
  - Only one thread can execute any monitor procedure at any time (the thread is “in the monitor”)
  - If a second thread invokes a monitor procedure when a first thread is already executing one, it blocks
    - » So the monitor has to have a wait queue…
  - If a thread within a monitor blocks, another one can enter
- What are the implications in terms of parallelism in monitor?

# Account Example

```
Monitor account {
  double balance;

  double withdraw(amount) {
    balance = balance – amount;
    return balance;
  }
}
```

**Threads block waiting to get into monitor**

withdraw(amount)
  balance = balance – amount;

withdraw(amount)

withdraw(amount)

  return balance (and exit)

  balance = balance – amount
  return balance;

  balance = balance – amount;
  return balance;

**When first thread exits, another can enter. Which one is undefined.**

- Hey, that was easy
- But what if a thread wants to wait inside the monitor?
  - » Such as “mutex(empty)” by reader in bounded buffer?

# Condition Variables

- Condition variables provide a mechanism to wait for events (a "rendezvous point")
  - Resource available, no more writers, etc.
- Condition variables support three operations:
  - Wait – release monitor lock, wait for C/V to be signaled
    - » So condition variables have wait queues, too
  - Signal – wakeup one waiting thread
  - Broadcast – wakeup all waiting threads
- Note: Condition variables are not boolean objects
  - "if (condition_variable) then" … does not make sense
  - "if (num_resources == 0) then wait(resources_available)" does
  - An example will make this more clear

# Monitor Bounded Buffer

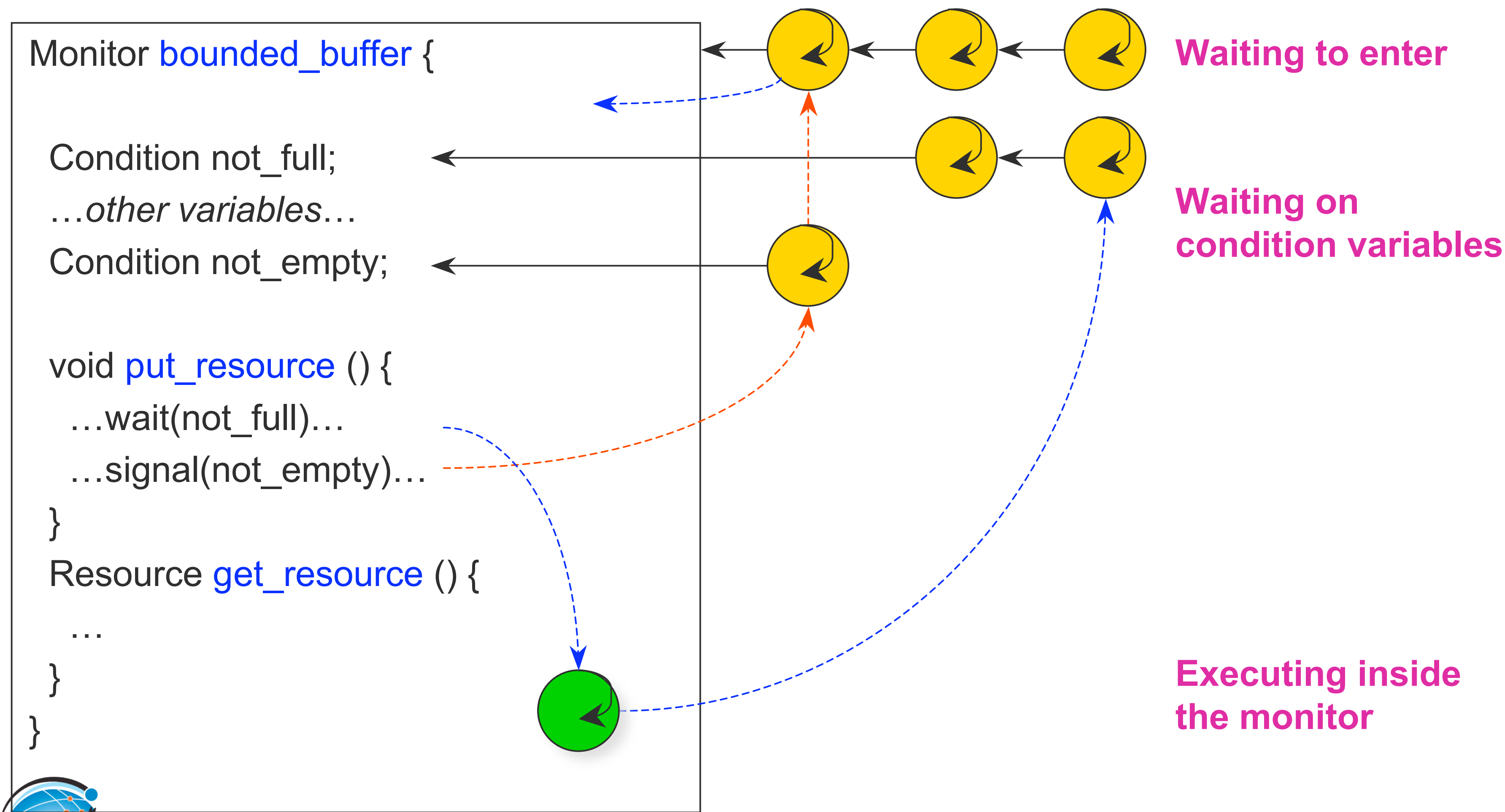
```
Monitor bounded_buffer {
  Resource buffer[N];
  // Variables for indexing buffer
  Condition not_full, not_empty;

  void put_resource (Resource R) {
    while (buffer array is full)
        wait(not_full);
    Add R to buffer array;
    signal(not_empty);
  }
```

```
  Resource get_resource() {
    while (buffer array is empty)
        wait(not_empty);
    Get resource R from buffer array;
    signal(not_full);
    return R;
  }
} // end monitor
```

- What happens if no threads are waiting when signal is called?

# Monitor Queues



# Condition Vars != Semaphores

- Condition variables != semaphores
  - Although their operations have the same names, they have entirely different semantics (such is life, worse yet to come)
  - However, they each can be used to implement the other
- Access to the monitor is controlled by a lock
  - wait() blocks the calling thread, and gives up the lock
    - » To call wait, the thread has to be in the monitor (hence has lock)
    - » Semaphore::wait just blocks the thread on the queue
  - signal() causes a waiting thread to wake up
    - » If there is no waiting thread, the signal is lost
    - » Semaphore::signal increases the semaphore count, allowing future entry even if no thread is waiting
    - » Condition variables have no history

# Signal Semantics

- There are two flavors of monitors that differ in the scheduling semantics of signal()
  - Hoare monitors (original)
    - signal() immediately switches from the caller to a waiting thread
    - The condition that the waiter was anticipating is guaranteed to hold when waiter executes
    - Signaler must restore monitor invariants before signaling
  - Mesa monitors (Mesa, Java)
    - signal() places a waiter on the ready queue, but signaler continues inside monitor
    - Condition is not necessarily true when waiter runs again
      - Returning from wait() is only a hint that something changed
      - Must recheck conditional case

# Hoare vs. Mesa Monitors

- Hoare

```
if (empty)
    wait(condition);
```

- Mesa

```
while (empty)
    wait(condition);
```

- Tradeoffs
  - Mesa monitors easier to use, more efficient
    - » Fewer context switches, easy to support broadcast
  - Hoare monitors leave less to chance
    - » Easier to reason about the program

# Condition Vars & Locks

- Condition variables are also used without monitors in conjunction with blocking locks
  - This is what you are implementing in Project 1
- A monitor is “just like” a module whose state includes a condition variable and a lock
  - Difference is syntactic; with monitors, compiler adds the code
- It is “just as if” each procedure in the module calls acquire() on entry and release() on exit
  - But can be done anywhere in procedure, at finer granularity
- With condition variables, the module methods may wait and signal on independent conditions

# Using Cond Vars & Locks

- Alternation of two threads (ping-pong)
- Each executes the following:

```
Lock lock;
Condition cond;

void ping_pong () {
  acquire(lock);
  while (1) {
     printf("ping or pong\n");
     signal(cond, lock);
     wait(cond, lock);
  }
  release(lock);
}
```

Must acquire lock before you can wait (similar to needing interrupts disabled to call Sleep in Nachos)

Wait atomically releases lock and blocks until signal()

Wait atomically acquires lock before it returns

# Monitors and Java

- A lock and condition variable are in every Java object
  - No explicit classes for locks or condition variables
- Every object is/has a monitor
  - At most one thread can be inside an object’s monitor
  - A thread enters an object’s monitor by
    - » Executing a method declared “synchronized”
      - Can mix synchronized/unsynchronized methods in same class
    - » Executing the body of a “synchronized” statement
      - Supports finer-grained locking than an entire procedure
      - Identical to the Modula-2 “LOCK (m) DO” construct
- Every object can be treated as a condition variable
  - Object::notify() has similar semantics as Condition::signal()

# Summary

- Semaphores
  - wait()/signal() implement blocking mutual exclusion
  - Also used as atomic counters (counting semaphores)
  - Can be inconvenient to use
- Monitors
  - Synchronizes execution within procedures that manipulate encapsulated data shared among procedures
    - » Only one thread can execute within a monitor at a time
  - Relies upon high-level language support
- Condition variables
  - Used by threads as a synchronization point to wait for events
  - Inside monitors, or outside with locks

# Project 1: Synchronization in Nachos

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# Locks & CVs

- Lock issues
  - A thread cannot Acquire a lock it already holds
  - A thread cannot Release a lock it does not hold
  - A lock cannot be deleted if a thread is holding it

- Condition Variable issues
  - A thread can only call Wait and Signal if it holds the mutex
  - Wait must Release the mutex before the thread sleeps
  - Wait must Acquire the mutex after the thread wakes up
  - A condition variable cannot be deleted if a thread is waiting on it

# Mailboxes

- Senders and receivers need to be synchronized
  - One sender and one receiver need to rendezvous
- Issues
  - Block all other senders while waiting for receiver in Send
  - Block all other receivers while waiting for sender in Receive
  - When a condition variable is signaled…
    - » The waiting thread is placed on the ready list
    - » But it has not necessarily re-acquired the lock
    - » It only reacquires the lock when it runs again
    - » If another thread runs before it does, that thread can acquire the lock before the waiter does
    - » Let's look at an example

# Synchronizing with Wait/Signal

```
while (1) {
    mutex->Acquire();
    printf("ping\n");
    cond>Signal(mutex);
    mutex->Release();
}
```

```
while (1) {
    mutex->Acquire();
    cond->Wait(mutex);
    printf("pong\n");
    mutex->Release();
}
```

**Signal places waiter on ready list, and then continues**

**BUT – the waiter now competes with the signaler to re-acquire the mutex**

**Output COULD be:**

**ping…ping…ping**

# Interlocking with Wait/Signal

```
Mutex *mutex;
Condition *cond;

void ping_pong () {
  mutex->Acquire();
  while (1) {
      printf("ping or pong\n");
      cond->Signal(mutex);
      cond->Wait(mutex);
  }
  mutex->Release();
}
```

**Waiting after signaling interlocks the two threads.**

**The thread that signals then does a wait, and cannot proceed until the other thread wakes up from its wait and follows with a signal.**

# Thread::Join

- Issues
  - A thread can only be Joined if specified during creation
  - A thread can only be Joined after it has forked
  - Only one thread can call Join on another
  - A thread cannot call Join on itself
  - A thread should be able to call Join on a thread that has already terminated
    - This is the tricky part
    - Should delay deleting thread object if it is to be joined
      - If it is not going to be Joined, then don't change how it is deleted
    - Where is it deleted now? Look for use of threadToBeDestroyed
    - Where should joined threads be deleted?
    - Need to delete synch primitives used by Join as well

# Thread::setPriority(int)

- Issues
  - Priorities have the entire range of an “int”
    - » Both negative and positive
  - If one thread has a priority value that is greater than another, that thread has a higher priority (simple integer comparisons)
  - List implementation in list.cc has sorting capabilities
  - Only adjust priority of thread when it is placed on ready list
  - When transferring priority from a high thread to a low thread, the transfer is only temporary
    - » When the low thread releases the lock, its priority reverts

# Mating Whales

- Issues
  - This is a synchronization problem like Bounded-Buffer and Readers/Writers
  - You do not need to implement anything inside of Nachos
    - » But you will use the synchronization primitives you implemented
    - » You can use any synch primitives you want
  - You will implement Male, Female, and Matchmaker as functions in threadtest.cc (or equivalent), and create and fork threads to execute these functions in ThreadTest:

```
T1->Fork(Male, 0);           // could fork many males
T2->Fork(Female, 0);         // could fork many females
T3->Fork(Matchmaker, 0);     // could fork many matchmakers
```

  - There is no API -- we will compile, run, and visually examine your code for correctness
  - Comments will help (both you and us)

# Tips

- Use DEBUG macro to trace the interaction of the synchronization primitives and thread context switches
  - Run “nachos –d s –d t” to enable synch and thread debugs
- Good advice available on the Web:
  - Nachos Road Map→Experience With Nachos Assignments→Synchronization