CS 318 Principles of Operating Systems

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Lecture 7: Semaphores and Monitors

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Slides adapted from Geoff Voelker's lectures

Administrivia

- **HW2 is out**
  - Do the exercise to check your understanding on lecture 3-5
- **Lab 1**
  - Due this Friday midnight
  - If you decide to use late hours, email cs318-staff@cs.jhu.edu
  - Reminder about cheating policy

Higher-Level Synchronization

- **We looked at using locks to provide mutual exclusion**
- **Locks work, but they have limited semantics**
  - Just provide mutual exclusion
- **Instead, we want synchronization mechanisms that**
  - Block waiters, leave interrupts enabled in critical sections
  - Provide semantics beyond mutual exclusion
- **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

- **An abstract data type to provide mutual exclusion to critical sections**
  - Described by Dijkstra in the "THE" system in 1968
- **Semaphores can also be used as atomic counters**
  - More later
- **Semaphores are "integers" that support two operations:**
  - `Semaphore::P()`: decrement, block until semaphore is open
    - after the Dutch word "Proberen" (to try), also `Wait()`
  - `Semaphore::V()`: increment, allow another thread to enter
    - after the Dutch word "Verhogen" (increment), also `Signal()`
  - That's it! No other operations – not even just reading its value
- **Semaphore safety property: the semaphore value is always greater than or equal to 0**

Blocking in Semaphores

- **Associated with each semaphore is a queue of waiting processes**
- **When `P()` is called by a thread:**
  - If semaphore is open, thread continues
  - If semaphore is closed, thread blocks on queue
- **Then `V()` 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, `V()` has "history" (c.f., condition vars later)
    - This "history" is a counter

Semaphore Types

- **Semaphores come in two types**
- **Mutex semaphore (or binary semaphore)**
  - Represents single access to a resource
  - Guarantees mutual exclusion to a critical section
- **Counting semaphore (or general 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;
}
```

critical section

Threads block

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

```
wait(S);
```

```
wait(S);
```

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

```
…
signal(S);
```

```
…
signal(S);
```

It is undefined which thread runs after a signal

Semaphores in Pintos

```
void sema_down(struct semaphore *sema)
{
  enum intr_level old_level;
  old_level = intr_disable();
  while (sema->value == 0) {
    list_push_back(&sema->waiters,
          &thread_current()->elem);
    thread_block();
  }
  sema->value--;
  intr_set_level(old_level);
}
```

```
void sema_up(struct semaphore *sema)
{
  enum intr_level old_level;
  old_level = intr_disable();
  if (!list_empty (&sema->waiters))
    thread_unblock(list_entry(
        list_pop_front(&sema->waiters),
             struct thread, elem));
  sema->value++;
  intr_set_level(old_level);
}
```

- **To reference current thread:** `thread_current()`
- `thread_block()` **assumes interrupts are disabled**
  - Note that interrupts are disabled only to enter/leave critical section
  - How can it sleep with interrupts disabled?

Interrupts Disabled During Context Switch

```
thread_yield() {
  Disable interrupts;
  add current thread to ready_list;
  schedule(); // context switch
  Enable interrupts;
}
```

```
sema_down(){
 Disable interrupts;
 while(value == 0) {
   add current thread to waiters;
   thread_block();
 }
 value--;
 Enable interrupts;
}
```

```
[thread_yield]
Disable interrupts;
add current thread to ready_list;
schedule();
```

```
[thread_yield]
(Returns from schedule())
Enable interrupts;
```

```
[sema_down]
Disable interrupts;
while(value == 0) {
  add current thread to waiters;
  thread_block();
}
```

```
[thread_yield]
(Returns from schedule())
Enable interrupts;
```

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
    - Let $\#r$ be the number of readers, $\#w$ be the number of writers
    - Safety: $(\#r \geq 0) \wedge (0 \leq \#w \leq 1) \wedge ((\#r > 0) \Rightarrow (\#w = 0))$
- **How can we use semaphores 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

```
// 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
}
```

Semaphores in Pintos

```
reader {
    wait(mutex);
    …
    signal(mutex);
    Read;
    wait(mutex);
    …
}
```

```
void sema_down(struct semaphore *sema)
{
  enum intr_level old_level;
  old_level = intr_disable();
  while (sema->value == 0) {
    list_push_back(&sema->waiters,
          &thread_current()->elem);
    thread_block();
  }
  sema->value--;
  intr_set_level(old_level);
}
```

```
void sema_up(struct semaphore *sema)
{
  enum intr_level old_level;
  old_level = intr_disable();
  if (!list_empty (&sema->waiters))
    thread_unblock(list_entry(
      list_pop_front(&sema->waiters),…));
  sema->value++;
  intr_set_level(old_level);
}
```

Readers/Writers Notes

- `w_or_r` **provides mutex between readers and writers**
  - writer wait/signal, reader wait/signal when `readcount` goes from 0 to 1 or from 1 to 0.
- **If a writer is writing, where will readers be waiting?**
- **Once a writer exits, all readers can fall through**
  - Which reader gets to go first?
  - Is it guaranteed that all readers will fall through?
- **If readers and writers are waiting, and a writer exits, who goes first?**
- **Why do readers use** `mutex`**?**
- **Why don't writers use** `mutex`**?**
- **What if the signal is above "**`if (readcount == 1)`**"?**

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
- **Safety:**
  - Sequence of consumed values is prefix of sequence of produced values
  - If nc is number consumed, np number produced, and N the size of the buffer, then $0 \leq np - nc \leq N$

Bounded Buffer (2)

- **$0 \le np - nc \le N$ and $0 \le (nc - np) + N \le N$**
- **Use three semaphores:**
  - empty – count of empty buffers
    - Counting semaphore
    - empty $= (nc - np) + N$
  - full – count of full buffers
    - Counting semaphore
    - $np - nc =$ full
  - mutex – mutual exclusion to shared set of buffers
    - Binary 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 has to hold for deadlock to occur?**
  - empty = 0 and full = 0
  - ($nc - np$) + N = 0 and np - nc = 0
  - N = 0
- **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 sync. problems**

Semaphore Questions

- **Are there any problems that can be solved with counting semaphores that cannot be solved with mutex semaphores?**
- **Does it matter which thread is unblocked by a signal operation?**
  - Hint: consider the following three threads sharing a semaphore mutex that is initially 1:

```
while (1) {
  wait(mutex);
  // in critical
  // section
  signal(mutex);
}
```

```
while (1) {
  wait(mutex);
  // in critical
  // section
  signal(mutex);
}
```

```
while (1) {
  wait(mutex);
  // in critical
  // section
  signal(mutex);
}
```

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)
    - Note that I had to use comments in the code to distinguish
  - 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 a 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?

Monitors, Monitor Invariants and Condition Variables

- **A monitor invariant is a safety property associated with the monitor, expressed over the monitored variables. It holds whenever a thread enters or exits the monitor.**
- **A condition variable is associated with a condition needed for a thread to make progress once it is in the monitor.**
  - alternative: busy waiting, bad

```
Monitor M {
  ... monitored variables
  Condition c;

  void enterMonitor (...) {
    if (extra property not true) wait(c);  waits outside of the monitor's mutex
    do what you have to do
    if (extra property true) signal(c);   brings in one thread waiting on condition
  }
```

Condition Variables

- **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

- **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
  // monitor invariant involves these vars
  Condition not_full; // space in buffer
  Condition not_empty; // value in buffer

  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
```

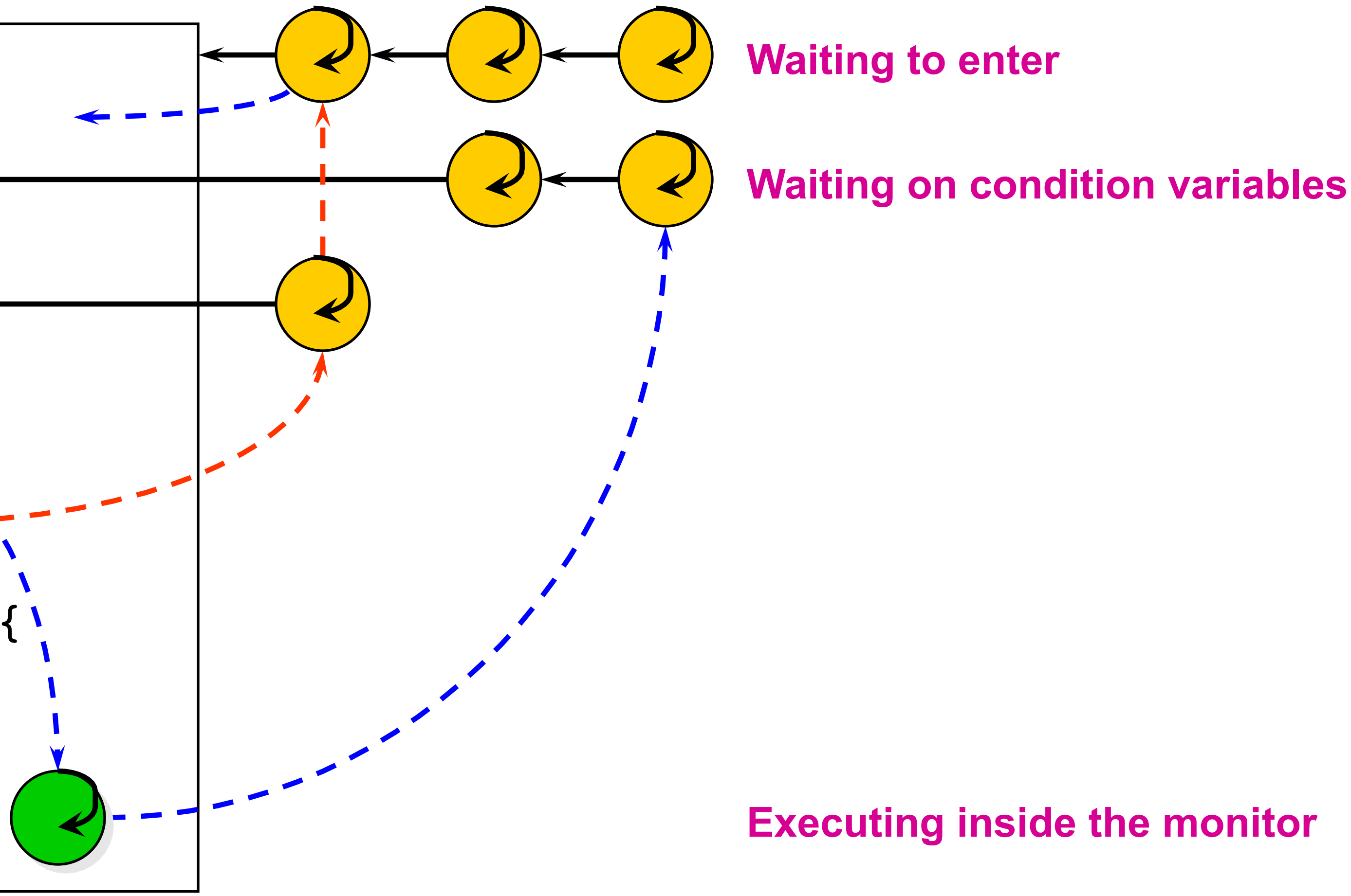
- What happens if no threads are waiting when signal is called?

Monitor Queues

```
Monitor bounded_buffer {

  Condition not_full;
  …other variables…
  Condition not_empty;

  void put_resource() {
    …wait(not_full)…
    …signal(not_empty)…
  }
  Resource get_resource() {
    …
  }
}
```



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

Monitor Readers and Writers

Using Mesa monitor semantics.

- **Will have four methods:** `StartRead`, `StartWrite`, `EndRead` **and** `EndWrite`
- **Monitored data:** `nr` **(number of readers) and** `nw` **(number of writers) with the monitor invariant**

$$(nr \geq 0) \wedge (0 \leq nw \leq 1) \wedge ((nr > 0) \Rightarrow (nw = 0))$$

- **Two conditions:**
  - `canRead`: $nw = 0$
  - `canWrite`: $(nr = 0) \wedge (nw = 0)$

Monitor Readers and Writers

- **Write with just `wait()`**
  - Will be safe, maybe not live – why?

```
Monitor RW {
  int nr = 0, nw = 0;
  Condition canRead, canWrite;

  void StartRead () {
    while (nw != 0) do wait(canRead);
    nr++;
  }

  void EndRead () {
    nr--;
  }
```

```
  void StartWrite {
    while (nr != 0 || nw != 0) do wait(canWrite);
    nw++;
  }

  void EndWrite () {
    nw--;
  }
} // end monitor
```

Monitor Readers and Writers

- **add** `signal()` **and** `broadcast()`

```
Monitor RW {
  int nr = 0, nw = 0;
  Condition canRead, canWrite;

  void StartRead () {
    while (nw != 0) do wait(canRead);
    nr++;
  }

  void EndRead () {
    nr--;
    if (nr == 0) signal(canWrite);
  }
```

can we put a signal here?

```
  void StartWrite () {
    while (nr != 0 || nw != 0) do wait(canWrite);
    nw++;
  }

  void EndWrite () {
    nw--;
    broadcast(canRead);
    signal(canWrite);
  }
} // end monitor
```

can we put a signal here?

Monitor Readers and Writers

- **Is there any priority between readers and writers?**
- **What if you wanted to ensure that a waiting writer would have priority over new readers?**

Condition Vars & Locks

- **C/Vs are also used without monitors in conjunction with locks**
  - `void cond_init (cond_t *, ...);`
  - `void cond_wait (cond_t *c, mutex_t *m);`
    - Atomically unlock `m` and sleep until `c` signaled
    - Then re-acquire m and resume executing
  - `void cond_signal (cond_t *c);`
  - `void cond_broadcast (cond_t *c);`
    - - Wake one/all threads waiting on c

Condition Vars & Locks

- **C/Vs are also used without monitors in conjunction with locks**
- **A monitor ≈ a module whose state includes a C/V 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**

Condition Vars & Locks

- **Why must** `cond_wait` **both release** `mutex_t` **& sleep?**
  - `void cond_wait(cond_t *c, mutex_t *m);`
- **Why not separate mutexes and condition variables?**

```
while (count == BUFFER_SIZE) {
    mutex_unlock(&mutex);
    cond_wait(&not_full);
    mutex_lock(&mutex);
}
```

Condition Vars & Locks

- **Why must** `cond_wait` **both release** `mutex_t` **& sleep?**
  - `void cond_wait(cond_t *c, mutex_t *m);`
- **Why not separate mutexes and condition variables?**

Producer

```
while (count == BUFFER_SIZE) {
    mutex_unlock(&mutex);



    cond_wait(&not_full);
    mutex_lock(&mutex);
}
```

Consumer

```
mutex_lock(&mutex);
... count--;
cond_signal(&not_full);
```

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 `thread_block` in Pintos)

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
  - The compiler generates code to acquire the object's lock at the start of the method and release it just before returning
    - The lock itself is implicit, programmers do not worry about it

Monitors and Java

- **Every object can be treated as a condition variable**
  - Half of Object's methods are for synchronization!
- **Take a look at the Java Object class:**
  - Object.wait(*) is Condition::wait()
  - Object.notify() is Condition::signal()
  - Object.notifyAll() is Condition::broadcast()

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

Next Time…

- **Read Chapter 32**