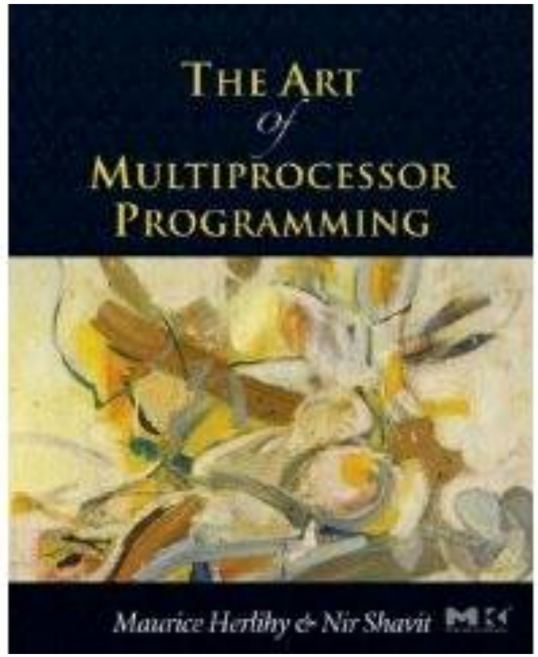
Department of Computer Science

COS 226

Chapter 8

Monitors and Blocking Synchronization

Acknowledgement



- Some of the slides are taken from the companion slides for “The Art of Multiprocessor Programming” by Maurice Herlihy & Nir Shavit

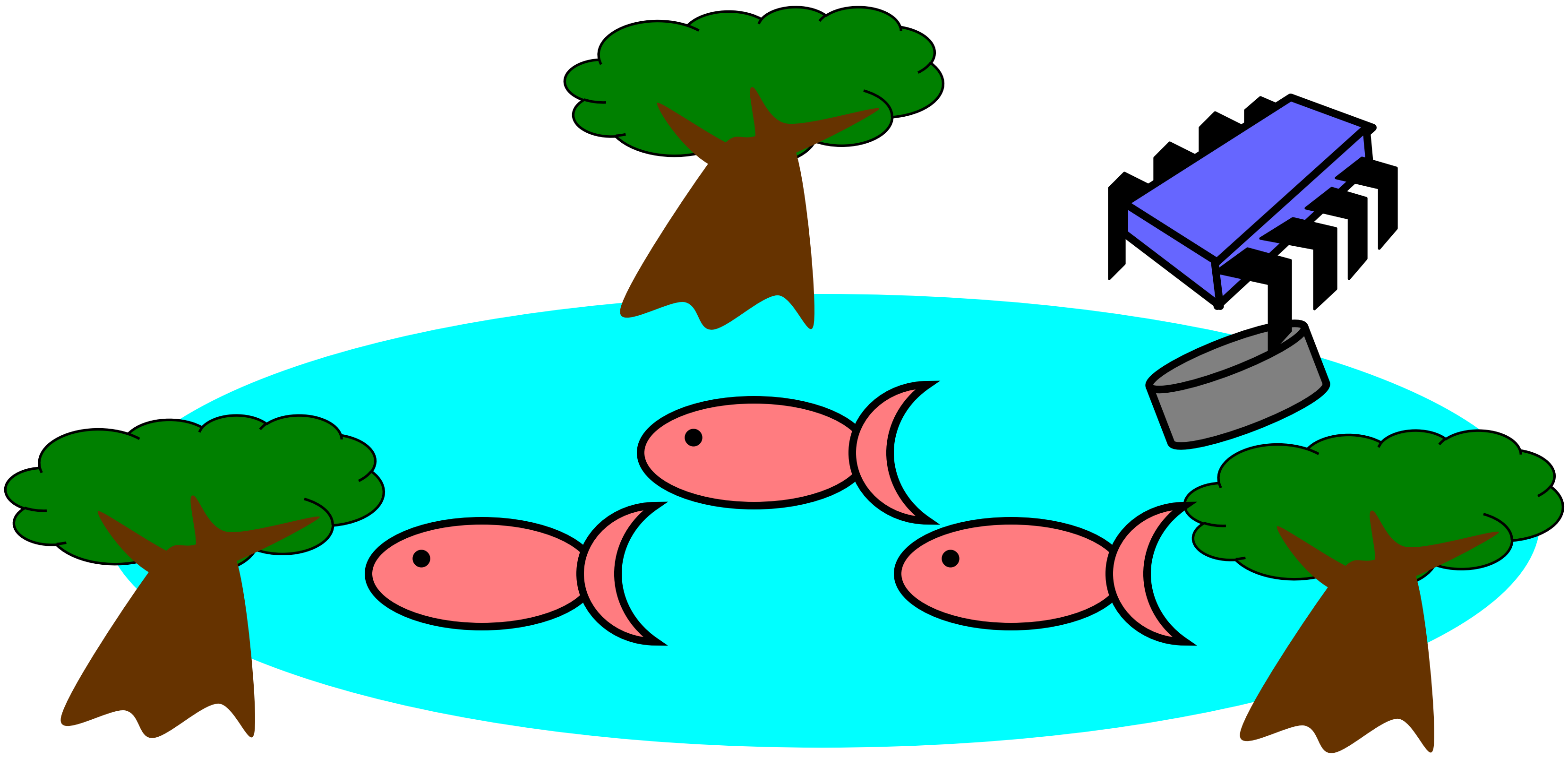
Monitors

- Structured way of combining synchronization and data
- Combines data, methods and synchronization in a single modular package

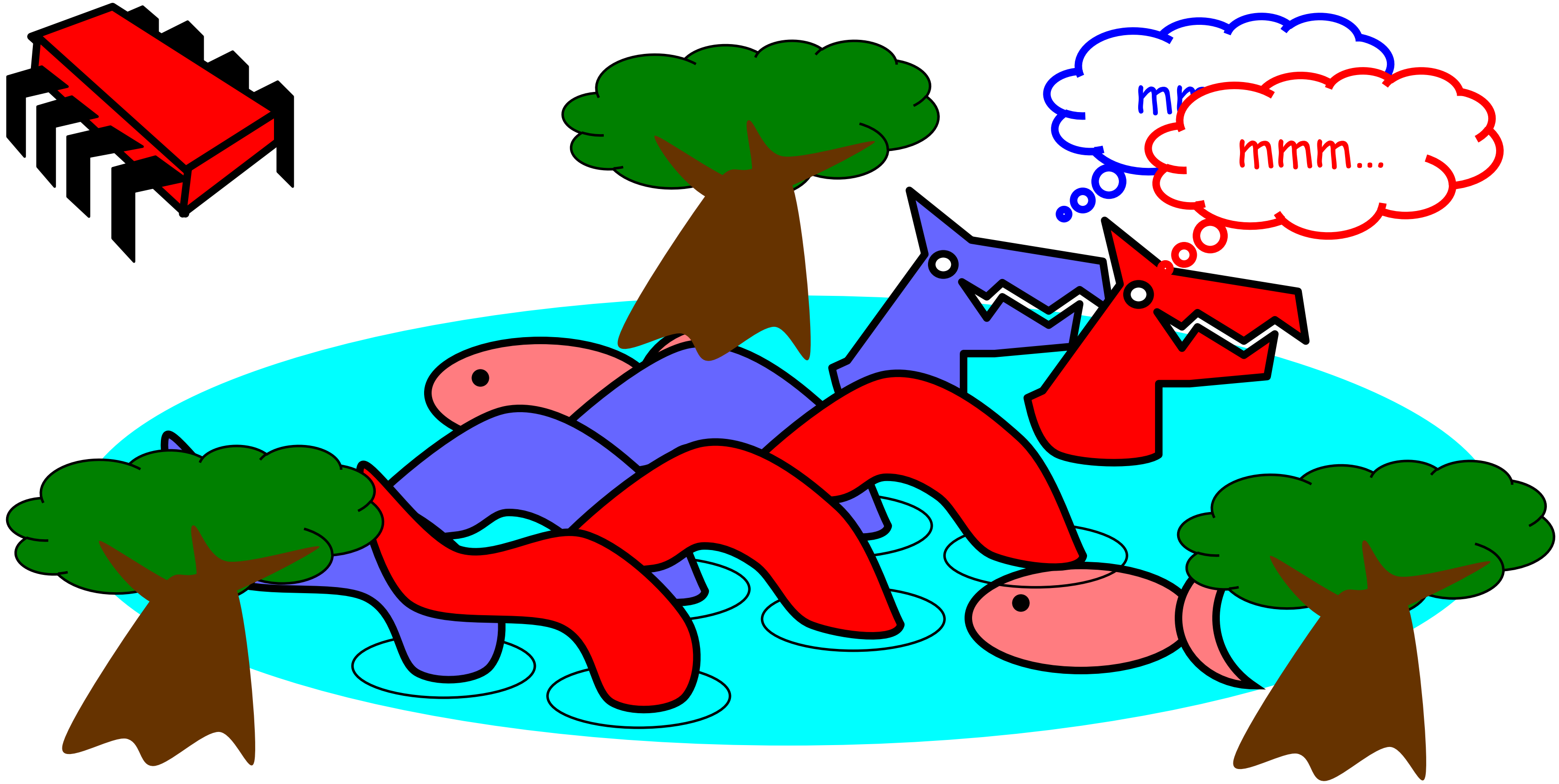
Producer-Consumer Problem

- Synchronization problem

Bob Puts Food in the Pond



Alice releases her pets to Feed



Producer/Consumer

- Alice and Bob can’t meet
  - Each has restraining order on other
  - So he puts food in the pond
  - And later, she releases the pets
- Avoid
  - Releasing pets when there’s no food
  - Putting out food if uneaten food remains

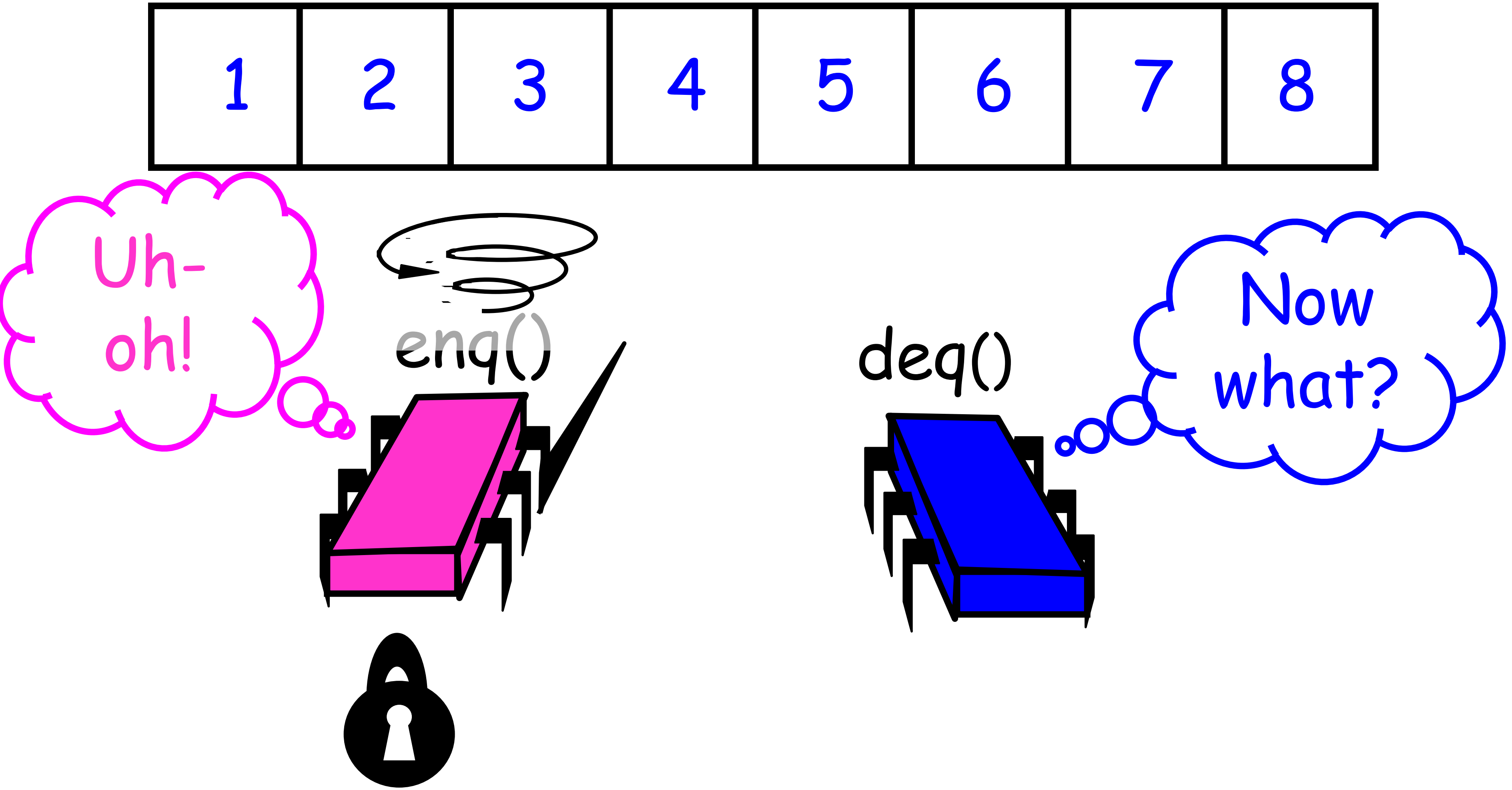
In real life…

- Imagine application with two threads – producer and consumer
- Two threads communicate through a shared FIFO queue
- Principles:
  - The producer generates data, puts it into the queue and start again
  - At the same time the consumer, consumes the data one piece at a time

Producer

```
mutex.lock()
try {
  queue.enq();
} finally {
  mutex.unlock();
}
```

Producer-Consumer



Problems

- What happens when the queue is full?
- Problem:
  - Producer should not try to add data if the buffer is full
  - Consumer should not try to remove data from an empty buffer
- Where should this be managed?

Sensible approach

- Allow each queue to manage its own synchronization
- The queue itself has its own internal lock, acquired by methods and released when it returns
  - For example, lock() can be called inside the enq() method
- If a thread then tries to enq() an item onto a full queue, the enq() method itself can detect the problem

Monitor Locks

- Only one thread at a time can *hold* a lock
- A thread *acquires* a lock when it starts to hold the lock
- A thread *releases* the lock when it stops holding the lock
- A monitor has methods each which acquires the lock when it is called and releases the lock when it returns

Monitor Locks

- When a thread cannot immediately acquire a lock it either:
  - Spins – repeatedly testing whether it is available
  - Blocks – suspends thread and creates new thread
- Spinning = short time
- Blocking = long time

Spinning vs. Blocking

- For example:
  - A thread waiting for another thread to release the lock should spin if lock is held briefly
  - A consumer thread waiting to dequeue an item from a empty queue should block
- Often spinning and blocking are combined
- Spinning does not work on uniprocessors

Producer-Consumer

- Need a way for a thread that has acquired a lock to release the lock for a while and then to reacquire it and try again

Conditions

- In java concurrency package
- Condition object provides ability to release a lock temporarily
- A Condition is related to a lock and is created by lock’s newCondition() method

Conditions

```
Condition condition = mutex.newCondition();
…
mutex.lock();
try {
  while (!property) {
     condition.await();
  } catch (InterruptedException e) {…}
…
}
```

Conditions

```
Condition condition = mutex.newCondition();
…
mutex.lock();
try {
  while (!property) {
     condition.await();
  } catch (InterruptedException e) {…}
…
}
```

Create Condition object that is related to lock

Conditions

```
Condition condition = mutex.newCondition();
…
mutex.lock();
try {
  while (!property) {
     condition.await();
  } catch (InterruptedException e) {…}
…
}
```

Acquires lock

Conditions

```
Condition condition = mutex.newCondition();
…
mutex.lock();
try {
  while (!property) {
      condition.await();
  } catch (InterruptedException e) {…}
…
}
```

Tests whether property holds

Conditions

```
Condition condition = mutex.newCondition();
…
mutex.lock();
try {
  while (!property) {
     condition.await();
  } catch (InterruptedException e) {…}
…
}
```

Releases the lock and suspends itself

Conditions

```
Condition condition = mutex.newCondition();
…
mutex.lock();
try {
  while (!property) {
     condition.await();
  } catch (InterruptedException e) {…}
…
}
```

Suspension can be interrupted by other thread

Producer

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
…
public void enq(T x) {
  lock.lock();
  try {
     while (items.length == max)
          isFull.await();
     ...
```

Producer

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
…
public void enq(T x) {
  lock.lock();
  try {
     while (items.length == max)
          isFull.await();
     ...
```

Condition to check whether queue is full

Producer

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
…
public void enq(T x) {
  lock.lock();
  try {
     while (items.length == max)
          isFull.await();
     ...
```

Array of elements with some max amount

Producer

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
…
public void enq(T x) {
   lock.lock();
   try {
      while (items.length == max)
            isFull.await();
      ...
```

Attempt to add item to queue

Producer

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
…
public void enq(T x) {
  lock.lock();
  try {
     while (items.length == max)
          isFull.await();
     ...
```

Acquires lock

Producer

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
…
public void enq(T x) {
  lock.lock();
  try {
     while (items.length == max)
          isFull.await();
     ...
```

Check whether queue is full

Producer

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
…
public void enq(T x) {
  lock.lock();
  try {
    while (items.length == max)
         isFull.await();
    ...
```

Sleep while queue is full

Conditions

- How does the Producer know when the queue is not full anymore?
- Options:
  - Can awaken on time constraints
  - Another thread (Consumer) will have to wake it.

Conditions

```
public interface Condition {
  void await()
  boolean await (long time)
  boolean awaitUntil (Date)
  long awaitNanos (long nanoSec)
```

- All of these methods uses time constraints

Conditions

- Another thread can also use signal() to notify threads that it has changed a certain property.

```
void signal()
void signalAll()
```

Conditions

- However, there is no guarantee that when the threads awakens after a specified time, the property will hold
- Thus the thread must retest the property when it awakes

Conditions

- When threads are woken up, they could still have to compete for the lock

Producer-Consumer queue

- If the Producer thread has been suspended because of a full queue, when should it be woken up again?
- And what about checking whether the queue is empty or not?

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
...
public void enq(T x) {
  lock.lock();
  try {
     while (items.length == max)
          isFull.await();
     items[tail] = x;
     ...
     isEmpty.signal();
  } finally {
     lock.unlock();
```

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
...
public void enq(T x) {
  lock.lock();
  try {
     while (items.length == max)
          isFull.await();
     items[tail] = x;
     ...
     isEmpty.signal();
  } finally {
     lock.unlock();
```

Second condition to test whether queue is empty

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
...
public void enq(T x) {
  lock.lock();
  try {
    while (items.length == max)
          isFull.await();
    items[tail] = x;
    ...
    isEmpty.signal();
  } finally {
    lock.unlock();
```

When thread wakes up it can access the CS – add an item

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
...
public void enq(T x) {
  lock.lock();
  try {
    while (items.length == max)
        isFull.await();
    items[tail] = x;
    ...
    isEmpty.signal();
  } finally {
    lock.unlock();
```

Since an item has been added it is not empty – alert Consumer

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
...
public T deq() {
  lock.lock();
  try {
     while (items.length == 0)
          isEmpty.await();
     T x = items[head]
     ...
     isFull.signal();
  } finally {
     lock.unlock();
```

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
...
public T deq() {
  lock.lock();
  try {
     while (items.length == 0)
           isEmpty.await();
     T x = items[head]
     ...
     isFull.signal();
  } finally {
     lock.unlock();
```

First acquire lock

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
...
public T deq() {
  lock.lock();
  try {
     while (items.length == 0)
          isEmpty.await();
     T x = items[head]
     ...
     isFull.signal();
  } finally {
     lock.unlock();
```

Check whether queue is empty

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
...
public T deq() {
  lock.lock();
  try {
     while (items.length == 0)
          isEmpty.await();
     T x = items[head]
     ...
     isFull.signal();
  } finally {
     lock.unlock();
```

Release and sleep if queue is empty

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
...
public T deq() {
  lock.lock();
  try {
     while (items.length == 0)
          isEmpty.await();
     T x = items[head]
     ...
     isFull.signal();
  } finally {
     lock.unlock();
```

Remove item from queue

```
class LockedQueue {
Lock lock = new ReentrantLock();
Condition isFull = lock.newCondition();
Condition isEmpty = lock.newCondition();
T[] items;
...
public T deq() {
  lock.lock();
  try {
    while (items.length == 0)
          isEmpty.await();
    T x = items[head]
    ...
    isFull.signal();
  } finally {
    lock.unlock();
```

Let Producer know that queue is not full anymore

Monitor

- The combination of methods, mutual exclusion locks and condition objects is called a **monitor**

Lost-Wakeup Problem

- Just like locks are vulnerable to deadlock, conditions are vulnerable to lost wakeups
- Lost wakeup:
  - One or more threads wait forever without realizing that the property for which they have been waiting has become true

```
public void enq(T x) {
  lock.lock();
  try {
     while (count == items.length)
          isFull.await();
     items[tail] = x;
     ++count;
     if (count == 1)
          isEmpty.signal();
     }
  } finally {
     lock.unlock();
  }
}
```

Lost-Wakeup Problem

- Always make sure that all necessary threads are signalled
- When using multiple consumer and producer threads (for example)
  - Make sure that you signal all processes waiting on a property and
  - Specify a timeout when waiting

Readers-Writers Locks

- Many shared objects have the property of having readers that only access the object without modifying it and writers that modify the object

Readers-Writers Locks

- Should readers be synchronized?
- Should writers be synchronized?
- How is synchronization achieved?

Readers-Writers Locks

- A readers-writers lock should allow multiple readers or a single writer to enter the critical section

Readers-Writers Locks Interface

```
public interface ReadWriteLock {
  Lock readLock();
  Lock writeLock();
}
```

Readers-Writers Locks

- The interface should satisfy the following properties:
  - No thread can acquire the write lock while any thread holds either the write lock or the read lock
  - No thread can acquire the read lock while any other thread holds the write lock

Questions

- How can we make sure that all other readers are finished before acquiring a write lock?
- How can we make sure that a writer is not currently holding a lock?
- When should the threads block?
- When should the threads wake up?

Solutions

- We need a way of specifying how many readers and writers are currently contending for the lock

SimpleReadWriteLock

```
public class SimpleReadWriteLock
  implements ReadWriteLock {
  boolean writer;
  int readers;
  Lock lock;
  Condition condition;
  Lock readLock, writeLock;
```

SimpleReadWriteLock

```
public SimpleReadWriteLock() {
  writer = false;
  readers = 0;
  lock = new ReentrantLock();
  readLock = new ReadLock();
  writeLock = new WriteLock();
  condition = lock.newCondition();
```

No initial writers

SimpleReadWriteLock

```
public SimpleReadWriteLock() {
  writer = false;
  readers = 0;
  lock = new ReentrantLock();
  readLock = new ReadLock();
  writeLock = new WriteLock();
  condition = lock.newCondition();
```

No initial readers

SimpleReadWriteLock

```
public SimpleReadWriteLock() {
  writer = false;
  readers = 0;
  lock = new ReentrantLock();
  readLock = new ReadLock();
  writeLock = new WriteLock();
  condition = lock.newCondition();
```

Separate locks for readers and writers

Reader Lock

```
class ReadLock implements Lock {
  public void lock() {
     lock.lock();
     try {
          while (writer)
               condition.await();
          readers++;
     } finally {
          lock.unlock();
  }
```

Reader Lock

```
class ReadLock implements Lock {
  public void lock() {
    lock.lock();
    try {
      while (writer)
        condition.await();
      readers++;
    } finally {
      lock.unlock();
  }
```

Acquire lock

Reader Lock

```
class ReadLock implements Lock {
  public void lock() {
    lock.lock();
    try {
      while (writer)
        condition.await();
      readers++;
    } finally {
      lock.unlock();
  }
```

Suspend while there is a writer

Reader Lock

```
class ReadLock implements Lock {
  public void lock() {
     lock.lock();
     try {
        while (writer)
           condition.await();
        readers++;
     } finally {
        lock.unlock();
  }
```

Increase number of readers

Reader Lock

```
public void unlock() {
  lock.lock();
  try {
     readers--;
     if (readers == 0)
          condition.signalAll();
  } finally {
     lock.unlock();
  }
```

Acquire Lock

Reader Lock

```
public void unlock() {
  lock.lock();
  try {
    readers--;
    if (readers == 0)
        condition.signalAll();
  } finally {
    lock.unlock();
  }
```

Decrease number of readers

Reader Lock

```
public void unlock() {
  lock.lock();
  try {
    readers--;
    if (readers == 0)
        condition.signalAll();
  } finally {
    lock.unlock();
  }
```

If there are no more readers, wake the writer

Writer Lock

```
class WriteLock implements Lock {
  public void lock() {
     lock.lock();
     try {
          while (readers > 0)
               condition.await();
          writer = true;
     } finally {
          lock.unlock();
  }
```

Writer Lock

```
public void unlock() {
  writer = false;
  condition.signalAll();
}
```

Readers-Writers Lock

- The SimpleReadWriteLock is correct, but is it fair?
- If readers are much more frequent than writers, the writers can be locked out for a long time

Fair Readers-Writers Lock

- A fair implementation would imply that no readers are allowed to acquire the lock after the writer has acquired it

FIFOReadWriteLock

```
public class FIFOReadWriteLock
  implements ReadWriteLock {
  boolean writer;
  int readAcquires, readReleases;
  Lock lock;
  Condition condition;
  Lock readLock, writeLock;
```

FIFOReadWriteLock

```
public class FIFOReadWriteLock
  implements ReadWriteLock {
  boolean writer;
  int readAcquires, readReleases;
  Lock lock;
  Condition condition;
  Lock readLock, writeLock;
```

Number of readers that have acquired the lock

FIFOReadWriteLock

```
public class FIFOReadWriteLock
  implements ReadWriteLock {
  boolean writer;
  int readAcquires, readReleases;
  Lock lock;
  Condition condition;
  Lock readLock, writeLock;
```

Number of readers that have released the lock

FIFO Reader Lock

```
class ReadLock implements Lock {
  public void lock() {
     lock.lock();
     try {
         while (writer)
              condition.await();
         readAcquires++;
     } finally {
         lock.unlock();
  }
```

FIFO Reader Lock

```
public void unlock() {
  lock.lock();
  try {
     readReleases++;
     if (readAcquires == readReleases)
          condition.signalAll();
  } finally {
     lock.unlock();
  }
```

FIFO Reader Lock

```
public void unlock() {
  lock.lock();
  try {
     readReleases++;
     if (readAcquires == readReleases)
         condition.signalAll();
  } finally {
     lock.unlock();
  }
```

If all the readers that have acquired the lock released the lock

FIFO Writer Lock

```
class WriteLock implements Lock {
  public void lock() {
     lock.lock();
     try {
          writer = true;
          while (readAcquires !=
          readReleases)
               condition.await();
     } finally {
          lock.unlock();
  }
```

FIFO Writer Lock

```
public void unlock() {
  writer = false;
  condition.signalAll();
}
```

Locks

- Using the locks described in Chapter 2 and 7, a thread that attempts to reacquire a lock it already holds will deadlock with itself
- This situation can arise if a method that acquires a lock makes a nested call to another method that acquires the same lock

ReentrantLock

- A lock is reentrant if it can be acquired multiple times by the same thread
- java.util.concurrent.locks package provides ReentrantLocks

ReentrantLock

- A ReentrantLock is owned by the last thread who successfully locked it, but not yet unlocked it
- A thread will successfully hold the lock when the lock is not owned by another thread
- The lock will return immediately if the current thread already holds the lock

Our own ReentrantLock

```
public class SimpleReentrantLock
  implements Lock {
  Lock lock;
  Condition condition;
  int owner;
  int holdCount;
…
```

Our own ReentrantLock

```
public class SimpleReentrantLock
  implements Lock {
  Lock lock;
  Condition condition;
  int owner;
  int holdCount;
…
```

The ID of the last thread to acquire the lock

Our own ReentrantLock

```
public class SimpleReentrantLock
  implements Lock {
  Lock lock;
  Condition condition;
  int owner;
  int holdCount;
…
```

Incremented each time lock is acquired

Our own ReentrantLock

```
public void lock() {
  int me = ThreadID.get();
  lock.lock();
  if (owner == me) {
     holdCount++;
     return;
  }
  while (holdCount != 0)
     condition.await;
  owner = me;
  holdCount = 1;
```

Our own ReentrantLock

```
public void lock() {
  int me = ThreadID.get();
  lock.lock();
  if (owner == me) {
     holdCount++;
     return;
  }
  while (holdCount != 0)
     condition.await;
  owner = me;
  holdCount = 1;
```

Do I already hold the lock? - then I can access the lock

Our own ReentrantLock

```
public void lock() {
  int me = ThreadID.get();
  lock.lock();
  if (owner == me) {
     holdCount++;
     return;
  }
  while (holdCount != 0)
     condition.await;
  owner = me;
  holdCount = 1;
```

Otherwise, if the holdCount it not 0 then another thread is holding the lock

Our own ReentrantLock

```
public void unlock() {
  lock.lock();
  try {
     if (holdCount == 0 | owner !=
     ThreadID.get())
          throw new
          IllegalMonitorStateException();
     holdCount--;
     if (holdCount == 0)
          condition.signal();
  } finally {
     lock.unlock();
```

You cannot unlock a lock that is not yours

Mutual exclusion locks

- A mutual exclusion lock guarantees that only one thread can enter the critical section
- If another thread wants to enter the critical section while it is occupied, it suspends itself until the other thread notifies it to try again

Semaphore

- A generalization of a mutual exclusion lock
- Instead of allowing only one thread into the CS, it allows at most c – where c is the capacity

Semaphore

```
public class Semaphore {
  Lock lock;
  Condition condition;
  int capacity;
  int state;
…
```

The max amount of threads allowed in the CS

Semaphore

```
public class Semaphore {
  Lock lock;
  Condition condition;
  int capacity;
  int state;
…
```

The current number of threads in the CS

Semaphores

```
public void lock() {
  lock.lock();
  try {
     while (state == capacity)
           condition.await;
     state++;
  } finally {
     lock.unlock();
}
```

Semaphores

```
public void unlock() {
  lock.lock();
  try {
     state--;
     condition.signalAll();
  } finally {
     lock.unlock();
}
```