Monitors

CS511

Review

- We've seen that semaphores are an efficient tool to solve synchronization problems
- However, they have some drawbacks
  1. They are low-level constructs
     - It is easy to forget an acquire or release
  2. They are not related to the data
     - They can appear in any part of the code

Monitors

- Combines ADTs and mutual exclusion
  - Proposed by Tony Hoare:

  Monitors: An Operating System Structuring Concept (Communications of the ACM, 17(10), 549-557, 1974).

- Adopted in many modern PLs
  - Java
  - C#
  - Python
  - Ruby

Main Ingredients

- A set of operations encapsulated in modules
- A unique lock that ensures mutual exclusion to all operations in the monitor
- Special variables called condition variables, that are used to program conditional synchronization

Counter Example

- Construct a counter with two operations:
  - inc()
  - dec()
- No two threads should be able to simultaneously modify the value of the counter
  - Think of a solution using semaphores
  - A solution using monitors

Counter using Semaphores

```java
class Counter {
  private int c = 0;
  private Semaphore mutex = new Semaphore(1);

  public void inc() {
     mutex.acquire();
     c++;
     mutex.release();
  }
  public void dec() {
     mutex.acquire();
     c--;
     mutex.release();
  }
}
```

Counter using Monitors

```
class Counter {

  private int counter = 0;

  public synchronized void inc() {
    counter++;
  }

  public synchronized void dec() {
    counter--;
  }

}
```

- Each object has its own lock called intrinsic or monitor lock
- It also has its own wait-set for this lock (more on this later)
- This code is both Groovy and Java code

Counter as Monitor in Groovy – Continued

```
Counter c = new Counter()

P = Thread.start {
    10.times {
        c.inc()
    }
}

Q = Thread.start {
    10.times {
        c.inc()
    }
}

P.join()
Q.join()
println c.counter
```

Condition Variables

- Apart from the lock, there are condition variables associated to the monitor
  - Built-in: called a wait set and associated to the intrinsic lock
  - User-declared
- They have
  1. Three operations:
     - `Cond.wait()/await()`
     - `Cond.notify()/signal()`
     - `Cond.notifyAll()/signalAll()`
  2. A set of blocked processes.

Condition Variables

`Cond.wait()/await()`

- Always blocks the process and places it in the waiting set of the variable `Cond`.
- When it blocks, it releases the mutex on the monitor.

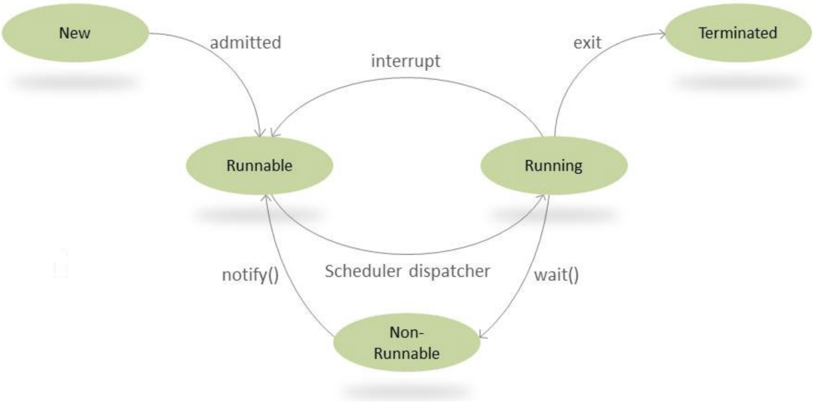
`Cond.notify()/signal()`

- Unblocks the first process in the waiting set of the variable `Cond` and sets it to the RUNNABLE state
- If there are no processes in the waiting set, it has no effect.

`Cond.notifyAll()/signalAll()`

- Unblocks all the processes in the waiting set of the variable `Cond` and sets them to the RUNNABLE state
- If there are no processes in the waiting set, it has no effect.

Condition Variables[1]



[1]Source: https://www.baeldung.com/java-wait-notify

Example: Buffer of Size 1 in Groovy

```
class Buffer {
  Object buffer = null; // shared buffer

  synchronized Object consume() {
    while (buffer == null)
      wait(); // wait on object's wait-set
    Object aux = buffer;
    buffer = null;
    notifyAll(); // signal on object's wait-set
    return aux;
  }

  synchronized void produce(Object o) {
   while (buffer != null)
      wait(); // wait on object's wait-set
    buffer = o;
    notifyAll(); // signal on object's wait-set
  }
}
```

- `wait`, `notify` and `notifyAll` must be called from synchronized methods or else an `IllegalMonitorStateException` is raised

Example: Buffer of Size 1 in Groovy (cont)

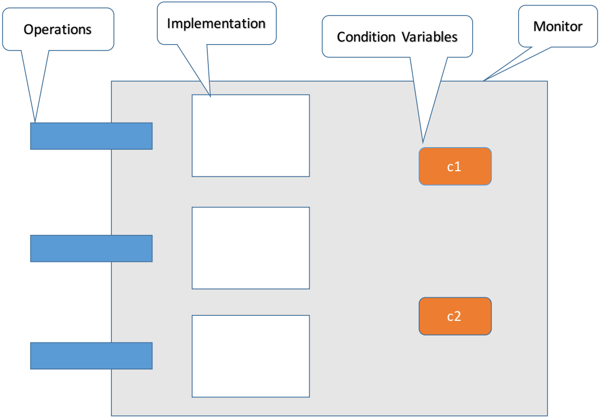
```
Buffer b =new Buffer();

20.times {
   int id=it
   Thread.start {
     println "consumer "+ b.consume();
   }
}

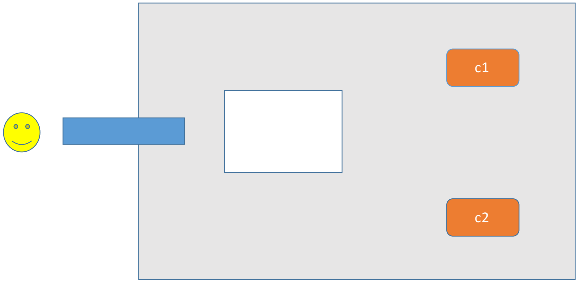
20.times {
    int id=it
    Thread.start {
      b.produce(id);
  }
}

return ;
```

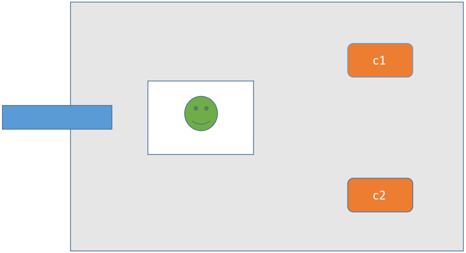
Explaining Monitors Graphically



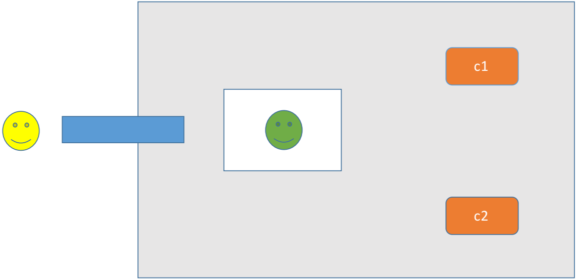
Typical Behavior



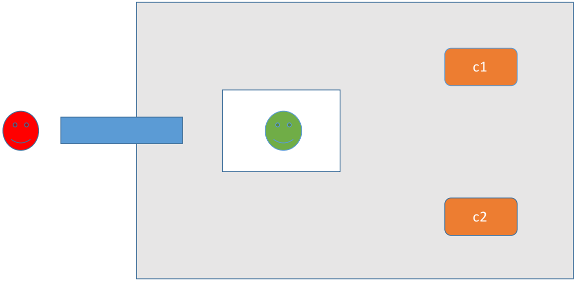
Typical Behavior



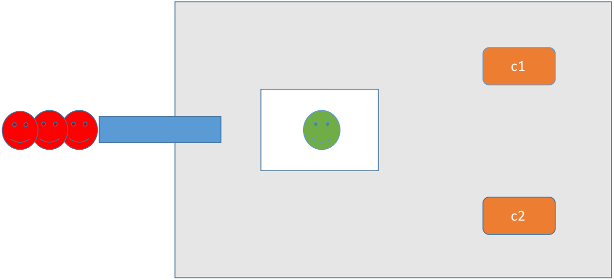
Typical Behavior



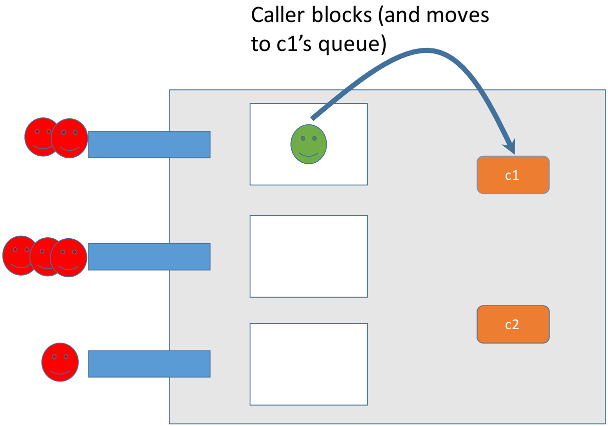
Typical Behavior



Typical Behavior

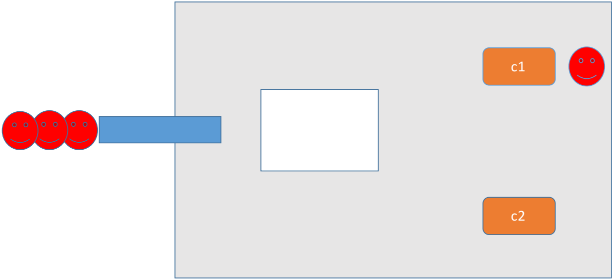


Wait



- Blocks process currently executing and associates it to variable's waiting set
- Upon blocking frees the lock allowing the entry of other processes

Wait



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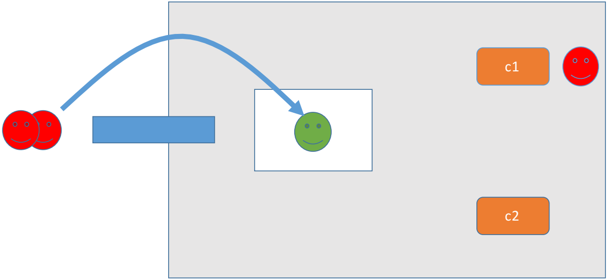
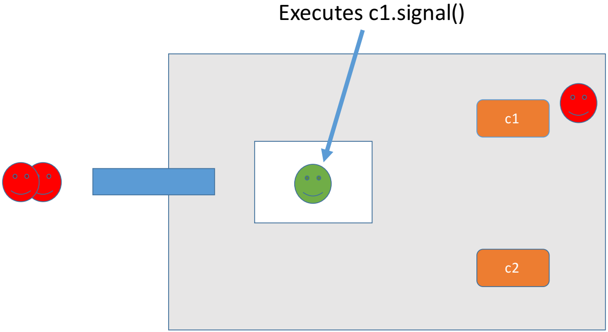
- Upon blocking frees the lock allowing the entry of other processes

Wait



- Blocks process currently executing and associates it to variable's waiting set
- Upon blocking frees the lock allowing the entry of other processes

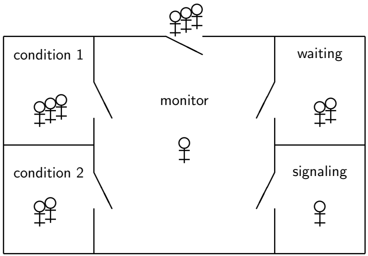
Signal



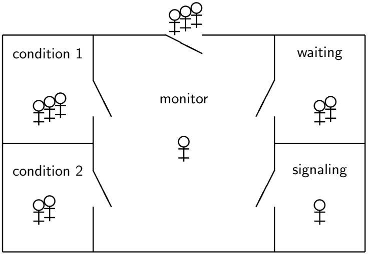
- Signalling process continues to execute after notifying on `c1`?
- Processes waiting in `c1`'s waiting-set start immediately running inside the monitor?
- What about the processes blocked on entry to the monitor?

Signal – States That a Process Can Be In

- Waiting to enter the monitor
- Executing within the monitor (only one)
- Blocked on condition variables
- Set of processes just released from waiting on a condition variable
- Set of processes that have just completed a `signal` operation



Notify



Two strategies:

- Signal and Urgent Wait: $E < S < W$ (classical monitors)
- Signal and Continue: $E = W < S$ (Java $\Leftarrow$ We adopt this)

where the letters denote the precedence of

- S: signalling processes
- W: waiting processes
- E: processes blocked on entry

Buffer of Size 1 in Groovy - Discussion

```
class Buffer {
  Object buffer = null; // shared buffer

  synchronized Object consume() {
    while (buffer == null)
      wait(); // wait on object's wait-set
    Object aux = buffer;
    buffer = null;
    notifyAll(); // signal on object's wait-set
    return aux;
  }

  synchronized void produce(Object o) {
   while (buffer != null)
      wait(); // wait on object's wait-set
    buffer = o;
    notifyAll(); // signal on object's wait-set
  }
}
```

Buffer of Size 1 in Groovy - Discussion

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class Buffer {
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    return aux;
  }

  synchronized void produce(Object o) {
   while (buffer != null)
      wait(); // wait on object's wait-set
    buffer = o;
    notify(); // signal on object's wait-set
  }
}
```

- What goes wrong and why?

Monitor that Defines a Semaphore

```java
class Semaphore {

  private int permissions;

  Semaphore(int n) {
    this.permissions = n;
  }

  synchronized void acquire() {
    while (permissions == 0)
      wait();
    permissions--;
  }

  synchronized void release() {
    permissions++;
    notifyAll();
  }

}
```

Monitor that Defines a Semaphore

```
c=0;
Semaphore mutex = new Semaphore(1);

P = Thread.start {
            20.times{
                mutex.acquire();
                c++;
                mutex.release();
            }
        }

Q = Thread.start {
        20.times {
            mutex.acquire();
            c++;
            mutex.release();
        }
    }

P.join();
Q.join();
println c;
```

Signal and Continue

- Must re-check the condition since may have gained entry long after it was notified

```
synchronized void acquire() {
    while (permissions == 0)
        nonZero.wait();
    permissions--;
}
```

Another reason for re-checking the condition:

- Spurious wakeups: "Implementations are permitted, although not encouraged, to perform "spurious wake-ups", that is, to remove threads from wait sets and thus enable resumption without explicit instructions to do so."[2]

[2] JLS for Java SE 17 (page 740). https://docs.oracle.com/javase/specs/jls/se17/jls17.pdf

Signal and Continue

```java
class Semaphore {
  private int permissions;

  Semaphore(int n) {
    this.permissions = n;
  }

  synchronized void acquire() {
    while (permissions == 0)
      wait();
    permissions--;
  }

  synchronized void release() {
    permissions++;
    notifyAll();
  }

}
```

- Is it fair?
- See *Specific Notification for Java Thread Synchronization* by Tom Cargill, 1996.[3]

[3] http://www.dre.vanderbilt.edu/%7Eschmidt/PDF/specific-notification.pdf

Buffer of Size 1 in Groovy - Discussion

```
class Buffer {
  Object buffer = null; // shared buffer

  synchronized Object consume() {
    while (buffer == null)
      wait(); // wait on object's wait-set
    Object aux = buffer;
    buffer = null;
    notifyAll(); // signal on object's wait-set
    return aux;
  }

  synchronized void produce(Object o) {
   while (buffer != null)
      wait(); // wait on object's wait-set
    buffer = o;
    notifyAll(); // signal on object's wait-set
  }
}
```

- Inefficient
- Much more efficient (and clearer) to have multiple wait-sets

Condition Variables

```java
import java.util.concurrent.locks.*;

class Buffer {
    Object buffer = null; // shared buffer
    final Lock lock = new ReentrantLock();
    final Condition empty = lock.newCondition();
    final Condition full = lock.newCondition();

    Object consume() {
        lock.lock();
        try {
            while (buffer == null)
                full.await();
            Object aux = buffer;
            buffer = null;
            empty.signal();
            return aux;
        } finally {
            lock.unlock();
        }
    }

    // continues in next slide
}
```

Condition Variables

```java
    void produce(Object o) {
        lock.lock();
        try {
            while (buffer != null)
                empty.await();
            buffer = o;
            full.signal();
        } finally {
            lock.unlock();
        }
    }
}
```

Condition Variables

```
Buffer b =new Buffer();


20.times {
     int id=it
     Thread.start {
          println "consumer "+ b.consume();
     }
}


20.times {
     int id=it
     Thread.start {
          b.produce(id);
     }
}



return ;
```

Buffer of Size *n*

```
import java.util.concurrent.locks.*;
class PC {
    private Integer[] data;
    private int begin = 0;
    private int end = 0;
    private final int N;
    final Lock lock = new ReentrantLock();
    final Condition notEmpty =  lock.newCondition();
    final Condition notFull =  lock.newCondition();


    public PC(int size) {
        this.N=size;
        data= new Integer[N];
    }

    public void produce(Integer o) {
        lock.lock();
        try {
            while (isFull()) {
                notFull.await();
            }
            println "Buffer size "+begin-end
            data[begin] = o;
            begin = (begin+1) % N;
            notEmpty.signal()
```

Buffer of Size *n*

```java

    public Integer consume() {
        lock.lock();
        try {
            while (isEmpty()) {
                notEmpty.await();
            }
            Integer result = data[end];
            end = (end+1) % N
            notFull.signal();
            return result;
        } finally {
            lock.unlock();
        }
    }

    private boolean isEmpty() { return begin == end; }
    private boolean isFull()  { return ((begin+1)%N) == end; }
}
```

Readers/Writers

```
monitor RW {
  ...

  public void read() {
    ...
  }

  public void write() {
    ...
  }

}
```

What is the problem with this setting?

Readers/Writers

```
monitor RW {
  int readers = 0;
  int writers = 0;
  condition OKtoRead, OKtoWrite;

  public void StartRead() {
    while (writers != 0 or not OKtoWrite.empty()) {
      OKtoRead.wait();
    }
    readers = readers + 1;
  }

  public void EndRead {
    readers = readers - 1;
    if (readers==0) {
      OKtoWrite.notify();
    }
  }
  // continues
```

Readers/Writers

```
  public void StartWrite() {
    while (writers != 0 or readers != 0) {
      OKtoWrite.wait();
    }
    writers = writers + 1;
  }

  public void EndWrite() {
    writers = writers - 1;
    OKtoWrite.signal();
    OKtoRead.signalAll();
   }
}
```

Assessment

- Upholds the readers-writers invariant.
- However, it gives priority to readers over writers:
  - new readers can enter the monitor without waiting as long as a reader is active
  - waiting writers have to wait until the last reader calls endRead and signals OKtoWrite
  - as long as readers keep arriving and waiting to enter the monitor, the waiting writers will never execute

Dining Philosophers

```
monitor ForkMonitor {
  int[] fork = {2,2,2,2,2};
  condition[] OKtoEat; // 0-4

  public void takeForks(integer i) {
    while (fork[i] != 2) {
        OKtoEat[i].wait();
    }
    fork[i+1] = fork[i+1] - 1;
    fork[i-1] = fork[i-1] - 1;
  }

  public void releaseForks(integer i) {
    fork[i+1] = fork[i+1] + 1;
    fork[i-1] = fork[i-1] + 1;
    if (fork[i+1] == 2) {
      OKtoEat[i+1].signal();
    }
    if (fork[i-1] == 2) {
      OKtoEat[i-1].signal();
    }
  }
}
```

`forks[i]` is number of forks available to philosopher *i*

Visibility

- Whether a thread can see the modifications of other threads
- Visibility is subtle because the compiler may
  - Reorder operations
  - Cache values in registers
- `synchronization`, used for atomicity, helps with visibility too:
  - All changes made in one synchronized method or block are visible with respect to other synchronized methods and blocks employing the same lock.

Volatile Variables

```
int n=0;
```

```
Thread.start { // P
  int local1, local2;
  n = some expression;
  computation not using n;
  local1 = (n+5)*7;
  local2 = n+5;
  n = local1 *  local2;
}
```

```
Thread.start { // Q
  int local;
  local = n+6;




}
```

The instruction in Q may be interleaved at any place during the execution of the instructions in P

Volatile Variables

An optimizing compiler could translate statements in thread P as:

```
tempReg1 = some expression
computation not using n
tempReg2 = tempReg1 + 5
local2 = tempReg2
local1 = tempReg2 * 7
n = local1 * local2
```

```
n = some expression;
computation not using n;
local1 = (n+5)*7;
local2 = n+5;
n = local1 *  local2;
.
```

- No assignment to n in the first statement. Original statements p3 and p4 are executed out of order
- Without concurrency, the translated code would be correct
- With concurrency and interleaving, the translated code may no longer be correct
- Specifying a variable as volatile instructs the compiler to load and store the value of the variable at each use, rather than to optimize away these loads and stores.

Example 1[4]

```java
public class SharedVariable {
   private static int  sharedVariable = 0;
   public static void main(String[] args) throws InterruptedExcept

   new Thread(new Runnable() {
      @Override
      public void run() {
         try { Thread.sleep(100); }
         catch (InterruptedException e) {
                e.printStackTrace();
         }
         sharedVariable = 1;
      }}).start();

   for(int i=0;i<1000;i++) {
      for(;;) {
         if(sharedVariable == 1) { break; }
      }
   }
   System.out.println("SharedVariable : " + sharedVariable);
   }
}
```

Try this code as is (loops due to compiler optimization), then add the qualified volatile to the declaration of `sharedVariable` and run

Example 2

```java
public class NoVisibility {
    private static boolean ready;
    private static int number;

    private static class ReaderThread extends Thread {
        public void run() {
            while (!ready)
                Thread.yield();
            System.out.println(number);
        }
    }

    public static void main(String[] args) {
        new ReaderThread().start();
        number = 42;
        ready = true;
    }
}
```

- `java.lang.Thread.yield()` causes the currently executing thread object to temporarily pause and allow other threads to execute
- What is the output?

Example 2

```java
public class NoVisibility {
    private static boolean ready;
    private static int number;

    private static class ReaderThread extends Thread {
        public void run() {
            while (!ready)
                Thread.yield();
            System.out.println(number);
        }
    }

    public static void main(String[] args) {
        new ReaderThread().start();
        number = 42;
        ready = true;
    }
}
```

- `java.lang.Thread.yield()` causes the currently executing thread object to temporarily pause and allow other threads to execute
- What is the output? Could loop forever or print 0!

Explicit Locks

- Apart from the intrinsic lock of an object, one can use explicit locks
- This is convenient for modeling condition variables
- We next present the `Lock` interface and the class `ReentrantLock` that implements it

Explicit Locks – An Example

- We take a look at the producers/consumers example
- We present two implementations:
  - Using intrinsic locks
  - Using explicit locks
- Source: Goetz's *Java Concurrency in Practice*, Addison-Wesley, 2006

Bounded Buffers Revisited

```java
public abstract class BaseBoundedBuffer <V> {
    private final V[] buf;
    private int tail;
    private int head;
    private int count;

    protected BaseBoundedBuffer(int capacity) {
        this.buf = (V[]) new Object[capacity];
    }

    protected synchronized final void doPut(V v) {
        buf[tail] = v;
        if (++tail == buf.length)
            tail = 0;
        ++count;
    }

   // continued
```

Bounded Buffers Revisited

```java

    protected synchronized final V doTake() {
        V v = buf[head];
        buf[head] = null;
        if (++head == buf.length)
            head = 0;
        --count;
        return v;
    }

    public synchronized final boolean isFull() {
        return count == buf.length;
    }

    public synchronized final boolean isEmpty() {
        return count == 0;
    }
}
```

Crude Blocking

```java
public class BoundedBuffer <V> extends BaseBoundedBuffer<V> {
    // CONDITION PREDICATE: not-full (!isFull())
    // CONDITION PREDICATE: not-empty (!isEmpty())
    public BoundedBuffer() {
        this(100);
    }

    public BoundedBuffer(int size) {
        super(size);
    }

    // BLOCKS-UNTIL: not-full
    public synchronized void put(V v) throws InterruptedException
        while (isFull())
            wait();
        doPut(v);
        notifyAll();
    }
    // continues
```

Crude Blocking

```
    // BLOCKS-UNTIL: not-empty
    public synchronized V take() throws InterruptedException {
        while (isEmpty())
            wait();
        V v = doTake();
        notifyAll();
        return v;
    }

    // BLOCKS-UNTIL: not-full
    // Alternate form of put() using conditional notification
    public synchronized void alternatePut(V v) throws InterruptedE
        while (isFull())
            wait();
        boolean wasEmpty = isEmpty();
        doPut(v);
        if (wasEmpty)
            notifyAll();
    }
}
```

Lock Interface

```java
public interface Lock {
 void lock();                   // Acquires the lock.
 void lockInterruptibly() throws InterruptedException;
                                // Acquires the lock unless
                                // the current thread is interrupted.
 boolean tryLock();             // Acquires the lock only if it is
                                // free at the time of invocation.
 boolean tryLock(long time, TimeUnit unit)
   throws InterruptedException; // Acquires the lock if it
        // is free within the given waiting time
        // and the current thread has not been interrupted.
 void unlock();                 // Releases the lock.
 Condition newCondition();      // Returns a new Condition instance
                                // that is bound to this Lock instance.
}
```

Using Locks

```java
Lock l = new ReentrantLock();
l.lock();
try {
    // access the resource protected by this lock
} finally {
    l.unlock();
}
```

Using Condition Interface

```java
public interface Condition {
  void await(); // Causes the current thread to wait until
                // it is signalled or interrupted.
  boolean await(long time, TimeUnit unit);
  long awaitNanos(long nanosTimeout);
  void awaitUninterruptibly();
  boolean awaitUntil(Date deadline);

  void signal();    // Wakes up one waiting thread.
  void signalAll(); // Wakes up all waiting threads.
}
```

- In condition objects we replace wait, notify and notifyAll by await, signal and signalAll

Using Condition Interface

```java
public class ConditionBoundedBuffer <T> {
    protected final Lock lock = new ReentrantLock();
    private final Condition notFull = lock.newCondition();
    private final Condition notEmpty = lock.newCondition();
    private static final int BUFFER_SIZE = 100;
    private final T[] items = (T[]) new Object[BUFFER_SIZE];
    private int tail, head, count;

    // BLOCKS-UNTIL: notFull
    public void put(T x) throws InterruptedException {
        lock.lock();
        try {
            while (count == items.length)
                notFull.await();
            items[tail] = x;
            if (++tail == items.length)
                tail = 0;
            ++count;
            notEmpty.signal();
        } finally {
            lock.unlock();
        }
    }
    // continues
```

Using Condition Interface

```
    // BLOCKS-UNTIL: notEmpty
    public T take() throws InterruptedException {
        lock.lock();
        try {
            while (count == 0)
                notEmpty.await();
            T x = items[head];
            items[head] = null;
            if (++head == items.length)
                head = 0;
            --count;
            notFull.signal();
            return x;
        } finally {
            lock.unlock();
        }
    }
}
```