ID2212 Network Programming with Java
Lecture 3

Multithreading with Java

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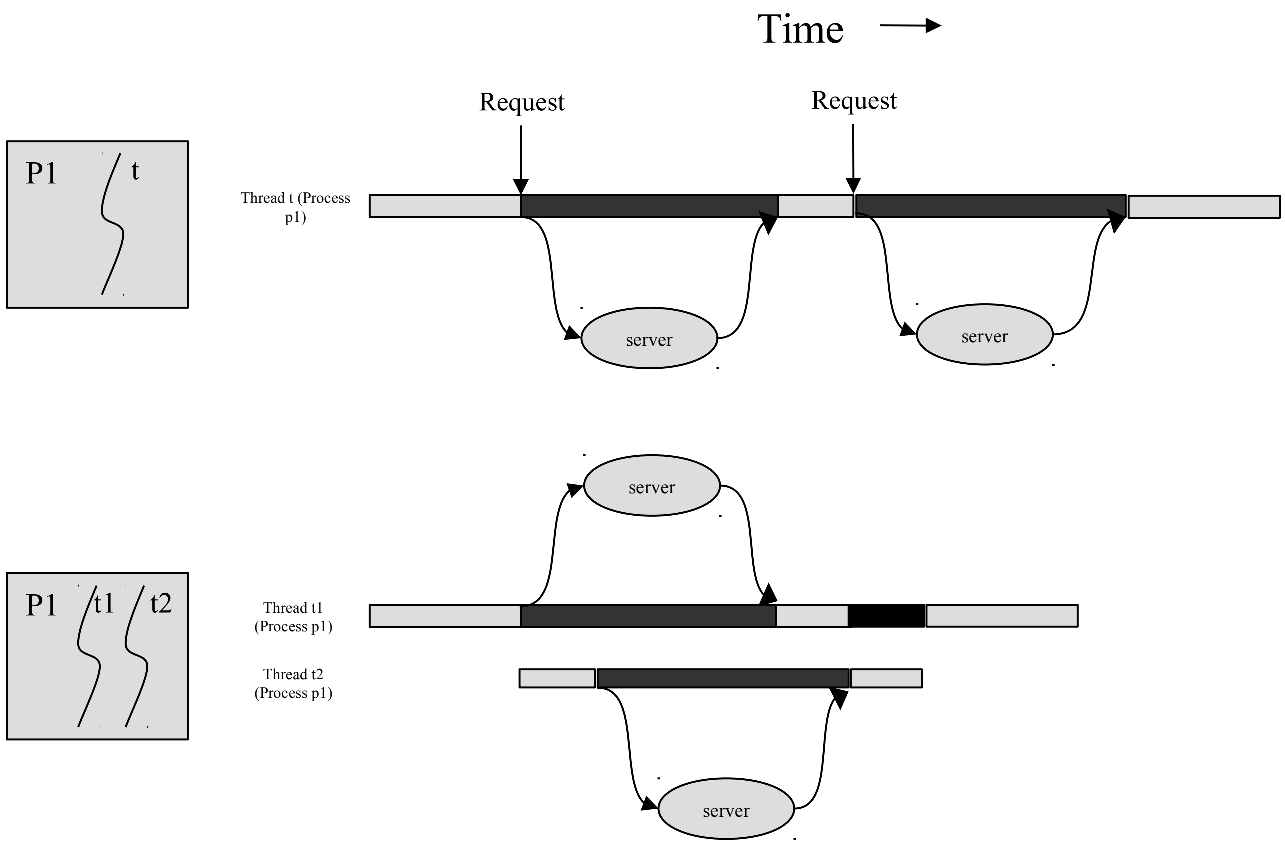
Outline

- Introduction to threads
- Multithreading with Java
  - `Thread` class and `Runnable` interface
  - Two ways of creating threads
- Java thread synchronization
  - `synchronized` methods and blocks
  - Shared objects as monitors; Bounded buffer (consumer-producer) example
- Concurrent utilities
  - Locks and Conditions;
  - The Executor framework; Example of using a thread pool
  - Synchronizers; Atomic variables; Concurrent collections
- Further reading: http://docs.oracle.com/javase/tutorial/essential/concurrency/

Process and Thread (1/2)

- **Process**: A unit of activity characterized by a sequence of instructions, a current state and an associated set of system resources
- **Thread**: A path of execution in a process characterized by an execution state, execution stack and local variables

Process and Thread (2/2)



General Benefits of Using Threads

- **Creating** threads takes less time
- **Terminating** threads takes less time
- **Switching** between threads takes less time
- Threads in a process can **communicate** to each other without interference of kernel

Multithreading in a Distributed Application

- Multiple threads in a client-server application (request-response interaction)
- Client side
  - Multithreading to hide communication latency
  - Responsive user interface
  - Typically two threads: one to interact with the user via (G)UI; another to interact with the server e.g. over TCP socket connection
  - The (G)UI thread communicates user's control actions and input to the communication thread through e.g. shared buffers or by method invocations on the communication thread object, e.g. to stop it
  - Communication thread passes server responses to the (G)UI thread by GUI call-backs (method invocations) or/and through shared buffers.
  - Access to shared buffers should be synchronized

Multithreading in a Distributed Application (cont'd)

- Server side
  - Multithreading for scalability and, as a consequence, for better performance (higher throughput)
  - One thread (the main thread) listens on the server port for client connection requests and assigns (creates) a thread for each client connected
  - Each client is served in its own thread on the server
  - The listening thread should provide client information (e.g. at least the connected socket) to the servicing thread
  - Typically servicing threads are independant, but might access shared resources, e.g. database, and therefore might need to be synchronized.

Multithreading in Java

- ***A Java thread*** is a light-weight process represented by an object of the **`Thread`** (sub)class that includes **`start`** and **`run`** methods
  - Stack and PC (Program Counter) register
  - Accesses all variables in its scope
- Each thread has a method **`void run()`**
  - Executes when the thread starts
  - Thread vanishes when it returns
  - You must implement this method
- Classes for multithreading:
  - **`public class Thread`**
  - **`public class ThreadGroup`**
  - **`public interface Runnable`**

First Way to Program and Create a Java Thread

1. Extend the **`Thread`** class
   - Override the **`run`** method and define other methods if needed;
   - Create and start a thread:
     - Instantiate the **`Thread`** subclass;
     - Call the **`start`** method on the thread object – creates a thread context and invokes **`run`** to be executed in a separate thread

Another Way to Program and Create Java Threads

2. Implement the **`Runnable`** interface in a class that represents a class of ***tasks*** to be execute in threads
   - Implement the **`run`** method;
   - Create and start a thread with the **`Runnable`** object, i.e. the thread is given a **`Runnable`** task to execute
     2. Create a **`Runnable`** object;
     3. Create a thread to execute that task by passing the **`Runnable`** object to a **`Thread`** constructor
     4. Call the **`start`** method on the thread object to start the thread.

Thread Class and Runnable Interface

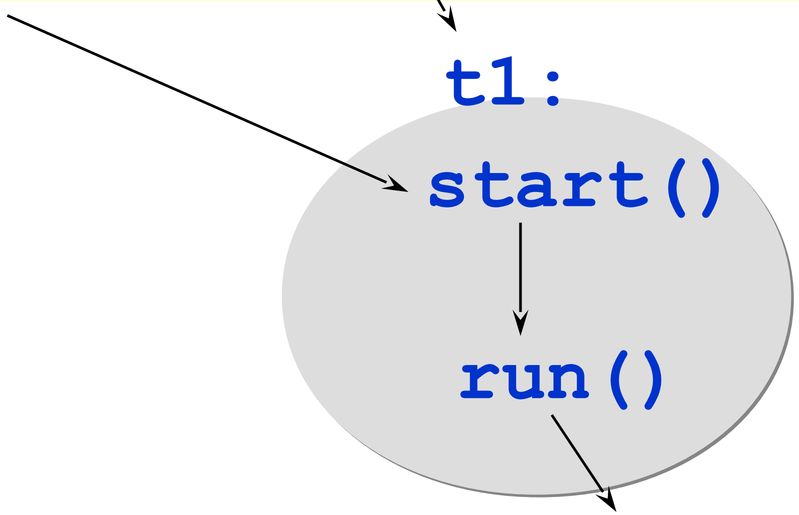
```
public class Thread extends Object implements Runnable {
    public Thread();
    public Thread(Runnable target);
    public Thread(String name);
    public Thread(Runnable target, String name);
      ...
    public synchronized native void start();
    public void run();
      ...
  }
public interface Runnable{
  public void run();
}
```

Example 1: Extending **`Thread`**

```
public class RunThreads {
   public static void main(String[] args) {
     OutputThread t1 = new OutputThread("One");
     OutputThread t2 = new OutputThread("Two");
     t1.start();
     t2.start();
   }
}
class OutputThread extends Thread {
   OutputThread(String name){ super(name); }
   public void run() {
   for (int i = 0; i < 3; i++) {
   System.out.println(getName());
   yield();
   }
   }
}
```

Starting a Thread

```
OutputThread t1 = new OutputThread("One");
t1.start();
```




```
for (int i = 0; i < 3; i++) {
   System.out.println(getName());
   yield();
}
```

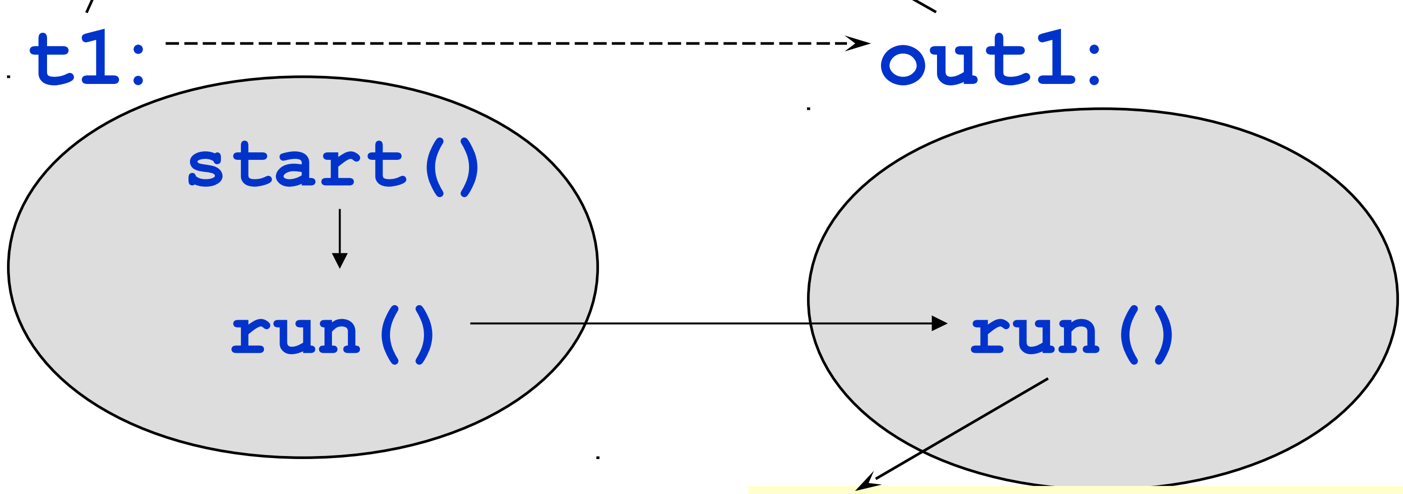
Example 2. Implementing **Runnable**

```
public class RunThreads1 {
   public static void main(String[] args) {
   OutputClass out1 = new OutputClass("One");
   OutputClass out2 = new OutputClass("Two");
   Thread t1 = new Thread(out1);
   Thread t2 = new Thread(out2);
   t1.start();
   t2.start();
   }
}
class OutputClass implements Runnable {
   String name;
   OutputClass(String s) {
   name = s;
   }
   public void run() {
   for ( int i=0; i<3; i++ ) {
   System.out.println(name);
   Thread.currentThread().yield();
   }
   }
}
```

Runnable interface

Thread with a **Runnable** Task

```
OutputClass out1 = new OutputClass("One");
Thread t1 = new Thread(out1);
t1.start();
```




```
for ( int i=0; i<3; i++ ) {
    System.out.println(name);
    yield();
}
```

Starting a Thread

```
t.start();
```

- Starts the new thread
- Caller returns immediately
- Caller & thread run in parallel

Joining a Thread

- What if you want to wait for a thread to finish?

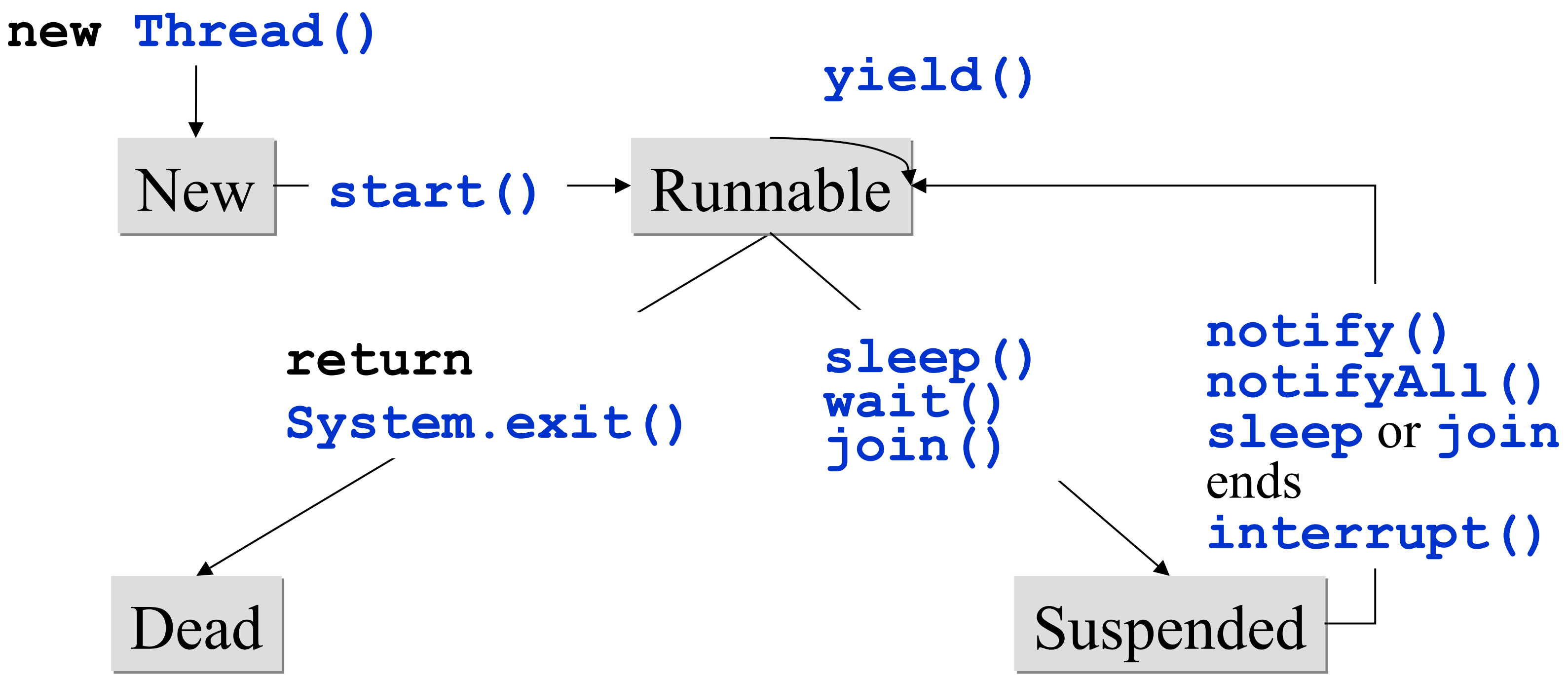
```
t.join();
```

- Blocks the caller
- Waits for the thread to finish
- Returns when the thread is done

Some Methods of the **`Thread`** Class

- **`run()`**
  - Should be overridden (the code of thread is placed here), otherwise does nothing and returns;
  - Should not be invoked directly but rather calling start().
- **`start()`**
  - Start the thread; JVM invokes the run method of this thread.
- **`join()`**
  - Wait for this thread to die.
- **`yield()`**
  - Causes a context switch.
- **`sleep(long)`**
  - The thread pauses for the specified number of milliseconds.
- **`interrupt()`**
  - Interrupt this thread.
- Get / set / check thread attributes:
  - **`setPriority(int)`**, **`getPriority()`**,
  - **`setName(String)`**, **`getName()`**,
  - **`setDaemon(boolean)`**, **`isDaemon()`**

Thread State Diagram



- IO operations affect states Runnable and Suspended in the ordinary way

Thread Interactions

- Threads in Java execute concurrently – at least conceptually.
- Threads communicate
  - By calling methods and accessing variables of Thread (Runnable) objects like ordinary objects;
  - Via pipes, TCP connections;
  - **Via shared objects**.
- An object is **shared** when multiple concurrent threads invoke its methods or access its variables.

Race Condition

```
int value = 0;

public int incrementValue() {

  return ++value;

}
```

T1: read the value, get 0, add 1, so value = 1
T2: read the value, get 0, add 1, so value = 1
T1: write 1 to the field value and return 1
T2: write 1 to the field value and return 1

To avoid race condition we need to run the method **atomically**.

`synchronized` Methods and Blocks

- A shared object may have synchronized methods or code blocks to be executed with mutual exclusion
- The **`synchronized`** modifier defines mutual exclusion for an entire method or a code block

`synchronized` Methods and Blocks (cont'd)

- Each object has an **implicit lock** associated with the object
- Each object has also **one implicit condition variable** called **wait set**
- Each synchronized block requires a lock object to be explicitly indicated
- A thread must obtain the lock when calling a synchronized method or block
  - A thread may hold locks of more then one objects; nested synchronized calls are closed
- A thread may wait on and signal to the wait set

synchronized Method

```
public class ComputeMax {

   private int max = Number.MIN_VALUE;

   public synchronized int getMax(int value) {
      if (value > max) max = value;
      return max;
   }
}
```

synchronized method

synchronized Block

```
public class ComputeMax {
  private int max = Number.MIN_VALUE;

  public int getMax(int value) {
    if (value > max) {
      synchronized (this) {
        if (value > max) max = value;
      }
    }
    return max;
  }
}
```

synchronized block

Monitors in Java

- **Java monitor** is an object of a class with `synchronized` methods, which can be invoked by one thread at a time.
  - A class may contain synchronized and ordinary non-synchronized methods – the latter are executed without synchronization.
- Each monitor has an implicit **monitor lock**
- Each monitor has an implicit **condition variable** (a.k.a. **wait set**)
  - `wait()`, `notify()` and `notifyAll()` in scope of a `synchronized` method;
  - No priority wait;
  - Signal-and-Continue policy of `notify()` and `notifyAll()`

Java Synchronized Methods (1/5)

```
public class Queue<T> {

  int head = 0, tail = 0;
  T[QSIZE] items;

  public synchronized T deq() {
   while (tail – head == 0)
     this.wait();
   T result = items[head % QSIZE]; head+
+;
   this.notifyAll();
   return result;
  }
  …
}}
```

Java Synchronized Methods (2/5)

```
public class Queue<T> {

  int head = 0, tail = 0;
  T[QSIZE] items;

  public synchronized T deq() {
   while (tail – head == 0)
     this.wait();
   T result = items[head % QSIZE]; head++;
   this.notifyAll();
   return result;
  }
  …
}}
```

Each object has an implicit lock with an implicit condition

Java Synchronized Methods (3/5)

```
public class Queue<T> {

  int head = 0, tail = 0;
  T[QSIZE] items;

  public synchronized T deq() {
   while (tail – head == 0)
     this.wait();
   T result = items[head % QSIZE]; head+
+;
   this.notifyAll();
   return result;
  }
  …
}}
```

Lock on entry, unlock on return

Java Synchronized Methods (4/5)

```
public class Queue<T> {

  int head = 0, tail = 0;
  T[QSIZE] items;

  public synchronized T deq() {
   while (tail – head == 0)
     this.wait();
   T result = items[head % QSIZE]; head+
+;
   this.notifyAll();
   return result;
  }
  …
}}
```

Wait on implicit condition

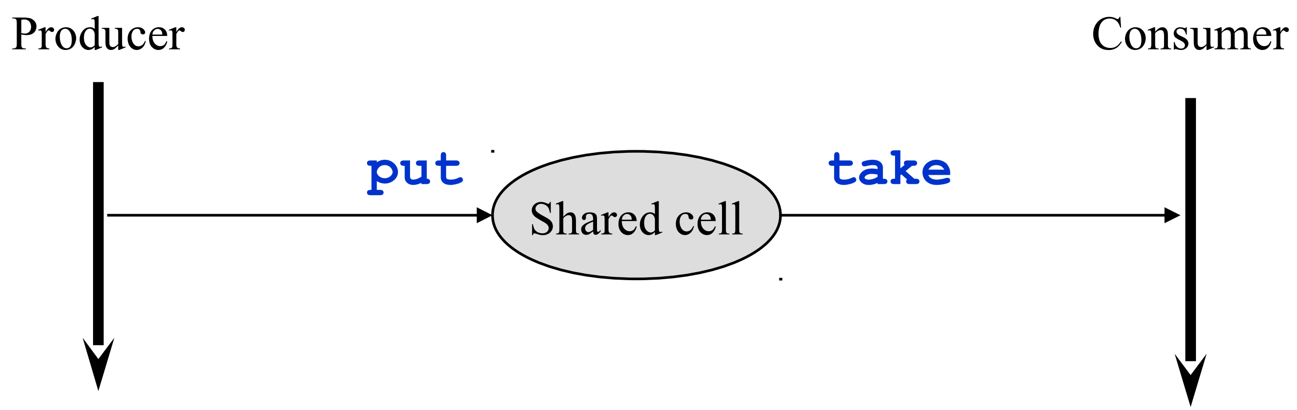
Java Synchronized Methods (5/5)

```
public class Queue<T> {

  int head = 0, tail = 0;
  T[QSIZE] items;

  public synchronized T deq() {
   while (tail – head == 0)
     this.wait();
   T result = items[head % QSIZE]; head++;
   this.notifyAll();
   return result;
  }
  …
}}
```

Signal all threads waiting on condition

Example 1: Producer/Consumer

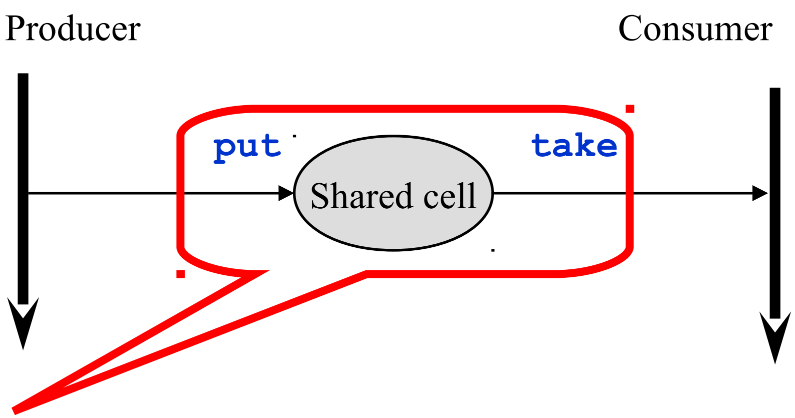
- Producer and Consumer threads are using a shared object (Shared Cell monitor) to interact in a dataflow fashion



- The "shared cell" (buffer) is a monitor
  - Methods **`put`** and **`take`** are synchronized to be executed with mutual exclusion.
  - An implicit condition variable ("wait set") is used for condition synchronization of Producer and Consumer.

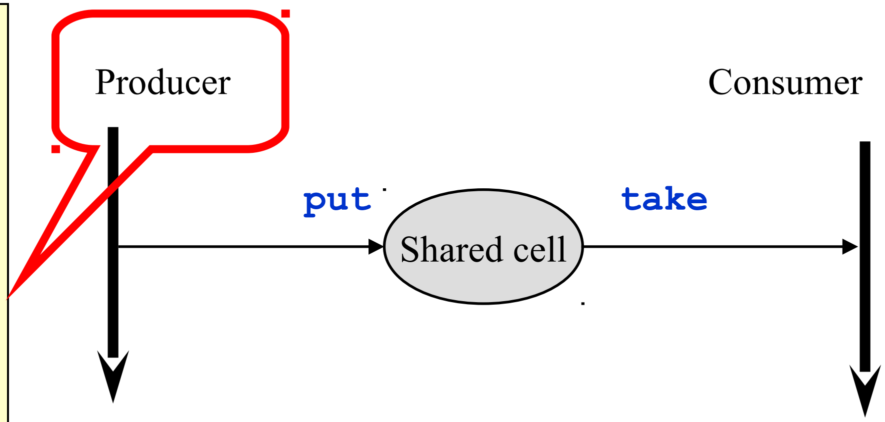
The Shared Cell Monitor

```
public class SharedCell {
  private int value;
  private boolean empty = true;
  public synchronized int take() {
    while (empty) {
      try {
        wait ();
      } catch (InterruptedException e) { }
    }
    empty = true;
    notify ();
    return value;
  }
  public synchronized void put(int value) {
    while (!empty) {
      try {
        wait ();
      } catch (InterruptedException e) { }
    }
    this.value = value;
    empty = false;
    notify ();
  }
}
```



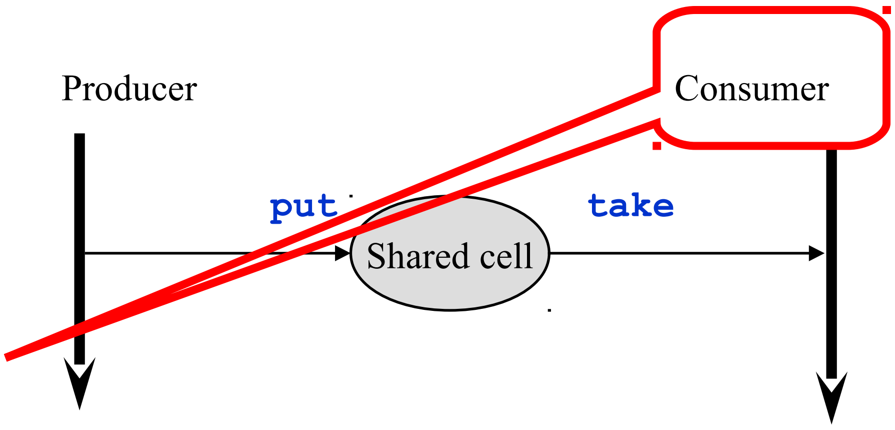
Producer Class

```
class Producer extends Thread {
  private SharedCell cell;
  private boolean Stop = false;
  public Producer (SharedCell cell) {
    this.cell = cell;
  }
  public void setStop () {
    Stop = true;
  }
  public void run () {
    int value;
    while (!Stop) {
        value = (int) (Math.random () * 100);
        cell.put (value);
        try {
          sleep (value);
        } catch (InterruptedException e) { }
     }
  }
}
```



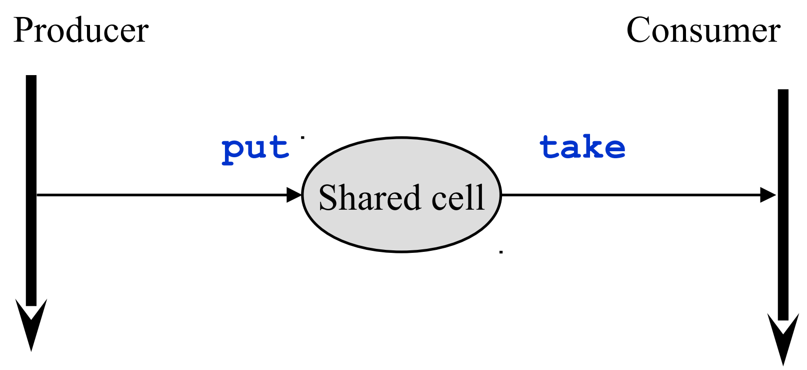
Consumer Class

```
class Consumer extends Thread {
  private SharedCell cell;
  private int n;
  public Consumer(SharedCell cell, int n)
    {
    this.cell = cell;
    this.n = n;
  }
  public void run () {
    int value;
    for (int i = 0; i < n; i++) {
      value = cell.take ();
      System.out.println ("Consumer: " +
    i + " value = " + value);
    }
  }
}
```



A Test Application

```
public class Exchange {
  public static void main(String args[])
    {
    SharedCell cell = new SharedCell ();
    Producer p = new Producer (cell);
    Consumer c = new Consumer (cell, 10);
    p.start ();
    c.start ();
    try {
      c.join ();
    } catch (InterruptedException e) { };
    p.setStop ();
    p.interrupt();
  }
}
```



Example 2: Synchronized Bounded Buffer

```
public class Bounded_Buffer {
   private Object[] items;
   private int count = 0, front = 0, rear = 0;
   private int n;

   public Bounded_Buffer(int n) {
       this.n = n;
       items = new Object[n];
   }
```

Synchronized Bounded Buffer (cont'd)

```
   public synchronized void put(Object x) {
      while (count == n)
         try { wait(); }
         catch (InterruptedException e) { }
      items[rear] = x; rear = (rear + 1) % n; count++;
      notifyAll();
   }
   public synchronized Object take() {
      while (count == 0)
         try { wait(); }
         catch (InterruptedException e) { }
      Object x = items[front];
      front = (front + 1) % n; count--;
      notifyAll();
      return x;
   }
}
```

Java Concurrency Utilities: `java.util.concurrent`

- **Locks** and **Conditions**
- **Synchronizers**
  - General purpose synchronization classes, including semaphores, mutexes, barriers, latches, and exchangers
- **The Executor framework**
  - for scheduling, execution, and control of asynchronous tasks (`Runnable` objects)
- **Nanosecond-granularity timing**
  - The actual precision of `System.nanoTime` is platform-dependent
  - Used for time-stamps and time estimates

Concurrency Utilities: (cont'd)

- **Atomic Variables**
  - Classes for atomically manipulating single variables (of primitive types and references)
  - E.g. `AtomicBoolean`, `AtomicInteger`, `AtomicLong`
  - For object references and arrays
  - E.g. `AtomicReference<V>`, `AtomicMarkableReference<V>`, `AtomicStampedReference<V>`
  - Used to implement concurrent collection classes
- **Concurrent Collections**
  - Pools of items
  - `Queue` and `BlockingQueue` interfaces
  - Concurrent implementations of `Map`, `List`, and `Queue`.

Locks and Conditions

- **`java.util.concurrent.locks`**
  - Classes and interfaces for locking and waiting for conditions
- **`ReentrantLock`** class
  - Represents a reentrant mutual exclusion lock
  - Allows to create condition variables to wait for conditions
- **`Condition`** interface
  - Represents a condition variable associated with a lock
  - Allows one thread to suspend execution (to "wait") until notified by another thread
  - The suspended thread releases the lock
- **`ReentrantLock`** locks (like **`synchronized`** objects) are monitors
  - Allow blocking on a condition rather than spinning
- Threads:
  - acquire and release lock
  - wait on a condition

The Java Lock Interface (1/5)

```
public interface Lock {
 void lock();
 void lockInterruptibly() throws
InterruptedException;
 boolean tryLock();
 boolean tryLock(long time, TimeUnit unit);
 Condition newCondition();
 void unlock;
}
```

Acquire lock

The Java Lock Interface (2/5)

```
public interface Lock {
 void lock();
 void lockInterruptibly() throws
InterruptedException;
 boolean tryLock();
 boolean tryLock(long time, TimeUnit unit);
 Condition newCondition();
 void unlock;
}
```

Release lock

The Java Lock Interface (3/5)

```
public interface Lock {
 void lock();
 void lockInterruptibly() throws
InterruptedException;
 boolean tryLock();
 boolean tryLock(long time, TimeUnit unit);
 Condition newCondition();
 void unlock;
}
```

Try for lock, but not too hard

The Java Lock Interface (4/5)

```
public interface Lock {
 void lock();
 void lockInterruptibly() throws
InterruptedException;
 boolean tryLock();
 boolean tryLock(long time, TimeUnit unit);
 Condition newCondition();
 void unlock;
}
```

Create condition to wait on

The Java Lock Interface (5/5)

```
public interface Lock {
 void lock();
 void lockInterruptibly() throws InterruptedException;
 boolean tryLock();
 boolean tryLock(long time, TimeUnit unit);
 Condition newCondition();
 void unlock;
}
```

Guess what this method does?

Lock Conditions (1/4)

```
public interface Condition {
  void await();
  boolean await(long time, TimeUnit
unit);
  …
  void signal();
  void signalAll();
 }
```

Lock Conditions (2/4)

```
public interface Condition {
  void await();
  boolean await(long time, TimeUnit unit);
  …
  void signal();
  void signalAll();
 }
```

Release lock and wait on condition

Lock Conditions (3/4)

```
public interface Condition {
  void await();
  boolean await(long time, TimeUnit unit);
  …
  void signal();
  void signalAll();
 }
```

Wake up one waiting thread

Lock Conditions (4/4)

```
public interface Condition {
  void await();
  boolean await(long time, TimeUnit
unit);
  …
  void signal();
  void signalAll();
 }
```

Wake up all waiting threads

Await, Signal and Signal All

```
q.await()
```

- Releases lock associated with `q`
- Sleeps (gives up processor)
- Awakens (resumes running) when signaled by `Signal` or `SignalAll`
- Reacquires lock & returns

```
q.signal();
```

- Awakens **one** waiting thread
  - Which will reacquire lock associated with `q`

```
q.signalAll();
```

- Awakens **all** waiting threads
  - Which will each reacquire lock associated with `q`

Example 3: Lock-Based Blocking Bounded Buffer

```
public class BoundedBuffer {
  final Lock lock = new ReentrantLock();
  final Condition notFull  = lock.newCondition();
  final Condition notEmpty = lock.newCondition();
  final Object[] items;
  int rear, front, count, n;

  public BoundedBuffer(int n) {
     this.n = n;
     items = new Object[n];
  }
```

```java
  public void put(Object x) throws InterruptedException {
    lock.lock();
    try {
      while (count == n) notFull.await();
      items[rear] = x; rear = (rear + 1) % n; count++;
      notEmpty.signal();
    } finally {
      lock.unlock();
    }
  }
  public Object take() throws InterruptedException {
    lock.lock();
    try {
      while (count == 0) notEmpty.await();
      Object x = items[front];
      front = (front + 1)% n; count--;
      notFull.signal();
      return x;
    } finally {
      lock.unlock();
    }
  }
}
```

The Executor Framework

- For scheduling, execution, and control of **asynchronous tasks** in concurrent threads according to a set of execution policies
- Allows creating an executor (a pool of threads) and assigning tasks to the executor
- An **`Executor`** object executes submitted tasks
- For example:

```
Executor e =
        Executors.newFixedThreadPool(numThreads);
e.execute(new RunnableTask1());
e.execute(new RunnableTask2());
```

Executor Interfaces

- An executor can have one of the following interfaces:
- **`Executor`**
  - A simple interface to launch void Runnable tasks
  - **`execute(Runnable)`**
- **`ExecutorService`**
  - Executor subinterface with additional features to manage lifecycle
  - To launch and control void Runnable tasks and Callable tasks, which return results
  - **`submit(Runnable)`** , **`submit(Callable<T>)`**, **`shutdown()`**, **`invokeAll(...)`**, **`awaitTermination(…)`**
  - **`Future<V>`** represents the result of an asynchronous computation
- **`ScheduledExecutorService`**
  - ExecutorService subinterface with support for future or periodic execution
  - For scheduling Runnable and Callable tasks

Example: Using an Executer (a Thread Pool)

```
public class Handler implements Runnable {
   private Socket socket;
   public Handler(Socket socket) {  this.socket = socket; }
   public void run() {
      try {
         BufferedReader rd = new BufferedReader(
                   new InputStreamReader(socket.getInputStream()));
         PrintWriter wr = new PrintWriter(socket.getOutputStream());
         String str;
         while ((str = rd.readLine()) != null) {
            for ( int i=str.length(); i > 0; i-- ) wr.print(str.charAt(i-1));
            wr.println();
            wr.flush();
         }
         socket.close();
       } catch ( IOException e ) {;}
    }
}
```

```java
public class ReverseServer {
    public static void main(String[] args) throws IOException {
        int poolSize = 3, port = 4444;
        ServerSocket serverSocket = null;
        try {
           if (args.length >1) poolSize = Integer.parseInt(args[1]);
           if (args.length >0) port = Integer.parseInt(args[0]);
        } catch (NumberFormatException e) {
           System.out.println("USAGE: java ReverseServer [poolSize] [port]");
           System.exit(1);
        }
        try {
            serverSocket = new ServerSocket(port);
        } catch (IOException e) {
            System.out.println("Can not listen on port: " + port);
            System.exit(1);
        }
        ExecutorService executor = Executors.newFixedThreadPool(poolSize);
        while (true) {
            Socket socket = serverSocket.accept();
            executor.execute( new Handler(socket) );
        }
    }
}
```

Java Collections Framework

- The **Java collections framework** (package **`java.util`**)
  - Includes collection interfaces and classes, e.g. **HashSet<E>**, **LinkedList<E>**

- A **collection** is an object that represents a group of elements (objects) of a specified type, i.e. **Vector<E>**
  - Operations: add, remove, put, replace, get, peek, poll, contains, size, list, isEmpty, etc.

- **Concurrent Collections** (**`java.util.concurrent`**)
  - Extends the Java Collection framework (**`java.util`**) with concurrent collections including the **`Queue`**, **`BlockingQueue`** and **`BlockingDeque`** interfaces, and high-performance, concurrent implementations of **`Map`**, **`List`**, and **`Queue`**.

Concurrent Collections (`java.util.concurrent`)

- Concurrent versions of some collections
  - `ConcurrentHashMap<K,V>`
  - `CopyOnWriteArrayList`
  - `CopyOnWriteArraySet`
- Different from similar "synchronized" classes
- **A concurrent collection is thread-safe, but not governed by a single exclusion lock.**
  - For example, `ConcurrentHashMap`, safely permits any number of concurrent reads as well as a tunable number of concurrent writes.

Unsynchronized, Synchronized, Concurrent Collections

- When to use which
- Unsynchronized collections
  - preferable when either collections are unshared, or are accessible only when holding other locks.
- ”Synchronized” versions
  - when you need to govern all access to a collection via a single lock, at the expense of poorer scalability.
- ”Concurrent" versions
  - normally preferable when multiple threads are expected to access a common collection.