Concurrent Programming

`class Thread`
`interface Runnable`
`class Object`

- *Multiprocessing*
  - Using Multiple Processors.
- *Multiprogramming* (`Batch`)
  - Switch and execute different jobs simultaneously, to improve CPU utilization.
- *Multitasking* (`Interactive`)
  - Perform more than one task at a time for each user, to improve response time.
- *Multithreading*
  - Threads in a user task (process) can *share* code, data, and system resources, and *access* them concurrently.
  - Each thread has a separate program counter, registers, and a run-time stack.

granularity

Multitasking

ls	ls
more a.txt	xclock &
emacs -nw a.java	netscape &
gcc a.c ;	emacs a.java &
a.out	javac a.java ;
…	java a
logout	...

Browser : A Multithreaded Application

- Concurrent Activities:
  - Scrolling a page.
  - Downloading an applet/image over the internet.
  - Playing animation and sound simultaneously.
  - Printing a page in the background.
  - Updating Stock Quotes automatically.
  - FTP-ing a remote file.
  - **...**
- *Browser is a mini-OS!*

Threads in Java

- A single sequential flow of control (of execution of expressions and statements) is called a ***thread***.
- A thread independently executes Java code, but may *share address space* with other threads. (cf. Process)

*Java primitives for concurrent programming are based on **Hoare's monitors**.*

Motivation

Application independent interleaving of threads.

- Support Concurrent Activities
  - Multimedia Applications
  - Advertisements, Sports/stocks ticker
- Improve user response
  - User input in interactive programs
  - I/O in networked programs "in the background"
- Improve CPU utilization
  - Demand-driven thread-scheduling

Overall Game Plan

- How to create and execute multiple threads?
  - Interleaved computations
  - Indiscriminate interleaving interferes with application semantics
- Introduce Mutual Exclusion constucts
  - *Example*: Printing documents on a shared printer
- Introduce Synchronization constructs
  - *Example*: Buffering on a shared printer

Java Primitives

- Mutual exclusion
  - `synchronized` methods in a class cannot be run concurrently on behalf of *different* threads.
  - `synchronized` statement locks an object.
    - "Object" is an instance of a class (*incl.* `class Class`).
- Synchronization / Cooperation
  - Methods `wait(), notify(), notifyAll()` etc. in `class Object` enable threads to communicate and regulate each other's progress.

Creating Threads

Creating and Running Threads

- Define subclass of `class Thread`. Override `run()` method.

```
public void  run() { }
```

- Create an instance of the subclass, and invoke `start()` on it. Now `run()` method executes in an *independent thread*.

Example using `class Thread`

```
class Echo extends Thread {
    int id;
    Echo(int i) {
       id = i;
    }
    public void run() {
       while (true)  {
          System.out.println(id +" ABC ");
          //  yield();
       }
    }
    public static void main (String[] args) {
              new Echo(1) . start();
              new Echo(2) . start();
    }
}
```



```
> javac Echo.java
> java  Echo
```

Solaris

```
1 ABC
1 ABC
1 ABC
1 ABC
1 ABC
1 ABC
1 ABC
1 ABC
1 ABC
...
```

Windows

```
1 ABC   1 ABC
1 ABC   2 ABC
1 ABC   2 ABC
1 ABC   2 ABC
2 ABC   1 ABC
2 ABC   1 ABC
2 ABC   2 ABC
2 ABC   2 ABC
2 ABC   2 ABC
1 ABC   2 ABC
1 ABC   2 ABC
2 ABC   1 ABC
2 ABC   1 ABC
2 ABC   1 ABC
1 ABC   ...
...
```

with **`yield()`** in both OS

```
1 ABC
2 ABC
1 ABC
2ABC
1 ABC
2 ABC
1ABC
2 ABC
1 ABC
2 ABC
...
```

Alternative :Creating and Running Threads

- Threads can also be created from an instance of a class implementing the `interface Runnable`.
  - Required when the class is defined by extension.

Example using `interface Runnable`

```
class Echo implements Runnable {
    int id;
    Echo(int i) {
       id = i;
    }
    public void run() {
       while (true)  {
           System.out.println(id +" ABC ");
          //  yield();
       }
    }
    public static void main (String[] args) {
               new Thread (new Echo(1)) . start();
               new Thread (new Echo(2)) . start();
    }
}
```


Same Example in C#

```
using System.Threading;

 class Echo {
    int id;
    Echo(int i) {
       id = i;
    }
    public void run() {
       while (true)
            System.Console.WriteLine(id + " ABC ");
    }
    public static void Main () {
         new Thread ( new ThreadStart
                     (new Echo(1).run)) . Start();
         new Thread ( new ThreadStart
                     (new Echo(2).run)) . Start();
    }
}
```


Alternate Rendition in Java

```
class  Echo  implements  Runnable {
   public  void  run() {
      try  {
             while (true) {
                   Thread.sleep(1000);
                   System.out.println("ABC");
             }
      } catch (InterruptedException e) {
                        return;
      }
   }
   public static  void  main (String[] args) {
               Runnable  r = new Echo();
               new Thread(r) . start();
   }
}
```

Threads and Applets

A Simple Bouncing Ball Animation


```
class Ball {
  static final int TOP = 10,  BOTTOM = 150;
  int incr = 2;
  int ypos = TOP;
  void paint(java.awt.Graphics g) {
      if  (ypos < TOP || ypos > BOTTOM)
                              incr= -incr;
      ypos += incr;
      g.setColor(java.awt.Color.cyan);
      g.fillOval(10,ypos, 10,10);
}}
```



```
// <applet code=Bounce.class height=200 width=50></applet>

public class Bounce extends java.applet.Applet {
        Ball b;
        public void init() {
                b = new Ball();
                setBackground(java.awt.Color.red);
        }
        public void paint(java.awt.Graphics g)  {
                b.paint(g);
                repaint(15);
                /* try  { while (true) {
                             Thread.sleep(15);
                             repaint();
                       }
                   }  catch (InterruptedException e) {}; */
        }
}
```


Threaded Applet

```
public class ThreadedBounce
              extends java.applet.Applet
              implements      Runnable    {
      Ball b;
      Thread t;
      public void init() {
            b = new Ball();
            setBackground(java.awt.Color.red);
            t = new Thread(this);
            t.start();
      }
                  ...
```

```
        ...
    public void paint(java.awt.Graphics g)    {
        b.paint(g);
        //  moved the code from here
    }
    public void run() {
        try  {
            while (true) {
               Thread.sleep(15);
               repaint();
            }
        } catch (InterruptedException e) {};
    }
}
```


Another version of Threaded Applet

```
public class ThreadedColorBounce
             extends java.applet.Applet
             implements     Runnable        {
    Ball b;
    Thread t;
    public void init() {
        b = new Ball();
        setBackground(java.awt.Color.red);
    }
    public void start() {
       if ( t == null) {
          t = new Thread(this);
          t.start();
    }}                ...
```



```
    public void stop() {
        t = null;
    }
    public void paint(java.awt.Graphics g)    {
        b.paint(g);
    }
    public void run() {
        try  {
            while (true) {
               Thread.sleep(15);
               repaint();
            }
        } catch (InterruptedException e) {};
    }
}
```


Color Changing Ball

```
class ColorBall extends Thread {
   static final int TOP = 10,  BOTTOM = 150;
   java.awt.Color c = java.awt.Color.cyan;
   int incr = 2;
   int ypos = TOP;
   public ColorBall(){
       start();
   }
   void paint(java.awt.Graphics g) {
       if  (ypos < TOP  ||  ypos > BOTTOM)
                                  incr= -incr;
       ypos += incr;
       g.setColor(c);
       g.fillOval(10,ypos, 10,10);
   }          ...
```

```
            ...
  public void run() {
    try {
       while (true) {
         sleep(600);
         c = new java.awt.Color(
               (float) Math.random(),
               (float) Math.random(),
               (float) Math.random() );
        }
    } catch (InterruptedException e) {};
  }
}
```


Mutual Exclusion

Sharing Data

Threads Sharing Data

```
class Shared {
    private  int  cnt = 0;
    // synchronized
    void  print(String Id) {
                System.out.print(Id + ":" + cnt );
                System.out.println( "-" +  ++cnt);
    }
}
```

```
class Shared {
     private  int  cnt = 0;
     void  print(String Id) {
             synchronized  (this)  {
                System.out.print(Id + ":" + cnt );
                System.out.println( "-" +  ++cnt);
             }
    }
}
```



```
class  SharingThread  extends  Thread  {
    private static Shared  s = new Shared();
    String Id;
    SharingThread (String Name) {
         Id = Name;
         start();
    }
    public  void run () {
          while (true) {
               s.print(Id); // yield();
          }
    }
    public static void main (String [] args) {
         new SharingThread("A") ;
         new SharingThread("B") ;
    }
}
```

Motivation for Mutual Exclusion

Concurrent Access

A:368-369
A:369-370
B:370-371
A:370-372
A:372-373
A:373-374
A:374-375
B:371-376
B:376-377
B:377-378
B:378-379
B:379A:375-381
A:381-382
A:382-383
A:383-384
-380

Mutual Exclusion

A:693-694
A:694-695
A:695-696
B:696-697
B:697-698
B:698-699
B:699-700
B:700-701
B:701-702
A:702-703
A:703-704
A:704-705
A:705-706
...

with `yield()`

A:828-829
B:829-830
B:830-831
A:831-832
B:832-833
A:833-834
B:834-835
A:835-836
B:836-837
B:837-838
A:838-839
B:839-840
...


```
// C# Equivalent
using System;
using System.Threading;
class Shared {
      private  int  cnt = 0;
      public void  print(String Id) {
             lock (this) {
                    Console.Write(Id +  ":" + cnt);
                    Console.WriteLine("-" +  ++cnt);
             };
      }
}
class  SharingThread  {
    private  static  Shared  s = new Shared();
    String Id;
    SharingThread (String Name) {
              Id = Name;
    }
    public  void   run () {
              while (true) {
                  s.print(Id);
              }
    }
    public   static   void   Main (string [] args) {
     new Thread (new ThreadStart (new SharingThread("A").run) ). Start() ;
     new Thread (new ThreadStart (new SharingThread("B").run) ). Start() ;
    }
}
```


Interaction of Language Features

`run()` method case study

Subclassing : Access Control

```
class Thread {  ...
      public  void  run() { }
}
class SubThread extends Thread {
      public  void  run() {  ...  }

   /*******************ILLEGAL********************
     void  run() {  ... }
   *******************ILLEGAL********************/
}
```

Thread t =
    new SubThread();
t.run()

- **Otherwise, `run()` can be invoked on a SubThread instance via (its reference in) a Thread variable (due to dynamic binding) in another package.**

Subclassing : Exception

```
class Thread {  ...
      public  void  run() { }
}
class SubThread extends Thread {
      public  void  run() {  ...  }

   /******************ILLEGAL*********************
     public void run() throws InterruptedException {
            sleep(1000);                          }
   ******************ILLEGAL*********************/
}
```

Thread t =
new SubThread();
t.run()

- **`run()` invoked on a SubThread instance via a Thread variable (by dynamic binding) can violate the contract that `run()` of `class Thread` does not throw any exception.**

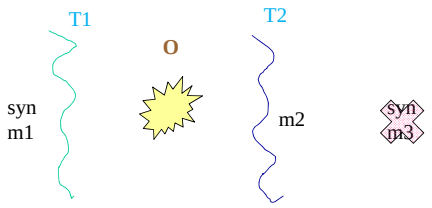
Subclassing : `synchronized`

- A `synchronized` method can override or be overridden by a non-`synchronized` method. However, this does not alter "*synchronized*"-status of the overridden method accessible using `super`.
- The locks are released when `synchronized` *statements* and `synchronized` *method invocations* complete abruptly by `throwing` *an* `exception`.
  - ❖Incorporating threads in the language enables dealing with problematic interactions with other language features.

`synchronized` methods

- A method that is *not* `synchronized` can run concurrently with a `synchronized` method on behalf of different threads.
  - The "locking"-analogy breaks down here.
  - For concreteness, consider an example involving two threads: (i) T1 running synchronized method m1 and (ii) T2 running ordinary method m2 on the same object O.
- A `synchronized` method can call another `synchronized` method in the same thread.
  - Recursion meaningful

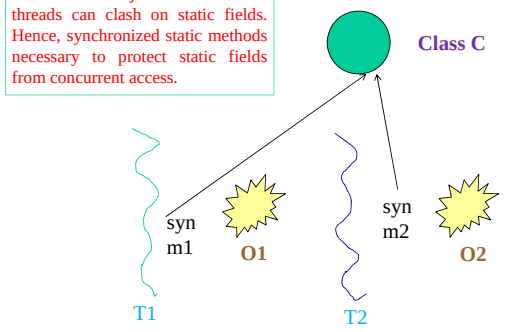
Synchronized instance methods can run concurrently with ordinary methods on the same object.



`synchronized` methods

- A `synchronized` instance (resp. `static`) method locks instance (resp. `static`) fields.
  - A `synchronized` instance method *does not* protect `static` fields, and they can corrupt it thro an update.
  - For concreteness, consider an example involving two threads T1 and T2 running synchronized instance methods m1 and m2 on objects O1 and O2 of the same class C. Both m1 and m2 are permitted to concurrently access the static fields of C, and there is potential for corruption. In such situations, static fields must be accessed in the body of instance methods using calls to synchronized static methods.

Synchronized instance methods run on distinct objects in different threads can clash on static fields. Hence, synchronized static methods necessary to protect static fields from concurrent access.



Thread Scheduling

Blocked Thread

- A thread is *blocked* (that is, it is not runnable) if it is:
  - sleeping.
  - suspended.
  - waiting.
  - executing a “blocked” method.
  - “blocked” for I/O.
- Java neither detects nor prevents deadlocks.

Thread Scheduling

- Java runs a *non-blocked* (*runnable*) highest-priority thread.
- A thread can be *preempted* by a higher priority thread that becomes runnable.
  - The scheduler may however choose to run lower priority thread, to avoid starvation.
- The same (highest) priority threads are run in *round-robin* fashion.

Scheduling Ambiguity

- JVM on `Windows` uses ***time-slicing*** to schedule same priority threads.
  ("Fair policy")
- JVM on `Solaris` chooses one of the same priority threads to run until the thread *voluntarily* relinquishes the CPU (by `sleep`ing, `yield`ing, or `exit`ing), or until a higher priority thread *preempts* it.

Cooperative Concurrent Threads

Producer-Consumer Problem

Bounded-Buffer Problem

(Clients and Servers : Resource Sharing)

Simplistic 1-Cell Buffer

```
class Buffer {
   Object x;
   // synchronized
   public void put (Object _x, String id) {
      System.out.println(
              "Done  << " + id + " puts " + _x);
      x = _x;
   }
   // synchronized
   public Object get (String id) {
      System.out.println(
              "Done  >> " + id + " gets " + x);
      return x;
   }
}
```

```
class Producer extends Thread {
   private Random r = new Random();
   Buffer b;       String id;
   public Producer(Buffer _b, String _id) {
            b = _b;            id = _id;
   }
   public void run () {
          int delay;           Integer ir;
       try {
         while (true) {
            delay = Math.abs(r.nextInt() % 1999) + 50;
            sleep(delay);      ir = new Integer(delay);
            System.out.println("Ready << "+id+" puts "+ ir);
                b.put(ir, id);
         }
       }catch (Exception e){System.out.println("Exception$ " + e);};
   }
}
```



```
class Consumer extends Thread {
   private Random r = new Random();
   Buffer b;       String id;
   public Consumer(Buffer _b, String _id) {
            b = _b;            id = _id;
   }
   public void run () {
     int delay;          Integer ir = null;
     try {
          while (true) {
            delay = Math.abs(r.nextInt() % 1999) + 50;
            sleep(delay);
            System.out.println("Ready >> " + id + " gets ");
            ir = (Integer) b.get(id);
          }
    } catch (Exception e) {System.out.println("Exception$ " + e);};
   }
}
```


Producer-Consumer : Bounded Buffer

```
public class PCB {
         public static void main(String[] args) {
             Buffer b = new Buffer();
             new Consumer(b,"C1") . start();
             new Producer(b,"P1") . start();
             try {Thread.sleep(1000);
             } catch (Exception e){};
             new Consumer(b,"C2") . start();
             new Producer(b,"P2") . start();

         }
}
```


Unfettered Run

```
Ready >> C1 gets
Ready << P2 puts 493
Done  >> C1 gets null
Done  << P2 puts 493
Ready << P1 puts 1591
Done  << P1 puts 1591
Ready << P1 puts 488
Done  << P1 puts 488
Ready >> C2 gets
Done  >> C2 gets 488
Ready >> C1 gets
Done  >> C1 gets 488
Ready >> C2 gets
Done  >> C2 gets 488
Ready << P1 puts 745
Done  << P1 puts 745
   ...
```

premature

(transient stability?!)

puts

gets

```
   ...
Ready << P2 puts 815
Done  << P2 puts 815
Ready >> C2 gets
Done  >> C2 gets 815
Ready << P1 puts 1223
Done  << P1 puts 1223
Ready >> C1 gets
Done  >> C1 gets 1223
Ready << P2 puts 403
Done  << P2 puts 403
Ready >> C2 gets
Done  >> C2 gets 403
   ...
```

Concurrency control : `class Buffer`

```
class Buffer {
   Object x;
   boolean empty = true;
   public synchronized void  put
        (Object _x, String id) throws Exception
                                   { ...}
   public synchronized Object get
        (String id)  throws Exception { ... }
}
```

- Two producers (consumers) cannot `put(get)` two items in (from) the same buffer slot *simultaneously.*
- Two producers (consumers) cannot `put(get)` two items in (from) the same buffer slot without an intervening consumer (producer).
- A consumer (producer) is not permitted to `get (put)` an item from (into) buffer if empty (full).


```
public synchronized void
   put (Object _x, String id) throws Exception {
      while (!empty)   wait();
      empty = ! empty;
      System.out.println("Done  << "+id+" puts "+ _x);
      x = _x;
      notifyAll();
}
```

- Note that `if-then` cannot replace `while` because `notifyAll`, due to a *consumer,* can wake up two `wait`ing *producers,* and only one producer will find the buffer empty. *("race condition")*


```
public synchronized Object
   get (String id) throws Exception {
      while (empty) wait();
      empty = ! empty;
      System.out.println("Done  >> "+id+" gets "+x);
      notifyAll();
      return x;
}
```

- Note that `notify` cannot always be used in place of `notifyAll` because a consumer may be woken up.
- `while` required because `notifyAll` due to a producer does not guarantee that `wait`-ing consumers will find an item in the buffer.

Synchonization and Mutual Exclusion

```
Ready >> C2 gets
Ready >> C1 gets
Ready << P1 puts 1672
Done  << P1 puts 1672
Done  >> C2 gets 1672
Ready << P2 puts 774
Done  << P2 puts 774
Done  >> C1 gets 774
Ready << P1 puts 168
Done  << P1 puts 168
Ready >> C1 gets
Done  >> C1 gets 168
Ready << P2 puts 1263
Done  << P2 puts 1263
Ready >> C1 gets
Done  >> C1 gets 1263
...
```

```
...
Ready << P1 puts 622
Done  << P1 puts 622
Ready >> C1 gets
Done  >> C1 gets 622
Ready >> C2 gets
Ready << P2 puts 1447
Done  << P2 puts 1447
Done  >> C2 gets 1447
Ready << P2 puts 96
Done  << P2 puts 96
Ready << P2 puts 95
Ready >> C1 gets
Done  >> C1 gets 96
Done  << P2 puts 95
...
```

Methods in `class Object`

- `public final void wait() throws InterruptedException {...}`
  - Current thread is suspended (after *atomically* releasing the lock on `this`) until some other thread invokes `notify()` or `notifyAll()` or *interrupts*.
- `public final void notify() {...}`
  - Notifies *exactly one* thread waiting on `this` object for a condition to change. The awakened thread cannot proceed until this thread relinquishes the lock.
- `public final void notifyAll() {...}`
  - These methods must be invoked inside `synchronized` code or else `IllegalMonitorStateException` will be thrown.

Single Cell Buffer in C#

```
using System;
using System.Threading;
class Buffer {
   Object x;
   bool empty = true;
   public void put (Object _x, string id) {
    lock(this){
        while (!empty) Monitor.Wait(this);
        empty = ! empty;
        Console.WriteLine("Done  << " + id + " puts " + _x);
        x = _x;
        Monitor.PulseAll(this);
    }
   }
public Object get (string id) {
    lock(this){
         while (empty) Monitor.Wait(this);
         empty = ! empty;
         Console.WriteLine("Done  >> " + id + " gets " + x);
         Monitor.PulseAll(this);
         return x;
    }
   }
}
```



```
class Producer {
   private System.Random r = new System.Random();
   Buffer b;       String id;
   public Producer(Buffer _b, String _id) {
           b = _b;            id = _id;
   }
   public void run () {
          int delay;
       try {
         while (true) {
                delay = r.Next(2000) + 50;
                Thread.Sleep(delay);
                Console.WriteLine("Ready << " + id + " puts " + delay);
                b.put(delay, id);
         }
       }  catch (Exception e){Console.WriteLine("Exception$ " + e);};
   }
}
```



```
class Consumer {
   private System.Random r = new System.Random();
   Buffer b;       String id;
   public Consumer(Buffer _b, String _id) {
           b = _b;           id = _id;
   }
   public void run () {
           int delay;
           try {
             while (true) {
               delay = r.Next(2000) + 50;
               Thread.Sleep(delay);
               Console.WriteLine("Ready >> " + id + " gets ");
               delay = (int)  b.get(id);
             }
           } catch (Exception e)
                {Console.WriteLine("Exception$ " + e);};
   }
}
```

```
public class PCB {
          public static void Main(string[] args) {
              Buffer b = new Buffer();
              new Thread( new ThreadStart(new Consumer(b,"C1").run)) . Start();
              new Thread( new ThreadStart(new Producer(b,"P1").run)) . Start();
            try {Thread.Sleep(1000);}
            catch (Exception e){Console.WriteLine("Exception$ " + e);};
              new Thread( new ThreadStart(new Consumer(b,"C2").run)) . Start();
              new Thread( new ThreadStart(new Producer(b,"P2").run)) . Start();
          }
}
```