Concurrent programming in the Java language

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Section 1. About this tutorial

Should I take this tutorial?

One of the important features of the Java language is support for multithreaded (also called concurrent) programming.

This tutorial is an introduction to the use of multiple threads in a Java program and will appeal to systems or application programmers who want to learn about multithreaded Java programming.

A multithreaded program can take advantage of the additional CPUs in a shared-memory multiprocessor architecture in order to execute more quickly. The use of multiple threads can also simplify the design of a program. As an example, consider a server program in which each incoming client request is handled by a dedicated thread.

However, to avoid race conditions and corruption of shared data, the threads in a concurrent program must be properly synchronized. Many example programs are used in this tutorial to illustrate these concepts.

This tutorial assumes a prior general knowledge of Java programming; the context and level of knowledge used in this tutorial is the equivalent of an undergraduate operating systems course. For a more explicit explanation of the experience needed to get the most out of this tutorial, see Assumptions and context on page 3 .

About the author

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Section 2. Introduction

Goals and objectives

The two goals of this tutorial are to:

* Learn the "nuts and bolts" of creating multiple threads of control in a Java program.
* Learn the pitfalls and areas that can trip you up when synchronizing those threads to avoid race conditions and corruption of shared data.

Assumptions and context

Before we move into the nuts and bolts of concurrent programming, let's elaborate on the knowledge and experience necessary to effectively wring the most use from this tutorial.

We assume that you have a general knowledge of concurrency issues, at a level commensurate with an undergraduate computer science operating systems course. We also assume a familiarity with the following terms and concepts: multiple threads, shared data, race conditions, critical sections, mutual exclusion, monitors, and semaphores. Finally, you should have knowledge of object-oriented programming and sequential Java: classes, objects, interfaces, inheritance, polymorphism, packages, and exceptions.

For further reference, Resources on page 122 at the end of the tutorial includes online and print resources on concurrent programming and the Java language.

Tutorial platform specifications

All example Java programs in this tutorial have been executed on a PC running *Red Hat's version 7.0 of Linux*, using the *IBM Java software developer kit version 1.3.0 for Linux*. This developer kit uses native threads and therefore time slices them automatically.

The examples are compiled and executed with the just-in-time compiler (JIT) disabled (command **`export JAVA_COMPILER=NONE`**) to facilitate the manifestation of race conditions in Example race.java on page 24 andExample rac2.java on page 25 .

You can download a zip file containing all example Java programs in this tutorial in Resources on page 122 .

Section 3. Starting Java threads

Two ways to start Java threads

There are two ways to start Java threads. One way is to subclass the **Thread** class:

```
class A extends Thread {
   public void run() {
      ... // code for the new thread to execute
   }
}
...
   A a = new A(); // create the thread object
   a.start();     // start the new thread executing
...
```

The second way is to implement the **Runnable** interface:

```
class B extends ... implements Runnable {
   public void run() {
      ... // code for the new thread to execute
   }
}
...
   B b = new B();              // create the Runnable object
   Thread t = new Thread(b); // create a thread object
   t.start();                // start the new thread
...
```

Example prit.java on page 6 demonstrates multithreaded prime number generation with one thread per number checked. Sample run of prit.java on page 7 shows the results. The Class Prime.java on page 7 is used. Unit testing of Prime.java on page 8 demonstrates unit testing of the **Prime.java** class.

Background material on threads

First a quick refresher on threading.

A *process* is an executing program. It has been allocated memory by the operating system. A *thread* is an execution or flow of control in the address space of a process; the program counter register points to the next instruction to be executed.

A process is a program with at least one thread. A process can have more than one thread. All the threads in a process have their own program counter and their own stack for local (also called *automatic*) variables and return addresses of invoked procedures.

In the Java language, a thread in the run-time interpreter calls the **main()** method of the class on the **java** command line. Each object created can have one or more threads, all sharing access to the data fields of the object.

The article "*An Introduction to Programming with Threads*" by Andrew D. Birrell (1989; a DEC research report) offers the following motivations for concurrent programming with threads:

* Shared memory multiprocessors are cheaper and more common so each thread can be allocated a CPU.

* It is less expensive and more efficient to create several threads in one process that share data than to create several processes that share data.

* I/O on slow devices (such as networks, terminals, and disks) can be done in one thread while another thread does useful computation in parallel.

* Multiple threads can handle the events (such as mouse clicks) in multiple windows in the windowing system on a workstation.

* In a LAN cluster of workstations or in a distributed operating system environment, a server running on one machine can spawn a thread to handle an incoming request in parallel with the main thread continuing to accept additional incoming requests.

When two threads perform a function such as **`N=N+1`** at about the same time, you have a *race condition*. Both threads are "racing" each other for access to the data and one of the updates can get lost. In general, race conditions are possible when two or more threads share data, they are reading and writing the shared data concurrently, and the final result depends on which one does what when.

Concurrently executing threads that share data need to synchronize their operations and processing to avoid race conditions on shared data. Thread synchronization can be done with *flag variables* and *busy waiting*. Because it uses a lot of CPU cycles, busy waiting is inefficient. Blocking would be better.

A *critical section* is a block of code in a thread that accesses one or more shared variables in a read-update-write fashion. In such a situation we want *mutual exclusion* in which only one thread can access (read-update-write) a shared variable at a time.

The *mutual exclusion problem* is how to keep two or more threads from being in their critical sections at the same time, where we make no assumptions about the number of CPUs or their relative speeds.

A thread outside its critical section should not keep other threads outside their critical sections from entering. This is also called a *safety* property (or absence of unnecessary delay).

Also, no thread should have to wait forever to enter its critical section. This is also called a *liveness* property (or eventual entry).

Andrews characterizes an *atomic action* as one that "makes an indivisible state transition: any intermediate state that might exist in the implementation of the action must not be visible to other threads." This means that nothing from another thread can be interleaved in the implementation of the action for it to be atomic.

Critical sections need to be defined as if they were one atomic action to avoid race conditions.

Here are the basic issues to keep in mind to solve the mutual exclusion problem when devising a pre-protocol and a post-protocol based on either hardware or software. The protocols must:

* Prevent two threads from being in their critical sections at the same time
* Have the desirable safety and liveness properties
* Allow critical sections to be executed atomically

The system's ground rules are as follows:

* It is a load/store register architecture.
* Multiple, concurrently executing threads are sharing data.
* There are single or multiple CPUs and we cannot make relative speed assumptions.
* Access to shared variables can be interleaved if two threads are in their critical sections at the same time.
* Threads may not halt in their pre- or post-protocols.
* Threads may not halt in their critical sections.
* Threads may halt outside their critical sections.

Thread Ti, i = 1, 2, 3, ...

```
while (true) {
   outsideCS();
   wantToEnterCS(i);    // pre-protocol
   insideCS();
   finishedInCS(i);     // post-protocol
}
```

The next several panels display the code described in this section. To view the code, click **Next**; or you can go directly to the next section, Thread states, priorities, and methods on page 9 , and return to the code samples at another time.

Example prit.java

```
class PrimeThread extends Thread {
   private int m = 0;
   PrimeThread(int m) { this.m = m; }
   public void run() {
      if (Prime.prime(m)) System.out.println(m + " is prime");
   }
}
class TestPrimeThreads {
   public static void main(String[] args) {
      int n1 = 0, n2 = 0;
      try {
         n1 = Integer.parseInt(args[0]);
         n2 = Integer.parseInt(args[1]);
      } catch (NumberFormatException e) {
         System.out.println("improper format");
         System.exit(1);
      } catch (ArrayIndexOutOfBoundsException e) {
         System.out.println("not enough command line arguments");
         System.exit(1);
      }
      if (n1 < 2 || n2 < 2 || n1 > n2) {
         System.out.println("illegal command line arguments "
            + n1 + ", " + n2 );
```

```
            System.exit(1);
         }
         System.out.println("printing primes from "
            + n1 + " to " + n2);
         new PseudoTimeSlicing(); // for Solaris, not Windows 95/NT
         for (int i = n1; i <= n2; i++) {
            Thread t = new PrimeThread(i);
            t.start();
         }
      }
   }
```

Sample run of prit.java

```
% javac prit.java
% java TestPrimeThreads 10 20
printing primes from 10 to 20
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
11 is prime
13 is prime
17 is prime
19 is prime
% java TestPrimeThreads 1000000 1000060
printing primes from 1000000 to 1000060
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
1000003 is prime
1000033 is prime
1000037 is prime
1000039 is prime
```

Class Prime.java

```
public class Prime {
   public static boolean prime(int k) {
      if (k < 2) return false;
      int limit = k/2;
      for (int i = 2; i <= k/2; i++) {
         if ((k % i) == 0) return false;
      }
      return true;
   }
   public static void main(String[] args) {
      int n = 0;
      try {
         n = Integer.parseInt(args[0]);
      } catch (NumberFormatException e) {
```

```
            System.out.println("improper format");
            System.exit(1);
        } catch (ArrayIndexOutOfBoundsException e) {
            System.out.println("no command line argument");
            System.exit(1);
        }
        if (n < 2) {
            System.out.println("command line argument " + n
                + " is too small");
            System.exit(1);
        }
        System.out.println("printing primes from 2 to " + n);
        for (int i = 2; i <= n; i++) {
            if (Prime.prime(i)) System.out.println(i + " is prime");
        }
    }
}
```

Unit testing of Prime.java

```
% javac Prime.java
% java Prime
no command line argument
% java Prime abc
improper format
% java Prime 0
command line argument 0 is too small
% java Prime 10
printing primes from 2 to 10
2 is prime
3 is prime
5 is prime
7 is prime
```

Section 4. Thread states, priorities, and methods

Thread states

Thread states are defined as:

* *New* before the thread's **`start()`** method is called

* *Runnable* if the thread is in the ready queue

* *Running* if the thread is executing on the CPU

* *Dead* after the thread's **`run()`** method completes or **`stop()`** method is called

* *Blocked* if the thread is blocked on I/O, a **`join()`** method call, or a **`sleep(`***ms***`)`**method call

* *Suspended* if the thread's **`suspend()`** method is called from the *running* or *runnable* states

* *Suspended-blocked* if the thread's **`suspend()`** method is called from the *blocked* state

Thread priorities

Thread priorities (class variables) are:

* **`MAX_PRIORITY`**
* **`NORM_PRIORITY`**
* **`MIN_PRIORITY`**

Priority **`set`** and **`get`** instance methods include:

* **`setPriority(Thread.`***priority***`)`**
* **`getPriority()`**

The JVM scheduler usually ensures that the highest priority thread is running on the CPU, pre-empting the currently running thread when necessary, but this is not a guarantee. (See page 415 of *The Java Language Specification,* in Resources on page 122 .)

Time slicing

Time slicing of threads is also known as *round-robin scheduling* . It is done by the JVM. The IBM JDK 1.3.0 for Linux and the Microsoft Windows JVMs perform this task; the Solaris version does not.

The Class PseudoTimeSlicing.java on page 11 implements "pseudo" time slicing. Using this class does not guarantee time slicing, but it works in practice.

Thread class methods

The following methods are **`static`** in class **`Thread`** and apply to the calling thread:

* **`Thread.sleep(`***ms***`)`** blocks the calling thread for the specified time.

* In **`Thread.yield()`**, the calling thread gives up the CPU (but is not guaranteed by the *JLS*).

* Any method can use **`Thread.currentThread()`** to get a reference to the thread that called the method, for example, **`Thread.currentThread().getPriority();`**.

* Use **`Thread.interrupted()`** to see if the thread's **`interrupt()`** method has been called (it clears the interrupted flag).

Instance methods

And here are the instance methods (for example, **`t.start()`** in which **`t`** is a reference variable to a **`Thread`** object):

* **`start()`**: Start a new thread executing the **`run()`** method.

* **`stop()`**: Terminate the thread (deprecated, do not use).

* **`suspend()`**: Suspend the thread (deprecated, do not use).

* **`resume()`**: Resume the suspended thread (deprecated, do not use).

* **`join()`**: Join with another thread when the latter terminates.

* **`interrupt()`**: Tell the thread to check for a change in what it should be doing.

* **`isInterrupted()`**: Check if the thread's **`interrupt()`** method has been called (this does not clear the interrupted flag).

* **`isAlive()`**: Check if the thread has terminated.

* **`setDaemon(`*`boolean`*`)`**: Make the thread a *daemon* (the JVM ignores this thread when determining if all threads in a program have terminated).

* **`isDaemon()`**: Check if the thread is a daemon.

* **`setPriority(`*`int`*`)`**: Change the priority of the thread.

* **`getPriority()`**: Return the prioritiy of the thread.

* **`setName(`*`string`*`)`**: Change the name of the thread to be equal to the argument **`name`**.

* **getName()**: Return the name of the thread.

Examples

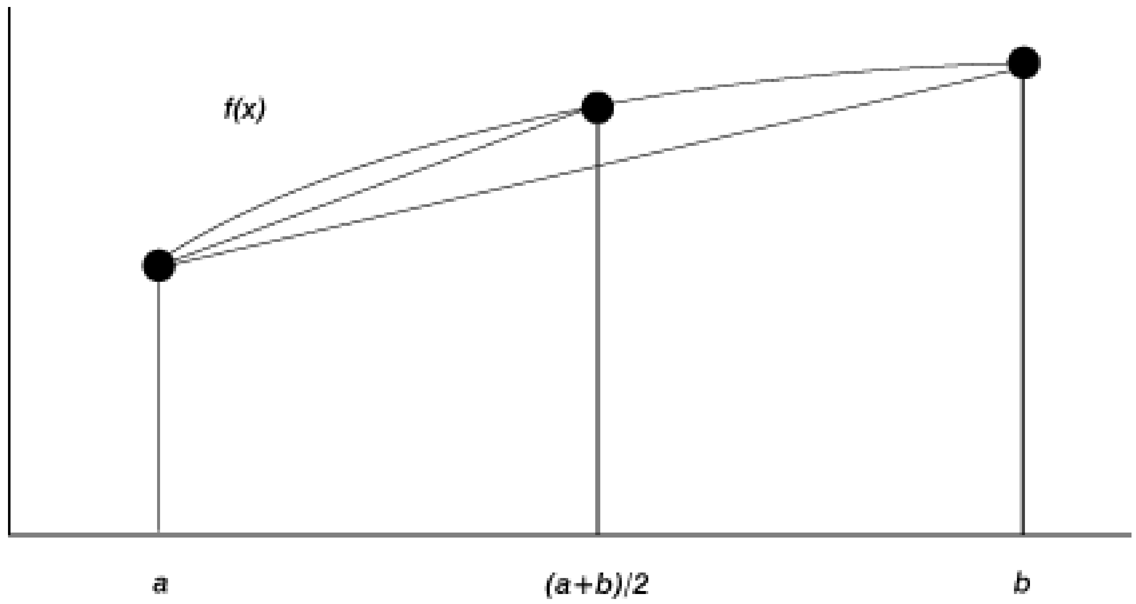
The following example programs demonstrate what we've just been covering.

Class Sugar.java on page 12 is "syntactic sugar." It provides class method**age()**, which returns the number of milliseconds since the program started, and class method **random(***range***)**.

Example beep.java on page 13 allows you to test a platform for timeslicing.Sample run of beep.java on page 14 shows the results.

Example quad.java on page 15 implements adaptive quadrature numerical integration with multiple threads and uses **join()** for synchronization. If the sum of the areas of the two sub-trapezoids is not close enough to the area of the trapezoid containing them, two threads are spawned to repeat the calculation for each sub-trapezoid. The spawning thread cannot continue until each of the two spawned threads finishes. Sample run of quad.java on page 16 shows the results.

This figure shows the implementation of adaptive quadrature numerical integration with multiple threads.



The next several panels display the code described in this section. To view the code, click **Next**; or you can go directly to the next section, The volatile modifier on page 18 , and return to the code samples at another time.

Class PseudoTimeSlicing.java

```
public class PseudoTimeSlicing implements Runnable {
```

```
    private static final String
       JAVA_VERSION = System.getProperty("java.version"),
       JAVA_VENDOR = System.getProperty("java.vendor"),
       OS_NAME = System.getProperty("os.name"),
       OS_ARCH = System.getProperty("os.arch"),
       OS_VERSION = System.getProperty("os.version");
    private static Thread me = null;
    private static int timeSlice;
    public PseudoTimeSlicing() { this(100); }
    public PseudoTimeSlicing(int ts) {
    // See http://www.javaworld.com/javaworld/jw-04-1999/
    // jw-04-toolbox_p.html for the correct way to do singletons
    // in a multithreaded situation.
       if (me == null) {
          System.out.println("Java version=" + JAVA_VERSION
             + "\nJava vendor=" + JAVA_VENDOR
             + "\nOS name=" + OS_NAME + "\nOS arch=" + OS_ARCH
             + "\nOS version=" + OS_VERSION);
          if (OS_NAME.equals("Solaris") ||
                (OS_NAME.equals("Linux") &&
                !JAVA_VENDOR.startsWith("IBM"))) {
             timeSlice = ts;
             me = new Thread(this);
             me.setPriority(Thread.MAX_PRIORITY);
             me.setDaemon(true);
             me.start();
             System.out.println("PseudoTimeSlicing installed");
          } else
             System.out.println("No PseudoTimeSlicing needed");
       } else System.out.println(
             "PseudoTimeSlicing already installed");
    }
    public void run() {
       if (Thread.currentThread() != me) return;
       // this highest-priority thread waking up sends the
       // currently executing thread back to the runnable set
       while (true) {
          try { Thread.sleep(timeSlice); }
          catch (InterruptedException e) { /* ignored */ }
       }
    }
 }
```

Class Sugar.java

```
 import java.util.Random;
 public abstract class Sugar {
    private static final long startTime
       = System.currentTimeMillis();
    private static final Random rnd = new Random();
       // utility methods
    protected static final long age() {
       return System.currentTimeMillis() - startTime;
    }
    protected static final double random() {
       return rnd.nextDouble(); // in range [0, 1)
    }
    protected static final double random(int ub) {
       return rnd.nextDouble()*ub; // in range [0, ub)
    }
    protected static final double random(int lb, int ub) {
```

```
      return lb + rnd.nextDouble()*(ub - lb); // in range [lb, ub)
   }
}
```

Example beep.java

```
class Beeper extends Sugar implements Runnable {
   private int beep = 0;
   private String name = null;
   public Beeper(String name, int beep) {
      this.name = name;
      this.beep = beep;
      System.out.println(name + " is alive, beep=" + beep);
   }
   public void run() {
      long value = 1;
      System.out.println("age()=" + age() + ", "
         + name + " running");
      // so main() thread has priority and
      // surely gets CPU later to interrupt() us
      Thread.currentThread().setPriority(
         Thread.currentThread().getPriority()-1);
      while (true) {
         if (value++ % beep == 0) {
            System.out.println("age()=" + age()
                + ", " + name + " beeps, value=" + value);
            if (Thread.interrupted()) {
               System.out.println("age=" + age() + ", "
                  + name + " interrupted");
               return;
            }
         }
      }
   }
}
class Beeping extends Sugar {
   public static void main(String[] args) {
      int numBeepers = 4;
      int beep = 100000;
      String timeSlice = "no";
      int runTime = 60;   // default in seconds
      try {
         numBeepers = Integer.parseInt(args[0]);
         beep = Integer.parseInt(args[1]);
         timeSlice = args[2];
         runTime = Integer.parseInt(args[3]);
      } catch (Exception e) { /* use defaults */ }
      System.out.println("Beeping: numBeepers=" + numBeepers
         + ", beep=" + beep + ", timeSlice=" + timeSlice
         + ", runTime=" + runTime);
      if (timeSlice.equals("yes"))
         // for Solaris, not Windows 95/NT
         new PseudoTimeSlicing();
      // start the Beeper threads
      Thread[] b = new Thread[numBeepers];
      for (int i = 0; i < numBeepers; i++)
         b[i] = new Thread(new Beeper("Beeper"+i, beep));
      for (int i = 0; i < numBeepers; i++) b[i].start();
      System.out.println("All Beeper threads started");
      // let the Beepers run for a while
      try {
```

```
            Thread.sleep(runTime*1000);
            System.out.println("age=" + age()
               + ", time to interrupt the Beepers and exit");
            for (int i = 0; i < numBeepers; i++)
               b[i].interrupt();
            for (int i = 0; i < numBeepers; i++)
               b[i].join();
         } catch (InterruptedException e) { /* ignored */ }
         System.out.println("All Beeper threads interrupted");
         System.exit(0);
      }
   }
```

Sample run of beep.java

```
% javac beep.java
% java Beeping 4 100000 no 3
Beeping: numBeepers=4, beep=100000, timeSlice=no, runTime=3
Beeper0 is alive, beep=100000
Beeper1 is alive, beep=100000
Beeper2 is alive, beep=100000
Beeper3 is alive, beep=100000
age()=36, Beeper0 running
age()=134, Beeper1 running
age()=195, Beeper2 running
All Beeper threads started
age()=225, Beeper3 running
age()=374, Beeper3 beeps, value=100001
age()=600, Beeper2 beeps, value=100001
age()=769, Beeper1 beeps, value=100001
age()=901, Beeper0 beeps, value=100001
age()=1050, Beeper0 beeps, value=200001
age()=1125, Beeper1 beeps, value=200001
age()=1287, Beeper3 beeps, value=200001
age()=1392, Beeper2 beeps, value=200001
age()=1671, Beeper1 beeps, value=300001
age()=1757, Beeper0 beeps, value=300001
age()=1988, Beeper3 beeps, value=300001
age()=2063, Beeper2 beeps, value=300001
age()=2209, Beeper2 beeps, value=400001
age()=2426, Beeper0 beeps, value=400001
age()=2499, Beeper1 beeps, value=400001
age()=2688, Beeper3 beeps, value=400001
age()=2979, Beeper1 beeps, value=500001
age()=3073, Beeper0 beeps, value=500001
age()=3219, Beeper0 beeps, value=600001
age=3234, time to interrupt the Beepers and exit
age()=3290, Beeper2 beeps, value=500001
age=3291, Beeper2 interrupted
age()=3321, Beeper3 beeps, value=500001
age=3322, Beeper3 interrupted
age()=3444, Beeper1 beeps, value=600001
age=3445, Beeper1 interrupted
age()=3578, Beeper0 beeps, value=700001
age=3578, Beeper0 interrupted
All Beeper threads interrupted
% java Beeping 4 100000 yes 3
Beeping: numBeepers=4, beep=100000, timeSlice=yes, runTime=3
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
```

```
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
Beeper0 is alive, beep=100000
Beeper1 is alive, beep=100000
Beeper2 is alive, beep=100000
Beeper3 is alive, beep=100000
age()=38, Beeper0 running
age()=168, Beeper1 running
age()=293, Beeper0 beeps, value=100001
age()=439, Beeper0 beeps, value=200001
age()=536, Beeper1 beeps, value=100001
age()=618, Beeper2 running
All Beeper threads started
age()=741, Beeper3 running
age()=855, Beeper2 beeps, value=100001
age()=922, Beeper1 beeps, value=200001
age()=1195, Beeper0 beeps, value=300001
age()=1319, Beeper3 beeps, value=100001
age()=1562, Beeper2 beeps, value=200001
age()=1702, Beeper0 beeps, value=400001
age()=1977, Beeper2 beeps, value=300001
age()=2078, Beeper1 beeps, value=300001
age()=2225, Beeper1 beeps, value=400001
age()=2266, Beeper3 beeps, value=200001
age()=2413, Beeper3 beeps, value=300001
age()=2561, Beeper1 beeps, value=500001
age()=2740, Beeper2 beeps, value=400001
age()=2743, Beeper0 beeps, value=500001
age()=3021, Beeper2 beeps, value=500001
age()=3124, Beeper0 beeps, value=600001
age()=3185, Beeper3 beeps, value=400001
age()=3322, Beeper1 beeps, value=600001
age()=3672, Beeper0 beeps, value=700001
age()=3723, Beeper3 beeps, value=500001
age=3748, time to interrupt the Beepers and exit
age()=3840, Beeper1 beeps, value=700001
age=3841, Beeper1 interrupted
age()=3906, Beeper2 beeps, value=600001
age=3906, Beeper2 interrupted
age()=4066, Beeper3 beeps, value=600001
age=4067, Beeper3 interrupted
age()=4108, Beeper0 beeps, value=800001
age=4109, Beeper0 interrupted
All Beeper threads interrupted
```

Example quad.java

```
interface TheFunction {
   public double evaluate(double x);
   public String toString();
}
class MyFunction implements TheFunction {
   public double evaluate(double x) { return x*x; }
   public String toString() { return " x**2"; }
}
class Area extends Thread {
   private double p, q, epsilon, result;
   private TheFunction f;
   public Area(double a, double b, double eps, TheFunction fn) {
      p = a;  q = b;  epsilon = eps;  f = fn;
```

```
    }
    public double getResult() { return result; }
    private static double trapezoidArea
          (double p, double q, TheFunction f) {
       double area =
          (Math.abs(q-p))/2 * (f.evaluate(p) + f.evaluate(q));
       return area;
    }
     public void run() {
        double bigArea = trapezoidArea(p, q, f);
        double leftSmallArea = trapezoidArea (p, ((p+q)/2), f);
        double rightSmallArea = trapezoidArea(((p+q)/2), q, f);
        double sumOfAreas = leftSmallArea + rightSmallArea;
        double relError = Math.abs(bigArea - sumOfAreas);
        if (relError <= (epsilon * sumOfAreas)) result = bigArea;
        else {
           Area leftArea =  new Area(p, (p+q)/2, epsilon, f);
           leftArea.start();
           Area rightArea = new Area((p+q)/2, q, epsilon, f);
           rightArea.start();
           try { leftArea.join(); }
              catch (InterruptedException e) { /* ignored */ }
           try { rightArea.join(); }
              catch (InterruptedException e) { /* ignored */ }
           result = leftArea.getResult() + rightArea.getResult();
       }
    }
 }
 class AdaptiveQuadrature {
    public static void main(String[] args) {
       double a = 0, b = 0, epsilon = 0;
       try {
          a = (Double.valueOf(args[0])).doubleValue();
          b = (Double.valueOf(args[1])).doubleValue();
          epsilon = (Double.valueOf(args[2])).doubleValue();
       } catch (NumberFormatException e) {
          System.out.println("improper format");
          System.exit(1);
       } catch (ArrayIndexOutOfBoundsException e) {
          System.out.println("not enough command line arguments");
          System.exit(1);
       }
       if (b <= a || epsilon <= 0) {
          System.err.println("b <= a || epsilon <=0, exit");
          System.exit(1);
       }
       TheFunction fn = new MyFunction();
       System.out.println("Adaptive Quadrature of" + fn + " from "
          + a + " to " + b + " with relative error " + epsilon);
       Area area = new Area(a, b, epsilon, fn);
       new PseudoTimeSlicing(); // for Solaris, not Windows 95/NT
       area.start();
       try { area.join(); }
          catch (InterruptedException e) { /* ignored */ }
       double result = area.getResult();
       System.out.println("Result for" + fn + " = " + result);
       System.exit(0);
    }
 }
```

Sample run of quad.java

```
% javac quad.java
% java AdaptiveQuadrature 0.5 1.5 0.001
Adaptive Quadrature of x**2 from 0.5 to 1.5 with relative error 0.0010
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
Result for x**2 = 1.084136962890625
```

Section 5. The volatile modifier

Some definitions

The **`volatile`** modifier tells the compiler that the variable is accessed by more than one thread at a time and inhibits inappropriate code optimizations by the compiler, such as caching the value of the variable in a CPU register instead of updating main memory with each assignment to the variable.

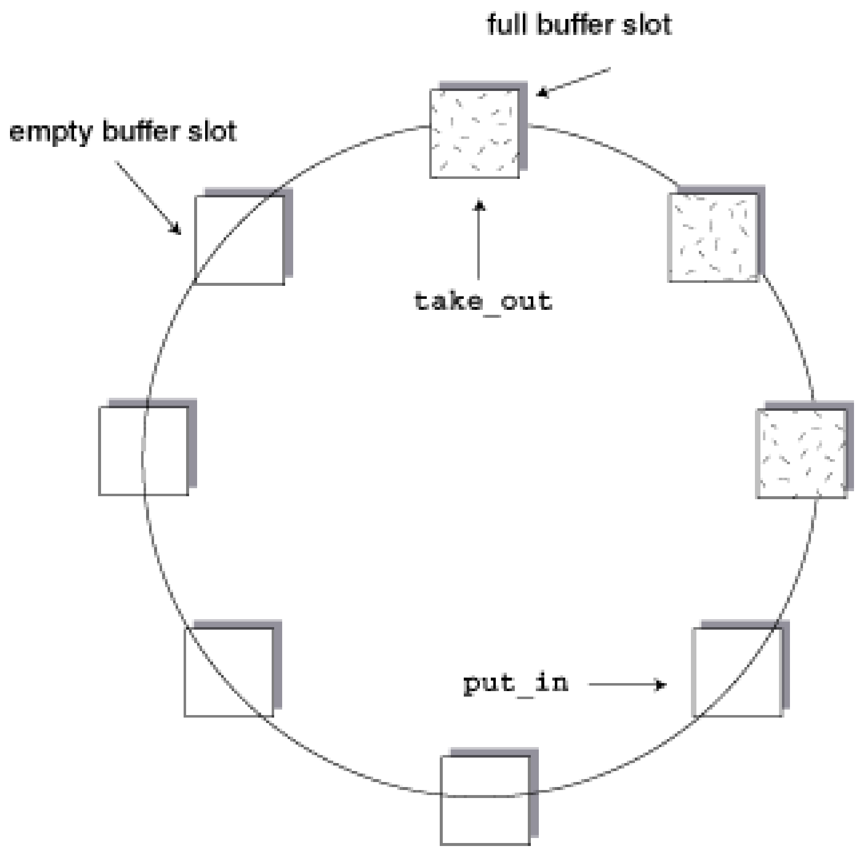
The *Java Language Specification* guarantees that updates to any one shared variable by a particular thread are seen by other threads in the order performed by that particular thread. However, the JLS does not require other threads to see updates to different shared variables in the order performed by the updating thread unless the variables are declared **`volatile`**.

Examples of the volatile modifier

Example bwbb.java on page 19 implements a busy waiting bounded buffer for a producer and consumer. The producer thread deposits items and busy waits if the bounded buffer fills up. The consumer thread fetches items and busy waits if the bounded buffer is empty.

The producer thread must "see" the **`value`** and **`occupied`** fields updated by the consumer thread in the exact order the updates are performed by the consumer thread (or the consumer must see the producer updates in the order performed). If not, the producer thread might overwrite an item in a buffer slot that the consumer has not yet read (or the consumer might read again an item from a buffer slot it has already read). Driver bbdr.java on page 20 creates the producer and consumer threads. Sample run of bwbb.java on page 22 shows the results of **`bwbb.java`**.

The figure below illustrates this interaction.



The next several panels display the code described in this section. To view the code, click **Next**; or you can go directly to the next section, Race conditions on page 24 , and return to the code samples at another time.

Example bwbb.java

```
class BufferItem {
   // multiple threads access so make these 'volatile'
   public volatile double value = 0;
   public volatile boolean occupied = false;
}
class BoundedBuffer {
   // designed for a single producer thread and
   // a single consumer thread
   private int numSlots = 0;
   private BufferItem[] buffer = null;
   private int putIn = 0, takeOut = 0;
   public BoundedBuffer(int numSlots) {
      if (numSlots <= 0)
         throw new IllegalArgumentException("numSlots <= 0");
      this.numSlots = numSlots;
      buffer = new BufferItem[numSlots];
      for (int i = 0; i < numSlots; i++)
         buffer[i] = new BufferItem();
   }
   public void deposit(double value)
         throws InterruptedException {
      while (buffer[putIn].occupied)  // busy wait
```

```
            Thread.currentThread().yield();
         buffer[putIn].value = value;
         buffer[putIn].occupied = true;
         putIn = (putIn + 1) % numSlots;
      }
      public double fetch()
            throws InterruptedException {
         double value;
         while (!buffer[takeOut].occupied)  // busy wait
            Thread.currentThread().yield();
         value = buffer[takeOut].value;
         buffer[takeOut].occupied = false;
         takeOut = (takeOut + 1) % numSlots;
         return value;
      }
   }
```

Driver bbdr.java

```
class Producer extends Sugar implements Runnable {
   private String name = null;
   private int pNap = 0; // milliseconds
   private BoundedBuffer bb = null;
   private Thread me = null;
   public Producer(String name, int pNap, BoundedBuffer bb) {
      this.name = name;
      this.pNap = pNap;
      this.bb = bb;
      (me = new Thread(this)).start();
   }
   public void timeToQuit() { me.interrupt(); }
   public void pauseTilDone() throws InterruptedException
      { me.join(); }
   public void run() {
      if (Thread.currentThread() != me) return;
      double item;
      int napping;
      while (true) {
         if (Thread.interrupted()) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted");
            return;
         }
         napping = 1 + (int) random(pNap);
         System.out.println("age=" + age() + ", " + name
            + " napping for " + napping + " ms");
         try { Thread.sleep(napping); }
         catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted from sleep");
            return;
         }
         item = random();
         System.out.println("age=" + age() + ", " + name
            + " produced item " + item);
         try { bb.deposit(item); }
         catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted from deposit");
            return;
         }
```

```
            System.out.println("age=" + age() + ", " + name
               + " deposited item " + item);
         }
      }
   }
   class Consumer extends Sugar implements Runnable {
      private String name = null;
      private int cNap = 0; // milliseconds
      private BoundedBuffer bb = null;
      private Thread me = null;
      public Consumer(String name, int cNap, BoundedBuffer bb) {
         this.name = name;
         this.cNap = cNap;
         this.bb = bb;
         (me = new Thread(this)).start();
      }
      public void timeToQuit() { me.interrupt(); }
      public void pauseTilDone() throws InterruptedException
         { me.join(); }
      public void run() {
         if (Thread.currentThread() != me) return;
         double item;
         int napping;
         while (true) {
            if (Thread.interrupted()) {
               System.out.println("age=" + age() + ", " + name
                  + " interrupted");
               return;
            }
            napping = 1 + (int) random(cNap);
            System.out.println("age=" + age() + ", " + name
               + " napping for " + napping + " ms");
            try { Thread.sleep(napping); }
            catch (InterruptedException e) {
               System.out.println("age=" + age() + ", " + name
                  + " interrupted from sleep");
               return;
            }
            System.out.println("age=" + age() + ", " + name
               + " wants to consume");
            try { item = bb.fetch(); }
            catch (InterruptedException e) {
               System.out.println("age=" + age() + ", " + name
                  + " interrupted from fetch");
               return;
            }
            System.out.println("age=" + age() + ", " + name
               + " fetched item " + item);
         }
      }
   }
   class ProducersConsumers extends Sugar {
      public static void main(String[] args) {
         int numSlots = 10;
         int numProducers = 1;
         int numConsumers = 1;
         int pNap = 2;       // defaults
         int cNap = 2;       // in
         int runTime = 60;   // seconds
         // following set true in srbb.java runs
         // so as not to try to join with a
         // suspended thread and thus deadlock
         boolean doJoin = true;
         try {
            numSlots = Integer.parseInt(args[0]);
```

```
         numProducers = Integer.parseInt(args[1]);
         numConsumers = Integer.parseInt(args[2]);
         pNap = Integer.parseInt(args[3]);
         cNap = Integer.parseInt(args[4]);
         runTime = Integer.parseInt(args[5]);
         doJoin = args[6].equals("yes");
      } catch (Exception e) { /* use defaults */ }
      System.out.println("ProducersConsumers:\n numSlots="
         + numSlots + ", numProducers=" + numProducers
         + ", numConsumers=" + numConsumers + ", pNap="
         + pNap + ", cNap=" + cNap + ", runTime=" + runTime);
      // create the bounded buffer
      BoundedBuffer bb = new BoundedBuffer(numSlots);
      // start the Producers and Consumers
      // (they have self-starting threads)
      Producer[] p = new Producer[numProducers];
      Consumer[] c = new Consumer[numConsumers];
      new PseudoTimeSlicing(); // for Solaris, not Windows 95/NT
      for (int i = 0; i < numProducers; i++)
         p[i] = new Producer("PRODUCER"+i, pNap*1000, bb);
      for (int i = 0; i < numConsumers; i++)
         c[i] = new Consumer("Consumer"+i, cNap*1000, bb);
      System.out.println("All threads started");
      // let them run for a while
      try {
         Thread.sleep(runTime*1000);
         System.out.println("age=" + age()
            + ", time to terminate the threads and exit");
         for (int i = 0; i < numProducers; i++)
            p[i].timeToQuit();
         for (int i = 0; i < numConsumers; i++)
            c[i].timeToQuit();
         Thread.sleep(1000);
         if (doJoin) {
            for (int i = 0; i < numProducers; i++)
               p[i].pauseTilDone();
            for (int i = 0; i < numConsumers; i++)
               c[i].pauseTilDone();
         } else
            System.out.println(" skipping pauseTilDone()");
      } catch (InterruptedException e) { /* ignored */ }
      System.out.println("age=" + age()
         + ", all threads are done");
      System.exit(0);
   }
}
```

Sample run of bwbb.java

```
% javac bwbb.java bbdr.java
% java ProducersConsumers 10 1 1 2 2 5
ProducersConsumers:
 numSlots=10, numProducers=1, numConsumers=1, pNap=2, cNap=2, runTime=5
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
age=47, PRODUCER0 napping for 1349 ms
age=66, Consumer0 napping for 201 ms
```

```
All threads started
age=286, Consumer0 wants to consume
age=1406, PRODUCER0 produced item 0.11775977233610768
age=1422, PRODUCER0 deposited item 0.11775977233610768
age=1423, PRODUCER0 napping for 1203 ms
age=1424, Consumer0 fetched item 0.11775977233610768
age=1426, Consumer0 napping for 39 ms
age=1475, Consumer0 wants to consume
age=2636, PRODUCER0 produced item 0.717652488961075
age=2637, PRODUCER0 deposited item 0.717652488961075
age=2638, PRODUCER0 napping for 143 ms
age=2640, Consumer0 fetched item 0.717652488961075
age=2641, Consumer0 napping for 1020 ms
age=2795, PRODUCER0 produced item 0.29972388090543556
age=2797, PRODUCER0 deposited item 0.29972388090543556
age=2798, PRODUCER0 napping for 1898 ms
age=3668, Consumer0 wants to consume
age=3668, Consumer0 fetched item 0.29972388090543556
age=3669, Consumer0 napping for 1046 ms
age=4708, PRODUCER0 produced item 0.5794441336470957
age=4709, PRODUCER0 deposited item 0.5794441336470957
age=4710, PRODUCER0 napping for 955 ms
age=4725, Consumer0 wants to consume
age=4726, Consumer0 fetched item 0.5794441336470957
age=4727, Consumer0 napping for 528 ms
age=5078, time to terminate the threads and exit
age=5081, PRODUCER0 interrupted from sleep
age=5082, Consumer0 interrupted from sleep
age=6088, all threads are done
```

Section 6. Race conditions

Some definitions

If two threads execute **`n=n+1`** on a shared variable **`n`** at about the same time, their load and store instructions might interleave so that one thread overwrites the update of the other.

This *lost update* leads to an erroneous result and is an example of a *race condition*. Race conditions are possible when two or more threads share data, they are reading and writing the shared data concurrently, and the final result of the computation depends on which one does what when.

Examples of race conditions

Example race.java on page 24 demonstrates a lost update in which**`sum=fn(sum,m)`** plays the role of **`n=n+1`**. Sample run of race.java on page 25 illustrates the results.

In Example rac2.java on page 25 , a race condition between an ATM thread and an Auditor thread in a bank exists. Sample run of rac2.java on page 26 shows the results.

Example srbb.java on page 27 shows we should not synchronize threads with**`suspend()`** and **`resume()`** because a race condition is possible. If we try to replace busy waiting with blocking in the bounded-buffer producer and consumer by having a thread suspend itself until resumed by the other thread, we run the risk of both the producer thread and the consumer thread becoming suspended, each waiting for the other to resume it.

Driver bbdr.java on page 20 creates the producer and consumer threads. Sample run of srbb.java on page 28 demonstrates a sample run.

The next several panels display the code described in this section. To view the code, click **Next**; or you can go directly to the next section, Synchronized blocks on page 30 , and return to the code samples at another time.

Example race.java

```
class Racer implements Runnable {
   // these two fields are shared by both threads since
   // there is only ONE object created from this class
   private int M = 0;
   private volatile long sum = 0;  // note `volatile'
   public Racer(int M) { this.M = M; }
   private long fn(long j, int k) {
      long total = j;
      for (int i = 1;  i <= k; i++) total += i;
      return total;
   }
   public void run() {
      for (int m = 1; m <= M; m++) sum = fn(sum, m);
      System.out.println("sum = " + sum);
   }
}
class Racing {
```

```
   public static void main(String[] args) {
      Racer racerObject = new Racer(2000);
      Thread racerThread1 = new Thread(racerObject);
      Thread racerThread2 = new Thread(racerObject);
      new PseudoTimeSlicing(); // for Solaris, not Windows 95/NT
      racerThread1.start();  racerThread2.start();
      try { racerThread1.join();  racerThread2.join(); }
      catch (InterruptedException e) { /* ignored */ }
   }
}
```

Sample run of race.java

```
% javac race.java
% java Racing
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
sum = 1335334000
sum = 1394734020
```

Example rac2.java

```
class SavingsAccount { public volatile int balance = 0; }
class ATM extends Sugar implements Runnable {
   private int numAccounts = 0;
   private SavingsAccount[] savingsAccount = null;
   public ATM(int numAccounts, SavingsAccount[] savingsAccount) {
      this.numAccounts = numAccounts;
      this.savingsAccount = savingsAccount;
   }
   public void run() {
      int fromAccount, toAccount, amount;
      while (true) {
         if (Thread.interrupted()) {
            System.out.println("age()=" + age()
               + ", ATM was interrupted");
            return;
         }
         fromAccount = (int) random(numAccounts);
         toAccount = (int) random(numAccounts);
         amount = 1 +
            (int) random(savingsAccount[fromAccount].balance);
         savingsAccount[fromAccount].balance -= amount;
         savingsAccount[toAccount].balance += amount;
      }
   }
}
class Auditor extends Sugar implements Runnable {
   private int numAccounts = 0;
   private SavingsAccount[] savingsAccount = null;
   public Auditor(int numAccounts, SavingsAccount[] savingsAccount) {
      this.numAccounts = numAccounts;
```

```
      this.savingsAccount = savingsAccount;
   }
   public void run() {
      int total;
      while (true) {
         try { Thread.sleep(1000); }
         catch (InterruptedException e) {
            System.out.println("age()=" + age()
            + ", Auditor interrupted from sleep");
            return;
         }
         total = 0;
         for (int i = 0; i < numAccounts; i++)
            total += savingsAccount[i].balance;
         System.out.println("age()=" + age()
            + ", total is $" + total);
         if (Thread.interrupted()) {
            System.out.println("age()=" + age()
               + ", Auditor was interrupted");
            return;
         }
      }
   }
}
class Bank extends Sugar {
   public static void main(String[] args) {
      int numAccounts = 100;
      int initialValue = 1000; // dollars
      SavingsAccount[] savingsAccount = null;
      try {
         numAccounts = Integer.parseInt(args[0]);
         initialValue = Integer.parseInt(args[1]);
      } catch (Exception e) { /* use defaults */ }
      savingsAccount = new SavingsAccount[numAccounts];
      for (int i = 0; i < numAccounts; i++) {
         savingsAccount[i] = new SavingsAccount();
         savingsAccount[i].balance = initialValue;
      }
      System.out.println("Bank open with " + numAccounts
         + " accounts, each starting with $" + initialValue);
      new PseudoTimeSlicing(); // for Solaris, not Windows 95/NT
      Thread atm = new Thread(
         new ATM(numAccounts, savingsAccount));
      Thread auditor = new Thread(
         new Auditor(numAccounts, savingsAccount));
      atm.start();  auditor.start();
      try {
         Thread.sleep(10000);
         atm.interrupt();  atm.join();
         Thread.sleep(3000);
         auditor.interrupt();  auditor.join();
      } catch (InterruptedException e) { /* ignored */ }
      System.exit(0);
   }
}
```

Sample run of rac2.java

```
% javac rac2.java
% java Bank
Bank open with 100 accounts, each starting with $1000
```

```
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
age()=1171, total is $100000
age()=2191, total is $100000
age()=3201, total is $100000
age()=4211, total is $100000
age()=5221, total is $100000
age()=6231, total is $100000
age()=7241, total is $100000
age()=8251, total is $100000
age()=9261, total is $99999
age()=10171, ATM was interrupted
age()=10271, total is $100000
age()=11283, total is $100000
age()=12291, total is $100000
age()=13182, Auditor interrupted from sleep
% java Bank 500000
Bank open with 500000 accounts, each starting with $1000
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
age()=10763, total is $499996968
age()=12418, total is $499992296
age()=14018, total is $499990606
age()=15669, total is $499986034
age()=17326, total is $500012696
age()=19020, total is $499974189
age()=19213, ATM was interrupted
age()=20968, total is $500000000
age()=23113, total is $500000000
age()=23114, Auditor was interrupted
```

Example srbb.java

```
class BufferItem {
   public volatile double value = 0;
   public volatile boolean occupied = false;
   public volatile Thread thread = null;
}
class BoundedBuffer {
   // designed for a single producer thread and
   // a single consumer thread
   private int numSlots = 0;
   private BufferItem[] buffer = null;
   private int putIn = 0, takeOut = 0;
   public BoundedBuffer(int numSlots) {
      if (numSlots <= 0)
         throw new IllegalArgumentException("numSlots <= 0");
      this.numSlots = numSlots;
      buffer = new BufferItem[numSlots];
      for (int i = 0; i < numSlots; i++)
         buffer[i] = new BufferItem();
   }
   public void deposit(double value)
```

```
         throws InterruptedException {
      if (buffer[putIn].occupied) {
         Thread producer = Thread.currentThread();
         buffer[putIn].thread = producer;
                              // context switch possible here
         producer.suspend();
         buffer[putIn].thread = null;
      }
      buffer[putIn].value = value;
      buffer[putIn].occupied = true;
      Thread consumer = buffer[putIn].thread;
      putIn = (putIn + 1) % numSlots;
      if (consumer != null) consumer.resume();
   }
   public double fetch()
         throws InterruptedException {
      double value;
      if (!buffer[takeOut].occupied) {
         Thread consumer = Thread.currentThread();
         buffer[takeOut].thread = consumer;
                              // context switch possible here
         consumer.suspend();
         buffer[takeOut].thread = null;
      }
      value = buffer[takeOut].value;
      buffer[takeOut].occupied = false;
      Thread producer = buffer[takeOut].thread;
      takeOut = (takeOut + 1) % numSlots;
      if (producer != null) producer.resume();
      return value;
   }
}
```

Sample run of srbb.java

```
% javac srbb.java bbdr.java
% java ProducersConsumers 10 1 1 2 2 5 no
ProducersConsumers:
 numSlots=10, numProducers=1, numConsumers=1, pNap=2, cNap=2, runTime=5
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
age=48, PRODUCER0 napping for 1549 ms
age=67, Consumer0 napping for 1861 ms
All threads started
age=1609, PRODUCER0 produced item 0.37648945305426074
age=1625, PRODUCER0 deposited item 0.37648945305426074
age=1626, PRODUCER0 napping for 974 ms
age=1949, Consumer0 wants to consume
age=1950, Consumer0 fetched item 0.37648945305426074
age=1952, Consumer0 napping for 381 ms
age=2347, Consumer0 wants to consume
age=2617, PRODUCER0 produced item 0.7493684193792439
age=2618, Consumer0 fetched item 0.7493684193792439
age=2619, Consumer0 napping for 377 ms
age=2638, PRODUCER0 deposited item 0.7493684193792439
age=2640, PRODUCER0 napping for 1014 ms
age=3009, Consumer0 wants to consume
```

```
age=3667, PRODUCER0 produced item 0.8117997960074402
age=3668, Consumer0 fetched item 0.8117997960074402
age=3669, Consumer0 napping for 365 ms
age=3686, PRODUCER0 deposited item 0.8117997960074402
age=3688, PRODUCER0 napping for 484 ms
age=4048, Consumer0 wants to consume
age=4187, PRODUCER0 produced item 0.8961043263431506
age=4188, Consumer0 fetched item 0.8961043263431506
age=4189, Consumer0 napping for 675 ms
age=4207, PRODUCER0 deposited item 0.8961043263431506
age=4208, PRODUCER0 napping for 504 ms
age=4727, PRODUCER0 produced item 0.34322613800540913
age=4728, PRODUCER0 deposited item 0.34322613800540913
age=4729, PRODUCER0 napping for 1195 ms
age=4877, Consumer0 wants to consume
age=4877, Consumer0 fetched item 0.34322613800540913
age=4878, Consumer0 napping for 19 ms
age=4906, Consumer0 wants to consume
age=5077, time to terminate the threads and exit
age=5098, PRODUCER0 interrupted from sleep
 skipping pauseTilDone()
age=6087, all threads are done
```

Section 7. Synchronized blocks

Object locks

Every Java object has a lock. A *synchronized block* uses an object's lock to act like a binary semaphore with the initial value "1", solving the mutual exclusion critical section problem:

```
Object obj = new Object();
   ...
synchronized (obj) {  // in a method
   ... // any code, e.g., critical section
}
```

The construct:

```
   ... synchronized method(...) {
      ...   // body of method
   }
```

is an abbreviation for:

```
   ... method(...) {
      synchronized (this) {
         ...   // body of method
      }
   }
```

That is, the entire body of the instance method is a synchronized block on the object (keyword **`this`**) the method is in.

The JLS does not guarantee that the thread that has waited the longest to lock an object will be the next to obtain the lock when the object is unlocked.

Examples of synchronized blocks

Example parp.java on page 31 offers multithreaded prime number generation with a fixed number of threads (using Class Prime.java on page 7). Sample run of parp.java on page 31 shows the results.

In Example norc.java on page 32 , only one thread at a time is allowed to execute **`sum=fn(sum,m)`**. Sample run of norc.java on page 32 demonstrates the sample run.

The next several panels contain an exercise and display the code described in this section. To view the exercise and code, click **Next**; or you can go directly to the next section, Monitors on page 33 , and return to the code samples at another time.

Try this exercise

Use a synchronized block to eliminate the race condition in Example rac2.java on page 25 .

Example parp.java

```
class ParallelPrimes implements Runnable {
   private static int n1, n2, nChecked, nThreads, next;
   private static boolean[] taken, isPrime;
   private Object mutex = this; // or = new Object();
   public void run() {
      int mine = 0;
      while (true) {
         synchronized (mutex) {
            while (next < nChecked && taken[next]) next++;
            mine = next;
            if (mine >= nChecked) return;
            taken[mine] = true;
         }
         if (Prime.prime(n1 + mine)) isPrime[mine] = true;
      }
   }
   public static void main(String[] args) {
      try {
         n1 = Integer.parseInt(args[0]);
         n2 = Integer.parseInt(args[1]);
         nThreads = Integer.parseInt(args[2]);
      } catch (NumberFormatException e) {
         System.out.println("improper format");
         System.exit(1);
      } catch (ArrayIndexOutOfBoundsException e) {
         System.out.println("not enough command line arguments");
         System.exit(1);
      }
      System.out.println("printing primes from " + n1 + " to "
         + n2 + " using " + nThreads + " threads");
      nChecked = n2 - n1 + 1;
      if (nChecked < 1 || nThreads > nChecked) {
         System.out.println("bad command line arguments");
         System.exit(1);
      }
      taken = new boolean[nChecked];
      isPrime = new boolean[nChecked];
      for (int i = 0; i < nChecked; i++)
         taken[i] = isPrime[i] = false;
      next = 0;
      Thread[] t = new Thread[nThreads];
      // All threads execute inside the SAME object and thus
      // SHARE all data.
      Runnable a = new ParallelPrimes();
      for (int i = 0; i < nThreads; i++) t[i] = new Thread(a);
      new PseudoTimeSlicing(); // for Solaris, not Windows 95/NT
      for (int i = 0; i < nThreads; i++) t[i].start();
      try {
         for (int i = 0; i < nThreads; i++) t[i].join();
      } catch (InterruptedException e) { /* ignored */ }
      for (int i = 0; i < nChecked; i++)
         if (isPrime[i])
            System.out.println((n1 + i)  + " is prime");
   }
}
```

Sample run of parp.java

```
% javac parp.java
% java ParallelPrimes 1000000 1000060 5
printing primes from 1000000 to 1000060 using 5 threads
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
1000003 is prime
1000033 is prime
1000037 is prime
1000039 is prime
```

Example norc.java

```
class Racer implements Runnable {
   // these two fields are shared by both threads since
   // there is only ONE object created from this class
   private int M = 0;
   private long sum = 0;  // `volatile' no longer needed
   public Racer(int M) { this.M = M; }
   private long fn(long j, int k) {
      long total = j;
      for (int i = 1;  i <= k; i++) total += i;
      return total;
   }
   public void run() {
      for (int m = 1; m <= M; m++)
         synchronized (this) { // entry protocol
            sum = fn(sum, m);  // critical section
         }                     // exit protocol
      System.out.println("sum = " + sum);
   }
}
```

Sample run of norc.java

```
% javac norc.java
% java Racing
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
sum = 1335334000
sum = 2670668000
```

Section 8. Monitors

Monitor structure and properties

Every Java object possesses a lock and these methods: **wait()**, **notify()**, and **notifyAll()**.

A thread invoking a **synchronized** method must acquire the lock of the object containing the method before executing the method's code. The thread blocks if the object is already locked.

A *monitor* has the following structure or pattern:

```
class Monitor extends ... {
   private ...  // data fields (state variables)
   Monitor(...) {...}  // constructor
   public synchronized type method1(...)
         throws InterruptedException {
      ...
      notifyAll(); // if any wait conditions altered
      while (!condition1) wait();
      ...
      notifyAll(); // if any wait conditions altered
   }
   public synchronized type method2(...)
         throws InterruptedException {
      ...
      notifyAll(); // if any wait conditions altered
      while (!condition2) wait();
      ...
      notifyAll(); // if any wait conditions altered
   }
   ...
}
```

A Java thread is *interrupted* when its **interrupt()** method is called by another thread. This call sets a flag in the interrupted thread that the latter can check periodically, allowing one thread to tell another thread to stop itself or return allocated resources if it is not in the middle of some critical operation. (A thread should check its interrupt flag before or after such operations and take appropriate action when interrupted.)

Note the following important points:

* The thread blocked the longest on a monitor **synchronized** method call is not guaranteed to be the next thread to acquire the monitor lock when the monitor lock is released.

* The thread blocked the longest in a monitor **wait()** call is not guaranteed to be the one removed from the wait set when a **notify()** is done by some other thread in the monitor.

* The signaling discipline is signal-and-continue so *barging* is possible -- a thread waiting for the monitor lock to execute a monitor **synchronized** method might get the lock before a signaled thread re-acquires it, even if the **notify()** occurred earlier than the monitor method call. Thus:

```
while (!condition) ... wait() ... notifyAll()
```

is safer than:

```
if (!condition) ... wait() ... notify()
```

* Each monitor object has a single nameless anonymous condition variable. We cannot signal with **`notify()`** one of several threads waiting on a specific condition. It is safer to use **`notifyAll()`** to awaken all waiting threads so they can recheck their waiting conditions.

* A **`notifyAll()`** needs to be done by a thread before a **`wait()`** if any state variables were altered by the thread after entering the monitor, which might affect other thread-waiting conditions. This also applies before leaving the monitor (returning from the method).

* The data fields in a monitor need not be declared **`volatile`** because all writes to shared variables by a thread are completed before obtaining and before releasing the monitor lock.

* If a thread that is blocked inside a call to **`sleep(`*`ms`*`)`**, **`join()`**, or **`wait()`** is interrupted, then these methods clear the thread's interrupt flag and throw an **`InterruptedException`** instead of returning normally. Note that no exception is thrown if a thread is interrupted while blocked waiting to acquire a monitor's lock to execute a synchronized method.

* In contrast, **`InterruptedException`** *is* thrown by **`wait()`** if a thread that has been notified is interrupted while blocked and waiting to reacquire the monitor lock. If an **`InterruptedException`** occurs while a thread is in **`wait()`**, the thread must reacquire the monitor lock before executing the code in the **`catch`** block.

* Ignoring **`InterruptedException`**, as in:

```
     while (!condition) try {  wait(); }
        catch (InterruptedException e) { }
```

is undesirable. The enclosing method should throw the exception back to the caller.

* The following code:

```
     if (!condition) try {  wait(); }
        catch (InterruptedException e) { }
```

is incorrect because a thread interrupted out of its **`wait()`** then re-enters the monitor without being notified.

* When a call to **`wait(`*`milliseconds`*`)`** returns, the program cannot tell for sure if the wait was notified or if the wait timed out after the number of milliseconds elapsed.

* In some situations, we can use **`notify()`** instead of **`notifyAll()`** and **`if ... wait()`** instead of **`while ... wait()`**. However, it is *extremely* tricky and not recommended because of a race condition between **`interrupt()`** and **`notify()`**.

Suppose several threads are blocked inside **`wait()`** and then one of them is notified and then interrupted before it reacquires the monitor lock. The **`notify()`** gets "lost" in that one of the other waiting threads should now proceed. We need to catch the exception when a thread is interrupted out of **`wait()`** and regenerate the **`notify()`**.

* It is usually wrong to **`Thread.sleep(`*`ms`*`)`** while inside a monitor object holding the lock (during a synchronized method invocation). Other threads wanting to enter the monitor will block to acquire the monitor object's lock and they cannot be interrupted from this state.

  It is better to set a flag and leave the monitor; other threads can then **`wait()`** for the flag to change. No thread holds the monitor's lock for any longer than to set or check this flag.

As the following examples show, monitors can be used to synchronize threads that request resources from and return resources to a server. This is called a *client/server* relationship.

The clients interact with the server but not with each other. The server monitor is a passive object in the sense that no independent thread executes inside it; the code in the monitor is executed only when a monitor method is invoked by a client thread.

Monitors can be awkward to use if the threads have a relationship other than a client/server one.

Background material on monitors

Semaphores are like gotos and pointers -- they work okay but are error prone and lack structure and "discipline."

For example, a disastrous typo such as:

V(S); criticalSection(); V(S)

can lead to deadlock:

P(S); criticalSection(); P(S).

Nested critical sections can also lead to deadlock:

P1: P(Q); P(S); ... V(S); V(Q);

P2: P(S); P(Q); ... V(Q); V(S);

A *monitor* is an object with some built-in mutual exclusion and thread-synchronization capabilities. Monitors are an integral part of the programming language so the compiler can generate the correct code to implement the monitor. Only one thread can be active at a time in the monitor ("active" meaning executing a method of the monitor).

Monitors also have *condition variables* on which a thread can *wait* if conditions are not right for it to continue executing in the monitor. Some other thread can then get in the monitor and perhaps change the state of the monitor. If conditions are now right, that thread can *signal* a waiting thread, moving the latter to the ready queue to get back into the monitor when it becomes free.

Monitors can use either a *signal-and-exit* or *signal-and-continue* signaling discipline. In *signal-and-exit* , a signaling thread must leave the monitor immediately, at which point it is guaranteed that the signaled thread is the next one in the monitor.

In *signal-and-continue* , the signaled thread is not guaranteed to be the next one in the monitor. In fact, *barging* can take place -- some thread that has called a monitor method and is blocked until the monitor is free can get into the monitor before a signaled thread.

Semaphores and monitors can be used to solve the so-called "classical" synchronization problems found in many operating systems books: the *sleeping barber*, the five *dining philosophers*, and the database *readers and writers*.

The sleeping barber. A barber waits to cut hair. Customers enter the waiting room and take a seat if one is available. If the waiting room is full, they try again later. Otherwise, they wait until their turn for a hair cut.

Five dining philosophers. Five philosophers sit around a table and think until hungry. Between each is a fork (for a total of five forks). To eat, a hungry philosopher must have exclusive access to both the fork on his left and right. If both forks are not free, the philosopher waits.

The algorithm in Example dpmo.java on page 39 does not deadlock (it never happens that all philosophers are hungry, each holding one fork and waiting for the other), allows maximal parallelism (a philosopher never picks up and holds a fork while waiting for the other fork to become available when the fork he is holding could be used for eating by its neighbor), but also allows starvation (a philosopher's two neighbors can collaborate and alternate their eating so the one in the middle never can use the forks).

If a philosopher can hold a fork while waiting for the other fork, deadlock is possible, an extreme case of not having maximal parallelism. However, starvation is not possible. Each fork is represented by a semaphore and each hungry philosopher does a "P" on its left fork and then its right fork.

We can fix the deadlock problem and retain no starvation, but we still do not have maximal parallelism. All philosophers pick up left then right except one designated philosopher who picks up right then left.

Philosopher starvation can also be prevented by introducing a new state: very hungry. A philosopher is put into this state if he is hungry, if one of his neighbors puts down his forks, and if he cannot eat because the other fork is in use. A new rule is added -- a hungry philosopher cannot eat if he has a very hungry neighbor. These changes prevent a collaboration of two philosophers trying to starve the philosopher between them.

Readers and writers. A database can be accessed concurrently by threads that only want to read, but a writer thread must have exclusive access with respect to other readers and writers.

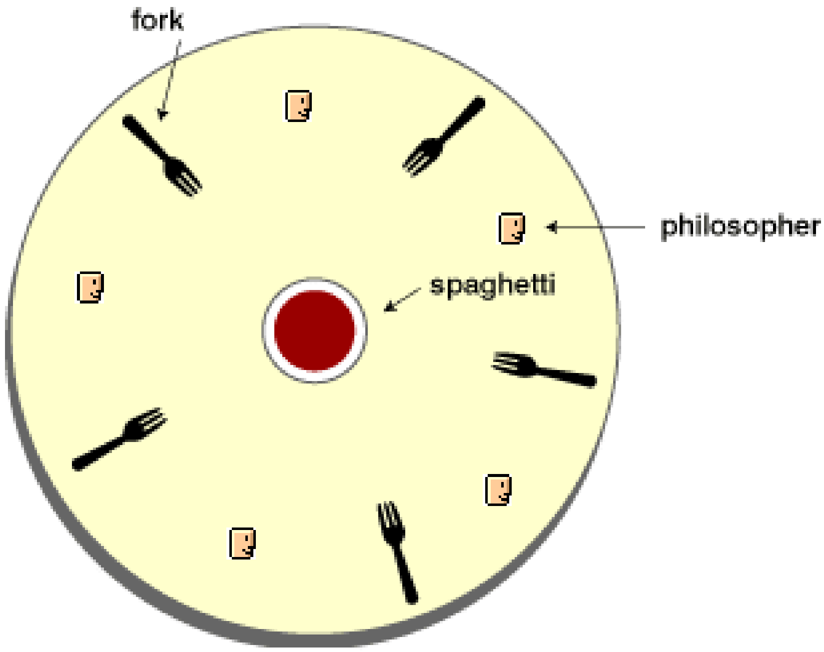
A solution might allow writers to starve if enough readers keep coming along to read the database so that the number of current readers is always above zero.

Writer starvation is prevented by requiring readers that come along to read the database to wait if there is a waiting writer even if other readers are currently reading the database. When the current readers finish, the waiting writer writes the database and then signals into the database a waiting reader. Each entering reader signals another waiting reader into the database.

Examples of monitors

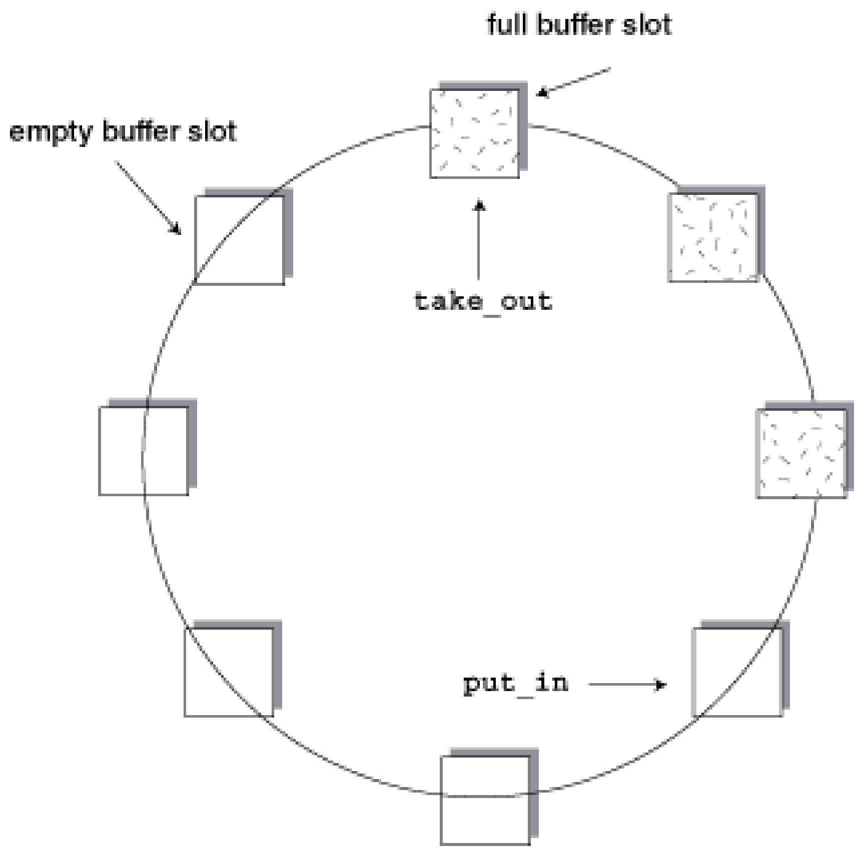
Example dpmo.java on page 39 illustrates the dining philosophers monitor. Five philosophers sit around a table and think until hungry. Between each pair of philosophers is one fork. A hungry philosopher must have exclusive simultaneous access to both its left and right forks in order to eat. If they are not both free, the philosopher waits. Driver dpdr.java on page 40 creates the philosopher threads. Sample run of dpmo.java on page 42 shows the sample run.

The figure below illustrates the dining philosophers monitor.



Example bbmo.java on page 42 shows a bounded buffer monitor for a producer and consumer. Multiple producer threads and multiple consumer threads are handled. A producer thread deposits items and blocks if the bounded buffer fills up. A consumer thread fetches items and blocks if the bounded buffer is empty. Driver bbdr.java on page 20 creates the producer and consumer threads. Sample run of bbmo.java on page 43 shows the sample run.

The figure below illustrates the bounded buffer monitor for a producer and consumer, handling multiple producer and consumer threads.

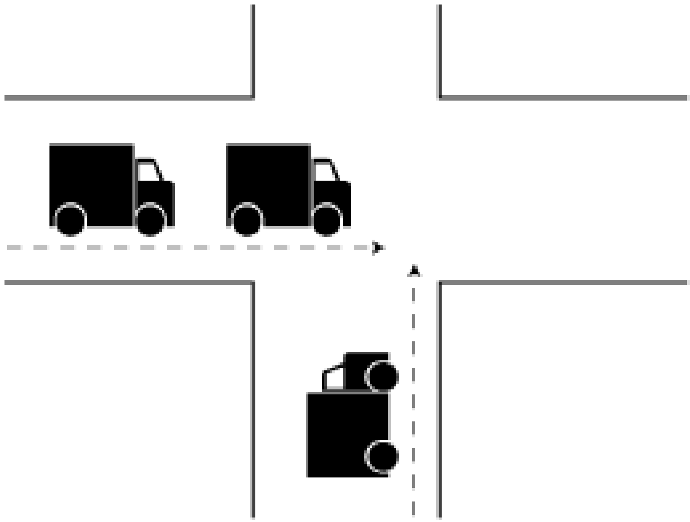


Example inmo.java on page 44 simulates cars crossing at an intersection of two one-way streets so that:

* Only one car can cross at a time
* A car can cross if there are no cars on the intersecting street waiting to cross
* If two cars approach the intersection at about the same time, one of them will cross (no deadlock)
* If there are cars on the intersecting streets waiting to cross, then cars from the intersecting streets take turns to prevent starvation

Driver indr.java on page 45 creates the car threads.Sample run of inmo.java on page 47 shows the results.

The following figure illustrates cars crossing at an intersection of two one-way streets.



The next several panels contain exercises and display the code described in this section. To view the exercises and code, click **Next**; or you can go directly to the next section, Semaphores on page 50 , and return to the code samples at another time.

Try these exercises

Exercise 1: Write a monitor for the database readers and writers problem. Multiple reader threads can read the database simultaneously, but writer threads must have exclusive access with respect to other reader and writer threads.

Exercise 2: Write a barrier monitor. Threads wait until all threads arrive at the barrier, then they are all released.

Exercise 3: When a **`notify()`** or **`notifyAll()`** is done inside a Java monitor, the next thread to get inside the monitor (acquire the lock) is arbitrary. Therefore, the cars in the intersection simulation going in the same direction do not necessarily go through the intersection in the order they arrived at it (it is not FCFS). Fix this.

Example dpmo.java

```
class DiningServer extends Sugar {
   private int numPhils = 0;
   private int[] state = null;
   private static final int THINKING = 0, HUNGRY = 1, EATING = 2;
   public DiningServer(int numPhils) {
      this.numPhils = numPhils;
      state = new int[numPhils];
      for (int i = 0; i < numPhils; i++) state[i] = THINKING;
   }
   public void dine(String name, int id, int napEat)
         throws InterruptedException {
      try {
         takeForks(id);
         eat(name, napEat);
```

```
      } finally {       // Make sure we return the
         putForks(id);  // forks if interrupted
      }
   }
   private final int left(int i)
      { return (numPhils + i - 1) % numPhils;}
   private final int right(int i)
      { return (i + 1) % numPhils; }
   private void test(int k) {
      if (state[left(k)] != EATING && state[k] == HUNGRY &&
            state[right(k)] != EATING)
         state[k] = EATING;
   }
   private void eat(String name, int napEat)
         throws InterruptedException {
      int napping;
      napping = 1 + (int) random(napEat);
      System.out.println("age=" + age() + ", " + name
         + " is eating for " + napping + " ms");
      Thread.sleep(napping);
   }
   private synchronized void takeForks(int i)
         throws InterruptedException {
      state[i] = HUNGRY;  test(i);
      while (state[i] != EATING) wait();
   }
   private synchronized void putForks(int i) {
      if (state[i] != EATING) return;
      state[i] = THINKING;
      test(left(i));  test(right(i));
      notifyAll();
   }
}
```

Driver dpdr.java

```
class Philosopher extends Sugar implements Runnable {
   private String name = null;
   private int id = 0;
   private int napThink = 0; // both are in
   private int napEat = 0;   // milliseconds
   private DiningServer ds = null;
   private Thread me = null;
   public Philosopher(int id, int napThink, int napEat,
         DiningServer ds) {
      this.name = "Philosopher " + id;
      this.id = id;
      this.napThink = napThink;
      this.napEat = napEat;
      this.ds = ds;
      (me = new Thread(this)).start();
   }
   public void timeToQuit() { me.interrupt(); }
   public void pauseTilDone() throws InterruptedException
      { me.join(); }
   private void think() throws InterruptedException {
      int napping;
      napping = 1 + (int) random(napThink);
      System.out.println("age=" + age() + ", " + name
         + " is thinking for " + napping + " ms");
      Thread.sleep(napping);
```

```
    }
    public void run() {
       if (Thread.currentThread() != me) return;
       while (true) {
          if (Thread.interrupted()) {
             System.out.println("age=" + age() + ", " + name
                + " interrupted");
             return;
          }
          try {
             think();
          } catch (InterruptedException e) {
             System.out.println("age=" + age() + ", " + name
                + " interrupted out of think");
             return;
          }
          System.out.println("age=" + age() + ", " + name
             + " wants to dine");
          try {
             ds.dine(name, id, napEat);
          } catch (InterruptedException e) {
             System.out.println("age=" + age() + ", " + name
                + " interrupted out of dine");
             return;
          }
       }
    }
 }
 class DiningPhilosophers extends Sugar {
    public static void main(String[] args) {
       int numPhilosophers = 5;
       int runTime = 60;      // seconds
       int napThink = 8, napEat = 2;
       try {
          numPhilosophers = Integer.parseInt(args[0]);
          runTime = Integer.parseInt(args[1]);
          napThink = Integer.parseInt(args[2]);
          napEat = Integer.parseInt(args[3]);
       } catch (Exception e) { /* use defaults */ }
       System.out.println("DiningPhilosophers: numPhilosophers="
          + numPhilosophers + ", runTime=" + runTime
          + ", napThink=" + napThink + ", napEat=" + napEat);
       // create the DiningServer object
       DiningServer ds = new DiningServer(numPhilosophers);
       // create the Philosophers
       // (they have self-starting threads)
       Philosopher[] p = new Philosopher[numPhilosophers];
       for (int i = 0; i < numPhilosophers; i++) p[i] =
          new Philosopher(i, napThink*1000, napEat*1000, ds);
       System.out.println("All Philosopher threads started");
       // let the Philosophers run for a while
       try {
          Thread.sleep(runTime*1000);
          System.out.println("age=" + age()
             + ", time to terminate the Philosophers and exit");
          for (int i = 0; i < numPhilosophers; i++)
             p[i].timeToQuit();
          Thread.sleep(1000);
          for (int i = 0; i < numPhilosophers; i++)
             p[i].pauseTilDone();
       } catch (InterruptedException e) { /* ignored */ }
       System.out.println("age=" + age()
          + ", all Philosophers are done");
       System.exit(0);
    }
```

```
}
```

Sample run of dpmo.java

```
% javac dpmo.java dpdr.java
% java DiningPhilosophers 5 6 4 1
DiningPhilosophers: numPhilosophers=5, runTime=6, napThink=4, napEat=1
age=37, Philosopher 0 is thinking for 2952 ms
age=56, Philosopher 1 is thinking for 3012 ms
age=59, Philosopher 2 is thinking for 508 ms
age=61, Philosopher 3 is thinking for 456 ms
All Philosopher threads started
age=63, Philosopher 4 is thinking for 120 ms
age=186, Philosopher 4 wants to dine
age=187, Philosopher 4 is eating for 205 ms
age=406, Philosopher 4 is thinking for 839 ms
age=525, Philosopher 3 wants to dine
age=526, Philosopher 3 is eating for 107 ms
age=575, Philosopher 2 wants to dine
age=646, Philosopher 2 is eating for 111 ms
age=646, Philosopher 3 is thinking for 1746 ms
age=776, Philosopher 2 is thinking for 3522 ms
age=1258, Philosopher 4 wants to dine
age=1259, Philosopher 4 is eating for 861 ms
age=2136, Philosopher 4 is thinking for 3759 ms
age=2406, Philosopher 3 wants to dine
age=2406, Philosopher 3 is eating for 878 ms
age=3008, Philosopher 0 wants to dine
age=3009, Philosopher 0 is eating for 881 ms
age=3086, Philosopher 1 wants to dine
age=3296, Philosopher 3 is thinking for 546 ms
age=3855, Philosopher 3 wants to dine
age=3856, Philosopher 3 is eating for 648 ms
age=3908, Philosopher 0 is thinking for 2945 ms
age=3909, Philosopher 1 is eating for 102 ms
age=4026, Philosopher 1 is thinking for 3699 ms
age=4316, Philosopher 2 wants to dine
age=4516, Philosopher 2 is eating for 10 ms
age=4517, Philosopher 3 is thinking for 414 ms
age=4536, Philosopher 2 is thinking for 1593 ms
age=4947, Philosopher 3 wants to dine
age=4948, Philosopher 3 is eating for 898 ms
age=5856, Philosopher 3 is thinking for 687 ms
age=5905, Philosopher 4 wants to dine
age=5906, Philosopher 4 is eating for 516 ms
age=6066, time to terminate the Philosophers and exit
age=6069, Philosopher 1 interrupted out of think
age=6070, Philosopher 2 interrupted out of think
age=6071, Philosopher 4 interrupted out of dine
age=6073, Philosopher 3 interrupted out of think
age=6086, Philosopher 0 interrupted out of think
age=7076, all Philosophers are done
```

Example bbmo.java

```
class BoundedBuffer {
```

```
   // designed for multiple producer threads and
   // multiple consumer threads
   private int numSlots = 0;
   private double[] buffer = null;
   private int putIn = 0, takeOut = 0;
   private int count = 0;
   public BoundedBuffer(int numSlots) {
      if (numSlots <= 0)
         throw new IllegalArgumentException("numSlots <= 0");
      this.numSlots = numSlots;
      buffer = new double[numSlots];
   }
   public synchronized void deposit(double value)
         throws InterruptedException {
      while (count == numSlots) wait();
      buffer[putIn] = value;
      putIn = (putIn + 1) % numSlots;
      count++;     // wake up all those waiting due to
      notifyAll(); // signal-and-continue and barging
   }
   public synchronized double fetch()
         throws InterruptedException {
      double value;
      while (count == 0) wait();
      value = buffer[takeOut];
      takeOut = (takeOut + 1) % numSlots;
      count--;     // wake up all those waiting due to
      notifyAll(); // signal-and-continue and barging
      return value;
   }
}
```

Sample run of bbmo.java

```
% javac bbmo.java bbdr.java
% java ProducersConsumers 10 2 3 2 3 6
ProducersConsumers:
 numSlots=10, numProducers=2, numConsumers=3, pNap=2, cNap=3, runTime=6
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
age=42, PRODUCER0 napping for 1248 ms
age=61, PRODUCER1 napping for 1702 ms
age=65, Consumer0 napping for 226 ms
age=67, Consumer1 napping for 94 ms
All threads started
age=69, Consumer2 napping for 2504 ms
age=171, Consumer1 wants to consume
age=301, Consumer0 wants to consume
age=1303, PRODUCER0 produced item 0.5251246705209369
age=1319, PRODUCER0 deposited item 0.5251246705209369
age=1320, PRODUCER0 napping for 889 ms
age=1321, Consumer0 fetched item 0.5251246705209369
age=1323, Consumer0 napping for 1049 ms
age=1781, PRODUCER1 produced item 0.9915848089197059
age=1782, PRODUCER1 deposited item 0.9915848089197059
age=1783, PRODUCER1 napping for 297 ms
age=1784, Consumer1 fetched item 0.9915848089197059
```

```
age=1785, Consumer1 napping for 1253 ms
age=2093, PRODUCER1 produced item 0.4866393343763298
age=2094, PRODUCER1 deposited item 0.4866393343763298
age=2095, PRODUCER1 napping for 1018 ms
age=2221, PRODUCER0 produced item 0.40569282834803577
age=2222, PRODUCER0 deposited item 0.40569282834803577
age=2223, PRODUCER0 napping for 974 ms
age=2380, Consumer0 wants to consume
age=2381, Consumer0 fetched item 0.4866393343763298
age=2382, Consumer0 napping for 1531 ms
age=2580, Consumer2 wants to consume
age=2581, Consumer2 fetched item 0.40569282834803577
age=2582, Consumer2 napping for 2197 ms
age=3051, Consumer1 wants to consume
age=3123, PRODUCER1 produced item 0.9581218200181911
age=3124, PRODUCER1 deposited item 0.9581218200181911
age=3125, PRODUCER1 napping for 1125 ms
age=3126, Consumer1 fetched item 0.9581218200181911
age=3127, Consumer1 napping for 2387 ms
age=3211, PRODUCER0 produced item 0.9155450402123771
age=3212, PRODUCER0 deposited item 0.9155450402123771
age=3213, PRODUCER0 napping for 118 ms
age=3340, PRODUCER0 produced item 0.2431689653301975
age=3342, PRODUCER0 deposited item 0.2431689653301975
age=3343, PRODUCER0 napping for 235 ms
age=3590, PRODUCER0 produced item 0.06587542278093239
age=3592, PRODUCER0 deposited item 0.06587542278093239
age=3593, PRODUCER0 napping for 1014 ms
age=3931, Consumer0 wants to consume
age=3931, Consumer0 fetched item 0.9155450402123771
age=3932, Consumer0 napping for 1100 ms
age=4261, PRODUCER1 produced item 0.2895572679671733
age=4262, PRODUCER1 deposited item 0.2895572679671733
age=4263, PRODUCER1 napping for 1776 ms
age=4624, PRODUCER0 produced item 0.08728828492428509
age=4625, PRODUCER0 deposited item 0.08728828492428509
age=4626, PRODUCER0 napping for 446 ms
age=4790, Consumer2 wants to consume
age=4791, Consumer2 fetched item 0.2431689653301975
age=4792, Consumer2 napping for 2471 ms
age=5041, Consumer0 wants to consume
age=5041, Consumer0 fetched item 0.06587542278093239
age=5042, Consumer0 napping for 1068 ms
age=5081, PRODUCER0 produced item 0.8313015436389664
age=5082, PRODUCER0 deposited item 0.8313015436389664
age=5083, PRODUCER0 napping for 1416 ms
age=5521, Consumer1 wants to consume
age=5521, Consumer1 fetched item 0.2895572679671733
age=5522, Consumer1 napping for 2887 ms
age=6051, PRODUCER1 produced item 0.14766226608250066
age=6052, PRODUCER1 deposited item 0.14766226608250066
age=6053, PRODUCER1 napping for 534 ms
age=6071, time to terminate the threads and exit
age=6074, PRODUCER1 interrupted from sleep
age=6075, Consumer0 interrupted from sleep
age=6077, Consumer2 interrupted from sleep
age=6078, Consumer1 interrupted from sleep
age=6091, PRODUCER0 interrupted from sleep
age=7081, all threads are done
```

Example inmo.java

```
class Intersection extends Sugar {
   public static final int LEFT = 0, RIGHT = 1;
   private int[] waiting = {0, 0};
   private int lastToCross = 0;
   private boolean crossing = false;
   public String how(int direction) {
      if (direction == LEFT) return "left";
      else if (direction == RIGHT) return "right";
      else return "invalid";
   }
   public void crossIntersection
         (String name, int direction, int cNap)
         throws InterruptedException {
      wantToCross(direction);
      try {
         cross(name, direction, cNap);
      } finally {
      // If we are interrupted while crossing, we must do this.
         doneCrossing();
      }
   }
   private int other(int direction) {
      if (direction == LEFT) return RIGHT;
      else if (direction == RIGHT) return LEFT;
      else return -1;
   }
   private synchronized void wantToCross (int direction)
         throws InterruptedException {
      waiting[direction]++;
      try {
         while (crossing || (waiting[other(direction)] > 0
            && lastToCross == direction))
               wait();
         lastToCross = direction;
         crossing = true;
      } finally {                // If we are interrupted while
         waiting[direction]--;   // waiting to cross, do this.
      }
   }
   private void cross(String name, int direction, int cNap)
         throws InterruptedException {
      int napping;
      napping = 1 + (int) random(cNap);
      System.out.println("age=" + age() + ", " + name
         + " CROSSING " + how(direction) + " for "
         + napping + " ms");
      Thread.sleep(napping);
   }
   private synchronized void doneCrossing () {
      crossing = false;
      notifyAll();
   }
}
```

Driver indr.java

```
class Car extends Sugar implements Runnable {
   private String name = null;
   private int dNap = 0; // milliseconds
   private int cNap = 0; // milliseconds
   private int direction;
```

```
   private Intersection in = null;
   private Thread me = null;
   public Car(String name, int dNap, int cNap,
         int direction, Intersection in) {
      this.name = name;
      this.dNap = dNap;
      this.cNap = cNap;
      this.direction = direction;
      this.in = in;
      (me = new Thread(this)).start();
   }
   public void timeToQuit() { me.interrupt(); }
   public void pauseTilDone() throws InterruptedException
      { me.join(); }
   public void run() {
      if (Thread.currentThread() != me) return;
      int napping;
      while (true) {
         if (Thread.interrupted()) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted");
            return;
         }
         napping = 1 + (int) random(dNap);
         System.out.println("age=" + age() + ", " + name
            + " napping for " + napping + " ms");
         try { Thread.sleep(napping); }
         catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted from sleep");
            return;
         }
         System.out.println("age=" + age() + ", " + name
            + " wants to cross " + in.how(direction));
         try { in.crossIntersection(name, direction, cNap); }
         catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted from crossing");
            return;
         }
         System.out.println("age=" + age() + ", " + name
            + " crossed " + in.how(direction));
      }
   }
}
class LeftRightCars extends Sugar {
   public static void main(String[] args) {
      int numLefts = 3;
      int numRights = 3;
      int lNap = 2;       // defaults
      int rNap = 2;       // are
      int cNap = 2;       // in
      int runTime = 60;   // seconds
      try {
         numLefts = Integer.parseInt(args[0]);
         numRights = Integer.parseInt(args[1]);
         lNap = Integer.parseInt(args[2]);
         rNap = Integer.parseInt(args[3]);
         cNap = Integer.parseInt(args[4]);
         runTime = Integer.parseInt(args[5]);
      } catch (Exception e) { /* use defaults */ }
      System.out.println("LeftsRights:\n numLefts=" + numLefts
         + ", numRights=" + numRights + ", lNap=" + lNap
         + ", rNap=" + rNap + ", cNap=" + cNap
         + ", runTime=" + runTime);
```

```
      // create the intersection
      Intersection in = new Intersection();
      // start the left crossing and right crossing
      // cars (they have self-starting threads)
      Car[] c = new Car[numLefts + numRights];
      for (int i = 0; i < numLefts + numRights; i++)
         c[i] = new Car("Car"+i, (i<numLefts?lNap:rNap)*1000,
            cNap*1000, (i<numLefts?in.LEFT:in.RIGHT), in);
      System.out.println("All threads started");
      // let them run for a while
      try {
         Thread.sleep(runTime*1000);
         System.out.println("age=" + age()
            + ", time to terminate the threads and exit");
         for (int i = 0; i < numLefts + numRights; i++)
            c[i].timeToQuit();
         Thread.sleep(1000);
         for (int i = 0; i < numLefts + numRights; i++)
            c[i].pauseTilDone();
      } catch (InterruptedException e) { /* ignored */ }
      System.out.println("age=" + age()
         + ", all threads are done");
      System.exit(0);
   }
}
```

Sample run of inmo.java

```
% javac inmo.java indr.java
% java LeftRightCars 3 3 2 2 2 5
LeftsRights:
 numLefts=3, numRights=3, lNap=2, rNap=2, cNap=2, runTime=5
age=40, Car0 napping for 1040 ms
age=59, Car1 napping for 1187 ms
age=62, Car2 napping for 1603 ms
age=64, Car3 napping for 1932 ms
age=66, Car4 napping for 986 ms
All threads started
age=68, Car5 napping for 1426 ms
age=1061, Car4 wants to cross right
age=1063, Car4 CROSSING right for 1791 ms
age=1088, Car0 wants to cross left
age=1258, Car1 wants to cross left
age=1509, Car5 wants to cross right
age=1679, Car2 wants to cross left
age=2011, Car3 wants to cross right
age=2869, Car2 CROSSING left for 1180 ms
age=2870, Car4 crossed right
age=2871, Car4 napping for 1441 ms
age=4061, Car2 crossed left
age=4062, Car2 napping for 580 ms
age=4063, Car3 CROSSING right for 974 ms
age=4329, Car4 wants to cross right
age=4648, Car2 wants to cross left
age=5051, Car2 CROSSING left for 405 ms
age=5052, Car3 crossed right
age=5052, Car3 napping for 1988 ms
age=5069, time to terminate the threads and exit
age=5072, Car2 interrupted from crossing
age=5073, Car4 interrupted from crossing
age=5075, Car3 interrupted from sleep
```

```
age=5076, Car5 interrupted from crossing
age=5089, Car0 interrupted from crossing
age=5090, Car1 interrupted from crossing
age=6079, all threads are done
% java LeftRightCars 5 1 1 5 1 5
LeftsRights:
 numLefts=5, numRights=1, lNap=1, rNap=5, cNap=1, runTime=5
age=33, Car0 napping for 550 ms
age=53, Car1 napping for 760 ms
age=55, Car2 napping for 123 ms
age=57, Car3 napping for 59 ms
age=59, Car4 napping for 874 ms
All threads started
age=61, Car5 napping for 1033 ms
age=122, Car3 wants to cross left
age=123, Car3 CROSSING left for 220 ms
age=191, Car2 wants to cross left
age=352, Car2 CROSSING left for 499 ms
age=353, Car3 crossed left
age=354, Car3 napping for 295 ms
age=591, Car0 wants to cross left
age=661, Car3 wants to cross left
age=821, Car1 wants to cross left
age=863, Car1 CROSSING left for 161 ms
age=865, Car2 crossed left
age=867, Car2 napping for 134 ms
age=944, Car4 wants to cross left
age=1011, Car2 wants to cross left
age=1042, Car0 CROSSING left for 867 ms
age=1043, Car1 crossed left
age=1043, Car1 napping for 936 ms
age=1111, Car5 wants to cross right
age=1924, Car0 crossed left
age=1925, Car0 napping for 129 ms
age=1926, Car5 CROSSING right for 682 ms
age=1992, Car1 wants to cross left
age=2062, Car0 wants to cross left
age=2622, Car0 CROSSING left for 377 ms
age=2623, Car5 crossed right
age=2624, Car5 napping for 276 ms
age=2914, Car5 wants to cross right
age=3012, Car0 crossed left
age=3012, Car0 napping for 417 ms
age=3013, Car5 CROSSING right for 740 ms
age=3441, Car0 wants to cross left
age=3762, Car0 CROSSING left for 95 ms
age=3763, Car5 crossed right
age=3764, Car5 napping for 2783 ms
age=3872, Car0 crossed left
age=3872, Car0 napping for 307 ms
age=3873, Car1 CROSSING left for 165 ms
age=4053, Car1 crossed left
age=4054, Car1 napping for 24 ms
age=4055, Car2 CROSSING left for 681 ms
age=4091, Car1 wants to cross left
age=4191, Car0 wants to cross left
age=4752, Car0 CROSSING left for 566 ms
age=4753, Car2 crossed left
age=4754, Car2 napping for 329 ms
age=5062, time to terminate the threads and exit
age=5065, Car1 interrupted from crossing
age=5067, Car2 interrupted from sleep
age=5068, Car4 interrupted from crossing
age=5069, Car3 interrupted from crossing
age=5070, Car5 interrupted from sleep
```

```
age=5082, Car0 interrupted from crossing
age=6072, all threads are done
```

Section 9. Semaphores

User-written classes

The following user-written semaphore classes are Java monitors:

* Abstract Class Semaphore.java on page 53
* Counting semaphore Class CountingSemaphore.java on page 54
* Binary semaphore Class BinarySemaphore.java on page 54
* Syntactic sugar Class SugarSM.java on page 54 so**`P(S)`** can be used instead of **`S.P()`**

Background material on semaphores

Semaphores can be used for mutual exclusion and thread synchronization. Instead of busy waiting and wasting CPU cycles, a thread can block on a semaphore (the operating system removes the thread from the CPU scheduling or "ready" queue) if it must wait to enter its critical section or if the resource it wants is not available.

Here's an example of mutual exclusion pseudocode:

```
semaphore S = 1; ...  P(S); N=N+1; V(S);
```

And here's an example of condition synchronization pseudocode (resource availability):

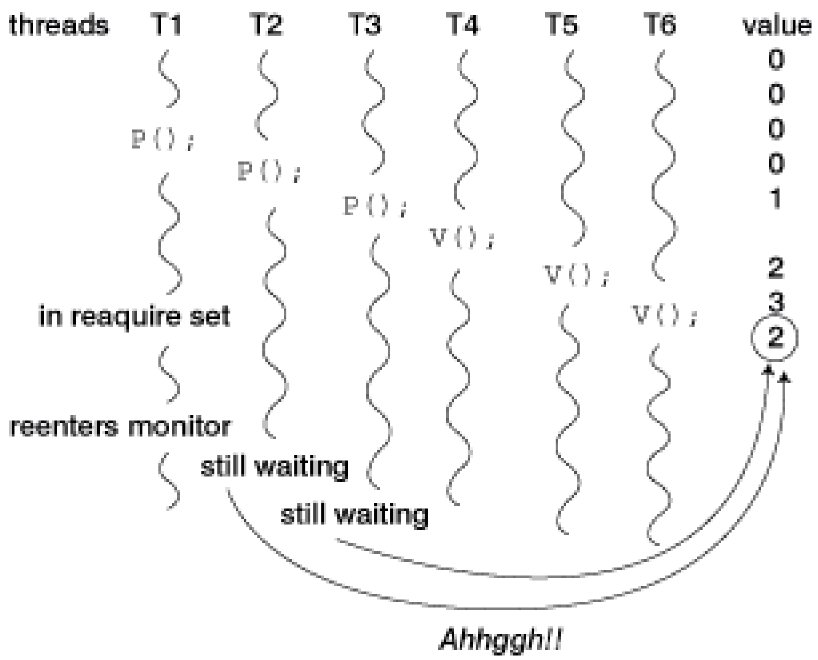
```
semaphore tapeDrives = 7; ... P(tapeDrives); useTapeDrive(); V(tapeDrives);
```

Java does not have explicit binary and *counting* semaphores, so they are provided as classes.

Pitfalls

The example of a counting semaphore shown in the following figure and in Class BadCountingSemaphore1.java on page 54 is not correct because of*barging*. We can repair the problem by changing the semantics of the semaphore **`value`** field. For code samples, see Class Semaphore.java on page 53 ,Class CountingSemaphore.java on page 54 ,Class BinarySemaphore.java on page 54 ,Class SugarSM.java on page 54 ,Class BadCountingSemaphore1.java on page 54 , andClass BadCountingSemaphore2.java on page 55 .

```
public class CountingSemaphore {
  private int value = 0;
  public CountingSemaphore(int initial)
    { value = initial; }
  public synchronized void P()
      throws InterruptedException {
    while (value == 0) wait();
    value--;
  }
  public synchronized void V() {
    if (value == 0) notify();
    value++;
  }
}
```



Suppose the semaphore's current value is "0". Three threads invoke the semaphore's **`P()`** method and wait. Then another thread calls **`V()`**, which moves one of the three waiting threads to the runnable set.

Now suppose a couple of other threads barge ahead of the signaled thread and perform two more **`V()`** operations on the semaphore. Because the semaphore's value is positive, **`notify()`** is not called and none of the waiting threads is moved to the runnable set.

Finally, the thread signaled by the first **`V()`** re-enters the semaphore monitor, decrements the semaphore value from "3" to "2", and leaves the monitor. The monitor has two waiting threads and a positive value. This is an inconsistent state for a counting semaphore.

To fix this, we could try changing the semantics of the semaphore **`value`** field, as in this counting semaphore, Class BadCountingSemaphore2.java on page 55 . The value is allowed to go negative, in which case its absolute value equals the number of waiting threads.

This approach fixes the barging problems but introduces an **`interrupt()`** problem. Suppose the semaphore value is "-1" due to one thread blocked in **`wait()`** inside **`P()`**. Then suppose that thread is interrupted. The value is left at "-1" even though no threads are blocked in **`P()`**. The next **`V()`** will increment the value to "0" whereas it should now be "1".

Another, more insidious problem is present: a race condition between **`interrupt()`** and **`notify()`**. Suppose several threads are blocked inside **`wait()`** and then one of them is notified and then interrupted before it reacquires the monitor lock. The **`notify()`** gets "lost" in that one of the other waiting threads should now proceed.

So we need to catch the exception when a thread is interrupted out of **`wait()`** and regenerate the **`notify()`**.

Examples of semaphores

Example bbou.java on page 56 shows the bounded buffer producer and consumer.Driver bbdr.java on page 20 creates the producer and consumer threads. Sample run of bbou.java on page 56 is the sample run.

Example dphi.java on page 57 highlights dining philosophers.Driver dpdr.java on page 40 creates the philosopher threads. The sample run is Sample run of dphi.java on page 58 .

Try these exercises

Exercise 1: Modify Example bbou.java on page 56 so that it correctly handles multiple producer and multiple consumer threads.

Exercise 2: Write a semaphore solution for the database readers and writers problem.

Exercise 3: Write a semaphore solution for the cars at an intersection problem.

Security issues in monitors and synchronization

The **`public void run()`** method in a **`Thread`** or **`Runnable`** object can be invoked by any thread that has a reference to the **`Thread`** or **`Runnable`** object. So we prevent that at the beginning of the **`run()`** method with **`if (Thread.currentThread() != me) return;`**.

An object's lock is accessible to any thread that has a reference to the object. This can upset the operation of a monitor if some thread decides to do something like this:

```
synchronized (monitor) {
   Thread.sleep(veryLongTime);
   // or
   invert(veryLargeMatrix);
}
```

The following technique is not so bad because of the **`while (!condition)`** loop that a **`wait()`** is done in. But it does add overhead:

```
    synchronized (monitor) {
       monitor.notifyAll();
    }
```

To protect our code from this mischief, we can code a monitor as follows, using a counting semaphore as an example. We use a wrapper class and delegate **`P()`** and **`V()`** to a private counting semaphore inside the wrapper class:

```
 class SecureCountingSemaphore {
    private CountingSemaphore S = null;
    SecureCountingSemaphore(int initial)
       { S = new CountingSemaphore(initial); }
    void P() throws InterruptedException { S.P(); }
    void V() { S.V(); }
 }
```

Another way is to use a private lock object inside the semaphore class and change synchronized methods to use the private lock:

```
 class SecureCountingSemaphore {
    private int value = 0;
    private Object mutex = new Object();
    SecureCountingSemaphore(int initial)
       { value = initial; }
    void P() throws InterruptedException {
       synchronized (mutex)
          { while (value == 0) mutex.wait();  value--; }
    }
    void V() {
       synchronized (mutex)
          { value++;  mutex.notifyAll(); }
    }
 }
```

The next several panels display the code described in this section. To view the code, click **Next**; or you can go directly to the next section, Message passing on page 60 , and return to the code samples at another time.

Class Semaphore.java

```
 public abstract class Semaphore {
    private int value = 0;
    public Semaphore() {}  // constructors
    public Semaphore(int initial) {
       if (initial >= 0) value = initial;
       else throw new IllegalArgumentException("initial < 0");
    }
    public final synchronized void P()
          throws InterruptedException {
       while (value == 0) wait();
       value--;
```

```
   }
   protected final synchronized void Vc() {
      value++;  notifyAll();
   }
   protected final synchronized void Vb() {
      this.Vc();  if (value > 1) value = 1;
   }
   public abstract void V();
   public String toString() { return ".value=" + value; }
}
```

Class CountingSemaphore.java

```
public final class CountingSemaphore extends Semaphore {
   public CountingSemaphore() { super(); }  // constructors
   public CountingSemaphore(int initial) { super(initial); }
   public final synchronized void V() { super.Vc(); }
}
```

Class BinarySemaphore.java

```
public final class BinarySemaphore extends Semaphore {
   public BinarySemaphore() { super(); }  // constructors
   public BinarySemaphore(int initial) {
      super(initial);
      if (initial > 1)
         throw new IllegalArgumentException("initial > 1");
   }
   public final synchronized void V() { super.Vb(); }
}
```

Class SugarSM.java

```
public abstract class SugarSM extends Sugar {
      // syntactic sugar for semaphores
   protected static final void P(Semaphore s)
      throws InterruptedException { s.P(); }
   protected static final void V(Semaphore s) { s.V(); }
}
```

Class BadCountingSemaphore1.java

```
public class BadCountingSemaphore1 {
   private int value = 0;
   public BadCountingSemaphore1(int initial)
      { if (initial > 0) value = initial; }
   public synchronized void P()
         throws InterruptedException {
```

```
      while (value == 0) wait();
      value--;
   }
   public synchronized void V() {
      if (value == 0) notify();  // barging causes problems
      value++;
   }
}
```

Class BadCountingSemaphore2.java

```
public class BadCountingSemaphore2 {
   private int value = 0;
   public BadCountingSemaphore2(int initial)
      { if (initial > 0) value = initial; }
   public synchronized void P()
         throws InterruptedException {
      value--;
      if (value < 0) wait();
   }
   public synchronized void V() {
      value++;
      if (value <= 0) notify(); // interrupt causes problems
   }
}
```

Class EfficientCountingSemaphore.java

```
public class EfficientCountingSemaphore {
  private int value = 0;
  private int waitCount = 0;
  private int notifyCount = 0;
  public EfficientCountingSemaphore() {}  // constructors
  public EfficientCountingSemaphore(int initial) {
    if (initial >= 0) value = initial;
    else throw new IllegalArgumentException("initial < 0");
  }
  public synchronized void P()
        throws InterruptedException {
    if (value <= waitCount) {
      waitCount++;
      try {
        do { wait(); }
          while (notifyCount == 0);
      } catch(InterruptedException e) {
        notify();
        throw e;
      } finally { waitCount--; }
      notifyCount--;
    } else {
      if (notifyCount > waitCount)
        notifyCount--;
    }
    value--;
  }
  public synchronized void V() {
```

```
    value++;
    if (waitCount > notifyCount) {
      notifyCount++;
      notify();
    }
  }
}
```

Example bbou.java

```
class BoundedBuffer extends SugarSM {
   // designed for a single producer thread and
   // a single consumer thread
   private int numSlots = 0;
   private double[] buffer = null;
   private int putIn = 0, takeOut = 0;
   private int count = 0;
   private BinarySemaphore mutex = null;
   private CountingSemaphore elements = null;
   private CountingSemaphore spaces = null;
   public BoundedBuffer(int numSlots) {
      if (numSlots <= 0)
         throw new IllegalArgumentException("numSlots <= 0");
      this.numSlots = numSlots;
      buffer = new double[numSlots];
      mutex = new BinarySemaphore(1);
      elements = new CountingSemaphore(0);
      spaces = new CountingSemaphore(numSlots);
   }
   public void deposit(double value)
         throws InterruptedException {
      P(spaces);
      buffer[putIn] = value;
      putIn = (putIn + 1) % numSlots;
      P(mutex);  count++;  V(mutex);
      V(elements);
   }
   public double fetch()
         throws InterruptedException {
      double value;
      P(elements);
      value = buffer[takeOut];
      takeOut = (takeOut + 1) % numSlots;
      P(mutex);  count--;  V(mutex);
      V(spaces);
      return value;
   }
}
```

Sample run of bbou.java

```
% javac bbou.java bbdr.java
% java ProducersConsumers 10 1 1 2 2 5
ProducersConsumers:
 numSlots=10, numProducers=1, numConsumers=1, pNap=2, cNap=2, runTime=5
Java version=1.3.0
```

```
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
age=44, PRODUCER0 napping for 1701 ms
age=63, Consumer0 napping for 982 ms
All threads started
age=1065, Consumer0 wants to consume
age=1763, PRODUCER0 produced item 0.8235080062047989
age=1779, PRODUCER0 deposited item 0.8235080062047989
age=1780, PRODUCER0 napping for 1223 ms
age=1781, Consumer0 fetched item 0.8235080062047989
age=1783, Consumer0 napping for 529 ms
age=2325, Consumer0 wants to consume
age=3016, PRODUCER0 produced item 0.5752891675481963
age=3018, PRODUCER0 deposited item 0.5752891675481963
age=3019, PRODUCER0 napping for 1794 ms
age=3020, Consumer0 fetched item 0.5752891675481963
age=3021, Consumer0 napping for 1824 ms
age=4825, PRODUCER0 produced item 0.5010012702583668
age=4826, PRODUCER0 deposited item 0.5010012702583668
age=4827, PRODUCER0 napping for 1299 ms
age=4852, Consumer0 wants to consume
age=4853, Consumer0 fetched item 0.5010012702583668
age=4854, Consumer0 napping for 273 ms
age=5074, time to terminate the threads and exit
age=5077, Consumer0 interrupted from sleep
age=5093, PRODUCER0 interrupted from sleep
age=6083, all threads are done
```

Example dphi.java

```
class DiningServer extends SugarSM {
   private int numPhils = 0;
   private int[] state = null;
   private static final int THINKING = 0, HUNGRY = 1, EATING = 2;
   private BinarySemaphore[] self = null;
   private BinarySemaphore mutex = null;
   public DiningServer(int numPhils) {
      this.numPhils = numPhils;
      state = new int[numPhils];
      for (int i = 0; i < numPhils; i++) state[i] = THINKING;
      self = new BinarySemaphore[numPhils];
      for (int i = 0; i < numPhils; i++)
         self[i] = new BinarySemaphore(0);
      mutex = new BinarySemaphore(1);
   }
   public void dine(String name, int id, int napEat)
         throws InterruptedException {
      try {
         takeForks(id);
         eat(name, napEat);
      } finally {       // Make sure we return the
         putForks(id);  // forks if interrupted
      }
   }
   private final int left(int i)
      { return (numPhils + i - 1) % numPhils;}
   private final int right(int i)
      { return (i + 1) % numPhils; }
```

```
   private void test(int k) {
      if (state[left(k)] != EATING && state[k] == HUNGRY &&
            state[right(k)] != EATING) {
         state[k] = EATING;
         V(self[k]);
      }
   }
   private void eat(String name, int napEat)
         throws InterruptedException {
      int napping;
      napping = 1 + (int) random(napEat);
      System.out.println("age=" + age() + ", " + name
         + " is eating for " + napping + " ms");
      Thread.sleep(napping);
   }
   private void takeForks(int i)
         throws InterruptedException {
      P(mutex);  state[i] = HUNGRY;  test(i);  V(mutex);
      P(self[i]);
   }
   private void putForks(int i)
         throws InterruptedException {
      if (state[i] != EATING) return;
      P(mutex);
         state[i] = THINKING;  test(left(i));  test(right(i));
      V(mutex);
   }
}
```

Sample run of dphi.java

```
% javac dphi.java dpdr.java
% java DiningPhilosophers 5 6 4 1
DiningPhilosophers: numPhilosophers=5, runTime=6, napThink=4, napEat=1
age=42, Philosopher 0 is thinking for 683 ms
age=61, Philosopher 1 is thinking for 437 ms
age=64, Philosopher 2 is thinking for 3039 ms
age=66, Philosopher 3 is thinking for 3190 ms
All Philosopher threads started
age=68, Philosopher 4 is thinking for 3893 ms
age=511, Philosopher 1 wants to dine
age=513, Philosopher 1 is eating for 82 ms
age=648, Philosopher 1 is thinking for 3631 ms
age=740, Philosopher 0 wants to dine
age=741, Philosopher 0 is eating for 699 ms
age=1453, Philosopher 0 is thinking for 2390 ms
age=3111, Philosopher 2 wants to dine
age=3111, Philosopher 2 is eating for 526 ms
age=3260, Philosopher 3 wants to dine
age=3651, Philosopher 2 is thinking for 2095 ms
age=3652, Philosopher 3 is eating for 448 ms
age=3850, Philosopher 0 wants to dine
age=3851, Philosopher 0 is eating for 324 ms
age=3973, Philosopher 4 wants to dine
age=4111, Philosopher 3 is thinking for 2346 ms
age=4191, Philosopher 0 is thinking for 3695 ms
age=4192, Philosopher 4 is eating for 477 ms
age=4290, Philosopher 1 wants to dine
age=4291, Philosopher 1 is eating for 259 ms
age=4561, Philosopher 1 is thinking for 127 ms
age=4681, Philosopher 4 is thinking for 751 ms
```

```
age=4700, Philosopher 1 wants to dine
age=4701, Philosopher 1 is eating for 355 ms
age=5073, Philosopher 1 is thinking for 3921 ms
age=5450, Philosopher 4 wants to dine
age=5451, Philosopher 4 is eating for 492 ms
age=5761, Philosopher 2 wants to dine
age=5761, Philosopher 2 is eating for 323 ms
age=5962, Philosopher 4 is thinking for 3225 ms
age=6071, time to terminate the Philosophers and exit
age=6074, Philosopher 1 interrupted out of think
age=6075, Philosopher 2 interrupted out of dine
age=6077, Philosopher 4 interrupted out of think
age=6078, Philosopher 3 interrupted out of think
age=6091, Philosopher 0 interrupted out of think
age=7081, all Philosophers are done
```

Section 10. Message passing

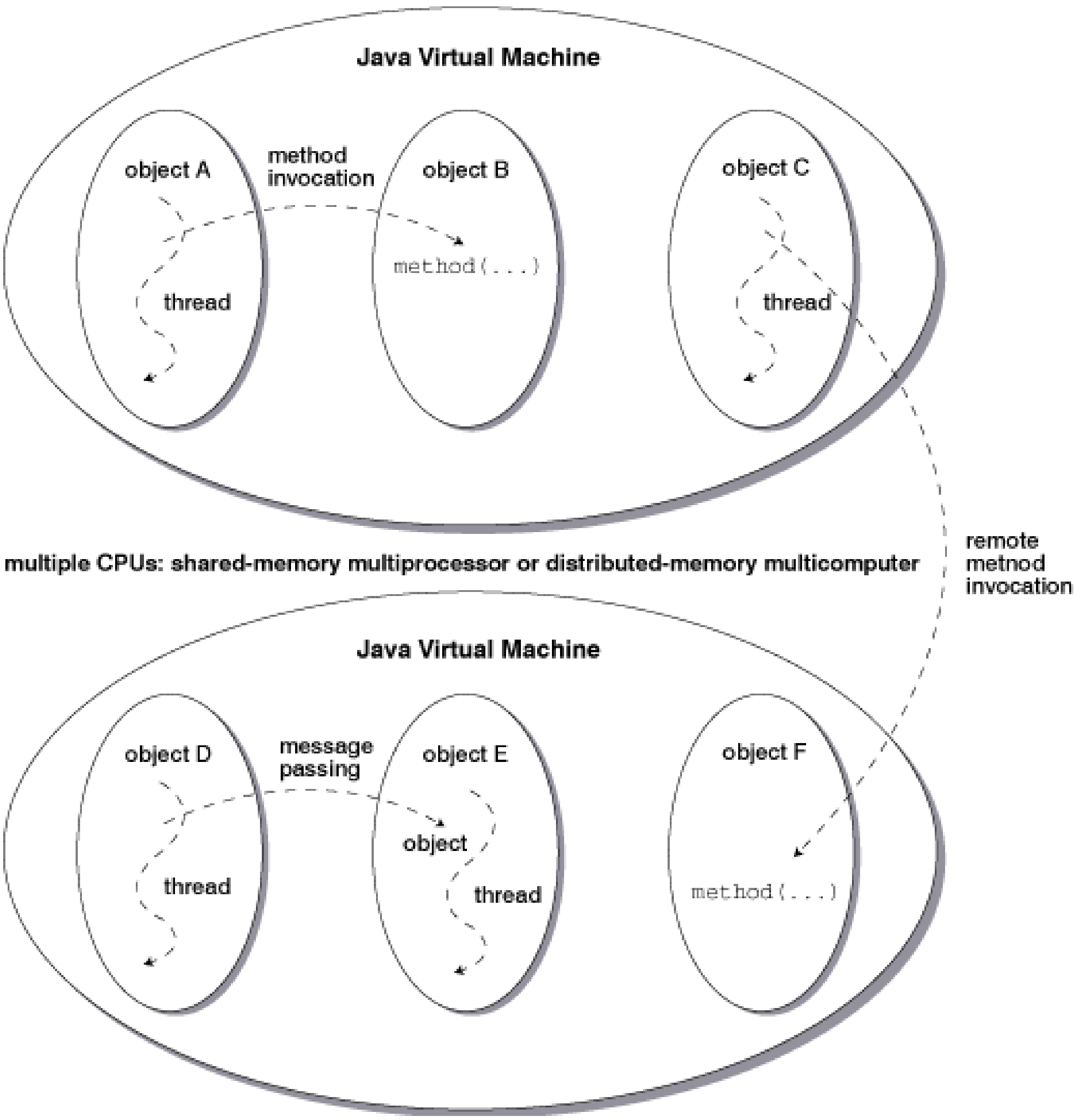
Some definitions

Object-oriented programming blurs the distinction between invoking a method and sending a message. It also blurs the distinction between shared and distributed memory computer architectures.

The figure below shows the difference between (1) invoking a method and (2) sending a message:

1. Thread leaves code in one object to execute code in another object, then comes back (shown at the top of the figure).
2. Thread sends an object to another thread, then optionally blocks until the other thread receives the message (shown at the bottom of the figure).

Message passing leads to "safer" concurrent programming since the receiving object only has one thread executing inside it.



It is important to note that multiple threads invoking methods in an object might lead to race conditions unless synchronization is properly done by making the object a monitor. With message passing, the receiving object has just one thread executing inside it, leading to "safer" concurrent programming.

If the threads have a relationship other than client/server, monitors can be awkward to use. Using message passing between the threads is easier in these situations. If the threads communicate with each other, they are called *peers* or *filters*. In this situation, the threads form a pipeline in which each thread gets its input from its predecessor in the pipeline and sends its output to its successor in the pipeline.

Options for user-written classes implementing synchronous (blocking send) and asynchronous (non-blocking send) message passing (receive always blocks) include:

* Sending object references from one thread to another within the same JVM
* Sending serialized objects through connected sockets from a thread in one JVM to a thread in another JVM

Each message passing class implements a *mailbox* or *channel* shared by a collection of threads. The one-way flow of information from sender to receiver in synchronous message passing is sometimes called a *simple rendezvous*. Following are examples:

* Shared type:
```
class Message { ... }
```
* Shared mailbox:
```
   // non-blocking sends:
MessagePassing mailbox = new MessagePassing();
   // capacity controlled:
MessagePassing mailbox = new MessagePassing(capacity);
```
* One thread:
```
Message ms = new Message(...);
send(mailbox, ms);
```
* Another thread:
```
Message mr;
mr = (Message) receive(mailbox);
```

Values like **`int`** and **`double`** can be sent using the wrapper classes **`Integer`** and **`Double`**.

Background material on message passing

Sometimes the phrase "send a message to an object" is used to describe a thread in one object calling a method in another object. Here, that phrase is used to describe a thread in one object sending a message to a thread in another object, where the message is itself an object.

This technique is used for thread communication and synchronization in a computing environment where the threads do not have shared memory (since the threads reside in different virtual or physical machines). Hence the threads cannot share semaphores or monitors and cannot use shared variables to communicate. Message passing can still be used, of course, in a shared memory platform.

Messages are sent through a port or channel with an operation like *send(channel, message)* and received from a port or channel with an operation like *receive(channel, message)*. Messages can be passed *synchronously*, meaning the sender blocks until the receiver does a receive and the receiver blocks until the sender does a send.

Because the sender and receiver are at specific known points in their code at a known specific instant of time, synchronous message passing is also called a *simple rendezvous* with a one-way flow of information from the sender to the receiver.

In *asynchronous* message passing, the sender does not block. If there is not a receiver waiting to receive the message, the message is queued or buffered. The receiver still blocks if there is no queued or buffered message when a receive is executed.

In *conditional* message passing, the message remains queued until some condition, specified by the receiver, becomes true. At that time, the message is passed to the receiver, unblocking it.

A two-way flow of information, perhaps over the network, is called an *extended rendezvous* and can be implemented with a pair of sends and receives. Typically a *client* thread uses this technique to communicate with a *server* thread and requests a service to be performed on its behalf.

A similar situation exists when a *worker* thread contacts a *master* thread, asking for more work to do. The client or worker sends a request and receives the reply. The server or master receives the request, performs the service, and sends the reply.

The Example qsrt.java on page 65 algorithm can be parallelized for a shared-memory, multiple-CPU machine by dedicating each CPU to a worker thread and using a message passing channel as a *bag of tasks*. The **`main()`** method puts the whole array to be sorted into the bag.

A worker extracts the task, chooses a pivot point, and partitions the array. Each of the two partitions is then put back into the bag as a task for one of the workers to perform.

Even though message passing is being used for a bag of tasks, shared memory is still required because the array is being sorted "in place" and the work requests being put into the bag are array index pairs and not pieces of the array itself.

A bag of tasks communication channel, object **`task`**, is shared by the quicksort worker threads:

```
MessagePassing task = new MessagePassing();
```

The quicksort worker threads get tasks from the **`task`** bag inside a **`while`** loop:

```
while (true) {
   m = (Task) receive(task);
   quickSort(id, m.left, m.right);
}
```

The quicksort worker threads create tasks and put them into the **`task`** bag:

```
if (right-(l+1) > 0) send(task, new Task(l+1, right));
if ((l-1)-left > 0) send(task, new Task(left, l-1));
```

User-written classes

The following are two user-written classes:

* Class SugarMP.java on page 64 provides syntactic sugar so that**`send(mailbox, ms)`** can be used instead of **`mailbox.send(ms)`** and **`mr = receive(mailbox)`** instead of **`mr = mailbox.receive()`**.

* Class MessagePassing.java on page 64 sends object references within one JVM asynchronously. Synchronous message passing can be done with the **`Rendezvous`** class, which we'll discuss later.

Examples of message passing

The first example contains *worker* threads and a bag of tasks, the second example contains *filter* threads, and the third example contains *peer* threads.

* Example qsrt.java on page 65 : Quicksort (worker threads).Sample run of qsrt.java on page 67 is the sample run.
* Example pasv.java on page 67 : Parallel Sieve of Eratosthenes (filter threads).Sample run of pasv.java on page 69 is the sample run.
* Example rads.java on page 69 : Parallel Radix Sort (peer threads).Sample run of rads.java on page 71 is the sample run.

You can use Remote Method Invocation (RMI) on page 98 to implement message passing between threads in different JVMs that may also be on different physical machines.

The next several panels display the code described in this section. To view the code, click **Next**; or you can go directly to the next section, Rendezvous on page 72 , and return to the code samples at another time.

Class SugarMP.java

```
public abstract class SugarMP extends Sugar {
      // syntactic sugar for message passing
   protected static final void send(MessagePassing mp, Object o)
      throws InterruptedException { mp.send(o); }
   protected static final Object receive(MessagePassing mp)
      throws InterruptedException { return mp.receive(); }
}
```

Class MessagePassing.java

```
import java.util.Vector;
public final class MessagePassing {
   // Implements asynchronous message passing:
   // sends do not block (until the message is
   // received), receives block of course until
   // a message is received.
   private int capacity = 0;  // for capacity control
   // messages are delivered FIFO (in the order they are sent)
   private final Vector messages = new Vector();
```

```
   // receivers get messages FIFO (in the order they call receive)
   private final Vector receivers = new Vector();
   public MessagePassing() { this(0); }
   public MessagePassing(int c) {  // capacity limit
      super();
      if (c < 0) throw new IllegalArgumentException("capacity < 0");
      // zero means no limit imposed here
      else if (c > 0) {
         capacity = c;
         messages.ensureCapacity(capacity);
      }
   }
   public final synchronized void send(Object m)
         throws InterruptedException {
      if (m == null) throw new NullPointerException("null message");
      if (capacity > 0)
         while (messages.size() == capacity) wait();
      messages.addElement(m);  // add at end
      notifyAll();
   }
   public final synchronized Object receive()
         throws InterruptedException {
      Object receivedMessage = null;
      Thread me = Thread.currentThread();
      receivers.addElement(me);  // add at end
      try {
         while (messages.isEmpty() || me != receivers.elementAt(0))
            wait();
         // If we are interrupted after being notified and there is a
         // message here for us, pretend we were interrupted before
         // being notified and leave the message for someone else.
         // Thus, there is no `catch (InterruptedException e) {...}'
         // block here.
         receivedMessage = messages.elementAt(0);
         messages.removeElementAt(0);
         return receivedMessage;
      } finally {
         // We need to do this if we get a message or if we were
         // interrupted.
         receivers.removeElement(me);
         // The notifyAll is needed because several messages
         // might be put in the messages vector before any
         // waiting receivers get back in.  The receiver who
         // is first in the receivers vector might not get back
         // in until last!  So it needs to cause the waiting
         // receivers to come back in again so the second in
         // line can get a message.
         notifyAll();
      }
   }
}
```

Example qsrt.java

```
class Task {
   public int left = -1, right = -1;
   public Task(int left, int right)
      { this.left = left; this.right = right; }
}
class QuickSort extends SugarMP implements Runnable {
   private static int N = 10;
```

```
private static int RANGE = 100;
private static int NCPU = 4;
private static final MessagePassing doneCount
   = new MessagePassing();
private static final MessagePassing task
   = new MessagePassing();
private static int[] nums = null;
private String name = null;
private int id = -1;
private Thread me = null;
private QuickSort(int id) {
   this.name = "Worker" + id;
   this.id = id;
   (me = new Thread(this)).start();
}
private static void quickSort
      (int worker, int left, int right)
      throws InterruptedException {
   int pivot = nums[left];
   int l = left, r = right;
   boolean done = false;
   Integer doneMessage = new Integer(worker);
   while (!done) {
      if (nums[l+1] > pivot) {
         while (r > l+1 && nums[r] > pivot) { r--; }
         if (r > l+1) { l++;
            int temp = nums[r]; nums[r] = nums[l];
            nums[l] = temp;
            done = l >= r-1;
         } else done = true;
      } else { l++; done = l >= r; }
   }
   int temp = nums[left]; nums[left] = nums[l];
   nums[l] = temp;
   if (right-(l+1) > 0) send(task, new Task(l+1, right));
   else if (right-(l+1) == 0) send(doneCount, doneMessage);
   send(doneCount, doneMessage);
   if ((l-1)-left > 0) send(task, new Task(left, l-1));
   else if ((l-1)-left == 0) send(doneCount, doneMessage);
}
public void timeToQuit() { me.interrupt(); }
public void pauseTilDone() throws InterruptedException
   { me.join(); }
public void run() {
   Task m = null;
   while (true) {
      if (Thread.interrupted()) {
         System.out.println("age=" + age() + ", " + name
            + " interrupted");
         return;
      }
      try {
         m = (Task) receive(task);
         quickSort(id, m.left, m.right);
      } catch (InterruptedException e) {
         System.out.println("age=" + age() + ", " + name
            + " interrupted out of send/receive");
         return;
      }
   }
}
public static void main(String[] args) {
   try {
      N = Integer.parseInt(args[0]);
      RANGE = Integer.parseInt(args[1]);
```

```
            NCPU = Integer.parseInt(args[2]);
         } catch (Exception e) { /* use defaults */ }
         System.out.println("Quick sorting " + N
            + " random numbers between 1 and " + RANGE
            + " using " + NCPU + " CPUs");
         nums = new int[N];
         for (int i = 0; i < N; i++)
            nums[i] = 1 + (int) (random()*RANGE);
         System.out.println("Original numbers:");
         for (int i = 0; i < N; i++)
            System.out.print(" " + nums[i]);  System.out.println();
         // create the workers with self-starting threads
         QuickSort[] q = new QuickSort[NCPU];
         new PseudoTimeSlicing(); // for Solaris, not Windows 95/NT
         for (int i = 0; i < NCPU; i++) q[i] = new QuickSort(i);
         try {
            send(task, new Task(0, N-1));
            // wait for enough "singletons" to be produced
            for (int i = 0; i < N; i++) receive(doneCount);
            System.out.println("Sorted   numbers:");
            for (int i = 0; i < N; i++)
               System.out.print(" " + nums[i]);
             System.out.println();
            for (int i = 0; i < NCPU; i++) q[i].timeToQuit();
            Thread.sleep(1000);
            for (int i = 0; i < NCPU; i++) q[i].pauseTilDone();
         } catch (InterruptedException e) { /* ignored */ }
         System.out.println("age()=" + age() + ", done");
         System.exit(0);
      }
   }
```

Sample run of qsrt.java

```
% javac qsrt.java
% java QuickSort 15 1000 3
Quick sorting 15 random numbers between 1 and 1000 using 3 CPUs
Original numbers:
 594 637 361 87 207 803 8 870 979 333 121 601 353 613 586
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
Sorted   numbers:
 8 87 121 207 333 353 361 586 594 601 613 637 803 870 979
age=77, Worker2 interrupted
age=96, Worker0 interrupted out of send/receive
age=97, Worker1 interrupted out of send/receive
age()=1087, done
```

Example pasv.java

```
class Filter extends SugarMP implements Runnable {
   private MessagePassing in = null, out = null;
```

```
   private int prime = 0, countIn = 0, countOut = 0;
   public Filter(MessagePassing in, MessagePassing out) {
      this.in = in;  this.out = out;
   }
   private void print() {
      System.out.println("age()=" + age() + " received prime " + prime
         + ", countIn=" + countIn + ", countOut=" + countOut);
   }
   public void run () {
      if (in == null) {    // source thread
         int number = 3;
         while (true) {
            try { send(out, new Integer(number)); }
            catch (InterruptedException e) { return; }
            number += 2;
         }
      } else {            // filter threads
         int number = 0;
         try { prime = ((Integer) receive(in)).intValue(); }
         catch (InterruptedException e) { return; }
         while (true) {
            if (Thread.interrupted()) { print();  return; }
            try {
               number = ((Integer) receive(in)).intValue();  countIn++;
               if (number % prime != 0) {
                  send(out, new Integer(number));  countOut++;
               }
            } catch (InterruptedException e) { print();  return; }
         }
      }
   }
}
class ParallelSieve extends SugarMP {
   public static void main(String[] args) {
      int n = 8;
      try { n = Integer.parseInt(args[0]); }
      catch (Exception e) { /* use default */ }
      if (n < 1) {
         System.out.println("Generate at least one prime number.");
         System.exit(1);
      }
      System.out.println("ParallelSieve: generating the first "
         + n + " prime numbers greater than 2");
      MessagePassing in = null, out = null;
      Thread[] filter = new Thread[n];
      for (int i = 0; i < n; i++) {
         // Use capacity control so the early threads do
         // not get way ahead of what is needed by the
         // latter threads and fill up JVM memory.
         out = new MessagePassing(n);
         filter[i] = new Thread(new Filter(in, out));
         in = out;
      }
      new PseudoTimeSlicing(); // for Solaris, not Windows 95/NT
      for (int i = 0; i < n; i++) filter[i].start();
      try {
         int prime = ((Integer) receive(out)).intValue();
         for (int i = 0; i < n; i++) filter[i].interrupt();
         for (int i = 0; i < n; i++) filter[i].join();
         System.out.println("age()=" + age() + " last     prime " + prime);
      } catch (InterruptedException e) { /* ignored */ }
      System.exit(0);
   }
}
```

Sample run of pasv.java

```
% javac pasv.java
% java ParallelSieve 20
ParallelSieve: generating the first 20 prime numbers greater than 2
Java version=1.3.0
Java vendor=IBM Corporation
OS name=Linux
OS arch=i586
OS version=#1 Mon Sep 27 10:25:54 EDT 1999.2.2.12-20
No PseudoTimeSlicing needed
age()=2158 received prime 11, countIn=458, countOut=416
age()=2165 received prime 13, countIn=395, countOut=365
age()=2166 received prime 7, countIn=559, countOut=479
age()=2167 received prime 5, countIn=725, countOut=580
age()=2169 received prime 29, countIn=230, countOut=223
age()=2171 received prime 19, countIn=301, countOut=284
age()=2172 received prime 17, countIn=344, countOut=322
age()=2174 received prime 43, countIn=133, countOut=132
age()=2175 received prime 23, countIn=263, countOut=251
age()=2176 received prime 47, countIn=111, countOut=110
age()=2178 received prime 37, countIn=177, countOut=176
age()=2179 received prime 31, countIn=202, countOut=198
age()=2180 received prime 3, countIn=1120, countOut=746
age()=2182 received prime 41, countIn=155, countOut=154
age()=2184 received prime 53, countIn=89, countOut=88
age()=2185 received prime 59, countIn=67, countOut=66
age()=2187 received prime 61, countIn=45, countOut=44
age()=2188 received prime 67, countIn=23, countOut=22
age()=2190 received prime 71, countIn=1, countOut=1
age()=2191 last     prime 73
```

Example rads.java

```
class Result { public int number, count;
   public Result(int n, int c) { number = n; count = c; }
}
class Peer extends SugarMP implements Runnable {
   private int N = -1, id = -1, mine = 0;
   private MessagePassing[] channel = null;
   private MessagePassing reply = null;
   public Peer(int N, int id, int mine, MessagePassing[] channel,
         MessagePassing reply) {
      this.N = N;
      this.id = id;
      this.mine = mine;
      this.channel = channel;
      this.reply = reply;
      new Thread(this).start();
   }
   public void run() {
      int count = 0, other = 0;
      try {
         // Send my number to all the other workers.
         for (int i = 0; i < N; i++)
            if (i != id) send(channel[i], new Integer(mine));
         // Of the N-1 numbers sent to me by the other workers,
```

```
            // count how many are less than my number.
            for (int i = 1; i < N; i++) {
               other = ((Integer) receive(channel[id])).intValue();
               if (other < mine) count++;
            }
            // Send my count of less-than-mine-seen back to main().
            send(reply, new Result(mine, count));
         } catch (InterruptedException e) { return; }
      }
   }
   class RadixSort extends SugarMP {
      public static void main(String[] args) {
         int N = 15;
         int RANGE = 1000;
         int[] nums = null;
         MessagePassing[] channel = null;
         MessagePassing reply = null;
         try {
            N = Integer.parseInt(args[0]);
            RANGE = Integer.parseInt(args[1]);
         } catch (Exception e) { /* use defaults */ }
         System.out.println("Radix sorting " + N
            + " random integers between 1 and " + RANGE);
         nums = new int[N];
         for (int i = 0; i < N; i++)
            nums[i] = 1 + (int)random(RANGE);
         System.out.println("Original numbers:");
         for (int i = 0; i < N; i++)
            System.out.print(" " + nums[i]);  System.out.println();
         // Set up the reply channel.
         reply = new MessagePassing();
         channel = new MessagePassing[N];
         // Set up the communication channels.
         for (int i = 0; i < N; i++)
            channel[i] = new MessagePassing();
         // Start the worker threads.
         for (int i = 0; i < N; i++)
            new Peer(N, i, nums[i], channel, reply);
         int[] tallyCounts = new int[N];
         for (int i = 0; i < N; i++) tallyCounts[i] = 0;
         try {
            // Gather the results.
            for (int i = 0; i < N; i++) {
               Result r = (Result) receive(reply);
               // Put the number where it belongs in the sorted order,
               // which is the value of the counter in which it recorded
               // the number of less-than-its-own numbers it saw.
               nums[r.count] = r.number;
               tallyCounts[r.count]++;
            }
         } catch (InterruptedException e) { /* ignored */ }
         System.out.println("Sorted   numbers:");
         for (int i = 0; i < N; i++)
            System.out.print(" " + nums[i]);  System.out.println();
         for (int i = 0; i < N; i++)
            // Zeros show where duplicates have occured.
            System.out.print(" " + tallyCounts[i]);  System.out.println();
         System.out.println("age()=" + age() + ", done");
         System.exit(0);
      }
   }
```

Sample run of rads.java

```
% javac rads.java
% java RadixSort 20 100
Radix sorting 20 random integers between 1 and 100
Original numbers:
 58 71 78 26 47 34 30 9 99 60 60 70 51 71 93 76 2 87 49 14
Sorted   numbers:
 2 9 14 26 30 34 47 49 51 58 60 70 70 71 93 76 78 87 93 99
 1 1 1 1 1 1 1 1 1 1 2 0 1 2 0 1 1 1 1 1
age()=164, done
```

Section 11. Rendezvous

Some definitions

In general client-server programming, a client thread interacts with the server thread by sending a request message followed immediately by a receive that blocks until the server sends a reply message containing the results of the request. This is called a *rendezvous* (or sometimes an *extended rendezvous*).

A monitor is a passive object and can be used to implement a server. An active object, in which an independent thread executes, can also act as a server by using the rendezvous style of message passing. Here are a few examples:

* Mailbox shared by the client and server:
```
MessagePassing mailbox = new MessagePassing();
```

* Client:
```
send(mailbox, request);
reply = receive(mailbox);
```

* Server:
```
request = receive(mailbox);
  compute reply;
send(mailbox, reply);
```

Background material on rendezvous

An extended rendezvous is also called a *remote procedure call* from a client to a server (or a worker to the master) because it resembles (and syntactic sugar can make it nearly identical to) a call to a procedure on a remote machine that is executed there.

Typically the call represents a request for service, such as reading a file that resides on the remote machine. The server may handle the request in its main thread or the server may spawn a new thread to handle the request while the server's main thread handles additional requests for service from other clients. The latter gives greater throughput and efficiency because a lengthy request would otherwise delay the handling of requests from the other clients.

An addressing mechanism is needed so the client can contact an appropriate server. In the local case (everything in the same JVM), an object can be used as the place for the client and server to "meet" and establish a rendezvous. The server calls a method in the object and blocks until the client calls a method.

At this point in time, both methods return a newly created object that the client and server subsequently use for the two-way flow of information. This object contains a message passing channel shared by them. In the remote case, the client uses the server's machine name and a TCP/IP port number to address the server; the server "listens" on the TCP/IP port. A client creates an addressing object using the server's machine name and port number in the object's constructor; the server uses just the port number.

When the rendezvous occurs, the object is constructed and returned to both the client and server. In the local case (within the same JVM), the client and server share this object and use it to transact (synchronous message passing of object references).

In the remote case (between JVMs that might be on different physical machines), each gets its own object and the object contains a socket to the other JVM (and machine). Objects are serialized through the socket.

User-written classes

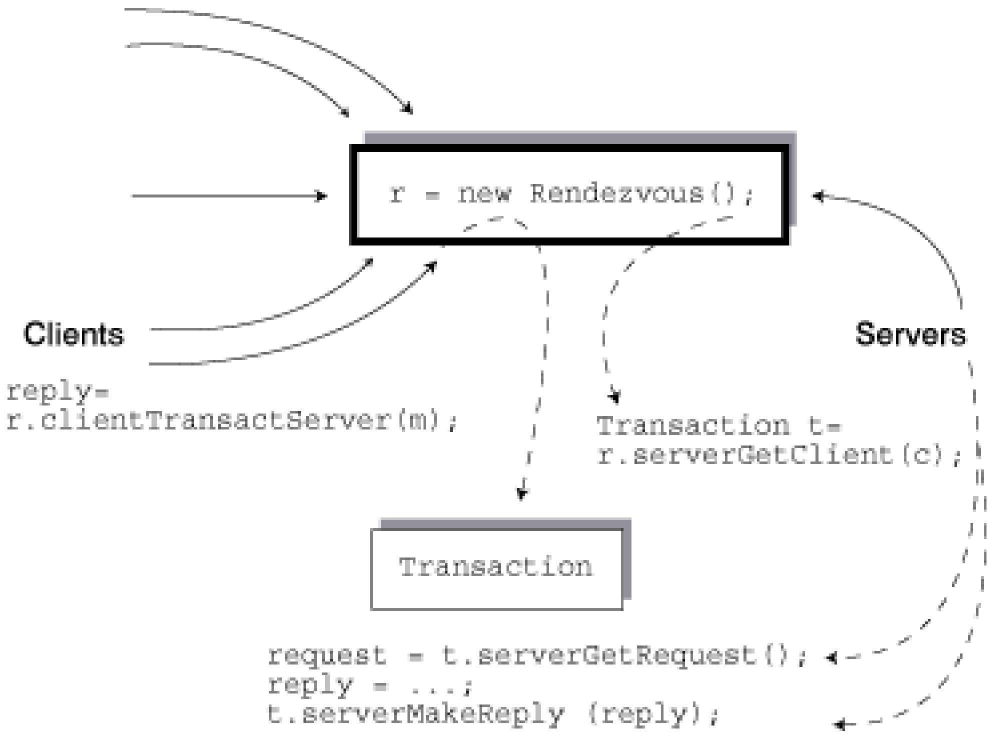
Now let's look at some user-written classes and definitions.

In a *transaction*, two threads exchange information synchronously. Class Transaction.java on page 76 is a user-written class used for one such exchange. Coding is as follows:

* Created by the client, shared by the client and server:
  ```
  Transaction t = new Transaction(request);
  ```
* Client:
  ```
  reply = t.clientAwaitReply();
  ```
* Server:
  ```
  request = t.serverGetRequest();
    compute reply;
  t.serverMakeReply(reply);
  ```

A *conditional rendezvous* builds on the idea of a transaction. It allows the server to specify criteria of whom to rendezvous with next.

The figure below illustrates the concepts of rendezvous.



Interface RendezvousCondition.java on page 76 demonstrates the criterion interface.

An object created from Class Rendezvous.java on page 77 is shared by the client and server.

Coding is as follows:

* Shared by the client and server:
```
Rendezvous r = new Rendezvous();
```

* Client:
```
reply = r.clientTransactServer(request);
```

* Server:
```
RendezvousCondition c =
  new RendezvousCondition(...);
Transaction t = r.serverGetClient(c);
Object request = t.serverGetRequest();
Object reply = ...;  // compute reply
t.serverMakeReply(reply);
```

Multiple servers can share a single **Rendezvous** object.

A server can call **serverGetClient(c)** (a "nested" call) again while in the middle of a transaction with a client (meaning after calling **serverGetClient** to get a client's request but before calling **`serverMakeReply`** to reply to that client).

Remote Method Invocation (RMI) on page 98 can be used to implement rendezvous between threads in different JVMs that may also be on different physical machines.

Peer-to-peer programming offers other options.

Class Rendezvous.java on page 77 has four more methods --**`send(m)`**, **`call(m)`**, **`receive(c)`**, and **`receive()`** -- that can be used for asynchronous and synchronous (conditional) message passing among a collection of peer threads.

A receiving peer can specify a condition for messages it is willing to receive, just as can be specified by a server for a rendezvous. To block until the message is received, use **`call(m)`** instead of **`send(m)`**.

Class SugarRE.java on page 79 provides syntactic sugar so that**`send(rn, ms)`** can be used instead of **`rn.send(ms)`** (ditto for **`call(ms)`**) and **`mr = receive(rn, rc)`** instead of **`mr = rn.receive(rc)`** (ditto for **`receive()`**).

Examples of rendezvous

Example of clients and a server include:

* Example dpre.java on page 79 : Rendezvous dining philosophers
* Driver dpdr.java on page 40 : Creates the philosopher threads
* Sample run of dpre.java on page 81 : Displays the sample run

Because the philosophers only need to block until their request is conditionally received by the server and because they are not interested in the reply message, the philosophers use **`call`** instead of **`clientTransactServer`**. Similarly, the server uses **`receive`** instead of **`serverGetClient`**.

Example pcre.java on page 82 is an example of producer and consumer peers in which a consumer specifies that it receive the message with the smallest value among the yet unreceived messages. A producer can act asynchronously by using **`send`** or synchronously to find out which consumer got its message by using **`clientTransactServer`**. Sample run of pcre.java on page 85 is the sample run.

The next several panels contain an exercise and display the code described in this section. To view the exercise and code, click **Next**; or you can go directly to the next section, Remote Method Invocation (RMI) on page 98 , and return to the code samples at another time.

Try this exercise

Consider a bank that makes loans and accepts loan repayments from its customers. Use nested **`serverGetClient(c)`** calls by the bank server thread to prevent starvation of a customer needing a particularly large loan: the bank accepts only repayments until it has enough funds to make the large loan.

Try implementing the same bank server as a passive monitor object. Which is easier?

Class Transaction.java

```
public class Transaction {
   // Designed to be used by exactly one client
   // transacting exactly once with one specific server.
   private Object request = null;
   private Object reply = null;
   public Transaction (Object m) {
      if (m == null)
         throw new NullPointerException("m == null");
      request = m;
   }
   public synchronized Object clientAwaitReply()
         throws InterruptedException {
      Object m = null;
      try {
         while (reply == null) wait();
      } catch (InterruptedException e) {
         // We have been interrupted while waiting for the
         // server to process our request and/or generate
         // a reply.  Since we no longer want the server to
         // process our request, we will null it out.  This
         // means the server must check for a null return
         // value from the serverGetRequest method.  If the
         // request is already null at this point, then the
         // server must have already gotten it.
         request = null;
         if (reply == null)
            throw new InterruptedException("reply not available");
         else
            Thread.currentThread().interrupt();  // reply available
      }
      m = reply;
      reply = null;
      return m;
   }
   public synchronized Object serverGetRequest() {
      Object m = request;
      request = null;
      return m;
   }
   public synchronized void serverMakeReply(Object m) {
      if (m == null)
         throw new NullPointerException("m == null");
      reply = m;
      notify();  // at most one thread (the client) waiting
   }
}
```

Interface RendezvousCondition.java

```
import java.util.Vector;
public interface RendezvousCondition {
/*
 * The information available to the checkCondition method is:
 *   the particular message being evaluated,
 *     blockedMessages.elementAt(messageNum);
 *   the queue of blocked messages itself, blockedMessages; and
 *   the number of blocked servers, numBlockedServers.
```

```
 * This is the state of the Rendezvous object.  The
 * particular message can be checked to see if it meets the
 * condition and this test may involve counting how many
 * blocked messages meet some other criterion and/or the number
 * of blocked servers.
 *
 * We are depending on the programmer not to mess with the
 * blockedMessages Vector.  The Rendezvous object is
 * graciously making it available, so do not abuse!
 */
   public abstract boolean checkCondition
      (int messageNum, Vector blockedMessages,
         int numBlockedServers);
}
```

Class Rendezvous.java

```
import java.util.Vector;
public final class Rendezvous {
   private final Vector messages = new Vector();
   private final Vector transactions = new Vector();
   private int numServers = 0;
// An anonymous class whose checkCondition method returns true.
   private RendezvousCondition alwaysTrue =
      new RendezvousCondition() {
         public boolean checkCondition(int messageNum,
               Vector blockedMessages, int numBlockedServers) {
            return true;
         }
      };
// If there are more waiting servers than messages, then
// starvation might occur among the waiting servers because
// no attempt is made to match a message with the longest
// waiting server.  On the other hand, messages are checked
// for a matching condition in the order the messages arrive.
   public Rendezvous() { super(); }
// The server calls this method to get the Transaction object to
// use with the client.  When this method returns, the server
// will do two things with the Transaction return value: invoke
// serverGetRequest() and then invoke serverMakeReply().
// The Transaction object is then discarded by the server.
   public synchronized Transaction serverGetClient
            (RendezvousCondition condition)
         throws InterruptedException {
      if (condition == null)
         throw new NullPointerException("null condition");
      numServers++;
      Transaction client = null;
      boolean matched = false;
      try {
         while (true) {
            int numMessages = messages.size();
            for (int j = 0; j < numMessages; j++) {
   /*
    * We are running security and protection risks making the
    * messages Vector available to the outside.
    * Caveat emptor!
    */
               if (condition.checkCondition(j, messages, numServers)) {
                  messages.removeElementAt(j);
                  client = (Transaction) transactions.elementAt(j);
```

```
                    transactions.removeElementAt(j);
                    matched = true;
                    break;
                 }
              }
              if (matched) return client;
              else wait();  // for another message to arrive
           }
        } finally {
           // We need to do this if we get a message or if we were
           // interrupted.
           numServers--;
           // Since we have changed numServers, we need to force
           // all servers to check for a match again because
           // numServers is passed to checkCondition().
           notifyAll();
        }
     }
  // Transact with any waiting client.
     public synchronized Transaction serverGetClient()
           throws InterruptedException {
        return serverGetClient(alwaysTrue);
     }
  // The client calls this method to transact with the server.
     public Object clientTransactServer(Object message)
           throws InterruptedException {
        return put(message, true);
     }
  // The client calls this method indirectly.
     private Object put(Object message, boolean synchronous)
           throws InterruptedException {
        if (message == null)
           throw new NullPointerException("null message");
        Transaction t = new Transaction(message);
        synchronized (this) {
           messages.addElement(message);
           transactions.addElement(t);
           this.notifyAll();
        }
        Object m = null;
        // If not synchronous, the server removes the message
        // and transaction from their vectors.
        if (synchronous) {
           try { m = t.clientAwaitReply(); }
           finally { // in case interrupted out of waiting
              synchronized (this) {
                 messages.removeElement(message);
                 transactions.removeElement(t);
              }
           }
        }
        return m;
     }
  // A peer calls this method to send asynchronously a message
  // to another peer (using receive).
     public void send(Object message)
           throws InterruptedException {
        put(message, false);
     }
  // A peer calls this method to send synchronously a message
  // to another peer.
     public void call(Object message)
           throws InterruptedException {
        put(message, true);  // Discard the reply.
     }
```

```
// A peer calls this method to receive a message conditionally
// from another peer.
   public Object receive(RendezvousCondition condition)
         throws InterruptedException {
      Transaction t = serverGetClient(condition);
      Object m = t.serverGetRequest();
      // A kludge just in case receive() is called
      // erroneously when a client is waiting inside t's
      // clientAwaitReply() inside clientTransactServer();
      // but really is needed when a client is waiting
      // inside call().
      t.serverMakeReply("Fake reply.");
      return m;
   }
// Receive any waiting message.
   public Object receive() throws InterruptedException {
      return receive(alwaysTrue);
   }
}
```

Class SugarRE.java

```
import java.rmi.*;
public abstract class SugarRE extends Sugar {
// syntactic sugar for rendezvous
   protected static final void send(Rendezvous rn, Object o)
      throws InterruptedException { rn.send(o); }
   protected static final void call(Rendezvous rn, Object o)
      throws InterruptedException { rn.call(o); }
   protected static final Object receive(Rendezvous rn,
         RendezvousCondition rc)
      throws InterruptedException { return rn.receive(rc); }
   protected static final Object receive(Rendezvous rn)
      throws InterruptedException { return rn.receive(); }
// syntactic sugar for remote rendezvous
   protected static final void send(RemoteRendezvous rn, Object o)
         throws RemoteException, InterruptedException
         { rn.send(o); }
   protected static final void call(RemoteRendezvous rn, Object o)
         throws RemoteException, InterruptedException
         { rn.call(o); }
   protected static final Object receive(RemoteRendezvous rn,
            RendezvousCondition rc)
         throws RemoteException, InterruptedException
         { return rn.receive(rc); }
   protected static final Object receive(RemoteRendezvous rn)
         throws RemoteException, InterruptedException
         { return rn.receive(); }
}
```

Example dpre.java

```
import java.util.Vector;
class EatCondition implements RendezvousCondition {
   private int numPhils = 0;
   private int[] state = null;
```

```
   private int EATING = -1;
   public EatCondition(int[] state, int EATING) {
      this.state = state;
      numPhils = state.length;
      this.EATING = EATING;
   }
   private final int left(int i)
      { return (numPhils + i-1) % numPhils; }
   private final int right(int i)
      { return (i+1) % numPhils; }
   public boolean checkCondition
            (int messageNum, Vector blockedMessages,
         int numBlockedServers) {
      Object message = blockedMessages.elementAt(messageNum);
      int id = ((Integer) message).intValue();
      int size = blockedMessages.size(); // not used
      if (id < 0) return true;           // putForks()
      else if (state[left(id)] != EATING
            && state[right(id)] != EATING)
         return true;                    // takeForks()
      else return false;
   }
}
class DiningServer extends SugarRE implements Runnable {
   private int numPhils = 0;
   private int[] state = null;
   private Rendezvous r = null;
   private static final int THINKING = 0, HUNGRY = 1, EATING = 2;
   private String name = "DiningServer";
   private Thread me = null;
   public DiningServer(int numPhils) {
      this.numPhils = numPhils;
      state = new int[numPhils];
      for (int i = 0; i < numPhils; i++) state[i] = THINKING;
      r = new Rendezvous();
      (me = new Thread(this)).start();
   }
   public void dine(String name, int id, int napEat)
         throws InterruptedException {
      try {
         takeForks(id);
         eat(name, napEat);
      } finally {       // Make sure we return the
         putForks(id);  // forks if interrupted
      }
   }
   private void eat(String name, int napEat)
         throws InterruptedException {
      int napping;
      napping = 1 + (int) random(napEat);
      System.out.println("age=" + age() + ", " + name
         + " is eating for " + napping + " ms");
      Thread.sleep(napping);
   }
   private void takeForks(int id) throws InterruptedException {
      state[id] = HUNGRY;                      // not used
      call(r, new Integer(id));
   }
   private void putForks(int id) throws InterruptedException {
      if (state[id] != EATING) return;
      call(r, new Integer(-id-1));
   }
   public void run() {  // makes atomic state changes
      if (Thread.currentThread() != me) return;
      while (true) {
```

```
         if (Thread.interrupted()) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted");
            return;
         }
         try {
            Object m = receive(r,
               new EatCondition(state, EATING));
            if (m != null) {
               int id = ((Integer) m).intValue();
               if (id < 0) state[-id-1] = THINKING;
               else state[id] = EATING;
            } else
               System.out.println("age=" + age() + ", " + name
                  + " received null request");
         } catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted out of rendezvous");
            return;
         }
      }
   }
}
```

Sample run of dpre.java

```
% javac dpre.java dpdr.java
% java DiningPhilosophers 5 6 4 1
DiningPhilosophers: numPhilosophers=5, runTime=6, napThink=4, napEat=1
age=315, Philosopher 0 is thinking for 3524 ms
age=323, Philosopher 1 is thinking for 1910 ms
age=325, Philosopher 2 is thinking for 2383 ms
age=327, Philosopher 3 is thinking for 1477 ms
All Philosopher threads started
age=329, Philosopher 4 is thinking for 3131 ms
age=1845, Philosopher 3 wants to dine
age=1851, Philosopher 3 is eating for 264 ms
age=2127, Philosopher 3 is thinking for 1336 ms
age=2234, Philosopher 1 wants to dine
age=2236, Philosopher 1 is eating for 151 ms
age=2405, Philosopher 1 is thinking for 143 ms
age=2564, Philosopher 1 wants to dine
age=2565, Philosopher 1 is eating for 680 ms
age=2724, Philosopher 2 wants to dine
age=3257, Philosopher 1 is thinking for 1453 ms
age=3258, Philosopher 2 is eating for 539 ms
age=3475, Philosopher 3 wants to dine
age=3476, Philosopher 4 wants to dine
age=3477, Philosopher 4 is eating for 963 ms
age=3805, Philosopher 2 is thinking for 3403 ms
age=3854, Philosopher 0 wants to dine
age=4458, Philosopher 0 is eating for 367 ms
age=4459, Philosopher 3 is eating for 502 ms
age=4459, Philosopher 4 is thinking for 814 ms
age=4725, Philosopher 1 wants to dine
age=4835, Philosopher 0 is thinking for 2087 ms
age=4836, Philosopher 1 is eating for 689 ms
age=4975, Philosopher 3 is thinking for 1231 ms
age=5285, Philosopher 4 wants to dine
age=5286, Philosopher 4 is eating for 857 ms
age=5535, Philosopher 1 is thinking for 3514 ms
```

```
age=6155, Philosopher 4 is thinking for 704 ms
age=6252, Philosopher 3 wants to dine
age=6253, Philosopher 3 is eating for 618 ms
age=6335, time to terminate the Philosophers and exit
age=6337, Philosopher 0 interrupted out of think
age=6339, Philosopher 1 interrupted out of think
age=6340, Philosopher 2 interrupted out of think
age=6342, Philosopher 3 interrupted out of dine
age=6343, Philosopher 4 interrupted out of think
age=7345, all Philosophers are done
```

Example pcre.java

```
import java.util.Vector;
class Producer extends SugarRE implements Runnable {
   private String name = null;
   private boolean synchronous = false;
   private int pNap = 0; // milliseconds
   private Rendezvous rn = null;
   private Thread me = null;
   public Producer(String name, boolean synchronous,
         int pNap, Rendezvous rn) {
      this.name = name;
      this.synchronous = synchronous;
      this.pNap = pNap;
      this.rn = rn;
      (me = new Thread(this)).start();
   }
   public void timeToQuit() { me.interrupt(); }
   public void pauseTilDone() throws InterruptedException
      { me.join(); }
   public void run() {
      if (Thread.currentThread() != me) return;
      double item;
      int napping;
      while (true) {
         if (Thread.interrupted()) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted");
            return;
         }
         napping = 1 + (int) random(pNap);
         System.out.println("age=" + age() + ", " + name
            + " napping for " + napping + " ms");
         try { Thread.sleep(napping); }
         catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted from sleep");
            return;
         }
         item = random();
         System.out.println("age=" + age() + ", " + name
            + " produced item " + item);
         try {
            Double d = new Double(item);
            if (synchronous) {
               Object reply = rn.clientTransactServer(d);
               System.out.println("age=" + age() + ", " + name
                  + ", reply= " + reply);
            } else send(rn, d);
         } catch (InterruptedException e) {
```

```
            System.out.println("age=" + age() + ", " + name
               + " interrupted from send");
            return;
         }
         System.out.println("age=" + age() + ", " + name
            + " sent item " + item);
      }
   }
}
class ConsumerCondition implements RendezvousCondition {
   public ConsumerCondition() { }
   public boolean checkCondition
            (int messageNum, Vector blockedMessages,
         int numBlockedServers) {
      int size = blockedMessages.size();
      if (size == 1) return true;
/*
 * Select the smallest value in the queue.
 */
      double smallest = ((Double) blockedMessages.elementAt(0)).doubleValue();
      int where = 0;
      for (int i = 1; i < size; i++) {
         double d = ((Double) blockedMessages.elementAt(i)).doubleValue();
         if (d < smallest) { smallest = d; where = i; }
      }
      if (where == messageNum) return true;
      else return false;
   }
}
class Consumer extends SugarRE implements Runnable {
   private String name = null;
   private boolean synchronous = false;
   private int cNap = 0; // milliseconds
   private Rendezvous rn = null;
   private Thread me = null;
   private RendezvousCondition rc = null;
   public Consumer(String name, boolean synchronous,
         int cNap, Rendezvous rn) {
      this.name = name;
      this.synchronous = synchronous;
      this.cNap = cNap;
      this.rn = rn;
      rc = new ConsumerCondition();
      (me = new Thread(this)).start();
   }
   public void timeToQuit() { me.interrupt(); }
   public void pauseTilDone() throws InterruptedException
      { me.join(); }
   public void run() {
      if (Thread.currentThread() != me) return;
      double item;
      int napping;
      while (true) {
         if (Thread.interrupted()) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted");
            return;
         }
         napping = 1 + (int) random(cNap);
         System.out.println("age=" + age() + ", " + name
            + " napping for " + napping + " ms");
         try { Thread.sleep(napping); }
         catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted from sleep");
```

```
            return;
         }
         System.out.println("age=" + age() + ", " + name
            + " wants to consume");
         try {
            if (synchronous) {
               Transaction t = rn.serverGetClient(rc);
               Double d = (Double) t.serverGetRequest();
               if (d != null) {
                  item = d.doubleValue();
                  t.serverMakeReply(name + " got it!");
                  System.out.println("age=" + age() + ", " + name
                     + " received item " + item);
               } else {
                  System.out.println("age=" + age() + ", " + name
                     + " received null item");
               }
            } else {
               Double d = (Double) receive(rn, rc);
               if (d != null) {
                  item = d.doubleValue();
                  System.out.println("age=" + age() + ", " + name
                     + " received item " + item);
               } else {
                  System.out.println("age=" + age() + ", " + name
                     + " received null item");
               }
            }
         } catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted from receive");
            return;
         }
      }
   }
}
class ProducersConsumers extends Sugar {
   public static void main(String[] args) {
      boolean synchronous = false;
      int numProducers = 1;
      int numConsumers = 1;
      int pNap = 2;       // defaults
      int cNap = 2;       // in
      int runTime = 60;   // seconds
      try {
         synchronous = args[0].equals("yes");
         numProducers = Integer.parseInt(args[1]);
         numConsumers = Integer.parseInt(args[2]);
         pNap = Integer.parseInt(args[3]);
         cNap = Integer.parseInt(args[4]);
         runTime = Integer.parseInt(args[5]);
      } catch (Exception e) { /* use defaults */ }
      System.out.println("ProducersConsumers:\n synchronous="
         + synchronous + ", numProducers="
         + numProducers + ", numConsumers=" + numConsumers
         + "\n pNap=" + pNap + ", cNap=" + cNap
         + ", runTime=" + runTime);
      // create the message passing channel
      Rendezvous rn = new Rendezvous();
      // start the Producers and Consumers
      // (they have self-starting threads)
      Producer[] p = new Producer[numProducers];
      Consumer[] c = new Consumer[numConsumers];
      for (int i = 0; i < numProducers; i++)
         p[i] = new Producer("PRODUCER"+i, synchronous, pNap*1000, rn);
```

```
      for (int i = 0; i < numConsumers; i++)
         c[i] = new Consumer("Consumer"+i, synchronous, cNap*1000, rn);
      System.out.println("All threads started");
      // let them run for a while
      try {
         Thread.sleep(runTime*1000);
         System.out.println("age=" + age()
            + ", time to terminate the threads and exit");
         for (int i = 0; i < numProducers; i++)
            p[i].timeToQuit();
         for (int i = 0; i < numConsumers; i++)
            c[i].timeToQuit();
         Thread.sleep(1000);
         for (int i = 0; i < numProducers; i++)
            p[i].pauseTilDone();
         for (int i = 0; i < numConsumers; i++)
            c[i].pauseTilDone();
      } catch (InterruptedException e) { /* ignored */ }
      System.out.println("age=" + age()
         + ", all threads are done");
      System.exit(0);
   }
}
```

Sample run of pcre.java

```
% javac pcre.java
% java ProducersConsumers yes 1 1 2 2 6
ProducersConsumers:
 synchronous=true, numProducers=1, numConsumers=1
 pNap=2, cNap=2, runTime=6
age=45, PRODUCER0 napping for 185 ms
age=64, Consumer0 napping for 1202 ms
All threads started
age=244, PRODUCER0 produced item 0.15382515179890965
age=1286, Consumer0 wants to consume
age=1289, PRODUCER0, reply= Consumer0 got it!
age=1290, PRODUCER0 sent item 0.15382515179890965
age=1292, PRODUCER0 napping for 745 ms
age=1292, Consumer0 received item 0.15382515179890965
age=1294, Consumer0 napping for 816 ms
age=2046, PRODUCER0 produced item 0.3602103173386145
age=2123, Consumer0 wants to consume
age=2124, PRODUCER0, reply= Consumer0 got it!
age=2125, PRODUCER0 sent item 0.3602103173386145
age=2126, PRODUCER0 napping for 1954 ms
age=2127, Consumer0 received item 0.3602103173386145
age=2128, Consumer0 napping for 313 ms
age=2453, Consumer0 wants to consume
age=4096, PRODUCER0 produced item 0.9710857065446037
age=4098, PRODUCER0, reply= Consumer0 got it!
age=4098, PRODUCER0 sent item 0.9710857065446037
age=4099, PRODUCER0 napping for 961 ms
age=4100, Consumer0 received item 0.9710857065446037
age=4101, Consumer0 napping for 1231 ms
age=5075, PRODUCER0 produced item 0.5231916912410289
age=5343, Consumer0 wants to consume
age=5344, PRODUCER0, reply= Consumer0 got it!
age=5345, PRODUCER0 sent item 0.5231916912410289
age=5346, PRODUCER0 napping for 113 ms
age=5347, Consumer0 received item 0.5231916912410289
```

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age=5348, Consumer0 napping for 661 ms
age=5473, PRODUCER0 produced item 0.5591064157961917
age=6024, Consumer0 wants to consume
age=6025, PRODUCER0, reply= Consumer0 got it!
age=6025, PRODUCER0 sent item 0.5591064157961917
age=6026, PRODUCER0 napping for 153 ms
age=6027, Consumer0 received item 0.5591064157961917
age=6028, Consumer0 napping for 721 ms
age=6074, time to terminate the threads and exit
age=6077, Consumer0 interrupted from sleep
age=6094, PRODUCER0 interrupted from sleep
age=7084, all threads are done
% java ProducersConsumers no  1 1 2 2 6
ProducersConsumers:
 synchronous=false, numProducers=1, numConsumers=1
 pNap=2, cNap=2, runTime=6
age=47, PRODUCER0 napping for 810 ms
age=66, Consumer0 napping for 48 ms
All threads started
age=126, Consumer0 wants to consume
age=875, PRODUCER0 produced item 0.7568324366583216
age=893, PRODUCER0 sent item 0.7568324366583216
age=894, PRODUCER0 napping for 308 ms
age=896, Consumer0 received item 0.7568324366583216
age=898, Consumer0 napping for 290 ms
age=1195, Consumer0 wants to consume
age=1206, PRODUCER0 produced item 0.5312913550562778
age=1207, PRODUCER0 sent item 0.5312913550562778
age=1208, PRODUCER0 napping for 1326 ms
age=1208, Consumer0 received item 0.5312913550562778
age=1209, Consumer0 napping for 1840 ms
age=2548, PRODUCER0 produced item 0.034237591810933
age=2550, PRODUCER0 sent item 0.034237591810933
age=2551, PRODUCER0 napping for 989 ms
age=3058, Consumer0 wants to consume
age=3059, Consumer0 received item 0.034237591810933
age=3060, Consumer0 napping for 1558 ms
age=3546, PRODUCER0 produced item 0.6571437055152907
age=3547, PRODUCER0 sent item 0.6571437055152907
age=3548, PRODUCER0 napping for 1848 ms
age=4627, Consumer0 wants to consume
age=4628, Consumer0 received item 0.6571437055152907
age=4629, Consumer0 napping for 1445 ms
age=5406, PRODUCER0 produced item 0.9481282378191348
age=5407, PRODUCER0 sent item 0.9481282378191348
age=5408, PRODUCER0 napping for 618 ms
age=6036, PRODUCER0 produced item 0.626005963354672
age=6037, PRODUCER0 sent item 0.626005963354672
age=6038, PRODUCER0 napping for 47 ms
age=6076, time to terminate the threads and exit
age=6097, PRODUCER0 interrupted from sleep
age=6098, Consumer0 interrupted from sleep
age=7086, all threads are done
% java ProducersConsumers yes 1 5 2 2 6
ProducersConsumers:
 synchronous=true, numProducers=1, numConsumers=5
 pNap=2, cNap=2, runTime=6
age=43, PRODUCER0 napping for 1429 ms
age=62, Consumer0 napping for 388 ms
age=66, Consumer1 napping for 657 ms
age=68, Consumer2 napping for 1679 ms
age=70, Consumer3 napping for 495 ms
All threads started
age=73, Consumer4 napping for 1088 ms
age=462, Consumer0 wants to consume
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age=571, Consumer3 wants to consume
age=731, Consumer1 wants to consume
age=1174, Consumer4 wants to consume
age=1482, PRODUCER0 produced item 0.5470149827381032
age=1501, PRODUCER0, reply= Consumer0 got it!
age=1503, PRODUCER0 sent item 0.5470149827381032
age=1504, PRODUCER0 napping for 847 ms
age=1505, Consumer0 received item 0.5470149827381032
age=1506, Consumer0 napping for 4 ms
age=1507, Consumer0 wants to consume
age=1752, Consumer2 wants to consume
age=2364, PRODUCER0 produced item 0.39132362870008386
age=2366, PRODUCER0, reply= Consumer0 got it!
age=2366, PRODUCER0 sent item 0.39132362870008386
age=2368, PRODUCER0 napping for 729 ms
age=2368, Consumer0 received item 0.39132362870008386
age=2370, Consumer0 napping for 1825 ms
age=3124, PRODUCER0 produced item 0.9201218658294597
age=3126, PRODUCER0, reply= Consumer1 got it!
age=3127, PRODUCER0 sent item 0.9201218658294597
age=3128, PRODUCER0 napping for 1292 ms
age=3129, Consumer1 received item 0.9201218658294597
age=3130, Consumer1 napping for 552 ms
age=3692, Consumer1 wants to consume
age=4203, Consumer0 wants to consume
age=4432, PRODUCER0 produced item 0.1103752768928924
age=4433, PRODUCER0, reply= Consumer0 got it!
age=4434, PRODUCER0 sent item 0.1103752768928924
age=4435, PRODUCER0 napping for 887 ms
age=4436, Consumer0 received item 0.1103752768928924
age=4437, Consumer0 napping for 947 ms
age=5332, PRODUCER0 produced item 0.615086398663721
age=5334, PRODUCER0, reply= Consumer1 got it!
age=5334, PRODUCER0 sent item 0.615086398663721
age=5335, PRODUCER0 napping for 1651 ms
age=5336, Consumer1 received item 0.615086398663721
age=5337, Consumer1 napping for 801 ms
age=5392, Consumer0 wants to consume
age=6082, time to terminate the threads and exit
age=6085, Consumer0 interrupted from receive
age=6087, Consumer1 interrupted from sleep
age=6088, Consumer3 interrupted from receive
age=6089, Consumer2 interrupted from receive
age=6091, Consumer4 interrupted from receive
age=6102, PRODUCER0 interrupted from sleep
age=7092, all threads are done
% java ProducersConsumers no  1 5 2 2 6
ProducersConsumers:
 synchronous=false, numProducers=1, numConsumers=5
 pNap=2, cNap=2, runTime=6
age=48, PRODUCER0 napping for 295 ms
age=77, Consumer0 napping for 1571 ms
age=98, Consumer1 napping for 162 ms
age=100, Consumer2 napping for 160 ms
age=102, Consumer3 napping for 39 ms
All threads started
age=104, Consumer4 napping for 848 ms
age=147, Consumer3 wants to consume
age=266, Consumer2 wants to consume
age=276, Consumer1 wants to consume
age=357, PRODUCER0 produced item 0.581001917177535
age=374, PRODUCER0 sent item 0.581001917177535
age=376, PRODUCER0 napping for 1586 ms
age=378, Consumer1 received item 0.581001917177535
age=379, Consumer1 napping for 596 ms
```

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age=959, Consumer4 wants to consume
age=986, Consumer1 wants to consume
age=1667, Consumer0 wants to consume
age=1969, PRODUCER0 produced item 0.5306153831037835
age=1970, PRODUCER0 sent item 0.5306153831037835
age=1971, PRODUCER0 napping for 1347 ms
age=1972, Consumer0 received item 0.5306153831037835
age=1973, Consumer0 napping for 636 ms
age=2617, Consumer0 wants to consume
age=3329, PRODUCER0 produced item 0.2682601940276499
age=3330, PRODUCER0 sent item 0.2682601940276499
age=3331, PRODUCER0 napping for 241 ms
age=3332, Consumer0 received item 0.2682601940276499
age=3333, Consumer0 napping for 400 ms
age=3587, PRODUCER0 produced item 0.47542284179688665
age=3588, PRODUCER0 sent item 0.47542284179688665
age=3589, PRODUCER0 napping for 371 ms
age=3590, Consumer3 received item 0.47542284179688665
age=3591, Consumer3 napping for 497 ms
age=3736, Consumer0 wants to consume
age=3978, PRODUCER0 produced item 0.1426846229950136
age=3979, PRODUCER0 sent item 0.1426846229950136
age=3980, PRODUCER0 napping for 539 ms
age=3981, Consumer0 received item 0.1426846229950136
age=3982, Consumer0 napping for 1760 ms
age=4096, Consumer3 wants to consume
age=4527, PRODUCER0 produced item 0.8579208083111102
age=4528, PRODUCER0 sent item 0.8579208083111102
age=4529, PRODUCER0 napping for 891 ms
age=4530, Consumer2 received item 0.8579208083111102
age=4531, Consumer2 napping for 744 ms
age=5287, Consumer2 wants to consume
age=5437, PRODUCER0 produced item 0.7190220228546758
age=5438, PRODUCER0 sent item 0.7190220228546758
age=5439, PRODUCER0 napping for 1192 ms
age=5440, Consumer1 received item 0.7190220228546758
age=5441, Consumer1 napping for 97 ms
age=5546, Consumer1 wants to consume
age=5746, Consumer0 wants to consume
age=6107, time to terminate the threads and exit
age=6110, Consumer3 interrupted from receive
age=6112, Consumer2 interrupted from receive
age=6113, Consumer1 interrupted from receive
age=6114, Consumer4 interrupted from receive
age=6127, PRODUCER0 interrupted from sleep
age=6128, Consumer0 interrupted from receive
age=7117, all threads are done
% java ProducersConsumers yes 5 1 2 2 6
ProducersConsumers:
 synchronous=true, numProducers=5, numConsumers=1
 pNap=2, cNap=2, runTime=6
age=46, PRODUCER0 napping for 904 ms
age=66, PRODUCER1 napping for 257 ms
age=67, PRODUCER2 napping for 1740 ms
age=70, PRODUCER3 napping for 1405 ms
age=73, PRODUCER4 napping for 670 ms
All threads started
age=76, Consumer0 napping for 1620 ms
age=335, PRODUCER1 produced item 0.17631033059969203
age=745, PRODUCER4 produced item 0.5982192991443873
age=967, PRODUCER0 produced item 0.346069281928469
age=1485, PRODUCER3 produced item 0.1777369982527307
age=1705, Consumer0 wants to consume
age=1708, PRODUCER1, reply= Consumer0 got it!
age=1709, PRODUCER1 sent item 0.17631033059969203
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age=1711, PRODUCER1 napping for 1185 ms
age=1712, Consumer0 received item 0.17631033059969203
age=1713, Consumer0 napping for 1381 ms
age=1815, PRODUCER2 produced item 0.11184681708602617
age=2907, PRODUCER1 produced item 0.03828430977553221
age=3105, Consumer0 wants to consume
age=3106, PRODUCER1, reply= Consumer0 got it!
age=3107, PRODUCER1 sent item 0.03828430977553221
age=3108, PRODUCER1 napping for 1362 ms
age=3108, Consumer0 received item 0.03828430977553221
age=3109, Consumer0 napping for 1281 ms
age=4407, Consumer0 wants to consume
age=4408, PRODUCER2, reply= Consumer0 got it!
age=4409, PRODUCER2 sent item 0.11184681708602617
age=4410, PRODUCER2 napping for 654 ms
age=4411, Consumer0 received item 0.11184681708602617
age=4412, Consumer0 napping for 1190 ms
age=4485, PRODUCER1 produced item 0.08158951384451485
age=5076, PRODUCER2 produced item 0.0983728197982997
age=5605, Consumer0 wants to consume
age=5606, PRODUCER1, reply= Consumer0 got it!
age=5606, PRODUCER1 sent item 0.08158951384451485
age=5608, PRODUCER1 napping for 969 ms
age=5608, Consumer0 received item 0.08158951384451485
age=5609, Consumer0 napping for 1542 ms
age=6085, time to terminate the threads and exit
age=6089, PRODUCER4 interrupted from send
age=6091, PRODUCER3 interrupted from send
age=6092, PRODUCER2 interrupted from send
age=6093, PRODUCER1 interrupted from sleep
age=6094, Consumer0 interrupted from sleep
age=6105, PRODUCER0 interrupted from send
age=7095, all threads are done
% java ProducersConsumers no  5 1 2 2 6
ProducersConsumers:
 synchronous=false, numProducers=5, numConsumers=1
 pNap=2, cNap=2, runTime=6
age=49, PRODUCER0 napping for 1009 ms
age=68, PRODUCER1 napping for 499 ms
age=89, PRODUCER2 napping for 570 ms
age=91, PRODUCER3 napping for 676 ms
age=94, PRODUCER4 napping for 1718 ms
All threads started
age=97, Consumer0 napping for 1153 ms
age=578, PRODUCER1 produced item 0.654109824432186
age=596, PRODUCER1 sent item 0.654109824432186
age=597, PRODUCER1 napping for 1240 ms
age=667, PRODUCER2 produced item 0.18068514475674902
age=669, PRODUCER2 sent item 0.18068514475674902
age=670, PRODUCER2 napping for 589 ms
age=778, PRODUCER3 produced item 0.4102712629046613
age=779, PRODUCER3 sent item 0.4102712629046613
age=780, PRODUCER3 napping for 1802 ms
age=1070, PRODUCER0 produced item 0.5091696195916051
age=1071, PRODUCER0 sent item 0.5091696195916051
age=1072, PRODUCER0 napping for 1319 ms
age=1268, PRODUCER2 produced item 0.11994991872131833
age=1269, PRODUCER2 sent item 0.11994991872131833
age=1270, PRODUCER2 napping for 1459 ms
age=1271, Consumer0 wants to consume
age=1274, Consumer0 received item 0.11994991872131833
age=1275, Consumer0 napping for 983 ms
age=1818, PRODUCER4 produced item 0.3179813502495561
age=1819, PRODUCER4 sent item 0.3179813502495561
age=1820, PRODUCER4 napping for 904 ms
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age=1848, PRODUCER1 produced item 0.6786836744500554
age=1849, PRODUCER1 sent item 0.6786836744500554
age=1850, PRODUCER1 napping for 584 ms
age=2270, Consumer0 wants to consume
age=2271, Consumer0 received item 0.18068514475674902
age=2272, Consumer0 napping for 1020 ms
age=2398, PRODUCER0 produced item 0.6765052327934625
age=2399, PRODUCER0 sent item 0.6765052327934625
age=2400, PRODUCER0 napping for 112 ms
age=2448, PRODUCER1 produced item 0.6087623006574409
age=2449, PRODUCER1 sent item 0.6087623006574409
age=2450, PRODUCER1 napping for 1110 ms
age=2527, PRODUCER0 produced item 0.2943617678806405
age=2529, PRODUCER0 sent item 0.2943617678806405
age=2530, PRODUCER0 napping for 52 ms
age=2597, PRODUCER0 produced item 0.43951489579213454
age=2599, PRODUCER0 sent item 0.43951489579213454
age=2600, PRODUCER0 napping for 1010 ms
age=2601, PRODUCER3 produced item 0.6752658089401261
age=2602, PRODUCER3 sent item 0.6752658089401261
age=2603, PRODUCER3 napping for 1878 ms
age=2738, PRODUCER2 produced item 0.3501856253437148
age=2739, PRODUCER2 sent item 0.3501856253437148
age=2740, PRODUCER2 napping for 163 ms
age=2741, PRODUCER4 produced item 0.08523336769878354
age=2742, PRODUCER4 sent item 0.08523336769878354
age=2743, PRODUCER4 napping for 1810 ms
age=2920, PRODUCER2 produced item 0.13301474356217313
age=2921, PRODUCER2 sent item 0.13301474356217313
age=2922, PRODUCER2 napping for 1163 ms
age=3355, Consumer0 wants to consume
age=3357, Consumer0 received item 0.08523336769878354
age=3358, Consumer0 napping for 1003 ms
age=3568, PRODUCER1 produced item 0.7517292199496083
age=3569, PRODUCER1 sent item 0.7517292199496083
age=3570, PRODUCER1 napping for 1800 ms
age=3618, PRODUCER0 produced item 0.268743465819824
age=3619, PRODUCER0 sent item 0.268743465819824
age=3620, PRODUCER0 napping for 337 ms
age=3969, PRODUCER0 produced item 0.32319739222576216
age=3970, PRODUCER0 sent item 0.32319739222576216
age=3971, PRODUCER0 napping for 1715 ms
age=4098, PRODUCER2 produced item 0.8618141010061056
age=4099, PRODUCER2 sent item 0.8618141010061056
age=4100, PRODUCER2 napping for 1896 ms
age=4377, Consumer0 wants to consume
age=4379, Consumer0 received item 0.13301474356217313
age=4380, Consumer0 napping for 1435 ms
age=4488, PRODUCER3 produced item 0.23912464069393813
age=4489, PRODUCER3 sent item 0.23912464069393813
age=4490, PRODUCER3 napping for 263 ms
age=4558, PRODUCER4 produced item 0.10655946770202618
age=4559, PRODUCER4 sent item 0.10655946770202618
age=4560, PRODUCER4 napping for 924 ms
age=4767, PRODUCER3 produced item 0.12318563460348397
age=4769, PRODUCER3 sent item 0.12318563460348397
age=4770, PRODUCER3 napping for 591 ms
age=5378, PRODUCER1 produced item 0.3722613130125716
age=5379, PRODUCER1 sent item 0.3722613130125716
age=5380, PRODUCER1 napping for 1625 ms
age=5381, PRODUCER3 produced item 0.16025856103329428
age=5382, PRODUCER3 sent item 0.16025856103329428
age=5383, PRODUCER3 napping for 1701 ms
age=5498, PRODUCER4 produced item 0.733038334914754
age=5499, PRODUCER4 sent item 0.733038334914754
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age=5500, PRODUCER4 napping for 688 ms
age=5698, PRODUCER0 produced item 0.5541625041131112
age=5699, PRODUCER0 sent item 0.5541625041131112
age=5700, PRODUCER0 napping for 1411 ms
age=5827, Consumer0 wants to consume
age=5830, Consumer0 received item 0.10655946770202618
age=5831, Consumer0 napping for 1386 ms
age=6008, PRODUCER2 produced item 0.7258819670653431
age=6009, PRODUCER2 sent item 0.7258819670653431
age=6010, PRODUCER2 napping for 1982 ms
age=6098, time to terminate the threads and exit
age=6101, PRODUCER4 interrupted from sleep
age=6103, PRODUCER3 interrupted from sleep
age=6104, PRODUCER2 interrupted from sleep
age=6105, PRODUCER1 interrupted from sleep
age=6106, Consumer0 interrupted from sleep
age=6118, PRODUCER0 interrupted from sleep
age=7108, all threads are done
% java ProducersConsumers yes 5 5 2 2 6
ProducersConsumers:
 synchronous=true, numProducers=5, numConsumers=5
 pNap=2, cNap=2, runTime=6
age=42, PRODUCER0 napping for 1664 ms
age=61, PRODUCER1 napping for 38 ms
age=64, PRODUCER2 napping for 1016 ms
age=65, PRODUCER3 napping for 1829 ms
age=69, PRODUCER4 napping for 60 ms
age=72, Consumer0 napping for 56 ms
age=74, Consumer1 napping for 1142 ms
age=76, Consumer2 napping for 1969 ms
age=78, Consumer3 napping for 1500 ms
All threads started
age=81, Consumer4 napping for 25 ms
age=111, PRODUCER1 produced item 0.9185428067197055
age=129, Consumer4 wants to consume
age=292, PRODUCER1, reply= Consumer4 got it!
age=294, PRODUCER1 sent item 0.9185428067197055
age=295, PRODUCER1 napping for 914 ms
age=296, Consumer4 received item 0.9185428067197055
age=297, Consumer4 napping for 766 ms
age=131, PRODUCER4 produced item 0.08777957250723711
age=190, Consumer0 wants to consume
age=299, Consumer0 received item 0.08777957250723711
age=300, Consumer0 napping for 620 ms
age=301, PRODUCER4, reply= Consumer0 got it!
age=302, PRODUCER4 sent item 0.08777957250723711
age=303, PRODUCER4 napping for 1479 ms
age=933, Consumer0 wants to consume
age=1070, Consumer4 wants to consume
age=1091, PRODUCER2 produced item 0.8940799526535598
age=1092, PRODUCER2, reply= Consumer4 got it!
age=1093, PRODUCER2 sent item 0.8940799526535598
age=1094, PRODUCER2 napping for 87 ms
age=1095, Consumer4 received item 0.8940799526535598
age=1096, Consumer4 napping for 1535 ms
age=1190, PRODUCER2 produced item 0.10081751591092203
age=1192, PRODUCER2, reply= Consumer0 got it!
age=1193, PRODUCER2 sent item 0.10081751591092203
age=1194, PRODUCER2 napping for 1821 ms
age=1195, Consumer0 received item 0.10081751591092203
age=1196, Consumer0 napping for 1396 ms
age=1221, PRODUCER1 produced item 0.3663133766503859
age=1230, Consumer1 wants to consume
age=1231, PRODUCER1, reply= Consumer1 got it!
age=1232, PRODUCER1 sent item 0.3663133766503859
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age=1233, PRODUCER1 napping for 918 ms
age=1234, Consumer1 received item 0.3663133766503859
age=1235, Consumer1 napping for 503 ms
age=1581, Consumer3 wants to consume
age=1721, PRODUCER0 produced item 0.16926696419542775
age=1722, PRODUCER0, reply= Consumer3 got it!
age=1723, PRODUCER0 sent item 0.16926696419542775
age=1724, PRODUCER0 napping for 1393 ms
age=1725, Consumer3 received item 0.16926696419542775
age=1726, Consumer3 napping for 1382 ms
age=1750, Consumer1 wants to consume
age=1791, PRODUCER4 produced item 0.24476649246179505
age=1792, Consumer1 received item 0.24476649246179505
age=1794, Consumer1 napping for 484 ms
age=1796, PRODUCER4, reply= Consumer1 got it!
age=1798, PRODUCER4 sent item 0.24476649246179505
age=1799, PRODUCER4 napping for 220 ms
age=1903, PRODUCER3 produced item 0.800190863174061
age=2021, PRODUCER4 produced item 0.8202427064995859
age=2051, Consumer2 wants to consume
age=2052, PRODUCER3, reply= Consumer2 got it!
age=2053, PRODUCER3 sent item 0.800190863174061
age=2054, PRODUCER3 napping for 1756 ms
age=2055, Consumer2 received item 0.800190863174061
age=2056, Consumer2 napping for 638 ms
age=2161, PRODUCER1 produced item 0.9924100353971543
age=2290, Consumer1 wants to consume
age=2291, Consumer1 received item 0.8202427064995859
age=2292, Consumer1 napping for 1935 ms
age=2293, PRODUCER4, reply= Consumer1 got it!
age=2294, PRODUCER4 sent item 0.8202427064995859
age=2295, PRODUCER4 napping for 816 ms
age=2600, Consumer0 wants to consume
age=2601, PRODUCER1, reply= Consumer0 got it!
age=2602, PRODUCER1 sent item 0.9924100353971543
age=2603, PRODUCER1 napping for 52 ms
age=2604, Consumer0 received item 0.9924100353971543
age=2605, Consumer0 napping for 203 ms
age=2640, Consumer4 wants to consume
age=2670, PRODUCER1 produced item 0.5720839002063113
age=2672, PRODUCER1, reply= Consumer4 got it!
age=2673, PRODUCER1 sent item 0.5720839002063113
age=2674, PRODUCER1 napping for 830 ms
age=2674, Consumer4 received item 0.5720839002063113
age=2676, Consumer4 napping for 135 ms
age=2700, Consumer2 wants to consume
age=2820, Consumer4 wants to consume
age=2821, Consumer0 wants to consume
age=3033, PRODUCER2 produced item 0.38032840213175745
age=3034, PRODUCER2, reply= Consumer2 got it!
age=3035, PRODUCER2 sent item 0.38032840213175745
age=3036, PRODUCER2 napping for 1095 ms
age=3037, Consumer2 received item 0.38032840213175745
age=3038, Consumer2 napping for 1230 ms
age=3120, Consumer3 wants to consume
age=3121, PRODUCER4 produced item 0.9604224841343072
age=3123, Consumer3 received item 0.9604224841343072
age=3124, Consumer3 napping for 1633 ms
age=3125, PRODUCER4, reply= Consumer3 got it!
age=3125, PRODUCER4 sent item 0.9604224841343072
age=3126, PRODUCER4 napping for 608 ms
age=3131, PRODUCER0 produced item 0.9650427611915405
age=3132, PRODUCER0, reply= Consumer4 got it!
age=3133, PRODUCER0 sent item 0.9650427611915405
age=3134, PRODUCER0 napping for 1713 ms
```

```
age=3135, Consumer4 received item 0.9650427611915405
age=3136, Consumer4 napping for 307 ms
age=3450, Consumer4 wants to consume
age=3511, PRODUCER1 produced item 0.918506532764693
age=3512, PRODUCER1, reply= Consumer4 got it!
age=3513, PRODUCER1 sent item 0.918506532764693
age=3514, PRODUCER1 napping for 1238 ms
age=3515, Consumer4 received item 0.918506532764693
age=3516, Consumer4 napping for 1264 ms
age=3740, PRODUCER4 produced item 0.754027144422452
age=3742, PRODUCER4, reply= Consumer0 got it!
age=3743, PRODUCER4 sent item 0.754027144422452
age=3744, PRODUCER4 napping for 1578 ms
age=3745, Consumer0 received item 0.754027144422452
age=3746, Consumer0 napping for 208 ms
age=3821, PRODUCER3 produced item 0.27122994909004716
age=3962, Consumer0 wants to consume
age=3963, PRODUCER3, reply= Consumer0 got it!
age=3964, PRODUCER3 sent item 0.27122994909004716
age=3965, PRODUCER3 napping for 579 ms
age=3966, Consumer0 received item 0.27122994909004716
age=3967, Consumer0 napping for 372 ms
age=4141, PRODUCER2 produced item 0.27589255387330824
age=4240, Consumer1 wants to consume
age=4241, PRODUCER2, reply= Consumer1 got it!
age=4242, PRODUCER2 sent item 0.27589255387330824
age=4243, PRODUCER2 napping for 1469 ms
age=4244, Consumer1 received item 0.27589255387330824
age=4245, Consumer1 napping for 1952 ms
age=4270, Consumer2 wants to consume
age=4350, Consumer0 wants to consume
age=4550, PRODUCER3 produced item 0.8619194399545967
age=4552, PRODUCER3, reply= Consumer2 got it!
age=4553, PRODUCER3 sent item 0.8619194399545967
age=4554, PRODUCER3 napping for 398 ms
age=4554, Consumer2 received item 0.8619194399545967
age=4556, Consumer2 napping for 472 ms
age=4761, PRODUCER1 produced item 0.7701099520047171
age=4762, PRODUCER1, reply= Consumer0 got it!
age=4763, PRODUCER1 sent item 0.7701099520047171
age=4764, PRODUCER1 napping for 1625 ms
age=4765, Consumer0 received item 0.7701099520047171
age=4766, Consumer0 napping for 129 ms
age=4771, Consumer3 wants to consume
age=4790, Consumer4 wants to consume
age=4861, PRODUCER0 produced item 0.2228435588271499
age=4862, PRODUCER0, reply= Consumer3 got it!
age=4863, PRODUCER0 sent item 0.2228435588271499
age=4864, PRODUCER0 napping for 951 ms
age=4864, Consumer3 received item 0.2228435588271499
age=4866, Consumer3 napping for 675 ms
age=4900, Consumer0 wants to consume
age=4961, PRODUCER3 produced item 0.6894975962370399
age=4962, PRODUCER3, reply= Consumer4 got it!
age=4963, PRODUCER3 sent item 0.6894975962370399
age=4964, PRODUCER3 napping for 743 ms
age=4965, Consumer4 received item 0.6894975962370399
age=4966, Consumer4 napping for 403 ms
age=5041, Consumer2 wants to consume
age=5331, PRODUCER4 produced item 0.8065414987883718
age=5332, Consumer2 received item 0.8065414987883718
age=5333, Consumer2 napping for 1824 ms
age=5334, PRODUCER4, reply= Consumer2 got it!
age=5334, PRODUCER4 sent item 0.8065414987883718
age=5336, PRODUCER4 napping for 1217 ms
```

```
age=5380, Consumer4 wants to consume
age=5551, Consumer3 wants to consume
age=5721, PRODUCER2 produced item 0.9920886064917681
age=5722, PRODUCER3 produced item 0.903554039796397
age=5723, PRODUCER3, reply= Consumer3 got it!
age=5724, PRODUCER3 sent item 0.903554039796397
age=5725, PRODUCER3 napping for 828 ms
age=5726, Consumer3 received item 0.903554039796397
age=5727, Consumer3 napping for 997 ms
age=5728, PRODUCER2, reply= Consumer4 got it!
age=5729, PRODUCER2 sent item 0.9920886064917681
age=5730, PRODUCER2 napping for 1454 ms
age=5731, Consumer4 received item 0.9920886064917681
age=5732, Consumer4 napping for 1344 ms
age=5831, PRODUCER0 produced item 0.13174758677755616
age=5832, PRODUCER0, reply= Consumer0 got it!
age=5833, PRODUCER0 sent item 0.13174758677755616
age=5834, PRODUCER0 napping for 689 ms
age=5835, Consumer0 received item 0.13174758677755616
age=5836, Consumer0 napping for 1170 ms
age=6091, time to terminate the threads and exit
age=6094, PRODUCER3 interrupted from sleep
age=6096, PRODUCER1 interrupted from sleep
age=6097, PRODUCER2 interrupted from sleep
age=6098, Consumer1 interrupted from sleep
age=6099, Consumer2 interrupted from sleep
age=6100, Consumer3 interrupted from sleep
age=6101, Consumer4 interrupted from sleep
age=6103, PRODUCER4 interrupted from sleep
age=6104, Consumer0 interrupted from sleep
age=6111, PRODUCER0 interrupted from sleep
age=7101, all threads are done
% java ProducersConsumers no  5 5 2 2 6
ProducersConsumers:
 synchronous=false, numProducers=5, numConsumers=5
 pNap=2, cNap=2, runTime=6
age=44, PRODUCER0 napping for 1548 ms
age=63, PRODUCER1 napping for 677 ms
age=66, PRODUCER2 napping for 1441 ms
age=68, PRODUCER3 napping for 1283 ms
age=71, PRODUCER4 napping for 435 ms
age=74, Consumer0 napping for 1925 ms
age=76, Consumer1 napping for 1681 ms
age=78, Consumer2 napping for 1632 ms
age=81, Consumer3 napping for 1953 ms
All threads started
age=83, Consumer4 napping for 1600 ms
age=513, PRODUCER4 produced item 0.3410400811142391
age=530, PRODUCER4 sent item 0.3410400811142391
age=532, PRODUCER4 napping for 1 ms
age=532, PRODUCER4 produced item 0.9047856169302597
age=533, PRODUCER4 sent item 0.9047856169302597
age=534, PRODUCER4 napping for 1025 ms
age=753, PRODUCER1 produced item 0.8843759516570732
age=754, PRODUCER1 sent item 0.8843759516570732
age=755, PRODUCER1 napping for 357 ms
age=1125, PRODUCER1 produced item 0.19197557779325958
age=1126, PRODUCER1 sent item 0.19197557779325958
age=1127, PRODUCER1 napping for 491 ms
age=1363, PRODUCER3 produced item 0.830373247233264
age=1364, PRODUCER3 sent item 0.830373247233264
age=1365, PRODUCER3 napping for 901 ms
age=1523, PRODUCER2 produced item 0.8098838675941346
age=1524, PRODUCER2 sent item 0.8098838675941346
age=1525, PRODUCER2 napping for 436 ms
```

```
age=1573, PRODUCER4 produced item 0.6027106304058345
age=1574, PRODUCER4 sent item 0.6027106304058345
age=1575, PRODUCER4 napping for 319 ms
age=1603, PRODUCER0 produced item 0.4292486419460507
age=1604, PRODUCER0 sent item 0.4292486419460507
age=1605, PRODUCER0 napping for 325 ms
age=1632, PRODUCER1 produced item 0.5872721123774989
age=1634, PRODUCER1 sent item 0.5872721123774989
age=1635, PRODUCER1 napping for 1474 ms
age=1693, Consumer4 wants to consume
age=1695, Consumer4 received item 0.19197557779325958
age=1697, Consumer4 napping for 1939 ms
age=1722, Consumer2 wants to consume
age=1723, Consumer2 received item 0.3410400811142391
age=1724, Consumer2 napping for 608 ms
age=1772, Consumer1 wants to consume
age=1773, Consumer1 received item 0.4292486419460507
age=1774, Consumer1 napping for 148 ms
age=1905, PRODUCER4 produced item 0.15349615717846132
age=1906, PRODUCER4 sent item 0.15349615717846132
age=1907, PRODUCER4 napping for 974 ms
age=1932, Consumer1 wants to consume
age=1933, Consumer1 received item 0.15349615717846132
age=1935, Consumer1 napping for 734 ms
age=1943, PRODUCER0 produced item 0.6143545981931535
age=1944, PRODUCER0 sent item 0.6143545981931535
age=1945, PRODUCER0 napping for 214 ms
age=1973, PRODUCER2 produced item 0.5517125342572194
age=1974, PRODUCER2 sent item 0.5517125342572194
age=1975, PRODUCER2 napping for 105 ms
age=2012, Consumer0 wants to consume
age=2014, Consumer0 received item 0.5517125342572194
age=2015, Consumer0 napping for 896 ms
age=2042, Consumer3 wants to consume
age=2043, Consumer3 received item 0.5872721123774989
age=2044, Consumer3 napping for 1964 ms
age=2093, PRODUCER2 produced item 0.6032968491632188
age=2094, PRODUCER2 sent item 0.6032968491632188
age=2095, PRODUCER2 napping for 1052 ms
age=2173, PRODUCER0 produced item 0.306508087515337
age=2174, PRODUCER0 sent item 0.306508087515337
age=2175, PRODUCER0 napping for 346 ms
age=2283, PRODUCER3 produced item 0.039727663768907906
age=2284, PRODUCER3 sent item 0.039727663768907906
age=2285, PRODUCER3 napping for 1444 ms
age=2342, Consumer2 wants to consume
age=2344, Consumer2 received item 0.039727663768907906
age=2345, Consumer2 napping for 32 ms
age=2392, Consumer2 wants to consume
age=2393, Consumer2 received item 0.306508087515337
age=2395, Consumer2 napping for 1172 ms
age=2533, PRODUCER0 produced item 0.9501617999455061
age=2534, PRODUCER0 sent item 0.9501617999455061
age=2535, PRODUCER0 napping for 1394 ms
age=2682, Consumer1 wants to consume
age=2683, Consumer1 received item 0.6027106304058345
age=2684, Consumer1 napping for 1554 ms
age=2902, PRODUCER4 produced item 0.9917188318473676
age=2903, PRODUCER4 sent item 0.9917188318473676
age=2904, PRODUCER4 napping for 940 ms
age=2922, Consumer0 wants to consume
age=2923, Consumer0 received item 0.6032968491632188
age=2924, Consumer0 napping for 1654 ms
age=3123, PRODUCER1 produced item 0.9290907832359444
age=3124, PRODUCER1 sent item 0.9290907832359444
```

```
age=3125, PRODUCER1 napping for 897 ms
age=3163, PRODUCER2 produced item 0.7092244510592798
age=3164, PRODUCER2 sent item 0.7092244510592798
age=3165, PRODUCER2 napping for 775 ms
age=3583, Consumer2 wants to consume
age=3584, Consumer2 received item 0.6143545981931535
age=3585, Consumer2 napping for 544 ms
age=3642, Consumer4 wants to consume
age=3644, Consumer4 received item 0.7092244510592798
age=3645, Consumer4 napping for 371 ms
age=3743, PRODUCER3 produced item 0.09280502991799322
age=3744, PRODUCER3 sent item 0.09280502991799322
age=3745, PRODUCER3 napping for 1858 ms
age=3853, PRODUCER4 produced item 0.7592324485274388
age=3854, PRODUCER4 sent item 0.7592324485274388
age=3855, PRODUCER4 napping for 366 ms
age=3943, PRODUCER0 produced item 0.7209106579261657
age=3944, PRODUCER0 sent item 0.7209106579261657
age=3946, PRODUCER0 napping for 1845 ms
age=3953, PRODUCER2 produced item 0.47272956301074043
age=3954, PRODUCER2 sent item 0.47272956301074043
age=3955, PRODUCER2 napping for 365 ms
age=4022, Consumer3 wants to consume
age=4024, Consumer3 received item 0.09280502991799322
age=4025, Consumer3 napping for 142 ms
age=4033, PRODUCER1 produced item 0.3280222480542785
age=4034, PRODUCER1 sent item 0.3280222480542785
age=4035, PRODUCER1 napping for 617 ms
age=4035, Consumer4 wants to consume
age=4037, Consumer4 received item 0.3280222480542785
age=4038, Consumer4 napping for 23 ms
age=4072, Consumer4 wants to consume
age=4074, Consumer4 received item 0.47272956301074043
age=4075, Consumer4 napping for 1886 ms
age=4142, Consumer2 wants to consume
age=4144, Consumer2 received item 0.7209106579261657
age=4145, Consumer2 napping for 245 ms
age=4182, Consumer3 wants to consume
age=4184, Consumer3 received item 0.7592324485274388
age=4185, Consumer3 napping for 1482 ms
age=4233, PRODUCER4 produced item 0.9186461316635379
age=4234, PRODUCER4 sent item 0.9186461316635379
age=4235, PRODUCER4 napping for 138 ms
age=4252, Consumer1 wants to consume
age=4253, Consumer1 received item 0.8098838675941346
age=4254, Consumer1 napping for 601 ms
age=4333, PRODUCER2 produced item 0.35806399650517884
age=4334, PRODUCER2 sent item 0.35806399650517884
age=4335, PRODUCER2 napping for 166 ms
age=4383, PRODUCER4 produced item 0.2058488238208972
age=4384, PRODUCER4 sent item 0.2058488238208972
age=4385, PRODUCER4 napping for 1147 ms
age=4402, Consumer2 wants to consume
age=4404, Consumer2 received item 0.2058488238208972
age=4405, Consumer2 napping for 1199 ms
age=4513, PRODUCER2 produced item 0.5743572081217496
age=4514, PRODUCER2 sent item 0.5743572081217496
age=4515, PRODUCER2 napping for 1721 ms
age=4593, Consumer0 wants to consume
age=4594, Consumer0 received item 0.35806399650517884
age=4595, Consumer0 napping for 1554 ms
age=4663, PRODUCER1 produced item 0.2768196943978283
age=4664, PRODUCER1 sent item 0.2768196943978283
age=4665, PRODUCER1 napping for 1674 ms
age=4872, Consumer1 wants to consume
```

```
age=4874, Consumer1 received item 0.2768196943978283
age=4875, Consumer1 napping for 17 ms
age=4902, Consumer1 wants to consume
age=4903, Consumer1 received item 0.5743572081217496
age=4905, Consumer1 napping for 8 ms
age=4923, Consumer1 wants to consume
age=4923, Consumer1 received item 0.830373247233264
age=4924, Consumer1 napping for 20 ms
age=4952, Consumer1 wants to consume
age=4953, Consumer1 received item 0.8843759516570732
age=4954, Consumer1 napping for 361 ms
age=5332, Consumer1 wants to consume
age=5333, Consumer1 received item 0.9047856169302597
age=5334, Consumer1 napping for 613 ms
age=5543, PRODUCER4 produced item 0.6109297009381629
age=5544, PRODUCER4 sent item 0.6109297009381629
age=5545, PRODUCER4 napping for 1325 ms
age=5613, PRODUCER3 produced item 0.874675354317203
age=5614, PRODUCER3 sent item 0.874675354317203
age=5615, PRODUCER3 napping for 664 ms
age=5615, Consumer2 wants to consume
age=5616, Consumer2 received item 0.6109297009381629
age=5617, Consumer2 napping for 1072 ms
age=5682, Consumer3 wants to consume
age=5683, Consumer3 received item 0.874675354317203
age=5684, Consumer3 napping for 474 ms
age=5804, PRODUCER0 produced item 0.1782579961776114
age=5806, PRODUCER0 sent item 0.1782579961776114
age=5808, PRODUCER0 napping for 640 ms
age=5963, Consumer1 wants to consume
age=5963, Consumer1 received item 0.1782579961776114
age=5965, Consumer1 napping for 1642 ms
age=5972, Consumer4 wants to consume
age=5973, Consumer4 received item 0.9186461316635379
age=5974, Consumer4 napping for 891 ms
age=6093, time to terminate the threads and exit
age=6096, PRODUCER4 interrupted from sleep
age=6098, Consumer0 interrupted from sleep
age=6099, Consumer1 interrupted from sleep
age=6100, Consumer4 interrupted from sleep
age=6101, Consumer3 interrupted from sleep
age=6103, Consumer2 interrupted from sleep
age=6113, PRODUCER0 interrupted from sleep
age=6114, PRODUCER1 interrupted from sleep
age=6115, PRODUCER2 interrupted from sleep
age=6116, PRODUCER3 interrupted from sleep
age=7103, all threads are done
```

Section 12. Remote Method Invocation (RMI)

Some definitions

RMI is a Java package (**`java.rmi`**) used to make *remote procedure calls*.

RMI allows a thread in one JVM to invoke a method in an object in another JVM that is perhaps on a different computer.

Object serialization is used to send an object from one JVM to another as an argument of a remote method invocation. This converts an object into a byte stream that is sent through a socket and converted into a copy of the object on the other end. A new thread is created in the remote object to execute the called method's code.

Example Compute.java on page 99 shows several clients accessing a remote server executing in a different JVM, which can be on a different physical machine. Sample run of Compute.java server on page 102 shows the sample server output. Sample run of Compute.java clients on page 105 shows the sample client output.

Notice that the sample output shows the clients' remote method invocations are interleaved -- that is, overlapping executions by new threads created in the server for each RMI. There are no race conditions or synchronization problems in this example because the clients are independent and do not share any data.

In the sample run, the clients all execute in one JVM and the server in another JVM. Both JVMs are on the same physical machine. If the clients are on a different physical machine, pass the name of the machine on which the server runs as a command-line argument when starting the clients.

RMI can be used by a thread in one JVM to send a message to or rendezvous with a thread in another JVM. A thread willing to receive or rendezvous registers an interface that other threads can use and implements the interface using a message passing or rendezvous object.

Background material on RMI

RMI, or remote method invocation, is the ability to make remote procedure calls. We use "remote procedure calls" to describe an extended rendezvous between two threads in different JVMs, perhaps on different physical machines.

Sun's RMI allows a thread in one JVM to invoke (call) a method in an object in another JVM that is perhaps on a different physical machine. A new thread is created in the other (remote) JVM to execute the called method.

The **`ComputeServer`** remote object implements a **`Compute`** interface containing a **`compute()`** method that a local **`Client`** can call, passing a **`Work`** object whose **`doWork()`** method the server calls. The client is using the remote server to have work performed on its behalf (adding vectors). Presumably the server is running on a computer architecture that can perform the work more efficiently. Parameters to the remote method and the method's return results, if any, are passed from one JVM to the other using object serialization over the network.

User-written classes

Rendezvous client and server classes for RMI include:

* Interface RemoteRendezvous.java on page 107
* Class RemoteRendezvousClient.java on page 108 . Used by client or peer
* Class RemoteRendezvousServer.java on page 109 . Used by server or peer

Examples of RMI

Rendezvous Example Transact.java on page 110 -- Several clients access a remote server executing in a different JVM, which can be on a different physical machine. Server and client output is in Sample run of Transact.java server on page 113 and Sample run of Transact.java clients on page 114 .

Multiple clients transact (read and write operations) with a database on a remote server. The transactions are serialized to avoid race conditions on the shared database maintained by the server. Also, the server gives client number zero highest priority by always handling its transaction first among those waiting to be performed.

In the sample run, the clients all execute in one JVM and the server in another JVM. Both JVMs are on the same physical machine. If the clients are on a different physical machine, pass the name of the machine on which the server runs as a command-line argument when starting the clients.

Message passing Example Ring.java on page 115 -- Several peers are arranged in a circular ring. Each ring member executes in its own JVM and the ring members need not all be on the same physical machine. A single token object is passed around the ring from each member to its successor. These are the sample outputs (Sample run of Ring.java ring member 0 on page 119, Sample run of Ring.java ring member 1 on page 120 , and Sample run of Ring.java ring member 2 on page 121) in a three-member ring.

In the sample run, the three ring members execute in different JVMs, all on the same physical machine. If the JVMs are on different physical machines, give each ring member on its command line the machine name of its successor. Each physical machine running one or more ring member JVMs needs to be executing one instance of **`rmiregistry`**, started either manually or internally by one of the ring members on that machine.

The next several panels display the code described in this section. To view the code, click **Next**; or you can go directly to the next section, Wrapup on page 122 , and return to the code samples at another time.

Example Compute.java

```
import java.io.Serializable;
import java.rmi.*;
import java.rmi.server.UnicastRemoteObject;
```

```
import java.rmi.registry.*;
public interface Compute extends Remote {
   public static final String SERVER_NAME = "ComputeServer";
   public static final String SERVER_MACHINE = "localhost";
   public static final int SERVER_PORT = 8989;
   public static final int RUN_TIME = 20;
   public abstract Work compute(Work w)
      throws RemoteException, InterruptedException;
}
class Work extends Sugar implements Serializable {
   private final int N = 3;
   private String name = null;
   private double[] a = null, b = null, c = null;
   private boolean performed = false;
   public Work(String name) {
      this.name = name;
      a = new double[N]; b = new double[N]; c = new double[N];
      for (int i = 0; i < N; i++) {
         a[i] = random(-N, N); b[i] = random(-N, N);
      }
   }
   public void doWork() throws InterruptedException {
      // sleep to simulate some computation time
      Thread.sleep(1+(int)random(1000*N));
      for (int i = 0; i < N; i++) c[i] = a[i] + b[i];
      performed = true;
   }
   public String toString() {
      String value = "\n" + name;
      value += "\na=";
      for (int i = 0; i < N; i++) value += " " + a[i];
      value += "\nb=";
      for (int i = 0; i < N; i++) value += " " + b[i];
      if (performed) {
         value += "\nc=";
         for (int i = 0; i < N; i++) value += " " + c[i];
      }
      return value;
   }
}
class ComputeServer extends UnicastRemoteObject
      implements Compute {
   public ComputeServer() throws RemoteException { }
   public Work compute(Work w)
         throws RemoteException, InterruptedException {
      System.out.println(SERVER_NAME + " " + Thread.currentThread()
         + " got work request:" + w);
      w.doWork();
      System.out.println(SERVER_NAME + " " + Thread.currentThread()
         + " sending reply:" + w);
      return w;
   }
   public static void main(String args[])  {
      int serverPort = Compute.SERVER_PORT;
      int runTime = Compute.RUN_TIME;   // seconds
      try {
         serverPort = Integer.parseInt(args[0]);
         runTime = Integer.parseInt(args[1]);
      } catch (Exception e) { /* use defaults */ }
      System.out.println("Server: serverMachine=" + SERVER_MACHINE
         + ", serverName=" + SERVER_NAME + ", serverPort="
         + serverPort + ", runTime=" + runTime);
      // create a registry and register this server
      try {
         Registry registry = LocateRegistry.createRegistry(serverPort);
```

```
         ComputeServer server = new ComputeServer();
         registry.bind(SERVER_NAME, server);
      } catch (Exception e) {
         System.err.println(SERVER_NAME + " exception " + e);
         System.exit(1);
      }
      System.out.println("server " + SERVER_NAME
         + " has been created and bound in the registry");
      try {
         Thread.sleep((runTime+10)*1000);
      } catch (InterruptedException e) { /* ignored */ }
      System.out.println("time to terminate the Server and exit");
      System.exit(0);
   }
}
class Client extends Sugar implements Runnable {
   private String name = null;
   private int id = -1;
   private Compute server = null;
   private int napTime = 0;
   private Thread me = null;
   private Client(int id, Compute server, int napTime) {
      this.name = "Client " + id;
      this.id = id;
      this.server = server;
      this.napTime = napTime;
      (me = new Thread(this)).start();
   }
   public void timeToQuit() { me.interrupt(); }
   public void pauseTilDone() throws InterruptedException
      { me.join(); }
   public void run() {
      int napping;
      Work w = null;
      if (Thread.currentThread() != me) return;
      while (true) {
         if (Thread.interrupted()) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted");
            return;
         }
         napping = 1 + (int) random(napTime);
         try {
            Thread.sleep(napping);
         } catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted out of sleep");
            return;
         }
         w = new Work(name);
         System.out.println("age=" + age() + ", "
            + name + " sending to server work:" + w);
         try {
            w = server.compute(w);
         } catch (Exception e) {
            System.err.println("Client exception " + e);
            return;
         }
         System.out.println("age=" + age() + ", "
            + name + " received from server reply:" + w);
      }
   }
   public static void main(String[] args) {
      String serverName = Compute.SERVER_NAME;
      String serverMachine = Compute.SERVER_MACHINE;
```

```
      int serverPort = Compute.SERVER_PORT;
      int numClients = 3;
      int napTime = 4;                  // both in
      int runTime = Compute.RUN_TIME;   // seconds
      try {
         serverMachine = args[0];
         serverName = args[1];
         serverPort = Integer.parseInt(args[2]);
         numClients = Integer.parseInt(args[3]);
         napTime = Integer.parseInt(args[4]);
         runTime = Integer.parseInt(args[5]);
      } catch (Exception e) { /* use defaults */ }
      System.out.println("Client: serverMachine=" + serverMachine
         + ", serverName=" + serverName + ", serverPort=" + serverPort
         + "\n numClients=" + numClients + ", napTime=" + napTime
         + ", runTime=" + runTime);
      Compute server = null;
      try {
         server = (Compute)
            Naming.lookup("rmi://" + serverMachine + ":"
               + serverPort + "/" + serverName);
      } catch (Exception e) {
         System.err.println("Client exception " + e);
         System.exit(1);
      }
      Client[] c = new Client[numClients];
      for (int i = 0; i < numClients; i++)
         c[i] = new Client(i, server, 1000*napTime);
      System.out.println("All Client threads started");
      // let the Clients run for a while
      try {
         Thread.sleep(runTime*1000);
         System.out.println("age=" + age()
            + ", time to terminate the Clients and exit");
         for (int i = 0; i < numClients; i++)
            c[i].timeToQuit();
         Thread.sleep(1000);
         for (int i = 0; i < numClients; i++)
            c[i].pauseTilDone();
      } catch (InterruptedException e) { /* ignored */ }
      System.out.println("age=" + age()
         + ", all Clients are done");
      System.exit(0);
   }
}
/* ............... To run:
machineA% javac Compute.java
machineA% rmic ComputeServer
machineA% java ComputeServer &
machineA% rsh machineB "java Client machineA"
*/
```

Sample run of Compute.java server

```
% javac Compute.java
% rmic ComputeServer
% java ComputeServer &
Server: serverMachine=localhost, serverName=ComputeServer, serverPort=8989, runTime=20
server ComputeServer has been created and bound in the registry
ComputeServer Thread[TCP Connection(4)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
```

```
Client 2
a= -2.6956833547799772 2.7056242913415076 1.5467036159966847
b= 0.9272845052351353 2.375308405708611 1.7315712879212102
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 1
a= 2.198285066955644 1.1014851982887102 2.1195367406109042
b= -2.40242980205884 -0.2716969010229877 1.7543779582559216
ComputeServer Thread[TCP Connection(4)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  sending reply:
Client 2
a= -2.6956833547799772 2.7056242913415076 1.5467036159966847
b= 0.9272845052351353 2.375308405708611 1.7315712879212102
c= -1.768398849544842 5.080932697050119 3.278274903917895
ComputeServer Thread[TCP Connection(6)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 0
a= 1.1018592459170318 2.998499863398912 -2.2753431857554913
b= 1.60740034099687 2.4918661638800934 -0.35813980483005325
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  sending reply:
Client 1
a= 2.198285066955644 1.1014851982887102 2.1195367406109042
b= -2.40242980205884 -0.2716969010229877 1.7543779582559216
c= -0.20414473510319597 0.8297882972657225 3.873914698866826
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 2
a= -0.8261092470419777 0.721414082931692 -0.42645707078792716
b= -0.5302742195582928 0.8483683515941847 -1.0025008898402417
ComputeServer Thread[TCP Connection(6)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  sending reply:
Client 0
a= 1.1018592459170318 2.998499863398912 -2.2753431857554913
b= 1.60740034099687 2.4918661638800934 -0.35813980483005325
c= 2.709259586913902 5.490366027279006 -2.6334829905855446
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  sending reply:
Client 2
a= -0.8261092470419777 0.721414082931692 -0.42645707078792716
b= -0.5302742195582928 0.8483683515941847 -1.0025008898402417
c= -1.3563834666002705 1.5697824345258766 -1.4289579606281688
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 2
a= -0.10302907032858588 2.122280172623806 -2.972889012811118
b= -2.1063144034959604 1.2484700810438456 -0.34516873732456776
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  sending reply:
Client 2
a= -0.10302907032858588 2.122280172623806 -2.972889012811118
b= -2.1063144034959604 1.2484700810438456 -0.34516873732456776
c= -2.2093434738245463 3.3707502536676515 -3.3180577501356856
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 1
a= 1.8732549025182514 1.6775852683316153 -1.3943090135761338
b= 0.4459518118556396 0.010579789697764852 -2.106450761604641
ComputeServer Thread[TCP Connection(6)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 0
a= -2.8410081979322523 2.5649645745053986 -0.026610740169620506
b= 0.7851856936449471 0.616151284898736 -2.9907779217992445
ComputeServer Thread[TCP Connection(4)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
```

```
Client 2
a= -1.5686083274058547 1.9379634892476183 0.7979989612913752
b= -2.4602035559398168 2.111407097419087 -0.13995152334940153
ComputeServer Thread[TCP Connection(4)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  sending reply:
Client 2
a= -1.5686083274058547 1.9379634892476183 0.7979989612913752
b= -2.4602035559398168 2.111407097419087 -0.13995152334940153
c= -4.028811883345671 4.049370586666705 0.6580474379419736
ComputeServer Thread[TCP Connection(6)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  sending reply:
Client 0
a= -2.8410081979322523 2.5649645745053986 -0.026610740169620506
b= 0.7851856936449471 0.616151284898736 -2.9907779217992445
c= -2.0558225042873053 3.1811158594041347 -3.017388661968865
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  sending reply:
Client 1
a= 1.8732549025182514 1.6775852683316153 -1.3943090135761338
b= 0.4459518118556396 0.010579789697764852 -2.106450761604641
c= 2.319206714373891 1.68816505802938 -3.5007597751807746
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 1
a= 1.13032496867271 1.7356634369443213 -1.039424286223417
b= 1.6589595605000858 -2.2151755327196945 -2.2322555512103297
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  sending reply:
Client 1
a= 1.13032496867271 1.7356634369443213 -1.039424286223417
b= 1.6589595605000858 -2.2151755327196945 -2.2322555512103297
c= 2.7892845291727957 -0.4795120957753731 -3.271679837433747
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 0
a= -0.27919433374176084 -1.6389486800885282 0.49400802045625003
b= -1.0951363826810552 -1.7985257452276389 1.0206951985241437
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  sending reply:
Client 0
a= -0.27919433374176084 -1.6389486800885282 0.49400802045625003
b= -1.0951363826810552 -1.7985257452276389 1.0206951985241437
c= -1.374330716422816 -3.437474425316167 1.5147032189803937
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 2
a= -2.657830948742076 0.9247497273131033 -1.1837878935327522
b= -0.7360974998678449 -2.5187722515825985 1.3749770142429956
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  sending reply:
Client 2
a= -2.657830948742076 0.9247497273131033 -1.1837878935327522
b= -0.7360974998678449 -2.5187722515825985 1.3749770142429956
c= -3.393928448609921 -1.5940225242694952 0.1911891207102434
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 0
a= 1.4082232953660423 -0.9931870973853112 1.3910761385634984
b= -2.889407167103009 -0.7824050505085749 2.903892793441319
ComputeServer Thread[TCP Connection(6)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 1
a= -0.955428681740063 -2.5673385086416904 -2.780364026600216
b= -1.8793447696742414 -1.1507818551369844 2.7499555247812895
ComputeServer Thread[TCP Connection(6)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
```

```
  sending reply:
Client 1
a= -0.955428681740063 -2.5673385086416904 -2.780364026600216
b= -1.8793447696742414 -1.1507818551369844 2.7499555247812895
c= -2.8347734514143044 -3.7181203637786746 -0.030408501818926403
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  sending reply:
Client 0
a= 1.4082232953660423 -0.9931870973853112 1.3910761385634984
b= -2.889407167103009 -0.7824050505085749 2.903892793441319
c= -1.4811838717369668 -1.775592147893886 4.294968932004817
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 2
a= 1.9275748750871307 -1.585790045655693 -0.5744877856676425
b= -1.6055158235742573 -2.439632153002778 -1.8423081956633163
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  sending reply:
Client 2
a= 1.9275748750871307 -1.585790045655693 -0.5744877856676425
b= -1.6055158235742573 -2.439632153002778 -1.8423081956633163
c= 0.3220590515128734 -4.025422198658471 -2.4167959813309587
ComputeServer Thread[TCP Connection(5)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 1
a= -2.0501067221742413 -0.8359759895038006 2.8004561794994416
b= 0.3434141542833764 1.5887901295117377 1.613726707462031
ComputeServer Thread[TCP Connection(6)-barry.popesteen.org/134.210.51.61,5,RMI runtime]
  got work request:
Client 0
a= 2.6637065224520526 2.744898828042219 2.6241017194381673
b= -2.120103401814829 2.031211204287832 -0.6996379517312672
time to terminate the Server and exit
```

Sample run of Compute.java clients

```
% java Client
Client: serverMachine=localhost, serverName=ComputeServer, serverPort=8989
 numClients=3, napTime=4, runTime=20
All Client threads started
age=2755, Client 2 sending to server work:
Client 2
a= -2.6956833547799772 2.7056242913415076 1.5467036159966847
b= 0.9272845052351353 2.375308405708611 1.7315712879212102
age=2848, Client 1 sending to server work:
Client 1
a= 2.198285066955644 1.1014851982887102 2.1195367406109042
b= -2.40242980205884 -0.2716969010229877 1.7543779582559216
age=3918, Client 0 sending to server work:
Client 0
a= 1.1018592459170318 2.998499863398912 -2.2753431857554913
b= 1.60740034099687 2.4918661638800934 -0.35813980483005325
age=4362, Client 2 received from server reply:
Client 2
a= -2.6956833547799772 2.7056242913415076 1.5467036159966847
b= 0.9272845052351353 2.375308405708611 1.7315712879212102
c= -1.768398849544842 5.080932697050119 3.278274903917895
age=4423, Client 1 received from server reply:
Client 1
a= 2.198285066955644 1.1014851982887102 2.1195367406109042
b= -2.40242980205884 -0.2716969010229877 1.7543779582559216
```

```
c= -0.20414473510319597 0.8297882972657225 3.873914698866826
age=4941, Client 2 sending to server work:
Client 2
a= -0.8261092470419777 0.721414082931692 -0.42645707078792716
b= -0.5302742195582928 0.8483683515941847 -1.0025008898402417
age=5193, Client 0 received from server reply:
Client 0
a= 1.1018592459170318 2.998499863398912 -2.2753431857554913
b= 1.60740034099687 2.4918661638800934 -0.35813980483005325
c= 2.709259586913902 5.490366027279006 -2.6334829905855446
age=5223, Client 2 received from server reply:
Client 2
a= -0.8261092470419777 0.721414082931692 -0.42645707078792716
b= -0.5302742195582928 0.8483683515941847 -1.0025008898402417
c= -1.3563834666002705 1.5697824345258766 -1.4289579606281688
age=5912, Client 2 sending to server work:
Client 2
a= -0.10302907032858588 2.122280172623806 -2.972889012811118
b= -2.1063144034959604 1.2484700810438456 -0.34516873732456776
age=8254, Client 2 received from server reply:
Client 2
a= -0.10302907032858588 2.122280172623806 -2.972889012811118
b= -2.1063144034959604 1.2484700810438456 -0.34516873732456776
c= -2.2093434738245463 3.3707502536676515 -3.3180577501356856
age=8431, Client 1 sending to server work:
Client 1
a= 1.8732549025182514 1.6775852683316153 -1.3943090135761338
b= 0.4459518118556396 0.010579789697764852 -2.106450761604641
age=8521, Client 0 sending to server work:
Client 0
a= -2.8410081979322523 2.5649645745053986 -0.026610740169620506
b= 0.7851856936449471 0.616151284898736 -2.9907779217992445
age=8621, Client 2 sending to server work:
Client 2
a= -1.5686083274058547 1.9379634892476183 0.7979989612913752
b= -2.4602035559398168 2.111407097419087 -0.13995152334940153
age=10054, Client 2 received from server reply:
Client 2
a= -1.5686083274058547 1.9379634892476183 0.7979989612913752
b= -2.4602035559398168 2.111407097419087 -0.13995152334940153
c= -4.028811883345671 4.049370586666705 0.6580474379419736
age=10343, Client 0 received from server reply:
Client 0
a= -2.8410081979322523 2.5649645745053986 -0.026610740169620506
b= 0.7851856936449471 0.616151284898736 -2.9907779217992445
c= -2.0558225042873053 3.1811158594041347 -3.017388661968865
age=11144, Client 1 received from server reply:
Client 1
a= 1.8732549025182514 1.6775852683316153 -1.3943090135761338
b= 0.4459518118556396 0.010579789697764852 -2.106450761604641
c= 2.319206714373891 1.68816505802938 -3.5007597751807746
age=11591, Client 1 sending to server work:
Client 1
a= 1.13032496867271 1.7356634369443213 -1.039424286223417
b= 1.6589595605000858 -2.2151755327196945 -2.2322555512103297
age=12303, Client 1 received from server reply:
Client 1
a= 1.13032496867271 1.7356634369443213 -1.039424286223417
b= 1.6589595605000858 -2.2151755327196945 -2.2322555512103297
c= 2.7892845291727957 -0.4795120957753731 -3.271679837433747
age=12431, Client 0 sending to server work:
Client 0
a= -0.27919433374176084 -1.6389486800885282 0.49400802045625003
b= -1.0951363826810552 -1.7985257452276389 1.0206951985241437
age=12709, Client 0 received from server reply:
```

```
Client 0
a= -0.27919433374176084 -1.6389486800885282 0.49400802045625003
b= -1.0951363826810552 -1.7985257452276389 1.0206951985241437
c= -1.374330716422816 -3.437474425316167 1.5147032189803937
age=12802, Client 2 sending to server work:
Client 2
a= -2.657830948742076 0.9247497273131033 -1.1837878935327522
b= -0.7360974998678449 -2.5187722515825985 1.3749770142429956
age=14454, Client 2 received from server reply:
Client 2
a= -2.657830948742076 0.9247497273131033 -1.1837878935327522
b= -0.7360974998678449 -2.5187722515825985 1.3749770142429956
c= -3.393928448609921 -1.5940225242694952 0.1911891207102434
age=15061, Client 0 sending to server work:
Client 0
a= 1.4082232953660423 -0.9931870973853112 1.3910761385634984
b= -2.889407167103009 -0.7824050505085749 2.903892793441319
age=15711, Client 1 sending to server work:
Client 1
a= -0.955428681740063 -2.5673385086416904 -2.780364026600216
b= -1.8793447696742414 -1.1507818551369844 2.7499555247812895
age=16123, Client 1 received from server reply:
Client 1
a= -0.955428681740063 -2.5673385086416904 -2.780364026600216
b= -1.8793447696742414 -1.1507818551369844 2.7499555247812895
c= -2.8347734514143044 -3.7181203637786746 -0.030408501818926403
age=17493, Client 0 received from server reply:
Client 0
a= 1.4082232953660423 -0.9931870973853112 1.3910761385634984
b= -2.889407167103009 -0.7824050505085749 2.903892793441319
c= -1.4811838717369668 -1.775592147893886 4.294968932004817
age=17761, Client 2 sending to server work:
Client 2
a= 1.9275748750871307 -1.585790045655693 -0.5744877856676425
b= -1.6055158235742573 -2.439632153002778 -1.8423081956633163
age=18914, Client 2 received from server reply:
Client 2
a= 1.9275748750871307 -1.585790045655693 -0.5744877856676425
b= -1.6055158235742573 -2.439632153002778 -1.8423081956633163
c= 0.3220590515128734 -4.025422198658471 -2.4167959813309587
age=19181, Client 1 sending to server work:
Client 1
a= -2.0501067221742413 -0.8359759895038006 2.8004561794994416
b= 0.3434141542833764 1.5887901295117377 1.613726707462031
age=19621, Client 0 sending to server work:
Client 0
a= 2.6637065224520526 2.744898828042219 2.6241017194381673
b= -2.120103401814829 2.031211204287832 -0.6996379517312672
age=20771, time to terminate the Clients and exit
age=20773, Client 2 interrupted out of sleep
age=21781, all Clients are done
```

Interface RemoteRendezvous.java

```
import java.rmi.*;
public interface RemoteRendezvous extends Remote {
   public abstract Transaction serverGetClient
            (RendezvousCondition condition)
         throws RemoteException, InterruptedException;
   public abstract Transaction serverGetClient()
         throws RemoteException, InterruptedException;
```

```
    public abstract Object clientTransactServer(Object message)
          throws RemoteException, InterruptedException;
    public abstract void send(Object message)
          throws RemoteException, InterruptedException;
    public abstract void call(Object message)
          throws RemoteException, InterruptedException;
    public abstract Object receive(RendezvousCondition condition)
          throws RemoteException, InterruptedException;
    public abstract Object receive()
          throws RemoteException, InterruptedException;
 }
```

Class RemoteRendezvousClient.java

```
import java.rmi.*;
import java.rmi.registry.*;
public class RemoteRendezvousClient implements RemoteRendezvous {
   private RemoteRendezvous server = null;
   public RemoteRendezvousClient(String serverName,
         String serverMachine, int serverPort)
         throws NotBoundException, UnknownHostException, RemoteException {
      Registry registry = null;
      System.out.println("RemoteRendezvousClient: calling getRegistry("
         + serverMachine + "," + serverPort + ")");
      if (serverPort > 0)
         registry = LocateRegistry.getRegistry(serverMachine, serverPort);
      else
         registry = LocateRegistry.getRegistry(serverMachine);
      System.out.println("RemoteRendezvousClient: getRegistry("
         + serverMachine + "," + serverPort + ") called");
      System.out.println("RemoteRendezvousClient: calling lookup("
         + serverName + ")");
      server = (RemoteRendezvous) registry.lookup(serverName);
      System.out.println("RemoteRendezvousClient: lookup("
         + serverName + ") called");
   }
   public RemoteRendezvousClient(String serverName, String serverMachine)
         throws NotBoundException, UnknownHostException, RemoteException {
      this(serverName, serverMachine, 0);
   }
   public Transaction serverGetClient
            (RendezvousCondition condition)
         throws RemoteException, InterruptedException {
      return server.serverGetClient(condition);
   }
   public Transaction serverGetClient()
         throws RemoteException, InterruptedException {
      return server.serverGetClient();
   }
   public Object clientTransactServer(Object message)
         throws RemoteException, InterruptedException {
      return server.clientTransactServer(message);
   }
   public void send(Object message)
         throws RemoteException, InterruptedException {
      server.send(message);
   }
   public void call(Object message)
         throws RemoteException, InterruptedException {
      server.call(message);
   }
```

```
    public Object receive(RendezvousCondition condition)
          throws RemoteException, InterruptedException {
       return server.receive(condition);
    }
    public Object receive()
          throws RemoteException, InterruptedException {
       return server.receive();
    }
 }
```

Class RemoteRendezvousServer.java

```
 import java.rmi.*;
 import java.rmi.registry.*;
 import java.rmi.server.UnicastRemoteObject;
 import java.rmi.server.ExportException;
 public class RemoteRendezvousServer extends UnicastRemoteObject
       implements RemoteRendezvous {
    private Rendezvous local = null;
    public RemoteRendezvousServer(String serverName, int serverPort)
          throws RemoteException, AccessException, AlreadyBoundException {
       super();
       local = new Rendezvous();
       Registry registry = null;
       try {
          // See if a registry already exists.
          System.out.println("RemoteRendezvousServer: calling createRegistry("
             + serverPort + ")");
          if (serverPort > 0)
             registry = LocateRegistry.createRegistry(serverPort);
          else
             registry = LocateRegistry.createRegistry(Registry.REGISTRY_PORT);
          System.out.println("RemoteRendezvousServer: createRegistry("
             + serverPort + ") called");
       } catch (ExportException e) {
          System.out.println("ExportException: A regsitry already exists.");
          System.out.println("RemoteRendezvousServer: calling getRegistry("
             + serverPort + ")");
          if (serverPort > 0)
             registry = LocateRegistry.getRegistry(serverPort);
          else
             registry = LocateRegistry.getRegistry();
          System.out.println("RemoteRendezvousServer: getRegistry("
             + serverPort + ") called");
       }
       System.out.println("RemoteRendezvousServer: calling bind("
          + serverName + ")");
       registry.bind(serverName, this);
       System.out.println("RemoteRendezvousServer: bind("
          + serverName + ") called");
    }
    public RemoteRendezvousServer(String serverName)
          throws RemoteException, AccessException, AlreadyBoundException {
       this(serverName, 0);
    }
    public Transaction serverGetClient
             (RendezvousCondition condition)
          throws RemoteException, InterruptedException {
       return local.serverGetClient(condition);
    }
    public Transaction serverGetClient()
```

```
            throws RemoteException, InterruptedException {
         return local.serverGetClient();
      }
      public Object clientTransactServer(Object message)
            throws RemoteException, InterruptedException {
         return local.clientTransactServer(message);
      }
      public void send(Object message)
            throws RemoteException, InterruptedException {
         local.send(message);
      }
      public void call(Object message)
            throws RemoteException, InterruptedException {
         local.call(message);
      }
      public Object receive(RendezvousCondition condition)
            throws RemoteException, InterruptedException {
         return local.receive(condition);
      }
      public Object receive()
            throws RemoteException, InterruptedException {
         return local.receive();
      }
   }
```

Example Transact.java

```
import java.util.Vector;
import java.io.Serializable;
import java.rmi.*;
public class Transact {
   public static final String SERVER_NAME = "TransactServer";
   public static final String SERVER_MACHINE = "localhost";
   public static final int SERVER_PORT = 8989;
   public static final int RUN_TIME = 20;
}
class Request extends Sugar implements Serializable {
   private String name = null;
   private int time;
   private int performed = 0;
   public Request(String name, int time) {
      this.name = name;
      this.time = time;
   }
   public void doRequest() throws InterruptedException {
      System.out.println("age=" + age() + ", performing:" + this);
      performed = 1+(int)random(time);
      // sleep to simulate some transaction time
      Thread.sleep(performed);
      System.out.println("age=" + age() + ", performed:" + this);
   }
   public String getName() { return name; }
   public String toString() {
      return "\n" + name + ", " + time + ", " + performed;
   }
}
class ServerCondition implements RendezvousCondition {
   public ServerCondition() { }
   public boolean checkCondition
         (int messageNum, Vector blockedMessages,
      int numBlockedServers) {
```

```
      Object message = blockedMessages.elementAt(messageNum);
      String client = ((Request) message).getName();
      if (client.equals("Client 0")) return true;
      int size = blockedMessages.size();
/*
 * If "Client 0" is not anywhere in the queue, then rendezvous
 * with any client.
 */
      for (int i = 0; i < size; i++) {
         message = blockedMessages.elementAt(i);
         client = ((Request) message).getName();
         if (client.equals("Client 0")) return false;
      }
      return true;
   }
}
class TransactServer extends SugarRE implements Runnable {
   private String serverName = null;
   private RemoteRendezvousServer rend = null;
   private ServerCondition sc = null;
   private Thread me = null;
   public TransactServer(String serverName, int serverPort)
         throws AlreadyBoundException, AccessException, RemoteException {
      this.serverName = serverName;
      rend = new RemoteRendezvousServer(serverName, serverPort);
      sc = new ServerCondition();
      (me = new Thread(this)).start();
   }
   public void run() {
      if (Thread.currentThread() != me) return;
      while (true) {
         if (Thread.interrupted()) {
            System.out.println("age=" + age() + ", " + serverName
               + " interrupted");
            return;
         }
         try {
            Transaction t = rend.serverGetClient(sc);
            Object m = t.serverGetRequest();
            if (m != null) {
               ((Request) m).doRequest();
               t.serverMakeReply(m);
            } else
               System.out.println(serverName + " got null request");
         } catch (RemoteException e) {
            System.out.println("age=" + age() + ", " + serverName
               + " rendezvous remote exception");
            e.printStackTrace();
         } catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + serverName
               + " interrupted out of rendezvous");
            return;
         }
      }
   }
   public static void main(String args[])  {
      String serverName = Transact.SERVER_NAME;
      String serverMachine = Transact.SERVER_MACHINE;
      int serverPort = Transact.SERVER_PORT;
      int runTime = Transact.RUN_TIME;   // seconds
      try {
         serverPort = Integer.parseInt(args[0]);
         runTime = Integer.parseInt(args[1]);
      } catch (Exception e) { /* use defaults */ }
      System.out.println("Server: serverMachine=" + serverMachine
```

```
            + ", serverName=" + serverName + ", serverPort="
            + serverPort + ", runTime=" + runTime);
         try {
            TransactServer server = new TransactServer(serverName, serverPort);
         } catch (Exception e) {
            System.err.println(serverName + " exception " + e);
            e.printStackTrace();
            System.exit(1);
         }
         System.out.println("age=" + age() + ", " + serverName
            + " has been created and bound in the registry");
         try {
            Thread.sleep((runTime+10)*1000);
         } catch (InterruptedException e) { /* ignored */ }
         System.out.println("age=" + age() + ", " + serverName
            + ", time to terminate and exit");
         System.exit(0);
      }
   }
   class Client extends SugarRE implements Runnable {
      private String name = null;
      private int id = -1;
      private RemoteRendezvousClient rend = null;
      private int napTime = 0;
      private Thread me = null;
      private Client(int id, RemoteRendezvousClient rend, int napTime) {
         this.name = "Client " + id;
         this.id = id;
         this.rend = rend;
         this.napTime = napTime;
         (me = new Thread(this)).start();
      }
      public void timeToQuit() { me.interrupt(); }
      public void pauseTilDone() throws InterruptedException
         { me.join(); }
      public void run() {
         int napping;
         Request r = null;
         if (Thread.currentThread() != me) return;
         while (true) {
            if (Thread.interrupted()) {
               System.out.println("age=" + age() + ", " + name
                  + " interrupted");
               return;
            }
            napping = 1 + (int) random(napTime);
            try {
               Thread.sleep(napping);
            } catch (InterruptedException e) {
               System.out.println("age=" + age() + ", " + name
                  + " interrupted out of sleep");
               return;
            }
            r = new Request(name, napTime);
            System.out.println("age=" + age() + ", "
               + name + " sending to server request:" + r);
            try {
               r = (Request) rend.clientTransactServer(r);
            } catch (Exception e) {
               System.err.println("Client exception " + e);
               e.printStackTrace();
               return;
            }
            System.out.println("age=" + age() + ", "
               + name + " received from server reply:" + r);
```

```
      }
   }
   public static void main(String[] args) {
      String serverName = Transact.SERVER_NAME;
      String serverMachine = Transact.SERVER_MACHINE;
      int serverPort = Transact.SERVER_PORT;
      int numClients = 3;
      int napTime = 4;                   // both in
      int runTime = Transact.RUN_TIME;   // seconds
      try {
         serverMachine = args[0];
         serverName = args[1];
         serverPort = Integer.parseInt(args[2]);
         numClients = Integer.parseInt(args[3]);
         napTime = Integer.parseInt(args[4]);
         runTime = Integer.parseInt(args[5]);
      } catch (Exception e) { /* use defaults */ }
      System.out.println("Client: serverMachine=" + serverMachine
         + ", serverName=" + serverName + ", serverPort=" + serverPort
         + "\n numClients=" + numClients + ", napTime=" + napTime
         + ", runTime=" + runTime);
      RemoteRendezvousClient rend = null;
      try {
         rend = new RemoteRendezvousClient(serverName,
            serverMachine, serverPort);
      } catch (Exception e) {
         System.err.println("Client exception " + e);
         e.printStackTrace();
         System.exit(1);
      }
      Client[] c = new Client[numClients];
      for (int i = 0; i < numClients; i++)
         c[i] = new Client(i, rend, 1000*napTime);
      System.out.println("All Client threads started");
      // let the Clients run for a while
      try {
         Thread.sleep(runTime*1000);
         System.out.println("age=" + age()
            + ", time to terminate the Clients and exit");
         for (int i = 0; i < numClients; i++)
            c[i].timeToQuit();
         Thread.sleep(1000);
         for (int i = 0; i < numClients; i++)
            c[i].pauseTilDone();
      } catch (InterruptedException e) { /* ignored */ }
      System.out.println("age=" + age()
         + ", all Clients are done");
      System.exit(0);
   }
}
/* ............... To run:
machineA% javac Transact.java
machineA% rmic RemoteRendezvousServer
machineA% java TransactServer &
machineA% rsh machineB "java Client machineA"
*/
```

Sample run of Transact.java server

```
% javac Transact.java
% rmic RemoteRendezvousServer
```

```
% java TransactServer &
Server: serverMachine=localhost, serverName=TransactServer, serverPort=8989, runTime=20
RemoteRendezvousServer: calling createRegistry(8989)
RemoteRendezvousServer: createRegistry(8989) called
RemoteRendezvousServer: calling bind(TransactServer)
RemoteRendezvousServer: bind(TransactServer) called
age=247, TransactServer has been created and bound in the registry
age=11737, performing:
Client 1, 4000, 0
age=13946, performed:
Client 1, 4000, 2194
age=13948, performing:
Client 0, 4000, 0
age=16815, performed:
Client 0, 4000, 2852
age=16816, performing:
Client 2, 4000, 0
age=19025, performed:
Client 2, 4000, 2193
age=19026, performing:
Client 1, 4000, 0
age=21025, performed:
Client 1, 4000, 1983
age=21026, performing:
Client 0, 4000, 0
age=22675, performed:
Client 0, 4000, 1637
age=22676, performing:
Client 2, 4000, 0
age=25345, performed:
Client 2, 4000, 2658
age=25346, performing:
Client 1, 4000, 0
age=26055, performed:
Client 1, 4000, 700
age=26211, performing:
Client 2, 4000, 0
age=26607, performed:
Client 2, 4000, 367
age=26619, performing:
Client 0, 4000, 0
age=29055, performed:
Client 0, 4000, 2427
age=29201, performing:
Client 1, 4000, 0
age=30255, TransactServer, time to terminate and exit
```

Sample run of Transact.java clients

```
% java Client
Client: serverMachine=localhost, serverName=TransactServer, serverPort=8989
 numClients=3, napTime=4, runTime=20
RemoteRendezvousClient: calling getRegistry(localhost,8989)
RemoteRendezvousClient: getRegistry(localhost,8989) called
RemoteRendezvousClient: calling lookup(TransactServer)
RemoteRendezvousClient: lookup(TransactServer) called
All Client threads started
age=1654, Client 1 sending to server request:
Client 1, 4000, 0
age=1850, Client 2 sending to server request:
Client 2, 4000, 0
```

```
age=2832, Client 0 sending to server request:
Client 0, 4000, 0
age=3908, Client 1 received from server reply:
Client 1, 4000, 2194
age=6121, Client 1 sending to server request:
Client 1, 4000, 0
age=6776, Client 0 received from server reply:
Client 0, 4000, 2852
age=8986, Client 2 received from server reply:
Client 2, 4000, 2193
age=9101, Client 0 sending to server request:
Client 0, 4000, 0
age=10860, Client 2 sending to server request:
Client 2, 4000, 0
age=10986, Client 1 received from server reply:
Client 1, 4000, 1983
age=12636, Client 0 received from server reply:
Client 0, 4000, 1637
age=13310, Client 1 sending to server request:
Client 1, 4000, 0
age=15306, Client 2 received from server reply:
Client 2, 4000, 2658
age=16015, Client 1 received from server reply:
Client 1, 4000, 700
age=16160, Client 2 sending to server request:
Client 2, 4000, 0
age=16430, Client 0 sending to server request:
Client 0, 4000, 0
age=16570, Client 2 received from server reply:
Client 2, 4000, 367
age=19015, Client 0 received from server reply:
Client 0, 4000, 2427
age=19150, Client 1 sending to server request:
Client 1, 4000, 0
age=20080, Client 2 sending to server request:
Client 2, 4000, 0
age=20290, Client 0 sending to server request:
Client 0, 4000, 0
age=20730, time to terminate the Clients and exit
age=21740, all Clients are done
```

Example Ring.java

```
import java.io.Serializable;
import java.rmi.*;
public class Ring {
   public static final String RING_NAME = "RingMember";
   public static final String RING_MACHINE = "localhost";
}
class Token implements Serializable {
   private int value = 0;
   private String owner = null;
   public Token(String o, int v) { owner = o;  value = v; }
   public String getOwner() { return owner; }
   public int getValue() { return value; }
   public void setOwner(String o) { owner = o; }
   public void setValue(int v) { value = v; }
   public String toString() {
      return "\n   Token: owner=" + owner + ", value=" + value;
   }
}
```

```
class RingMember extends SugarRE implements Runnable {
   private RemoteRendezvousServer channel = null;
   private String name = null;
   private int id = 0;
   private RemoteRendezvousClient successor = null;
   private String successorMachine = null;
   private String successorName = null;
   private int napTime = 0;       // seconds
   private Thread me = null;
   public RingMember(int d, String i, String m, String n, int t)
         throws AlreadyBoundException, AccessException, RemoteException {
      id = d;
      name = i;
      successorMachine = m;
      successorName = n;
      napTime = t;
      channel = new RemoteRendezvousServer(name);
   }
   private void start() { (me = new Thread(this)).start(); }
   public void timeToQuit() { me.interrupt(); }
   public void pauseTilDone() throws InterruptedException
      { me.join(); }
   public void run() {
      Token t = null;
      if (Thread.currentThread() != me) return;
      System.out.println("age=" + age() + ", " + name + " go!");
      if (id == 0) {
         // Special case: create the token and pause
         // for all other ring members to initialize
         // and register themselves.
         try {
            Thread.sleep(5000);  // Yes, this is a kludge!
         } catch (InterruptedException e) { }
         try {
            successor =
               new RemoteRendezvousClient(successorName, successorMachine);
            System.out.println("age=" + age() + ", " + name
               + ", successor looked up");
         } catch (Exception e) {
            System.err.println("age=" + age() + ", " + name
                + ", successor exception " + e);
            e.printStackTrace();
            return;
         }
         t = new Token(name, 1000);
         System.out.println("age=" + age() + ", " + name
            + " creating initial token" + t);
         try {
            send(successor, t);
         } catch (Exception e) {
            System.err.println("age=" + age() + ", " + name
                + ", initial token exception " + e);
            e.printStackTrace();
            return;
         }
         System.out.println("age=" + age() + ", " + name
            + " passed initial token to successor " + successorName);
         while (true) {
            if (Thread.interrupted()) {
               System.out.println("age=" + age() + ", " + name
                  + " interrupted in run");
               return;
            }
            t = null;
            try {
```

```
            t = (Token) receive(channel);
         } catch (RemoteException e) {
            System.out.println("age=" + age() + ", " + name
               + " rendezvous remote exception");
            e.printStackTrace();
         } catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted in receive");
            return;
         }
         int napping = 1 + (int) (Math.random()*1000*napTime);
         System.out.println("age=" + age() + ", " + name
            + " sleeping for " + napping
            + " ms after receiving token" + t);
         try {
            Thread.sleep(napping);
         } catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted in sleep");
            return;
         }
         t.setOwner(name);  t.setValue(t.getValue()+1);
         System.out.println("age=" + age() + ", " + name
            + " passing token" + t);
         try {
            send(successor, t);
         } catch (Exception e) {
            System.err.println("age=" + age() + ", " + name
               + ", pass exception " + e);
            e.printStackTrace();
            return;
         }
         System.out.println("age=" + age() + ", " + name
            + " token passed to successor " + successorName);
      }
   } else {
      // Everybody else waits to get the token before passing it on.
      while (true) {
         if (Thread.interrupted()) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted in run");
            return;
         }
         t = null;
         try {
            t = (Token) receive(channel);
         } catch (RemoteException e) {
            System.out.println("age=" + age() + ", " + name
               + ", rendezvous remote exception");
            e.printStackTrace();
         } catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted in receive");
            return;
         }
         int napping = 1 + (int) (Math.random()*1000*napTime);
         System.out.println("age=" + age() + ", " + name
            + " sleeping for " + napping
            + " ms after receiving token" + t);
         try {
            Thread.sleep(napping);
         } catch (InterruptedException e) {
            System.out.println("age=" + age() + ", " + name
               + " interrupted in sleep");
            return;
```

```
            }
            t.setOwner(name);  t.setValue(t.getValue()+1);
            System.out.println("age=" + age() + ", " + name
               + " passing token" + t);
            if (successor == null) {
               // Don't do this until you get the token from
               // your predecessor to make sure your successor
               // is registered
               try {
                  successor = new
                     RemoteRendezvousClient(successorName, successorMachine);
                  System.out.println("age=" + age() + ", " + name
                     + ", successor looked up");
               } catch (Exception e) {
                  System.err.println("age=" + age() + ", " + name
                      + ", successor exception " + e);
                  e.printStackTrace();
                  return;
               }
            }
            try {
               send(successor, t);
            } catch (Exception e) {
               System.err.println("age=" + age() + ", " + name
                   + ", pass exception " + e);
               e.printStackTrace();
               return;
            }
            System.out.println("age=" + age() + ", " + name
               + " token passed to successor " + successorName);
         }
      }
   }
   public static void main(String args[])  {
      int id = 0;
      int successorId = 1;
      String successorMachine = Ring.RING_MACHINE;
      String myMachine = Ring.RING_MACHINE;
      int napTime = 4;       // both in
      int runTime = 30;      // seconds
      try {
         id = Integer.parseInt(args[0]);
         successorId = Integer.parseInt(args[1]);
         successorMachine = args[2];
         myMachine = args[3];
         napTime = Integer.parseInt(args[4]);
         runTime = Integer.parseInt(args[5]);
      } catch (Exception e) { /* use defaults */ }
      String name = Ring.RING_NAME + id;
      String successorName = Ring.RING_NAME + successorId;
      System.out.println("age=" + age() + ", " + name
         + "\n  id = " + id
         + "\n  successor machine = " + successorMachine
         + "\n  successor name = " + successorName);
      RingMember member = null;
      try {
         member = new RingMember(id, name, successorMachine,
            successorName, napTime);
      } catch (Exception e) {
         System.err.println("age=" + age() + ", " + name
            + ", exception " + e);
         e.printStackTrace();
         System.exit(1);
      }
      System.out.println("age=" + age() + ", " + name
```

```
            + " has been created and bound in the registry");
         member.start();
         try {
            Thread.sleep(1000*runTime);
            System.out.println("age=" + age() + ", " + name
                + ", time to terminate and exit");
            member.timeToQuit();
            Thread.sleep(1000);
            member.pauseTilDone();
         } catch (InterruptedException e) { /* ignored */ }
         System.exit(0);
   }
}
/* ............... To run:
machineA% javac Ring.java
machineA% rmic RemoteRendezvousServer
machineA% rsh machineC "rmiregistry &"
machineA% rsh machineC "java RingMember 2 0 machineA &"
machineA% rsh machineB "rmiregistry &"
machineA% rsh machineB "java RingMember 1 2 machineC &"
machineA% rmiregistry &
machineA% java RingMember 0 1 machineB &
*/
```

Sample run of Ring.java ring member 0

```
% javac Ring.java
% rmic RemoteRendezvousServer
% java RingMember 0 1
age=10, RingMember0
  id = 0
  successor machine = localhost
  successor name = RingMember1
RemoteRendezvousServer: calling createRegistry(0)
RemoteRendezvousServer: createRegistry(0) called
RemoteRendezvousServer: calling bind(RingMember0)
RemoteRendezvousServer: bind(RingMember0) called
age=600, RingMember0 has been created and bound in the registry
age=610, RingMember0 go!
RemoteRendezvousClient: calling getRegistry(localhost,0)
RemoteRendezvousClient: getRegistry(localhost,0) called
RemoteRendezvousClient: calling lookup(RingMember1)
RemoteRendezvousClient: lookup(RingMember1) called
age=5655, RingMember0, successor looked up
age=5658, RingMember0 creating initial token
   Token: owner=RingMember0, value=1000
age=5694, RingMember0 passed initial token to successor RingMember1
age=9451, RingMember0 sleeping for 21 ms after receiving token
   Token: owner=RingMember2, value=1002
age=9486, RingMember0 passing token
   Token: owner=RingMember0, value=1003
age=9493, RingMember0 token passed to successor RingMember1
age=13681, RingMember0 sleeping for 490 ms after receiving token
   Token: owner=RingMember2, value=1005
age=14175, RingMember0 passing token
   Token: owner=RingMember0, value=1006
age=14182, RingMember0 token passed to successor RingMember1
age=20491, RingMember0 sleeping for 321 ms after receiving token
   Token: owner=RingMember2, value=1008
age=20825, RingMember0 passing token
   Token: owner=RingMember0, value=1009
```

```
age=20832, RingMember0 token passed to successor RingMember1
age=24211, RingMember0 sleeping for 2132 ms after receiving token
   Token: owner=RingMember2, value=1011
age=26355, RingMember0 passing token
   Token: owner=RingMember0, value=1012
age=26362, RingMember0 token passed to successor RingMember1
age=29581, RingMember0 sleeping for 3991 ms after receiving token
   Token: owner=RingMember2, value=1014
age=30615, RingMember0, time to terminate and exit
age=30618, RingMember0 interrupted in sleep
```

Sample run of Ring.java ring member 1

```
% java RingMember 1 2 &
age=10, RingMember1
  id = 1
  successor machine = localhost
  successor name = RingMember2
RemoteRendezvousServer: calling createRegistry(0)
ExportException: A regsitry already exists.
RemoteRendezvousServer: calling getRegistry(0)
RemoteRendezvousServer: getRegistry(0) called
RemoteRendezvousServer: calling bind(RingMember1)
RemoteRendezvousServer: bind(RingMember1) called
age=1838, RingMember1 has been created and bound in the registry
age=1844, RingMember1 go!
age=5782, RingMember1 sleeping for 2703 ms after receiving token
   Token: owner=RingMember0, value=1000
age=8502, RingMember1 passing token
   Token: owner=RingMember1, value=1001
RemoteRendezvousClient: calling getRegistry(localhost,0)
RemoteRendezvousClient: getRegistry(localhost,0) called
RemoteRendezvousClient: calling lookup(RingMember2)
RemoteRendezvousClient: lookup(RingMember2) called
age=8709, RingMember1, successor looked up
age=8747, RingMember1 token passed to successor RingMember2
age=9571, RingMember1 sleeping for 183 ms after receiving token
   Token: owner=RingMember0, value=1003
age=9771, RingMember1 passing token
   Token: owner=RingMember1, value=1004
age=9783, RingMember1 token passed to successor RingMember2
age=14258, RingMember1 sleeping for 3099 ms after receiving token
   Token: owner=RingMember0, value=1006
age=17370, RingMember1 passing token
   Token: owner=RingMember1, value=1007
age=17379, RingMember1 token passed to successor RingMember2
age=20908, RingMember1 sleeping for 1294 ms after receiving token
   Token: owner=RingMember0, value=1009
age=22210, RingMember1 passing token
   Token: owner=RingMember1, value=1010
age=22219, RingMember1 token passed to successor RingMember2
age=26438, RingMember1 sleeping for 1491 ms after receiving token
   Token: owner=RingMember0, value=1012
age=27950, RingMember1 passing token
   Token: owner=RingMember1, value=1013
age=27958, RingMember1 token passed to successor RingMember2
age=31850, RingMember1, time to terminate and exit
age=31857, RingMember1 interrupted in receive
```

Sample run of Ring.java ring member 2

```
% java RingMember 2 0 &
age=10, RingMember2
  id = 2
  successor machine = localhost
  successor name = RingMember0
RemoteRendezvousServer: calling createRegistry(0)
ExportException: A regsitry already exists.
RemoteRendezvousServer: calling getRegistry(0)
RemoteRendezvousServer: getRegistry(0) called
RemoteRendezvousServer: calling bind(RingMember2)
RemoteRendezvousServer: bind(RingMember2) called
age=1964, RingMember2 has been created and bound in the registry
age=2024, RingMember2 go!
age=8926, RingMember2 sleeping for 474 ms after receiving token
   Token: owner=RingMember1, value=1001
age=9413, RingMember2 passing token
   Token: owner=RingMember2, value=1002
RemoteRendezvousClient: calling getRegistry(localhost,0)
RemoteRendezvousClient: getRegistry(localhost,0) called
RemoteRendezvousClient: calling lookup(RingMember0)
RemoteRendezvousClient: lookup(RingMember0) called
age=9689, RingMember2, successor looked up
age=9712, RingMember2 token passed to successor RingMember0
age=9963, RingMember2 sleeping for 3952 ms after receiving token
   Token: owner=RingMember1, value=1004
age=13933, RingMember2 passing token
   Token: owner=RingMember2, value=1005
age=13942, RingMember2 token passed to successor RingMember0
age=17559, RingMember2 sleeping for 3179 ms after receiving token
   Token: owner=RingMember1, value=1007
age=20743, RingMember2 passing token
   Token: owner=RingMember2, value=1008
age=20752, RingMember2 token passed to successor RingMember0
age=22400, RingMember2 sleeping for 2053 ms after receiving token
   Token: owner=RingMember1, value=1010
age=24463, RingMember2 passing token
   Token: owner=RingMember2, value=1011
age=24472, RingMember2 token passed to successor RingMember0
age=28139, RingMember2 sleeping for 1687 ms after receiving token
   Token: owner=RingMember1, value=1013
age=29833, RingMember2 passing token
   Token: owner=RingMember2, value=1014
age=29842, RingMember2 token passed to successor RingMember0
age=32035, RingMember2, time to terminate and exit
age=32038, RingMember2 interrupted in receive
```

Section 13. Wrapup

Tutorial summary

In this tutorial, we examined one of the Java language's most important features -- support for multithreaded (concurrent) programming.

One benefit of multithreaded programs is that they can take advantage of the additional CPUs in a shared-memory multiprocessor architecture in order to execute more quickly.

Using multiple threads can also simplify the design of a program, as in the example of a server program in which each incoming client request is handled by a dedicated thread.

Thread synchronization is extremely important, and this tutorial provides many examples to illustrate this concept.

This tutorial has also illustrated the following concepts by providing definitions, examples, resources, and sample code: Starting Java threads; thread states, priorities, and methods; volatile modifiers; race conditions; synchronized blocks; monitors; semaphores; message passing; rendezvous; and Remote Method Invocation.

Resources

Download code.zip, a zip file containing all example Java programs used in this tutorial.

The following online and print resources will help you follow up on the material presented in this tutorial:

* All example Java programs in this tutorial have been executed on a PC running *Red Hat's version 7.0 of Linux*, using the *IBM Java software developer kit version 1.3.0 for Linux*.

* In "*Writing multithreaded Java applications*" (developerWorks, March 2001), Alex Roetter explains the Java Thread API, outlines issues involved in multithreading, and offers solutions to common problems.

* Multithreaded programming expert Brian Goetz can help you understand the tricks and traps of the Java threading model in this developerWorks forum, "*Multithreaded Java programming*."

* Brian Goetz also offers *Threading lightly* -- a series on threaded programming.

  * The first installment, "*Synchronization is not the enemy*" (developerWorks, July 2001), explains when you have to synchronize and how expensive it is.

  * The second article, "*Reducing contention*" (developerWorks, September 2001), explores several techniques for reducing contention to improve scalability in programs.

* The third article, "*Sometimes it's best not to share*" (developerWorks, October 2001), gives tips on exploiting the power of ThreadLocal.

* In "*Writing efficient thread-safe classes* " (developerWorks, April 2000), Neel V. Kumar uses programming examples to explain how language-level support for locking objects and for inter-thread signaling makes writing thread-safe classes easy.

* Andrew D. Birrell's "*An Introduction to Programming with Threads*" (1989; a DEC research report) provides excellent guidance on threading.

* Doug Lea's *Java concurrent programming package* provides standardized, efficient versions of utility classes commonly encountered in concurrent Java programming. The author also explains how to use the Java platform's threading model more precisely by illuminating the patterns and trade-offs associated with concurrent programming in his book, *Concurrent Programming in Java: Design Principles and Patterns*, second edition (Addison Wesley, 2000).

* *JCSP* is a Java class library providing a base range of CSP primitives found at the University of Kent, Canterbury, UK. (CSP, or Communicating Sequential Processes, is a mathematical theory for specifying and verifying complex patterns of behavior arising from interactions between concurrent objects.)

* JavaPP introduces the CSP model into Java threads, enabling Java active processes to communicate and synchronize via CSP synchronization primitives, helping to eliminate race hazards, deadlock, livelock, and starvation. Two good JavaPP sites exist -- at the *University of Bristol* and the *University of Twente*.

* This Bill Venners' article, "*Design for thread safety*" (JavaWorld, August 1998), offers design guidelines for thread safety and provides a background on the concept of thread safety with several examples of objects -- both thread safe and not thread safe; it also delivers guidelines to help determine when thread safety is appropriate and how best to achieve it.

* Allen Holub's "*Programming Java threads in the real world, Parts 1 through 9*" (JavaWorld, September 1998 - June 1999), is a series that purports to deliver everything you need to know to effectively program threads in real-world applications and situations.

* *Concurrent Programming: Principles and Practice* by Gregory R. Andrews (Benjamin/Cummings, 1991) provides an in-depth overview of principles and practical techniques that can be used to design concurrent programs.

* *Foundations of Multithreaded, Parallel, and Distributed Programming* by Gregory R. Andrews (Addison Wesley, 2000) covers such current programming techniques as semaphores, locks, barriers, monitors, message passing, and remote invocation, providing examples with complete programs, both shared and distributed.

* Stephen Hartley's book, *Concurrent Programming: The Java Programming Language* (Oxford University Press, 1998) shows readers how to use the Java language to code semaphores, monitors, message passing, remote procedure calls, and the rendezvous for thread synchronization and communication.

* *Java Thread Programming* by Paul Hyde (Sams, 1999) demonstrates how to leverage Java's thread facilities to increase program efficiency and to avoid common mistakes.

* *Concurrency: State Models and Java Programs* by Jeff Magee and Jeff Kramer (John Wiley & Sons, 1999) provides a systematic and practical approach to designing, analyzing, and implementing concurrent programs.

* Other, more generic books on operating-system and Java-language programming that have expanded sections on multithreading and concurrent programming include:

    * *Operating Systems: Internals and Design Principles*, fourth edition, by William Stallings (Prentice Hall, 2001) reflects ongoing changes in thread and process management and concurrency.

    * *Modern Operating Systems*, second edition, by Andrew Tanenbaum (Prentice Hall, 2001) has expanded its coverage of process management, threads, and security issues.

    * *The Java Language Specification* by James Gosling, Bill Joy, and Guy Steele (Addison-Wesley, 1996) covers all aspects of the Java execution model, including exceptions, threads, and binary compatibility.

    * *Core Java 2, Volume II: Advanced Features*, fifth edition, by Cay Horstmann and Gary Cornell (Prentice Hall, 2002), which starts with a chapter on multithreading, is fully updated for Sun's JDK 2 Version 1.3 and 1.4.

Your feedback

Please let us know whether this tutorial was helpful to you and how we could make it better. We'd also like to hear about other tutorial topics you'd like to see covered. Thanks!

Colophon

This tutorial was written entirely in XML, using the developerWorks Toot-O-Matic tutorial generator. The open source Toot-O-Matic tool is an XSLT stylesheet and several XSLT extension functions that convert an XML file into a number of HTML pages, a zip file, JPEG heading graphics, and two PDF files. Our ability to generate multiple text and binary formats from a single source file illustrates the power and flexibility of XML. (It also saves our production team a great deal of time and effort.)

You can get the source code for the Toot-O-Matic at www6.software.ibm.com/dl/devworks/dw-tootomatic-p. The tutorial Building tutorials with the Toot-O-Matic demonstrates how to use the Toot-O-Matic to create your own tutorials. developerWorks also hosts a forum devoted to the Toot-O-Matic; it's available at www-105.ibm.com/developerworks/xml_df.nsf/AllViewTemplate?OpenForm&RestrictToCategory=11. We'd love to know what you think about the tool.