PARALLEL PROGRAMMING IN JAVA

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SCHEDULE AND TOPICS

9:00am	Introduction and goals Parallel computing architectures and middleware standards Shared memory multiprocessor (SMP) parallel programming
10:00am	Hands-On Exercise 1
	Break
10:30am	Cluster parallel programming
11:00am	Hands-On Exercise 2
	Break
11:30am	Further examples of parallel programs Hybrid SMP cluster parallel programming
12:00pm	Done

GOALS OF THE WORKSHOP

- To convince you that all computing students need to learn parallel programming.
- To demonstrate that it is possible to write high-performance parallel programs in Java—
  —Without needing to write in C or Fortran.
  —Without needing to write low-level threading code or networking code.
- To introduce Parallel Java (PJ)—
  —An API and middleware for parallel programming in 100% Java.

PARALLEL JAVA RESOURCES

- Alan Kaminsky. *Building Parallel Programs: SMPs, Clusters, and Java.*
  To be published by Thomson Course Technology, tentative publication date January 2009.
  Draft chapters: http://www.cs.rit.edu/~ark/bpp/
- Parallel Computing I course web site. http://www.cs.rit.edu/~ark/531/
- Parallel Computing II course web site. http://www.cs.rit.edu/~ark/532/
- Parallel Java distribution. http://www.cs.rit.edu/~ark/pj.shtml
- Parallel Java documentation (Javadoc). http://www.cs.rit.edu/~ark/pj/doc/index.html

BASIC PARALLEL PROGRAMMING BOOKS

- Bruce P. Lester. *The Art of Parallel Programming, Second Edition.* 1st World Publishing, 2006.
- Kenneth A. Berman and Jerome L. Paul. *Algorithms: Sequential, Parallel, and Distributed.* Thomson Course Technology, 2005.
- Timothy G. Mattson, Beverly A. Sanders, and Berna L. Massingill. *Patterns for Parallel Programming.* Addison-Wesley, 2005.
- Barry Wilkinson and Michael Allen. *Parallel Programming: Techniques and Applications Using Networked Workstations and Parallel Computers, Second Edition.* Prentice-Hall, 2005.
- Michael J. Quinn. *Parallel Programming in C with MPI and OpenMP.* McGraw-Hill, 2004.
- Ananth Grama, Anshul Gupta, George Karypis, and Vipin Kumar. *Introduction to Parallel Computing, Second Edition.* Addison-Wesley, 2003.
- Harry F. Jordan and Gita Alaghband. *Fundamentals of Parallel Processing.* Prentice-Hall, 2003.
- Russ Miller and Laurence Boxer. *Algorithms Sequential & Parallel: A Unified Approach.* Prentice-Hall, 2000.

ADVANCED PARALLEL PROGRAMMING BOOKS

- El-Ghazali Talbi, editor. *Parallel Combinatorial Optimization.* John Wiley & Sons, 2006.
- Albert Y. Zomaya, editor. *Parallel Computing for Bioinformatics and Computational Biology.* John Wiley & Sons, 2006.
- Sverre J. Aarseth. *Gravitational N-Body Simulations: Tools and Algorithms.* Cambridge University Press, 2003.
- George Em Karniadakis and Robert M. Kirby II. *Parallel Scientific Computing in C++ and MPI: A Seamless Approach to Parallel Algorithms and Their Implementation.* Cambridge University Press, 2003.
- William H. Press, Saul A. Teukolsky, William T. Vetterling, and Brian P. Flannery. *Numerical Recipes in Fortran 90: The Art of Parallel Scientific Computing, Second Edition.* Cambridge University Press, 1996.

OpenMP RESOURCES

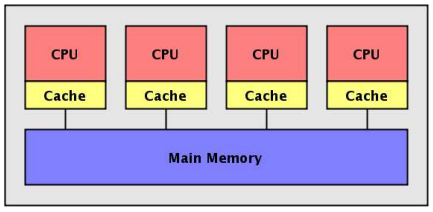
- OpenMP Home Page. http://www.openmp.org/
- Barry Wilkinson and Michael Allen. *Parallel Programming: Techniques and Applications Using Networked Workstations and Parallel Computers, Second Edition.* Prentice-Hall, 2005.
- Michael J. Quinn. *Parallel Programming in C with MPI and OpenMP.* McGraw-Hill, 2004.
- Rohit Chandra, Leonardo Dagum, Dave Kohr, Dror Maydan, Jeff McDonald, and Ramesh Menon. *Parallel Programming in OpenMP.* Academic Press, 2001.

MPI RESOURCES

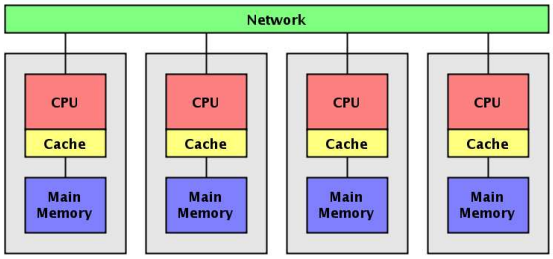
- MPI Forum Home Page. http://www.mpi-forum.org/
- Michael J. Quinn. *Parallel Programming in C with MPI and OpenMP.* McGraw-Hill, 2004.
- George Em Karniadakis and Robert M. Kirby II. *Parallel Scientific Computing in C++ and MPI: A Seamless Approach to Parallel Algorithms and Their Implementation.* Cambridge University Press, 2003.
- William Gropp, Ewing Lusk, and Anthony Skjellum. *Using MPI: Portable Parallel Programming with the Message Passing Interface, Second Edition.* MIT Press, 1999.
- Peter S. Pacheco. *Parallel Programming with MPI.* Morgan Kaufmann, 1997.

PARALLEL COMPUTER ARCHITECTURES

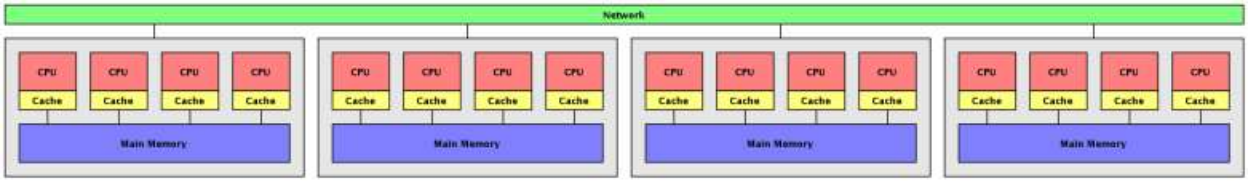
Shared memory multiprocessor (SMP) parallel computers
—Standard programming API: OpenMP



Cluster parallel computers
—Standard programming API: Message Passing Interface (MPI)



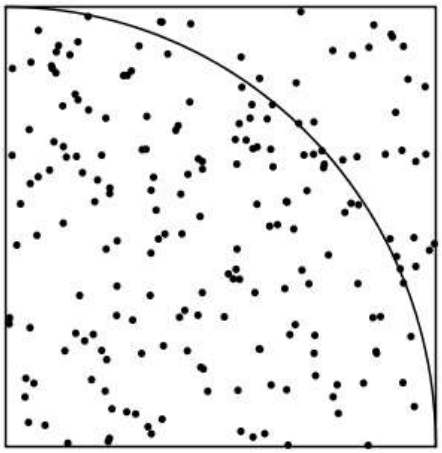
Hybrid SMP cluster parallel computers
—Standard programming API: ???



The RIT CS Department's hybrid SMP cluster parallel computer

- Frontend computer — `tardis.cs.rit.edu` — UltaSPARC-IIe CPU, 650 MHz clock, 512 MB main memory
- 10 backend computers — `dr00` through `dr09` — each with two AMD Opteron 2218 dual-core CPUs, four processors, 2.6 GHz clock, 8 GB main memory
- 1-Gbps switched Ethernet backend interconnection network
- Aggregate 104 GHz clock speed, 80 GB main memory

PROBLEM: COMPUTING π



Monte Carlo technique for computing an approximate value of π:

- The area of the unit square is 1
- The area of the circle quadrant is $\pi/4 = 0.78540$
- Generate a large number of points at random in the unit square
- Count how many of them fall within the circle quadrant, i.e. distance from origin ≤ 1
- The fraction of the points within the circle quadrant gives an approximation for $\pi/4$
- 4 times this fraction gives an approximation for π

SEQUENTIAL PROGRAM FOR COMPUTING π

```
//*************************************************************************
//
// File:    PiSeq.java
// Package: ---
// Unit:    Class PiSeq
//
// This Java source file is copyright (C) 2006 by Alan Kaminsky. All rights
// reserved. For further information, contact the author, Alan Kaminsky, at
// ark@cs.rit.edu.
//
// This Java source file is part of the Parallel Java Library ("PJ"). PJ is free
// software; you can redistribute it and/or modify it under the terms of the GNU
// General Public License as published by the Free Software Foundation; either
// version 2 of the License, or (at your option) any later version.
//
// PJ is distributed in the hope that it will be useful, but WITHOUT ANY
// WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR
// A PARTICULAR PURPOSE. See the GNU General Public License for more details.
//
// A copy of the GNU General Public License is provided in the file gpl.txt. You
// may also obtain a copy of the GNU General Public License on the World Wide
// Web at http://www.gnu.org/licenses/gpl.html or by writing to the Free
// Software Foundation, Inc., 59 Temple Place, Suite 330, Boston, MA 02111-1307
// USA.
//
//*************************************************************************

import edu.rit.pj.Comm;

import edu.rit.util.Random;

/**
 * Class PiSeq is a sequential program that calculates an approximate value for
 * &pi; using a Monte Carlo technique. The program generates a number of random
 * points in the unit square (0,0) to (1,1) and counts how many of them lie
 * within a circle of radius 1 centered at the origin. The fraction of the
 * points within the circle is approximately &pi;/4.
 * <P>
 * Usage: java PiSeq <I>seed</I> <I>N</I>
 * <BR><I>seed</I> = Random seed
 * <BR><I>N</I> = Number of random points
 * <P>
 * The computation is performed sequentially in a single processor. The program
 * uses class edu.rit.util.Random for its pseudorandom number generator. The
 * program measures the computation's running time. This establishes a benchmark
 * for measuring the computation's running time on a parallel processor.
 *
 * @author  Alan Kaminsky
 * @version 21-Dec-2006
 */
public class PiSeq
    {

// Prevent construction.

    private PiSeq()
        {
        }
```

```
// Program shared variables.

    // Command line arguments.
    static long seed;
    static long N;

    // Pseudorandom number generator.
    static Random prng;

    // Number of points within the unit circle.
    static long count;

// Main program.

    /**
     * Main program.
     */
    public static void main
        (String[] args)
        throws Exception
        {
        Comm.init (args);

        // Start timing.
        long time = -System.currentTimeMillis();

        // Validate command line arguments.
        if (args.length != 2) usage();
        seed = Long.parseLong (args[0]);
        N = Long.parseLong (args[1]);

        // Set up PRNG.
        prng = Random.getInstance (seed);

        // Generate n random points in the unit square, count how many are in
        // the unit circle.
        count = 0L;
        for (long i = 0L; i < N; ++ i)
            {
            double x = prng.nextDouble();
            double y = prng.nextDouble();
            if (x*x + y*y <= 1.0) ++ count;
            }

        // Stop timing.
        time += System.currentTimeMillis();

        // Print results.
        System.out.println
            ("pi = 4 * " + count + " / " + N + " = " + (4.0 * count / N));
        System.out.println (time + " msec");
        }

// Hidden operations.

    /**
     * Print a usage message and exit.
     */
    private static void usage()
        {
        System.err.println ("Usage: java PiSeq <seed> <N>");
```

```
        System.err.println ("<seed> = Random seed");
        System.err.println ("<N> = Number of random points");
        System.exit (1);
        }

    }
```

SMP PARALLEL PROGRAM FOR COMPUTING π

```
//******************************************************************************
//
// File:    PiSmp.java
// Package: ---
// Unit:    Class PiSmp
//
// This Java source file is copyright (C) 2006 by Alan Kaminsky. All rights
// reserved. For further information, contact the author, Alan Kaminsky, at
// ark@cs.rit.edu.
//
// This Java source file is part of the Parallel Java Library ("PJ"). PJ is free
// software; you can redistribute it and/or modify it under the terms of the GNU
// General Public License as published by the Free Software Foundation; either
// version 2 of the License, or (at your option) any later version.
//
// PJ is distributed in the hope that it will be useful, but WITHOUT ANY
// WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR
// A PARTICULAR PURPOSE. See the GNU General Public License for more details.
//
// A copy of the GNU General Public License is provided in the file gpl.txt. You
// may also obtain a copy of the GNU General Public License on the World Wide
// Web at http://www.gnu.org/licenses/gpl.html or by writing to the Free
// Software Foundation, Inc., 59 Temple Place, Suite 330, Boston, MA 02111-1307
// USA.
//
//******************************************************************************

import edu.rit.pj.Comm;
import edu.rit.pj.ParallelTeam;
import edu.rit.pj.ParallelRegion;

import edu.rit.pj.reduction.SharedLong;

import edu.rit.util.LongRange;
import edu.rit.util.Random;

/**
 * Class PiSmp is an SMP parallel program that calculates an approximate value
 * for &pi; using a Monte Carlo technique. The program generates a number of
 * random points in the unit square (0,0) to (1,1) and counts how many of them
 * lie within a circle of radius 1 centered at the origin. The fraction of the
 * points within the circle is approximately &pi;/4.
 * <P>
 * Usage: java -Dpj.nt=<I>K</I> PiSmp <I>seed</I> <I>N</I>
 * <BR><I>K</I> = Number of parallel threads
 * <BR><I>seed</I> = Random seed
 * <BR><I>N</I> = Number of random points
 * <P>
 * The computation is performed in parallel in multiple threads. The program
 * uses class edu.rit.util.Random for its pseudorandom number generator. To
 * improve performance, each thread has its own pseudorandom number generator,
 * and the program uses the reduction pattern to determine the count. The
 * program uses the "sequence splitting" technique with the pseudorandom number
 * generators to yield results identical to the sequential version. The program
 * measures the computation's running time.
 *
 * @author  Alan Kaminsky
 * @version 21-Dec-2006
```

```
 */
public class PiSmp
    {

// Prevent construction.

    private PiSmp()
        {
        }

// Program shared variables.

    // Command line arguments.
    static long seed;
    static long N;

    // Number of points within the unit circle.
    static SharedLong count;

// Main program.

    /**
     * Main program.
     */
    public static void main
        (String[] args)
        throws Exception
        {
        Comm.init (args);

        // Start timing.
        long time = -System.currentTimeMillis();

        // Validate command line arguments.
        if (args.length != 2) usage();
        seed = Long.parseLong (args[0]);
        N = Long.parseLong (args[1]);

        // Generate n random points in the unit square, count how many are in
        // the unit circle.
        count = new SharedLong (0L);
        new ParallelTeam().execute (new ParallelRegion()
            {
            public void run()
                {
                // Set up per-thread PRNG and counter.
                Random prng_thread = Random.getInstance (seed);
                long count_thread = 0L;

                // Determine range of iterations for this thread.
                LongRange range_thread =
                    new LongRange (0, N-1)
                        .subrange (getThreadCount(), getThreadIndex());
                long N_thread = range_thread.length();

                // Skip PRNG ahead over the random numbers the lower-indexed
                // threads will generate.
                prng_thread.skip (2 * range_thread.lb());

                // Generate random points.
                for (long i = 0L; i < N_thread; ++ i)
                    {
```

```
                    double x = prng_thread.nextDouble();
                    double y = prng_thread.nextDouble();
                    if (x*x + y*y <= 1.0) ++ count_thread;
                    }

                // Reduce per-thread counts into shared count.
                count.addAndGet (count_thread);
                }
            });

        // Stop timing.
        time += System.currentTimeMillis();

        // Print results.
        System.out.println
            ("pi = 4 * " + count + " / " + N + " = " +
             (4.0 * count.doubleValue() / N));
        System.out.println (time + " msec");
        }

// Hidden operations.

    /**
     * Print a usage message and exit.
     */
    private static void usage()
        {
        System.err.println ("Usage: java -Dpj.nt=<K> PiSmp <seed> <N>");
        System.err.println ("<K> = Number of parallel threads");
        System.err.println ("<seed> = Random seed");
        System.err.println ("<N> = Number of random points");
        System.exit (1);
        }

    }
```

HANDS-ON EXERCISE 1A
π SMP PROGRAM PERFORMANCE

1. Log into the Macintosh workstation if necessary. Username: student Password: student

2. Start a web browser to look at the Tardis job queue. http://tardis.cs.rit.edu:8080/

3. Start a terminal window.

4. Remote login to the Tardis parallel computer. Password: 1ebd_13bf_3c70_4195

   ```
   ssh paraconf@tardis.cs.rit.edu
   ```

5. Change into your working directory. Replace *dir* with your email name.

   ```
   cd dir
   ```

6. Run the sequential π program. The first argument is the random seed. The second argument is the number of iterations. Try different seeds. Try different numbers of iterations. Notice the running times.

   ```
   java PiSeq 142857 10000000
   ```

7. Run the SMP parallel π program. The number after `-Dpj.nt=` is the number of parallel threads. You can specify from 1 to 4 threads. Try different numbers of iterations and different numbers of threads. Notice the running times.

   ```
   java -Dpj.nt=1 PiSmp 142857 10000000
   ```

8. Pick a number of iterations that yields a running time of about 30 seconds for the sequential program. Run the sequential program three times and record the running times on the next page. Run the parallel program three times each with 1, 2, 3, and 4 threads and record the running times. Calculate and record the median running time, speedup, and efficiency for each trial.

   Speedup = (Median sequential time) / (Median parallel time)

   Efficiency = (Speedup) / (Number of threads)

9. What do you notice about the speedup and efficiency as the number of threads increases?

10. Do the same measurements as Step 8 for larger numbers of iterations. What do you notice about the speedup and efficiency as the number of iterations increases?

HANDS-ON EXERCISE 1A (cont.)

Random seed: ________________ Number of iterations: ________________

# of threads	T1 (msec)	T2 (msec)	T3 (msec)	Median T	Speedup	Efficiency
Sequential					—	—
1						
2						
3						
4						

Random seed: ________________ Number of iterations: ________________

# of threads	T1 (msec)	T2 (msec)	T3 (msec)	Median T	Speedup	Efficiency
Sequential					—	—
1						
2						
3						
4						

Random seed: ________________ Number of iterations: ________________

# of threads	T1 (msec)	T2 (msec)	T3 (msec)	Median T	Speedup	Efficiency
Sequential					—	—
1						
2						
3						
4						

HANDS-ON EXERCISE 1B
WRITE YOUR OWN SMP PROGRAM

A **three-dimensional random walk** is defined as follows. A particle is initially positioned at (0, 0, 0) in the X-Y-Z coordinate space. The particle does a sequence of N steps. At each step, the particle chooses one of the six directions left, right, ahead, back, up or down at random, then moves one unit in that direction. Specifically, if the particle is at (x, y, z):

With probability 1/6 the particle moves left to $(x–1, y, z)$;
With probability 1/6 the particle moves right to $(x+1, y, z)$;
With probability 1/6 the particle moves back to $(x, y–1, z)$;
With probability 1/6 the particle moves ahead to $(x, y+1, z)$;
With probability 1/6 the particle moves down to $(x, y, z–1)$;
With probability 1/6 the particle moves up to $(x, y, z+1)$.

Write a sequential program and an SMP parallel program to calculate the particle's final position. The program's command line arguments are the random seed and the number of steps N. The program prints the particle's final position (x, y, z) as well as the distance of the particle from the origin.

1. Log into the Macintosh workstation if necessary. Username: student Password: student

2. Start a web browser to look at the Tardis job queue. http://tardis.cs.rit.edu:8080/

3. Start a terminal window.

4. Remote login to the Tardis parallel computer. Password: 1ebd_13bf_3c70_4195

   ```
   ssh paraconf@tardis.cs.rit.edu
   ```

5. Change into your working directory. Replace *dir* with your email name.

   ```
   cd dir
   ```

6. Use your favorite terminal editor to write the Java source file for the sequential program. Suggested class name: `WalkSeq` File name: `WalkSeq.java`

   ```
   vi WalkSeq.java
   ```

7. Compile the sequential random walk program.

   ```
   javac WalkSeq.java
   ```

HANDS-ON EXERCISE 1B (cont.)

8. Run the sequential random walk program. The first argument is the random seed. The second argument is the number of iterations. Try different seeds. Try different numbers of iterations. Notice the running times.

```
java WalkSeq 142857 10000000
```

9. Use your favorite terminal editor to write the Java source file for the SMP parallel program. Suggested class name: `WalkSmp` File name: `WalkSmp.java`

```
vi WalkSmp.java
```

10. Compile the parallel random walk program.

```
javac WalkSmp.java
```

11. Run the parallel random walk program. The number after `-Dpj.nt=` is the number of parallel threads. You can specify from 1 to 4 threads. Try different numbers of iterations and different numbers of threads. Notice the running times.

```
java -Dpj.nt=1 WalkSmp 142857 10000000
```

12. Do you see a speedup as you increase the number of threads?

13. What happens to the speedup as you increase the number of iterations?

CLUSTER PARALLEL PROGRAM FOR COMPUTING π

```
//******************************************************************************
//
// File:    PiClu.java
// Package: ---
// Unit:    Class PiClu
//
// This Java source file is copyright (C) 2007 by Alan Kaminsky. All rights
// reserved. For further information, contact the author, Alan Kaminsky, at
// ark@cs.rit.edu.
//
// This Java source file is part of the Parallel Java Library ("PJ"). PJ is free
// software; you can redistribute it and/or modify it under the terms of the GNU
// General Public License as published by the Free Software Foundation; either
// version 2 of the License, or (at your option) any later version.
//
// PJ is distributed in the hope that it will be useful, but WITHOUT ANY
// WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR
// A PARTICULAR PURPOSE. See the GNU General Public License for more details.
//
// A copy of the GNU General Public License is provided in the file gpl.txt. You
// may also obtain a copy of the GNU General Public License on the World Wide
// Web at http://www.gnu.org/licenses/gpl.html or by writing to the Free
// Software Foundation, Inc., 59 Temple Place, Suite 330, Boston, MA 02111-1307
// USA.
//
//******************************************************************************

import edu.rit.mp.buf.LongItemBuf;

import edu.rit.pj.Comm;

import edu.rit.pj.reduction.LongOp;

import edu.rit.util.LongRange;
import edu.rit.util.Random;

/**
 * Class PiClu is a cluster parallel program that calculates an approximate
 * value for &pi; using a Monte Carlo technique. The program generates a number
 * of random points in the unit square (0,0) to (1,1) and counts how many of
 * them lie within a circle of radius 1 centered at the origin. The fraction of
 * the points within the circle is approximately &pi;/4.
 * <P>
 * Usage: java -Dpj.np=<I>K</I> PiClu <I>seed</I> <I>N</I>
 * <BR><I>K</I> = Number of parallel processes
 * <BR><I>seed</I> = Random seed
 * <BR><I>N</I> = Number of random points
 * <P>
 * The computation is performed in parallel in multiple threads. The program
 * uses class edu.rit.util.Random for its pseudorandom number generator. To
 * improve performance, each process has its own pseudorandom number generator,
 * and the program uses the reduction pattern to determine the count. The
 * program uses the "sequence splitting" technique with the pseudorandom number
 * generators to yield results identical to the sequential version. The program
 * measures the computation's running time.
 *
 * @author  Alan Kaminsky
 * @version 27-Jun-2007
```

```
 */
public class PiClu
    {

// Prevent construction.

    private PiClu()
        {
        }

// Program shared variables.

    // World communicator.
    static Comm world;
    static int size;
    static int rank;

    // Command line arguments.
    static long seed;
    static long N;

    // Pseudorandom number generator.
    static Random prng;

    // Number of points within the unit circle.
    static long count;

// Main program.

    /**
     * Main program.
     */
    public static void main
        (String[] args)
        throws Exception
        {
        // Start timing.
        long time = -System.currentTimeMillis();

        // Initialize middleware.
        Comm.init (args);
        world = Comm.world();
        size = world.size();
        rank = world.rank();

        // Validate command line arguments.
        if (args.length != 2) usage();
        seed = Long.parseLong (args[0]);
        N = Long.parseLong (args[1]);

        // Determine range of iterations for this thread.
        LongRange range = new LongRange (0, N-1) .subrange (size, rank);
        long my_N = range.length();

        // Set up PRNG and skip ahead over the random numbers the lower-ranked
        // processes will generate.
        prng = Random.getInstance (seed);
        prng.skip (2 * range.lb());

        // Generate random points in the unit square, count how many are in the
        // unit circle.
        count = 0L;
```

```
        for (long i = 0L; i < my_N; ++ i)
            {
            double x = prng.nextDouble();
            double y = prng.nextDouble();
            if (x*x + y*y <= 1.0) ++ count;
            }

        // Reduce all processes' counts together into process 0.
        LongItemBuf buf = new LongItemBuf();
        buf.item = count;
        world.reduce (0, buf, LongOp.SUM);
        count = buf.item;

        // Stop timing.
        time += System.currentTimeMillis();

        // Print results.
        System.out.println (time + " msec total " + rank);
        if (rank == 0)
            {
            System.out.println
                ("pi = 4 * " + count + " / " + N + " = " +
                 (4.0 * count / N));
            }
        }

// Hidden operations.

    /**
     * Print a usage message and exit.
     */
    private static void usage()
        {
        System.err.println ("Usage: java -Dpj.np=<K> PiClu <seed> <N>");
        System.err.println ("<K> = Number of parallel processes");
        System.err.println ("<seed> = Random seed");
        System.err.println ("<N> = Number of random points");
        System.exit (1);
        }

    }
```

HANDS-ON EXERCISE 2A
π CLUSTER PROGRAM PERFORMANCE

1. Log into the Macintosh workstation if necessary. Username: student Password: student

2. Start a web browser to look at the Tardis job queue. http://tardis.cs.rit.edu:8080/

3. Start a terminal window.

4. Remote login to the Tardis parallel computer. Password: 1ebd_13bf_3c70_4195

   ```
   ssh paraconf@tardis.cs.rit.edu
   ```

5. Change into your working directory. Replace *dir* with your email name.

   ```
   cd dir
   ```

6. Run the sequential π program. The first argument is the random seed. The second argument is the number of iterations. Try different seeds. Try different numbers of iterations. Notice the running times.

   ```
   java PiSeq 142857 10000000
   ```

7. Run the cluster parallel π program. The number after `-Dpj.np=` is the number of parallel processes. You can specify from 1 to 10 processes. Try different numbers of iterations and different numbers of processes. Notice the running times.

   ```
   java -Dpj.np=1 PiClu 142857 10000000
   ```

8. Pick a number of iterations that yields a running time of about 30 seconds for the sequential program. Run the sequential program three times and record the running times on the next page. Run the parallel program three times each with 1, 2, 4, and 8 processes and record the running times. Calculate and record the median running time, speedup, and efficiency for each trial.

   Speedup = (Median sequential time) / (Median parallel time)

   Efficiency = (Speedup) / (Number of threads)

9. What do you notice about the speedup and efficiency as the number of processes increases?

10. Do the same measurements as Step 8 for larger numbers of iterations. What do you notice about the speedup and efficiency as the number of iterations increases?

HANDS-ON EXERCISE 2A (cont.)

Random seed: ________________ Number of iterations: ________________

# of procs.	T1 (msec)	T2 (msec)	T3 (msec)	Median T	Speedup	Efficiency
Sequential					—	—
1						
2						
4						
8						

Random seed: ________________ Number of iterations: ________________

# of procs.	T1 (msec)	T2 (msec)	T3 (msec)	Median T	Speedup	Efficiency
Sequential					—	—
1						
2						
4						
8						

Random seed: ________________ Number of iterations: ________________

# of procs.	T1 (msec)	T2 (msec)	T3 (msec)	Median T	Speedup	Efficiency
Sequential					—	—
1						
2						
4						
8						

HANDS-ON EXERCISE 2B
WRITE YOUR OWN CLUSTER PROGRAM

A **three-dimensional random walk** is defined as follows. A particle is initially positioned at (0, 0, 0) in the X-Y-Z coordinate space. The particle does a sequence of *N* steps. At each step, the particle chooses one of the six directions left, right, ahead, back, up or down at random, then moves one unit in that direction. Specifically, if the particle is at (*x*, *y*, *z*):

With probability 1/6 the particle moves left to (*x*–1, *y*, *z*);
With probability 1/6 the particle moves right to (*x*+1, *y*, *z*);
With probability 1/6 the particle moves back to (*x*, *y*–1, *z*);
With probability 1/6 the particle moves ahead to (*x*, *y*+1, *z*);
With probability 1/6 the particle moves down to (*x*, *y*, *z*–1);
With probability 1/6 the particle moves up to (*x*, *y*, *z*+1).

Write a sequential program and a cluster parallel program to calculate the particle's final position. The program's command line arguments are the random seed and the number of steps *N*. The program prints the particle's final position (*x*, *y*, *z*) as well as the distance of the particle from the origin.

1. Log into the Macintosh workstation if necessary. Username: student Password: student

2. Start a web browser to look at the Tardis job queue. http://tardis.cs.rit.edu:8080/

3. Start a terminal window.

4. Remote login to the Tardis parallel computer. Password: 1ebd_13bf_3c70_4195

   ```
   ssh paraconf@tardis.cs.rit.edu
   ```

5. Change into your working directory. Replace *dir* with your email name.

   ```
   cd dir
   ```

6. Use your favorite terminal editor to write the Java source file for the sequential program. Suggested class name: `WalkSeq` File name: `WalkSeq.java`

   ```
   vi WalkSeq.java
   ```

7. Compile the sequential random walk program.

   ```
   javac WalkSeq.java
   ```

HANDS-ON EXERCISE 2B (cont.)

8. Run the sequential random walk program. The first argument is the random seed. The second argument is the number of iterations. Try different seeds. Try different numbers of iterations. Notice the running times.

   ```
   java WalkSeq 142857 10000000
   ```

9. Use your favorite terminal editor to write the Java source file for the cluster parallel program. Suggested class name: `WalkClu` File name: `WalkClu.java`

   ```
   vi WalkClu.java
   ```

10. Compile the parallel random walk program.

    ```
    javac WalkClu.java
    ```

11. Run the parallel random walk program. The number after `-Dpj.np=` is the number of parallel processes. You can specify from 1 to 10 processes. Try different numbers of iterations and different numbers of processes. Notice the running times.

    ```
    java -Dpj.nt=1 WalkClu 142857 10000000
    ```

12. Do you see a speedup as you increase the number of processes?

13. What happens to the speedup as you increase the number of iterations?