Practical Concurrent and Parallel Programming 4

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Plan for today

- Performance measurements
- Back-of-the-envelope estimates
- A class for measuring elapsed wall-clock time
- Mark0-5: Towards reliable measurements
- Mark6-7: Automated general measurements
- Cost of thread creation, start, exec, volatile ...
- Measuring the prime counting example
- Scatter charts, or x-y plots
- General advice, warnings and pitfalls
How long does this method take?

```java
private static double multiply(int i) {
    double x = 1.1 * (double)(i & 0xFF);
    return x * x * x * x * x * x * x * x * x * x * x * x * x * x * x * x * x * x * x * x * x;
}
```

- There are 20 floating-point multiplications, an integer op. and an int-double conversion
- Takes at least 20 * 0.4 = 8 ns
- Tricks used in this code:
  - Make result depend on i to avoid caching (C only)
  - The i & 0xFF is in range 0—255 to avoid overflow
  - Multiply i & 0xFF by 1.1 to make it floating-point
Back-of-the envelope calculations

- 2.4 GHz processor = 0.4 ns/cycle = 0.4×10^{-9} \text{s}

- Throughput:
  - Addition or multiplication takes 1 cycle
  - Division maybe 15 cycles
  - Transcendental functions, $\sin(x)$ maybe 100-200?

- Instruction-level parallelism
  - 2-3 integer operations/cycle, only sometimes

- Memory latency
  - Registers: 1 cycle
  - L1 cache: a few cycles
  - L2 cache: many cycles
  - RAM: hundreds of cycles – expensive cache misses!
A Timer class for Java

- We measure elapsed wall-clock time
  - This is what matters in reality
  - Measured uniformly on Linux, MacOS, Windows
  - Enables comparison Java/C#/C/Scala/F# etc

```
public class Timer {
    private long start, spent = 0;
    public Timer() { play(); }
    public double check() {
        return (System.nanoTime()-start+spent)/1e9;
    }
    public void pause() { spent += System.nanoTime()-start; }
    public void play() { start = System.nanoTime(); }
}
```

- Alternatives: total CPU time, or user + kernel
- Never use imprecise, slow `new Date().getTime()`
- Q: Reasons to measure total CPU time?
Mark0: naïve attempt

public static void Mark0() {
    Timer t = new Timer();
    double dummy = multiply(10);
    double time = t.check() * 1e9;
    System.out.printf("%6.1f ns%n", time);
}

• Useless because
  - Timer resolution too coarse, likely 100 ns
  - Runtime start-up costs larger than execution time
  - So result are unrealistic and vary a lot

  5000.0 ns
  6000.0 ns
  4500.0 ns
Mark1: Measure many operations

- Measure 1 million calls; better but fragile:
  - If \texttt{count} is larger, optimizer may notice that result of \texttt{multiply} is not used, and remove call
  - So-called “dead code elimination”
  - May give completely unrealistic results

```java
public static void Mark1() {
    Timer t = new Timer();
    Integer count = 1_000_000;
    for (int i=0; i<count; i++) {
        double dummy = multiply(i);
    }
    double time = t.check() * 1e9 / count;
    System.out.printf("%6.1f ns\n", time);
}
```

Quite useless

- 5.0 ns
- 5.5 ns
- 5.0 ns
- 0.1 ns
- 0.1 ns
- 0.0 ns
• The **javac** compiler is simple, makes no optimizations
• The **java** runtime system (JIT) is clever, makes many
Mark2: Avoid dead code elimination

```java
public static double Mark2() {
    Timer t = new Timer();
    int count = 100_000_000;
    double dummy = 0.0;
    for (int i=0; i<count; i++)
        dummy += multiply(i);
    double time = t.check() * 1e9 / count;
    System.out.printf("%6.1f ns\n", time);
    return dummy;
}
```

- Much more reliable
Mark3: Automate multiple samples

```java
int n = 10;
int count = 100_000_000;
double dummy = 0.0;
for (int j=0; j<n; j++) {
    Timer t = new Timer();
    for (int i=0; i<count; i++)
        dummy += multiply(i);
    double time = t.check() * 1e9 / count;
    System.out.printf("%6.1f ns\n", time);
}
```

- Multiple samples gives an impression of reproducibility
The standard deviation $\sigma$ summarizes the variation around the mean, in a single number.

```java
int count = 100_000_000;
double st = 0.0, sst = 0.0;
for (int j=0; j<n; j++) {
    Timer t = new Timer();
    for (int i=0; i<count; i++)
        dummy += multiply(i);
    double time = t.check() * 1e9 / count;
    st += time;
    sst += time * time;
}
double mean = st/n, sdev = Math.sqrt(sst/n - mean*mean);
System.out.printf("%6.1f ns +/- %6.3f \n", mean, sdev);
```

30.3 ns +/- 0.137
Statistics: Central limit theorem

• The average of \( n \) independent identically distributed observations \( t_1, t_2, \ldots, t_n \) tends to follow the normal distribution \( N(\mu, \sigma^2) \) where

\[
\mu = \frac{1}{n} \sum_{j=1}^{n} t_j
\]

\[
\sigma = \sqrt{\frac{1}{n} \sum_{j=1}^{n} t_j^2 - \mu^2}
\]

when \( n \) tends to infinity

• Eg with probability 68.3% the “real” result is between 30.163 ns and 30.437 ns
The normal distribution $N(\mu, \sigma^2)$

- $68.3\%$ of observations in $[\mu - \sigma, \mu + \sigma]$, between blue lines
- $95.4\%$ of observations in $[\mu - 2\sigma, \mu + 2\sigma]$, between red lines
int n = 10, count = 1, totalCount = 0;
double dummy = 0.0, runningTime = 0.0;
do {
    count *= 2;
    double st = 0.0, sst = 0.0;
    for (int j=0; j<n; j++) {
        Timer t = new Timer();
        for (int i=0; i<count; i++)
            dummy += multiply(i);
        runningTime = t.check();
        double time = runningTime * 1e9 / count;
        st += time;
        sst += time * time;
        totalCount += count;
    }
    double mean = st/n, sdev = Math.sqrt(sst/n - mean*mean);
    System.out.printf("%6.1f ns +/- %8.2f %10d%n", mean, ...);
} while (runningTime < 0.25 && count < Integer.MAX_VALUE/2);
return dummy / totalCount;
### Example results from Mark5

<table>
<thead>
<tr>
<th>mean time</th>
<th>sdev</th>
<th>count</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.0 ns +/-</td>
<td>200.00</td>
<td>2</td>
</tr>
<tr>
<td>100.0 ns +/-</td>
<td>122.47</td>
<td>4</td>
</tr>
<tr>
<td>62.5 ns +/-</td>
<td>62.50</td>
<td>8</td>
</tr>
<tr>
<td>50.0 ns +/-</td>
<td>37.50</td>
<td>16</td>
</tr>
<tr>
<td>46.9 ns +/-</td>
<td>15.63</td>
<td>32</td>
</tr>
<tr>
<td>40.6 ns +/-</td>
<td>10.36</td>
<td>64</td>
</tr>
<tr>
<td>39.8 ns +/-</td>
<td>2.34</td>
<td>128</td>
</tr>
<tr>
<td>36.3 ns +/-</td>
<td>1.79</td>
<td>256</td>
</tr>
<tr>
<td>36.5 ns +/-</td>
<td>1.25</td>
<td>512</td>
</tr>
<tr>
<td>35.6 ns +/-</td>
<td>0.49</td>
<td>1024</td>
</tr>
<tr>
<td>111.1 ns +/-</td>
<td>232.18</td>
<td>2048</td>
</tr>
<tr>
<td>36.1 ns +/-</td>
<td>1.75</td>
<td>4096</td>
</tr>
<tr>
<td>33.7 ns +/-</td>
<td>0.84</td>
<td>8192</td>
</tr>
<tr>
<td>32.5 ns +/-</td>
<td>1.07</td>
<td>16384</td>
</tr>
<tr>
<td>35.6 ns +/-</td>
<td>4.84</td>
<td>32768</td>
</tr>
<tr>
<td>30.4 ns +/-</td>
<td>0.26</td>
<td>65536</td>
</tr>
<tr>
<td>33.1 ns +/-</td>
<td>5.06</td>
<td>131072</td>
</tr>
<tr>
<td>30.3 ns +/-</td>
<td>0.49</td>
<td>262144</td>
</tr>
<tr>
<td>...</td>
<td>....</td>
<td>......</td>
</tr>
</tbody>
</table>

Outlier, maybe due to other program activity
Advantages of Mark5

• The early rounds (2, 4, ...) serve as warm-up
  – Make sure the code is in memory and cache

• Measured code loop runs at least 0.25 sec
  – Roughly 500 million CPU cycles
  – Lessen impact of other activity on computer
  – Makes sure code has been JIT compiled

• Still, total time spent measuring at most 1 sec
  – Because last measurement runs at most 0.5 sec
  – and sum of previous times is same time as last one
    • because $2 + 4 + 8 + ... + 2^n < 2^{n+1}$

• Independent of problem and hardware
Development of the benchmarking method

- Mark0: Measure one call, useless
- Mark1: Measure many calls, nearly useless
- Mark2: Avoid dead code elimination
- Mark3: Automate multiple samples
- Mark4: Compute standard deviation
- Mark5: Automate choice of iteration count

- But need to measure not just multiply!
public interface IntToDouble {
    double call(int i);
}

public static double Mark6(String msg, IntToDouble f) {
    ...  
    do {
        ... 
        for (int j=0; j<n; j++) {
            ... 
            for (int i=0; i<count; i++)
                dummy += f.call(i);
            ... 
        }
        ... 
        System.out.printf("%-25s %15.1f ns %10.2f %10d\n", ...);
    } while (runningTime<0.25 && count<Integer.MAX_VALUE/2);
    return dummy / totalCount;
}
Example use of Mark6

Function to be measured is given as anonymous inner class

```java
Mark6("multiply", new IntToDouble() {
    public double call(int i) { return multiply(i); } });
```

<table>
<thead>
<tr>
<th>multiply</th>
<th>Time (ns)</th>
<th>Result</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>multiply</td>
<td>800.0</td>
<td>1435.27</td>
<td>2</td>
</tr>
<tr>
<td>multiply</td>
<td>250.0</td>
<td>0.00</td>
<td>4</td>
</tr>
<tr>
<td>multiply</td>
<td>212.5</td>
<td>80.04</td>
<td>8</td>
</tr>
<tr>
<td>multiply</td>
<td>187.5</td>
<td>39.53</td>
<td>16</td>
</tr>
<tr>
<td>multiply</td>
<td>200.0</td>
<td>82.92</td>
<td>32</td>
</tr>
<tr>
<td>multiply</td>
<td>57.8</td>
<td>24.26</td>
<td>64</td>
</tr>
<tr>
<td>multiply</td>
<td>46.9</td>
<td>4.94</td>
<td>128</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>multiply</td>
<td>30.6</td>
<td>0.61</td>
<td>2097152</td>
</tr>
<tr>
<td>multiply</td>
<td>30.0</td>
<td>0.10</td>
<td>4194304</td>
</tr>
<tr>
<td>multiply</td>
<td>30.1</td>
<td>0.15</td>
<td>8388608</td>
</tr>
</tbody>
</table>
public static double Mark7(String msg, IntToDouble f) {
    ... 
    do {
        ...
    } while (runningTime<0.25 && count<Integer.MAX_VALUE/2);

    double mean = st/n, sdev = Math.sqrt(sst/n - mean*mean);
    System.out.printf("%-25s %15.1f ns %10.2f %10d%n", msg + f, mean, sdev, count);
    return dummy / totalCount;
}

Mark7("pow", new IntToDouble() { 
    public double call(int i) { return Math.pow(10.0, 0.1 * (i & 0xFF)); } });
Mark7("exp", new IntToDouble() { 
    public double call(int i) { return Math.exp(0.1 * (i & 0xFF)); } });
Mark7("log", new IntToDouble() { 
    public double call(int i) { return Math.log(0.1 + 0.1 * (i & 0xFF)); } });
Mark7("sin", new IntToDouble() { 
    public double call(int i) { return Math.sin(0.1 * (i & 0xFF)); } });
Mark7("cos", new IntToDouble() { 
    public double call(int i) { return Math.cos(0.1 * (i & 0xFF)); } });
Mark 7 benchmarking results for Java mathematical functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Time (ns)</th>
<th>Floating-Point</th>
<th>Integer</th>
</tr>
</thead>
<tbody>
<tr>
<td>pow</td>
<td>75.5</td>
<td>0.43</td>
<td>4194304</td>
</tr>
<tr>
<td>exp</td>
<td>54.9</td>
<td>0.19</td>
<td>8388608</td>
</tr>
<tr>
<td>log</td>
<td>31.4</td>
<td>0.16</td>
<td>8388608</td>
</tr>
<tr>
<td>sin</td>
<td>116.3</td>
<td>0.41</td>
<td>4194304</td>
</tr>
<tr>
<td>cos</td>
<td>116.6</td>
<td>0.33</td>
<td>4194304</td>
</tr>
<tr>
<td>tan</td>
<td>143.6</td>
<td>0.48</td>
<td>2097152</td>
</tr>
<tr>
<td>asin</td>
<td>229.7</td>
<td>2.24</td>
<td>2097152</td>
</tr>
<tr>
<td>acos</td>
<td>217.0</td>
<td>2.46</td>
<td>2097152</td>
</tr>
<tr>
<td>atan</td>
<td>54.3</td>
<td>0.84</td>
<td>8388608</td>
</tr>
</tbody>
</table>

- 2.4 GHz Intel i7; MacOS 10.9.4; 64-bit JVM 1.8.0_11

- So \( \text{sin}(x) \) takes 116.3 ns \( \times \) 2.4 GHz = 279 cycles
  - approximately
Saving measurements to a text file

- Command line in Linux, MacOS, Windows
  
  ```
  java Benchmark > benchmark-20140831.txt
  ```

- In Linux, MacOS get both file and console
  
  ```
  java Benchmark | tee benchmark-20140831.txt
  ```
public static void SystemInfo() {
    System.out.printf("# OS:   %s; %s; %s\n", 
                     System.getProperty("os.name"), 
                     System.getProperty("os.version"), 
                     System.getProperty("os.arch"));
    System.out.printf("# JVM:  %s; %s\n", 
                     System.getProperty("java.vendor"), 
                     System.getProperty("java.version"));
    // This line works only on MS Windows:
    System.out.printf("# CPU:  %s\n", System.getenv("PROCESSOR_IDENTIFIER"));
    java.util.Date now = new java.util.Date();
    System.out.printf("# Date: %s\n", 
                     new java.text.SimpleDateFormat("yyyy-MM-dd'T'HH:mm:ssZ").format(now));
}

• Output information about date and platform:

  # OS:   Mac OS X; 10.9.4; x86_64
  # JVM:  Oracle Corporation; 1.8.0_11
  # CPU:  null
  # Date: 2014-08-31T14:46:56+0200

31 August 2014 at 14:46 in UTC+2h
Measuring task creation, start-up etc

• First: how long to create an ordinary object?

```java
class Point {
    public final int x, y;
    public Point(int x, int y) { this.x = x; this.y = y; }
}
```

```java
Mark6("Point creation",
    new IntToDouble() { public double call(int i) {
        Point p = new Point(i, i);
        return p.hashCode();
    }});
```

• Result on i7, approximately 80 ns
• Q: Why return \texttt{p.hashCode()}?
• Computing the hash code takes 3.3 ns
  – Q: How can I know that?
Cost of thread create

- Takes 1030 ns, or 13 x slower than a Point
  - So a Thread object must be somewhat complicated

```java
final AtomicInteger ai = new AtomicInteger();
Mark6("Thread create",
    new IntToDouble() { public double call(int i) {
        Thread t = new Thread(new Runnable() { public void run() {
            for (int j=0; j<1000; j++)
                ai.getAndIncrement();
        }});
        return t.hashCode();
    }});
```

Actual work, not run
Cost of thread create + start

- Takes 49000 ns
- So a lot of work goes into setting up a task
  - Even after creating it
- Note: does not include executing the loop

```java
Mark6("Thread create start",
    new IntToDouble() { public double call(int i) {
        Thread t = new Thread(new Runnable() { public void run() {
            for (int j=0; j<1000; j++)
                ai.getAndIncrement();
        }});
        t.start();
        return t.hashCode();
    }});
```
Cost of thread create+start+run+join

- Takes 72700 ns
- Of this, the actual work is 6580 ns, in loop
- Thus 1080 ns to create; 48000 ns to start; 13000 ns run and join; 6580 ns actual work
- Never create threads for small computations

```java
Mark6("Thread create start join",
   new IntToDouble() { public double call(int i) {
      Thread t = new Thread(new Runnable() { public void run() {
         for (int j=0; j<1000; j++)
            ai.getAndIncrement();
     });
      t.start();
      try { t.join(); }
      catch (InterruptedException exn) { }
      return t.hashCode();
   });
```

Actual work
is done

because of join()
Cost of taking a free lock

- Takes 4.1 ns although sometime 20 ns instead
- Both are very fast
  - The result of much engineering on the Java VM
  - Taking a free lock was much slower in early Java
  - Today no need to use “double-checked-locking”, Goetz antipattern p. 349
- Q: Possible to measure time to take a lock already held by another thread?

```java
class TestTimeThreads {  
    public static void main(String[] args) {  
        Mark6("Uncontended lock",  
            new IntToDouble() {  
                public double call(int i) {  
                    synchronized (obj) {  
                        return i;  
                    }  
                }  
            });  
    }
}  
```
Cost of volatile

class IntArrayVolatile {
    private volatile int[] array;
    public IntArray(int length) { array = new int[length]; ... } 
    public boolean isSorted() {
        for (int i=1; i<array.length; i++)
            if (array[i-1] > array[i])
                return false;
        return true;
    }
}

<table>
<thead>
<tr>
<th>Class</th>
<th>Time (us)</th>
<th>Latency (us)</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>IntArray</td>
<td>3.4</td>
<td>0.01</td>
<td>131072</td>
</tr>
<tr>
<td>IntArrayVolatile</td>
<td>17.2</td>
<td>0.14</td>
<td>16384</td>
</tr>
</tbody>
</table>

- Volatile read is 5 x slower in this case
- Because
  - Memory barriers at runtime for cache consistency
  - JIT compiler cannot perform certain optimizations
# Full measurements on two platforms

<table>
<thead>
<tr>
<th>Operation</th>
<th>Time 1</th>
<th>Time 2</th>
<th>Time 3</th>
<th>Time 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>hashCode()</code></td>
<td>3.3 ns</td>
<td>0.02</td>
<td>134217728</td>
<td></td>
</tr>
<tr>
<td>Point creation</td>
<td>80.9 ns</td>
<td>1.06</td>
<td>4194304</td>
<td></td>
</tr>
<tr>
<td>Thread's work</td>
<td>6581.5 ns</td>
<td>37.64</td>
<td>65536</td>
<td></td>
</tr>
<tr>
<td>Thread create</td>
<td>1030.3 ns</td>
<td>20.17</td>
<td>262144</td>
<td></td>
</tr>
<tr>
<td>Thread create start</td>
<td>48929.6 ns</td>
<td>320.94</td>
<td>8192</td>
<td></td>
</tr>
<tr>
<td>Thread create start join</td>
<td>72758.9 ns</td>
<td>1204.68</td>
<td>4096</td>
<td></td>
</tr>
<tr>
<td>Uncontended lock</td>
<td>4.1 ns</td>
<td>0.06</td>
<td>67108864</td>
<td></td>
</tr>
</tbody>
</table>

Intel i7, 2.4 GHz, 4 core
45 W, Sep 2012, $378

<table>
<thead>
<tr>
<th>Operation</th>
<th>Time 1</th>
<th>Time 2</th>
<th>Time 3</th>
<th>Time 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>hashCode()</code></td>
<td>15.5 ns</td>
<td>0.01</td>
<td>16777216</td>
<td></td>
</tr>
<tr>
<td>Point creation</td>
<td>184.1 ns</td>
<td>0.43</td>
<td>2097152</td>
<td></td>
</tr>
<tr>
<td>Thread's work</td>
<td>30802.5 ns</td>
<td>18.65</td>
<td>8192</td>
<td></td>
</tr>
<tr>
<td>Thread create</td>
<td>3690.2 ns</td>
<td>7.99</td>
<td>131072</td>
<td></td>
</tr>
<tr>
<td>Thread create start</td>
<td>153097.2 ns</td>
<td>11142.30</td>
<td>2048</td>
<td></td>
</tr>
<tr>
<td>Thread create start join</td>
<td>165992.8 ns</td>
<td>3916.62</td>
<td>2048</td>
<td></td>
</tr>
<tr>
<td>Uncontended lock</td>
<td>16.9 ns</td>
<td>0.01</td>
<td>16777216</td>
<td></td>
</tr>
</tbody>
</table>

AMD 6386 SE, 2.8 GHz, 16 core
140 W, Nov 2012, $1392
Measuring TestCountPrimes

```java
final int range = 100_000;
Mark6("countSequential", new IntToDouble() {
    public double call(int i) {
        return countSequential(range);
    }
});
Mark6("countParallel", new IntToDouble() {
    public double call(int i) {
        return countParallelN(range, 10);
    }
});
```

- Include Mark6 and Mark7 in source file
  - Modified to show microseconds not nanoseconds
- Reduce range to 100,000
- Threads must be join()’ed to measure time
  - Else you just measure the time to create and start, not the time to actually compute
### TestCountPrimes results, 10 threads

<table>
<thead>
<tr>
<th>Method</th>
<th>Time (us)</th>
<th>Speedup</th>
<th>Threads</th>
</tr>
</thead>
<tbody>
<tr>
<td>countSequential</td>
<td>11117.3</td>
<td>501.25</td>
<td>2</td>
</tr>
<tr>
<td>countSequential</td>
<td>10969.3</td>
<td>82.93</td>
<td>4</td>
</tr>
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- So 10 threads is $\frac{10970}{3239} = 3.4$ x faster
- What about 1 thread, 2, ..., 32 threads?
Measuring different thread counts

```java
final int range = 100_000;
Mark7("countSequential", new IntToDouble() {
    public double call(int i) {
        return countSequential(range);
    }
});
for (int c=1; c<=32; c++) {
    final int threadCount = c;
    Mark7(String.format("countParallel %6d", threadCount),
          new IntToDouble() {
            public double call(int i) {
                return countParallelN(range, threadCount);
            }
        });
}
```
TestCountPrimes results

- One thread slower than sequential
- Max speedup 4.1x
- From some point, more threads are worse
- How choose best thread count?
- Tasks and executors are better than threads, week 5

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Making plots of measurements

- Zillions of plotting and charting programs, including Excel, Gnuplot, R, Ploticus, ...
- Always use scatter (x-y) plots, no smoothing
General advice

• To avoid interference with measurements, shut down other programs: mail, Skype, browsers, Dropbox, iTunes, MS Office ...

• Disable logging and debugging messages

• Compile with optimizations enabled

• Never measure inside IDEs such as Eclipse

• Turn off power-savings modes

• Run on mains power, not on battery

• Lots of differences between
  – Runtime systems: Oracle, IBM Java; Mono, .NET
  – CPUs: Intel i5, i7, Xeon, AMD, ARM, …
Mistakes and pitfalls

- Windows Upgrade etc may ruin measurements
  - Runs at unpredictable times, and is slow
- Some CPUs have a temporary “turbo mode”
  - May increase clock speed, will ruin measurements
- Some CPUs do “thermal throttling” if too hot
  - May reduce clock speed, will ruin measurements
- Measure the right thing
  - Eg when measuring binary search, do not search for the same item repeatedly (notes §11)
- Beware of irrelevant overheads
  - For instance random number generation
  - (But now you know how to measure the overhead!)
Timing threads à la Goetz & Bloch

• A countdown N-latch is a use-once gate
  – When latch.countDown() has been called N times, all threads blocked on latch.await() are unblocked

• Can use it to measure thread wall-clock time
  – excluding thread creation and start-up

• But thread start costs seems relevant too…
Timing threads à la Goetz & Bloch

- All threads start nearly at the same time
- Measure excludes thread creation overhead

```java
final CountDownLatch startGate = new CountDownLatch(1);
final CountDownLatch endGate = new CountDownLatch(threadCount);
for (int i = 0; i < threadCount; i++) {
    Thread t = new Thread(new Runnable() {
        public void run() {
            try {
                startGate.await();
                try { task.run(); }
                finally { endGate.countDown(); }
            } catch (InterruptedException ignored) { }
        }
    });
    t.start();
}
Timer timer = new Timer();
startGate.countDown();
endGate.await();
double time = timer.check();
```

Goetz p. 96

See also Bloch p. 275
Throughput versus latency

- Throughput is results per second
- Latency is time to first result

Water pipe analogy:
- Pipe diameter determines throughput, drops/sec
- Pipe length determines latency, time to first drop

We measure inverse throughput, sec/result
This week

• Reading
  – Sestoft: Microbenchmarks in Java and C#
  – (Optional) McKenney chapter 3

• Exercises week 4 = Mandatory hand-in 2
  – Conduct meaningful performance measurements and comparisons, and discuss the results

• Read before next week’s lecture
  – Goetz chapters 6 and 8
  – Bloch items 68, 69