Practical Concurrent and Parallel Programming III

Performance Measurements

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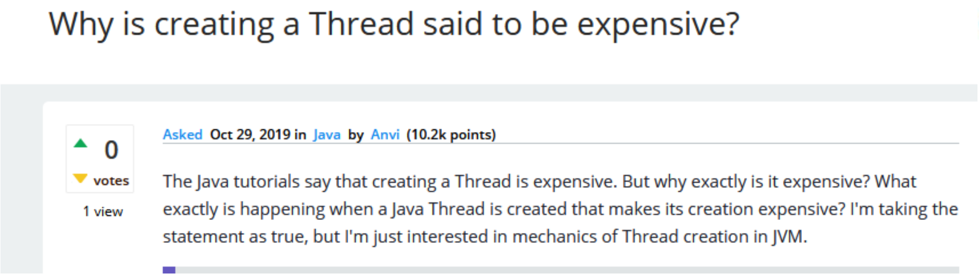
Motivations for Concurrency

Inherent: User interfaces and other kinds of input/output

Exploitation: Hardware capable of simultaneously executing multiple streams of statements

Hidden: Enabling several programs to share some resources in a manner where each can act as if they had sole ownership

Motivation for performance measurements - 1



Why is creating a Thread said to be expensive?

0 votes
1 view

Asked Oct 29, 2019 in Java by Anvi (10.2k points)

The Java tutorials say that creating a Thread is expensive. But why exactly is it expensive? What exactly is happening when a Java Thread is created that makes its creation expensive? I'm taking the statement as true, but I'm just interested in mechanics of Thread creation in JVM.

Threads are expensive

But how expensive ?
~600 ns to create (on this laptop)
~20 times more time than creating a simple object

40000 ns to start a thread !!! (on this laptop)

Today: How to get such numbers !

Motivation for performance measurements - 2

Sorting 1_000_000 numbers with Quicksort takes 9 µs (using 1 Thread)

How fast can we do it using N threads?

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Explanation and animation:

https://en.wikipedia.org/wiki/Quicksort

Agenda

Performance measurements: motivation and introduction

Pitfalls (and avoiding them)

Calculating means and variance (efficiently)

Measurements of thread and lock overhead

Algorithms for parallel computing

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(Performance) Measurements

Key in many sciences (experiments, observations, predictions, ...)

A bit of statistics
A bit of numerical analysis
A bit of computer architecture (number representation)
Code for measuring execution time

Based on Microbenchmarks in Java and C# by Peter Sestoft (see benchmarkingNotes.pdf in material for this week)

All numbers in these slides were measured in August 2021 on a:

Intel Core i5-1035G4 CPU @ 1.10GHz, 4 Core(s), 8 Logical Processor(s)

Example: measuring a (simple) function

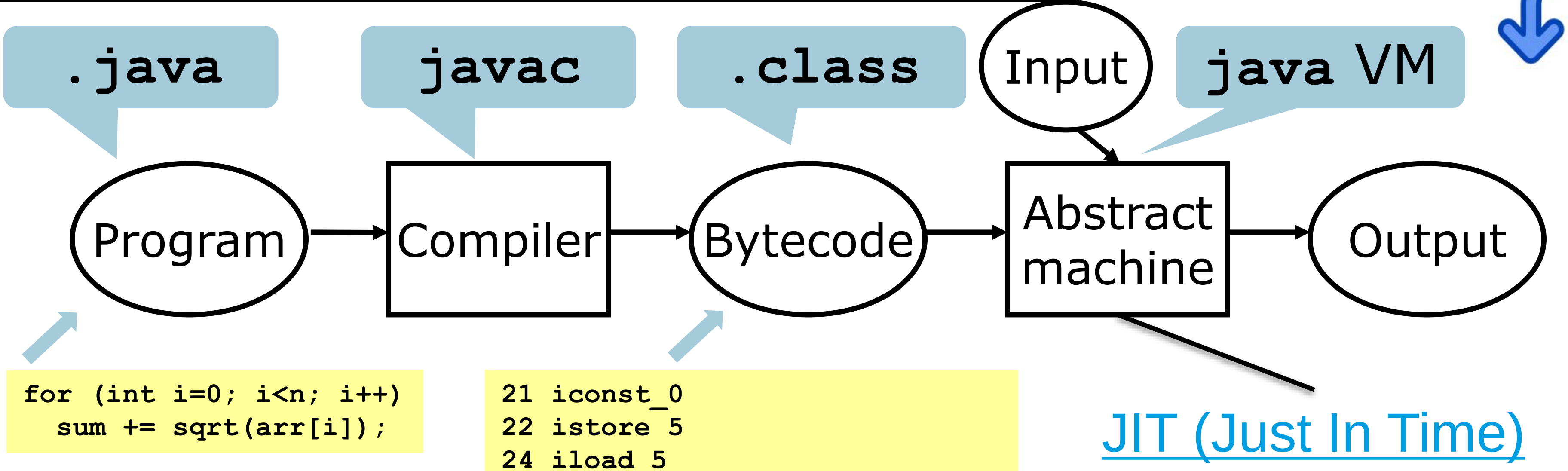
```
private static int multiply(int i) {
  return i * i;
}
```

```
start= System.nanoTime();
multiply(126465);
end= System.nanoTime();

System.out.println(end-start+" ns");
```

```
1700 ns
1500 ns
2500 ns

~ 1 - 2ns
```

What is going on?

Java compiler and virtual machine



JIT (Just In Time)

```
for (int i=0; i<n; i++)
  sum += sqrt(arr[i]);
```

```
21 iconst_0
22 istore 5
24 iload 5
26 iload 2
27 if_icmpge     46
30 dload 3
31 aload 1
32 iload 5
34 daload
35 invokestatic Math.sqrt:(D)D
38 dadd
39 dstore 3
40 iinc 5, 1
43 goto 24
```

JVM

```
19 xorl %ebx,%ebx
1b jmp 3a
1d leal 0x00(%ebp),%ebp
20 fldl 0xec(%ebp)
23 cmpl %ebx,0x0c(%edi)
26 jbe 49
2c leal
0x10(%edi,%ebx,8),%eax
…
```

x86

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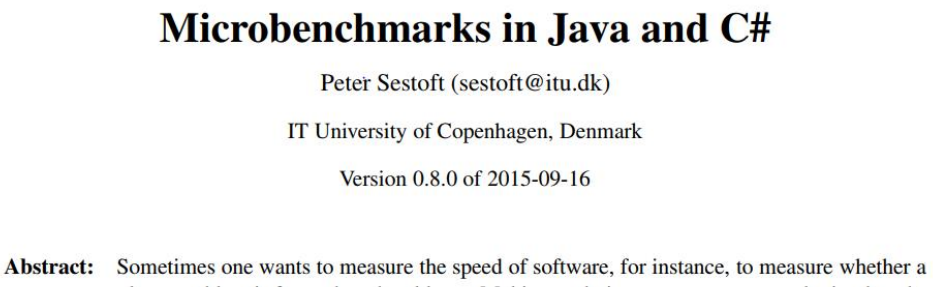
Benchmarking note



Microbenchmarks in Java and C#

Peter Sestoft (sestoft@itu.dk)

IT University of Copenhagen, Denmark

Version 0.8.0 of 2015-09-16

Abstract: Sometimes one wants to measure the speed of software, for instance, to measure whether a

A goldmine of good advice

Accompanying code: Benchmark.java

```
class Benchmark {
  public static void main(String[] args) { new Benchmark(); }

  public Benchmark() {
    SystemInfo();
    // Mark0();
    // Mark1();
    Mark2();
    ...
    // Mark8("random_index", i -> rnd.nextInt(n));
    ...
    // SortingBenchmarks();
    ...
```

Example: measuring a simple function

```
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;
}
```

```
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;
 }
```

```
# OS:   Windows 10; 10.0; amd64
# JVM:  Oracle Corporation; 1.8.0_181
# CPU:  Intel64 Family 6 Model 126 Stepping 5, GenuineIntel; 8 "cores"
# Date: 2021-09-12T09:14:34+0200
  24.0 ns
```

Get the code from

`timingMultiplication.java`

Try running it yourself

Report result in poll

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The Timer class (in Benchmark.java)

A simple Timer class for Java

Works on all platforms (Linux, MacOS, Windows)

```java
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(); }
}
```

Automating multiple runs (Mark3)

Results will usually vary

```
public static double Mark3() {
  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);
  }
  return dummy;
}
```

```
24.6 ns
24.6 ns
24.5 ns
24.6 ns
24.4 ns
24.3 ns
24.5 ns
24.4 ns
24.7 ns
24.6 ns
```

What is the running time?

What should you report as the result, when the observations are:

30.7 ns 30.3 ns 30.1 ns 30.7 ns 30.5 ns 30.4 ns 30.9 ns 30.3 ns 30.5 ns 30.8 ns ??

Mean: 30.4 ns

What if they are:

30.7 ns 100.2 ns 30.1 ns 30.7 ns 20.2 ns 30.4 ns 2.0 ns 30.3 ns 30.5 ns 5.4 ns ??

Mean: 31.0 ns

Standard deviation/variance

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

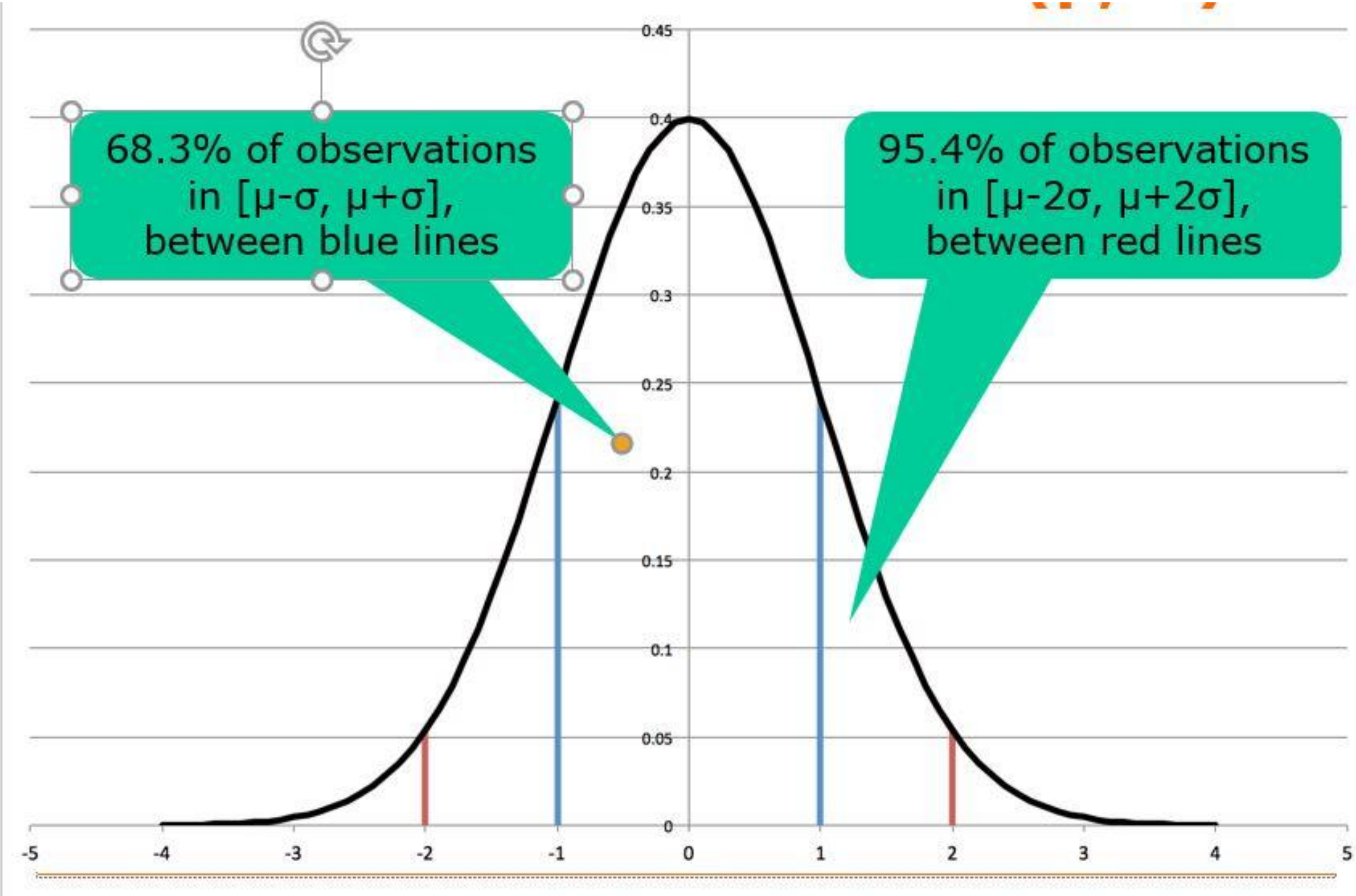
$$\sigma = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(t_j-\mu)^2}$$

Benchmark note p6

30.7 ns 30.3 ns 30.1 ns 30.7 ns 50.2 ns 30.4 ns 30.9 ns 30.3 ns 30.5 ns 30.8 ns ??

Mean: 32.5 ns Standard deviation: 6.2

Normal distribution



68.3% of observations in [μ-σ, μ+σ], between blue lines

95.4% of observations in [μ-2σ, μ+2σ], between red lines

Outliers

What should you report as the result, when the observations are:

30.7 ns 30.3 ns 30.1 ns 30.7 ns 50.2 ns 30.4 ns 30.9 ns 30.3 ns 30.5 ns 30.8 ns ??

Mean: 32.5 ns Standard deviation: 6.2

50.2 is an outlier

because there is a probability of less than 4.6 % that 50.2 is a correct observation

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Computing the variance

$$\mu = \tfrac{1}{n}\sum_{j=1}^{n} t_j$$

$$\sigma = \sqrt{\tfrac{1}{n-1}\sum_{j=1}^{n}(t_j-\mu)^2}$$

Requires two passes through the data

$$\sigma^2 = \tfrac{1}{n(n-1)}(n\sum_{j=1}^{n} t_j^2 - (\tfrac{1}{n}\sum_{j=1}^{n} t_j)^2)$$

Can be done in one pass (on-line alg.)

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

The two formulas give the same result

$$\left.\begin{aligned}\mu &= \tfrac{1}{n}\textstyle\sum_{j=1}^{n} t_j \\ \sigma &= \sqrt{\tfrac{1}{n-1}\textstyle\sum_{j=1}^{n}(t_j-\mu)^2}\end{aligned}\right\}$$

Formula in Benchmark note

$$\sigma = \sqrt{\tfrac{1}{n-1}\textstyle\sum_{j=1}^{n}(t_j^2+\mu^2-2t_j\mu)}$$

$$\sigma^2 = \tfrac{1}{n-1}\textstyle\sum_{j=1}^{n}(t_j^2+\mu^2-2t_j\mu)$$

$$\sigma^2 = \tfrac{1}{n-1}(\textstyle\sum_{j=1}^{n} t_j^2 + \sum_{j=1}^{n}(\mu^2-2t_j\mu))$$

$$\sigma^2 = \tfrac{1}{n-1}(\textstyle\sum_{j=1}^{n} t_j^2 + n\mu^2 - 2\mu\sum_{j=1}^{n} t_j)$$

See exercises03.pdf

$$\sigma^2 = \tfrac{1}{n-1}(\textstyle\sum_{j=1}^{n} t_j^2 + n\mu^2 - 2\mu n\mu)$$

$$\sigma^2 = \tfrac{1}{n-1}(\textstyle\sum_{j=1}^{n} t_j^2 - n\mu^2)$$

$$\sigma^2 = \tfrac{1}{n(n-1)}(n\textstyle\sum_{j=1}^{n} t_j^2 - \mu^2)$$

also https://en.wikipedia.org/wiki/Algorithms_for_calculating_variance

$$\left.\sigma^2 = \tfrac{1}{n(n-1)}(n\textstyle\sum_{j=1}^{n} t_j^2 - (\tfrac{1}{n}\sum_{j=1}^{n} t_j)^2)\right\}$$

Formula used in code (one pass algorithm)

Warning

$$\sigma^2 = \frac{1}{n(n-1)}\left(n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2\right)$$

```
int n = 10;
...
for (int j=0; j<n; j++) {
  Timer t = new Timer();
  for (int i=0; i<count; i++)
        ...
  double time = t.check() * 1e9 / count;
  st += time;
  sst += time * time;
}
double mean = st/n, sdev = Math.sqrt((sst - mean*mean*n)/(n-1));
System.out.printf("%6.1f ns +/- %6.3f%n", mean, sdev);
```

Beware: sst - mean * mean * n can be a very small number

Digit loss

Beware of cancellation when subtracting numbers that are close to each other:

```
 1010101000010110110001110101.111
-1010101000010110110001110001.100
 --------------------------------
 0000000000000000000000000100.011
```

Digit loss

Beware of cancellation when subtracting numbers that are close to each other:

```
 1010101000010110110001110101.111
-1010101000010110110001110001.100
 -------------------------------
 0000000000000000000000000100.011
```

(sst - mean*mean)   can be problematic.

How to do it: https://en.wikipedia.org/wiki/Algorithms_for_calculating_variance

Mark5 - computes mean and variance

```
public static double Mark5() {
  int n = 10, count = 1, totalCount = 0;
  double dummy = 0.0, runningTime = 0.0, st = 0.0, sst = 0.0;
  do {
    count *= 2;
    st = 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 - mean*mean*n)/(n-1));
    System.out.printf("%6.1f ns +/- %8.2f %10d%n", mean, sdev, count);
  } while (runningTime < 0.25 && count < Integer.MAX_VALUE/2);
  return dummy / totalCount;
}
```

Mark5 - computes mean and variance

```
public static double Mark5() {
  int n = 10, count = 1, totalCount = 0;
  double dummy = 0.0, runningTime = 0.0, st = 0.0, sst = 0.0;
  do {
    count *= 2;
    st = 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 - mean*mean*n)/(n-1));
    System.out.printf("%6.1f ns +/- %8.2f %10d%n", mean, sdev, count);
  } while (runningTime < 0.25 && count < Integer.MAX_VALUE/2);
  return dummy / totalCount;
}
```

Mark 6

```
private static double multiply(int i) {
. . .
}
```

Java: **`multiply(i)`** **is a number**

Java: $\underbrace{\texttt{i -> multiply(i)}}$ **is a function**

https://docs.oracle.com/javase/tutorial/java/javaOO/lambdaexpressions.html

```
Mark6( . . . , i -> multiply(i));
```

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Mark6 - introducing a functional argument

```
public static double Mark6(String msg, IntToDoubleFunction f) {
  int n = 10, count = 1, totalCount = 0;
  double dummy = 0.0, runningTime = 0.0, st = 0.0, sst = 0.0;
  do {
    count *= 2;
    st = sst = 0.0;
    for (int j=0; j<n; j++) {
      Timer t = new Timer();
      for (int i=0; i<count; i++) dummy += f.applyAsDouble(i);
      runningTime = t.check();
      double time = runningTime * 1e9 / count;
      st += time;  sst += time * time; totalCount += count;
    }
    double mean = st/n, sdev = Math.sqrt((sst - mean*mean*n)/(n-1));
    System.out.printf("%-25s %15.1f ns %10.2f %10d%n", msg, mean, sdev, count);
  } while (runningTime < 0.25 && count < Integer.MAX_VALUE/2);
  return dummy / totalCount;
}
public interface IntToDoubleFunction { double applyAsDouble(int i); }

Mark6("multiply", i -> multiply(i));
// same as line above, for motivation see here
// https://docs.oracle.com/javase/tutorial/java/javaOO/methodreferences.html
```

The function f is benchmarked

Example use of Mark6

```
Mark6("multiply", i -> multiply(i));
```

```
multiply      800.0 ns    1435.27          2
multiply      250.0 ns       0.00          4
multiply      212.5 ns      80.04          8
multiply      187.5 ns      39.53         16
multiply      200.0 ns      82.92         32
multiply       57.8 ns      24.26         64
multiply       46.9 ns       4.94        128
...
multiply       30.6 ns       0.61    2097152
multiply       30.0 ns       0.10    4194304
multiply       30.1 ns       0.15    8388608
```

Mark7 - printing only final values

```
public static double Mark7(String msg, IntToDoubleFunction f) {
  ...
  do {
  ...
  } while (runningTime < 0.25 && count < Integer.MAX_VALUE/2);
  double mean = st/n, sdev = Math.sqrt((sst - mean*mean*n)/(n-1));
  System.out.printf("%-25s %15.1f %10.2f %10d%n", msg, mean, sdev, count);
  return dummy / totalCount;
}
```

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Thread creation

```
Mark7("Thread create",
  i -> {
        Thread t = new Thread(() -> {
          for (int j=0; j<1000; j++)   // not executed
            ai.getAndIncrement();      // thread t created, but not started
        });
  return t.hashCode();
});
```

Takes 700 ns

Slow or fast?

Creating an object

A thread is an object, so let us start finding the cost of creating a simple object.

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

Mark7("hashCode()", i -> myPoint.hashCode());

Mark7("Point creation",
      i -> {
        Point p = new Point(i, i);
        return p.hashCode();
      });
```

hashCode()	3 ns
Point creation	50 ns

So object creation is: ~ 47 ns

Thread creation: 700 ns

Thread create + start

```
Mark6("Thread create start",
      i -> {
        Thread t = new Thread(() -> {
          for (int j=0; j<1000; j++)  //most iterations not done
            ai.getAndIncrement();     // Why?
        });
        t.start();
        return t.hashCode();
      });
```

Takes ~ 47000 ns

- So, a lot of work goes into starting a thread
- Even after creating it
- Note: does not include executing the loop (why?)

Never create threads for small computations

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Algorithms for parallel computing

Quicksort: https://www.chrislaux.com/quicksort.html

```
private static void qsort(int[] arr, int a, int b) {
  if (a < b) {
    int i = a, j = b;
    int x = arr[(i+j) / 2];
    do {
      while (arr[i] < x) i++;
      while (arr[j] > x) j--;
      if (i <= j) { swap(arr, i, j); i++; j--; }
    } while (i <= j);
    qsort(arr, a, j); qsort(arr, i, b);
  }
}
```

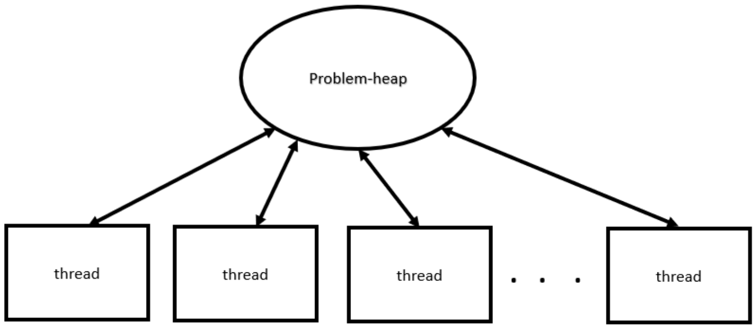
see SearchAndSort.java in week 03 material

Prime counting: https://www.dcode.fr/prime-number-pi-count

```
long count = 0;
final int from = 0, to = range;
for (int i=from; i<to; i++) if (isPrime(i))  count++;
```

see TestCountPrimes.java in week 03 material

Multi-threaded version of Quicksort



```
class Problem {
      public int[] arr;
      public int low, high;
}

class ProblemHeap {
      list<Problem> heap= new List<Problem>;
... }
```

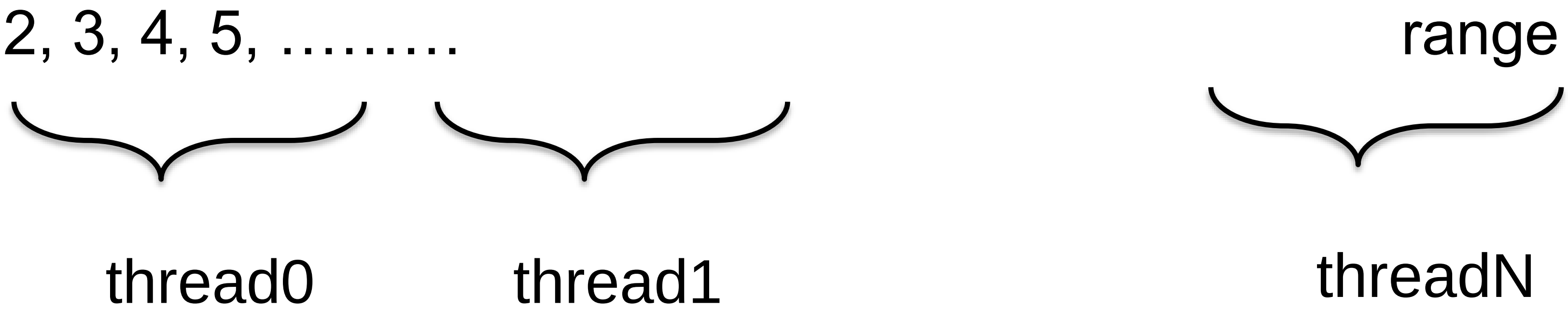
```
private static void qsort(Problem problem, ProblemHeap heap) {
  int[] arr= problem.arr;
  int a= problem.a;
  int.b= problem.b;
  ...
  heap.add(new Problem(arr, a, j); //qsort(arr, a, j);
  heap.add(new Problem(arr, i, b));//qsort(arr, i, b);
}
```

Mark 8 Quicksort

```
Quicksort 1      14196896.3 ns  136477.51
Quicksort 2       8112412.2 ns   67791.32
Quicksort 4       4912498.3 ns   71961.04
Quicksort 8       3880639.1 ns   32812.31
Quicksort 16      4553503.8 ns   40945.07
Quicksort 32      6312270.0 ns   43905.97
```

Disappointing ?

Multithreaded version of CountPrimes



Code for exercises week03: `testCountPrimes.java`

Mark7 Count Primes

```
countSequential             5922958.0 ns  289879.33
countParallel  1            7107236.6 ns  448417.55
countParallel  2            6069944.7 ns  802224.61
countParallel  3            3621185.5 ns  152693.03
countParallel  4            3124067.0 ns  640480.51
countParallel  5            3699514.7 ns  364428.77
countParallel  6            4114074.2 ns  642562.19
countParallel  7            2049595.7 ns   26888.15
countParallel  8            1801465.6 ns   12532.85
countParallel  9            1793099.1 ns   11017.57
countParallel 10            1798921.4 ns   11541.43
countParallel 11            1807408.3 ns    9763.61
```

To be continued in week 6