Practical Concurrent and Parallel Programming V

Performance Measurements

Jørgen Staunstrup

Agenda

- Performance measurements: motivation and introduction
- Pitfalls (and avoiding them)
- Calculating means and variance (efficiently)
- Measurements of thread overhead
- Algorithms for parallel computing

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Motivations for Concurrency

From Week01

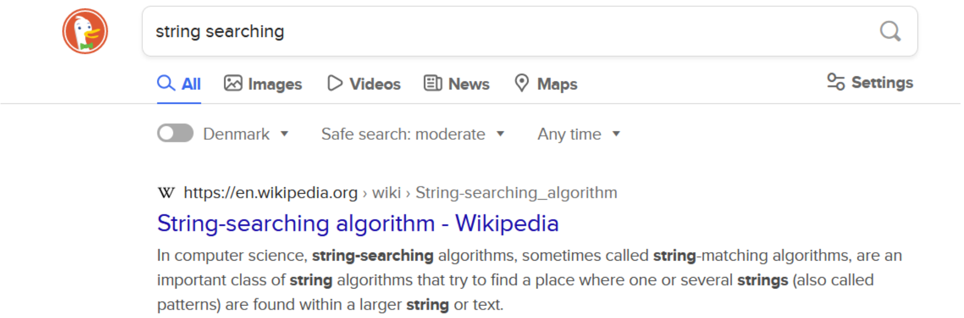
Inherent: User interfaces and other kinds of input/output

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 1: Time consuming computations

Searching in a (large) text



https://www.geeksforgeeks.org/applications-of-string-matching-algorithms/

Computing prime numbers

2, 3, 5, 7, 11, 13, 17, 19, 23,
29, 31, 37, 41, 43, 47, 53, 59,
61, 67, 71, 73, 79, 83, 89, 97,
...

Cornerstone of all computer security

https://science.howstuffworks.com/math-concepts/prime-numbers.htm

Motivation 2: Analyzing code

Thread creation is expensive ?

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.

> *Thread lifecycle overhead. Thread creation and teardown are not free. The actual overhead*

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 !

(Performance) Measurements

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

A bit of statistics
A bit of numerical analysis
A bit of computer architecture (cores, caches, 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)

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Example: measuring a (simple) function

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

```
cd code-exercises
gradle -PmainClass=exercises05.timingMultiplication run
```

Try to do this, what result do you get?

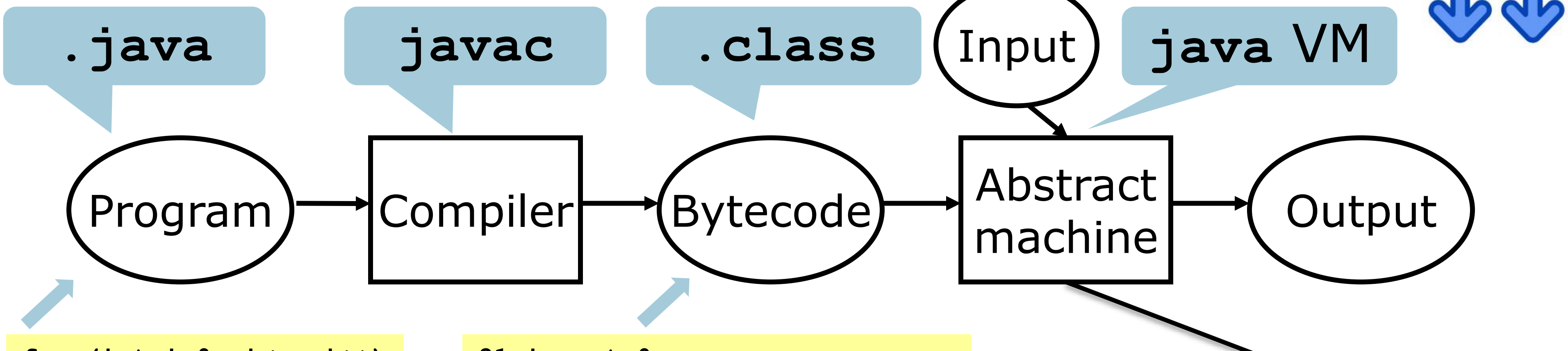
```
start= System.nanoTime();
multiply(126465);
end= System.nanoTime();

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

```
1100 ns
1000 ns
1200 ns
```

```
~ 2 - 5 ns
```

What is going on?

Java compiler and virtual machine




```
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

[JIT (Just In Time)]()

```
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

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

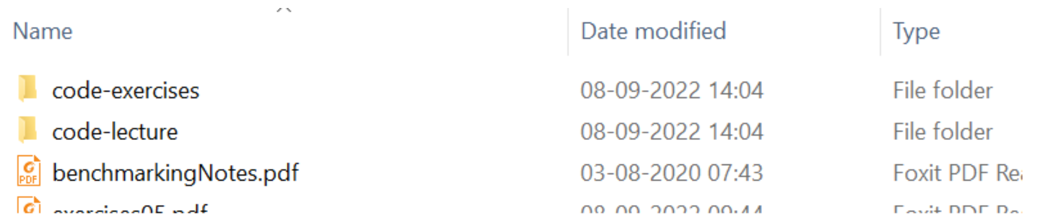
Accompanying code: `Benchmark.java`

On PCPP GitHub (week05)

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

  public Benchmark() {
    // SystemInfo();
    // Mark0();
    // Mark1();
    ...
    Mark6("multiply#, i -> multiply(i));
    ...
    // SortingBenchmarks();
    ...
```

How to use Benchmark

Go to the directory for Week 5



What do you see?

```
cd code-exercises
gradle -PmainClass=exercises05.Benchmark run

# OS:   Windows 10; 10.0; amd64
# JVM:  Oracle Corporation; 1.8.0_181
# CPU:  Intel64 Family 6 Model 126 Stepping 5, GenuineIntel; …
# Date: 2022-09-08T14:10:56+0200
   ...
```

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 [Benchmark.java]()
Try running Mark2

A simple Timer class for Java

Works on all platforms (Linux, MacOS, Windows)

```
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(); }
}
```

What does 1e9 mean?

In what time unit do we get the results?

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

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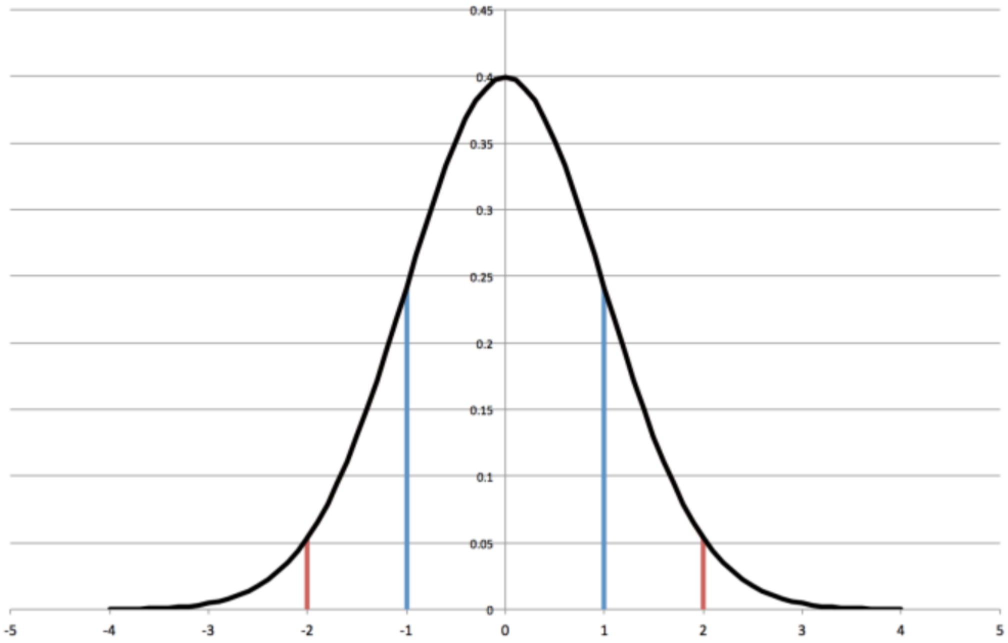
Normal distribution



Measuring physical properties

Your exam grades

Course evaluations

Fabrication faults

Running time of Java code

...

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;
}
```

Mark5

Can we give the function to measured as a parameter?

```
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;
}
```

Lambda

Yes we give the function to measured as a parameter?

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

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

Java: `i -> multiply(i)` **is a function**

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

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

See lambda video
in material for week07

Mark6 - introduce 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));
```

The function f is benchmarked

lambda

Mark6 - introduce 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));
```

Example use of Mark6

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

```
multiply                              595.0 ns    1407.81          2
multiply                              147.5 ns      90.10          4
multiply                              212.5 ns     152.53          8
multiply                              170.6 ns      59.44         16
multiply                              201.9 ns     157.69         32
multiply                               60.8 ns      34.55         64
multiply                               65.1 ns      59.83        128
multiply                               54.3 ns      14.85        256
...
multiply                               24.6 ns       0.75     524288
multiply                               24.6 ns       0.88    1048576
multiply                               24.9 ns       2.71    2097152
multiply                               24.3 ns       0.85    4194304
multiply                               24.2 ns       0.72    8388608
multiply                               25.0 ns       1.38   16777216
```

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++)
            ai.getAndIncrement();
        });
  return t.hashCode();  // to confuse compiler to not optimize
});
```

Takes 700 ns

What are we really measuring?

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 ~ 650ns

Thread create + start

```
Mark6("Thread create start",
      i -> {
        Thread t = new Thread(() -> {
          for (int j=0; j<1000; j++)
            ai.getAndIncrement();
        });
        t.start();
        return t.hashCode();
      });
```

What are we really measuring?

Thread create + start

```
Mark6("Thread create start",
      i -> {
        Thread t = new Thread(() -> {
          for (int j=0; j<1000; j++)
            ai.getAndIncrement();
        });
        t.start();
        return t.hashCode();
      });
```

For loop not included, why?

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

Never create threads for small computations !!!

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

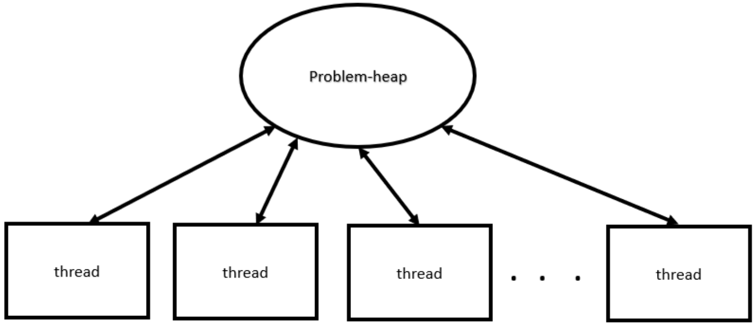
```
private static void qsort(int[] arr, int a, int b) {
  if (a < b) {
    int i = a, j = b;
    int x = arr[(i+j) / 2];
    do {
      while (arr[i] < x) i++;
      while (arr[j] > x) j--;
      if (i <= j) { swap(arr, i, j); i++; j--; }
    } while (i <= j);
    qsort(arr, a, j); qsort(arr, i, b);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

see SearchAndSort.java in week 05 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++;
```

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;
  if (b-a<limit) { quicksort(arr, a, b); return }

  ...
  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

2, 3, 4, 5, ... range

thread0 thread1 threadN

Code for exercises week05: testCountPrimesThreads.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
```

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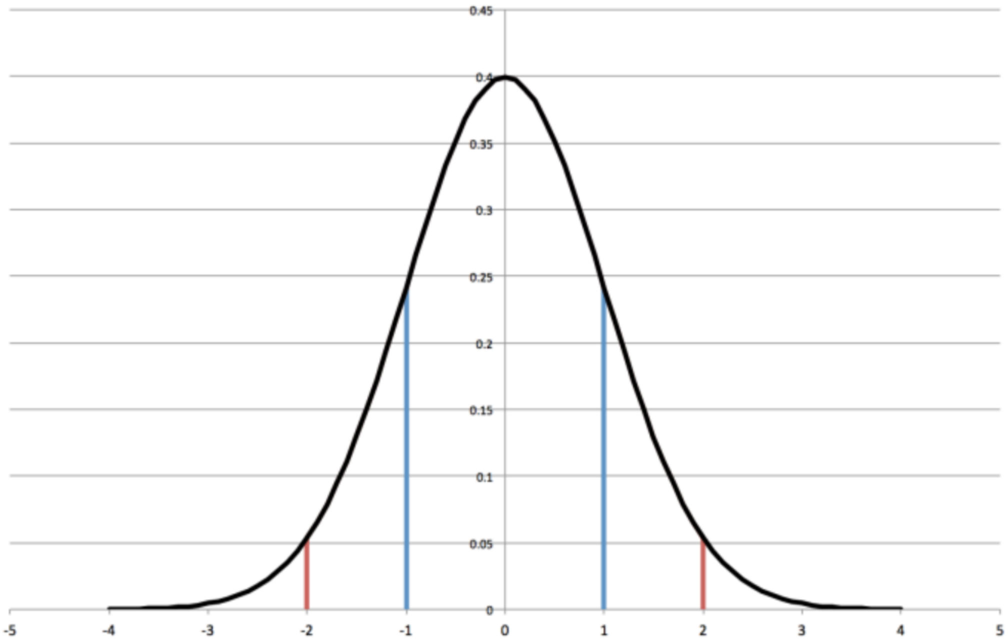
Normal distribution



Measuring physical properties

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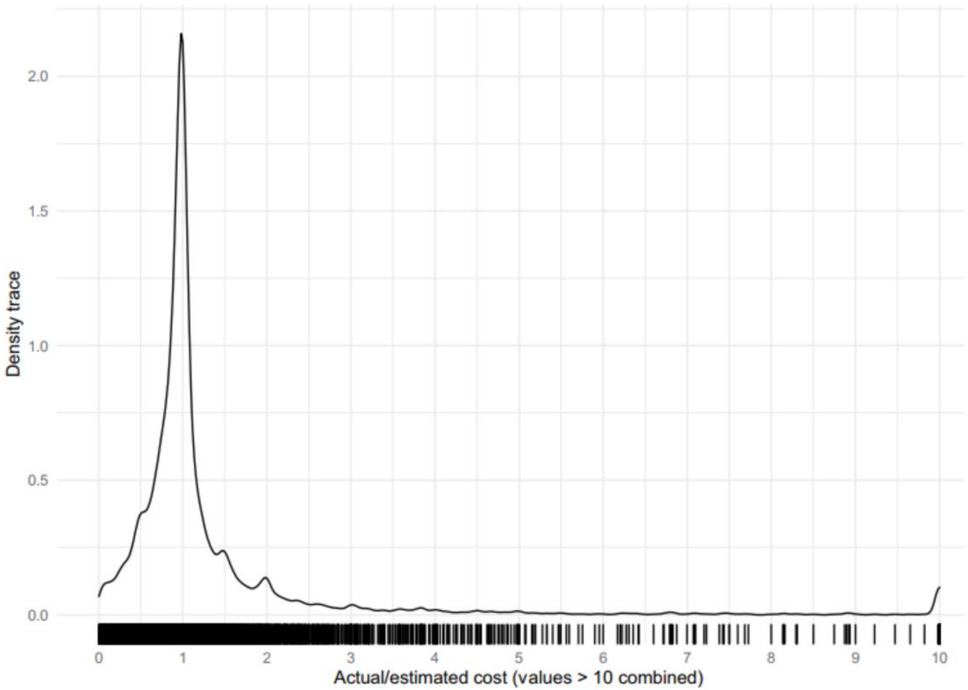
...

But there are exceptions



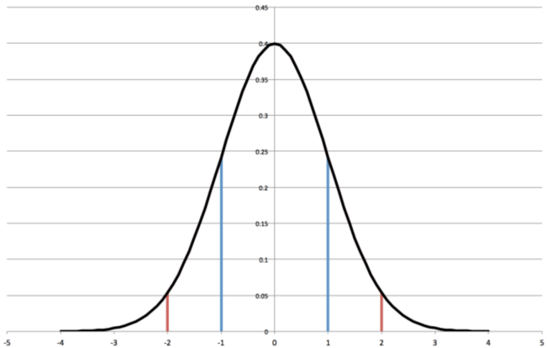
Source: Bent Flyvbjerg, Alexander Budzier, Jong Seok Lee, Mark Keil, Daniel Lunn & Dirk W. Bester (2022) The Empirical Reality of IT Project Cost Overruns: Discovering A Power-Law Distribution, Journal of Management Information Systems, 39:3, 607-639, DOI: 10.1080/07421222.2022.2096544

Standard deviation/variance

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

Mean

Benchmark note p6



Standard deviation/variance

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

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

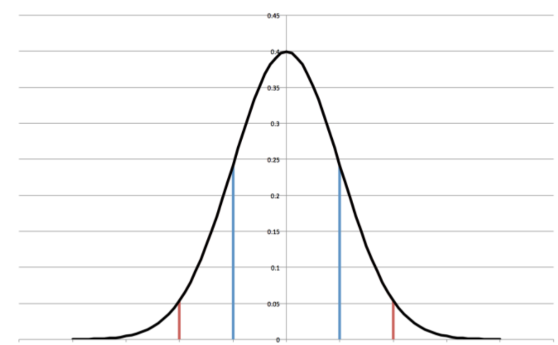
Mean

Standard deviation

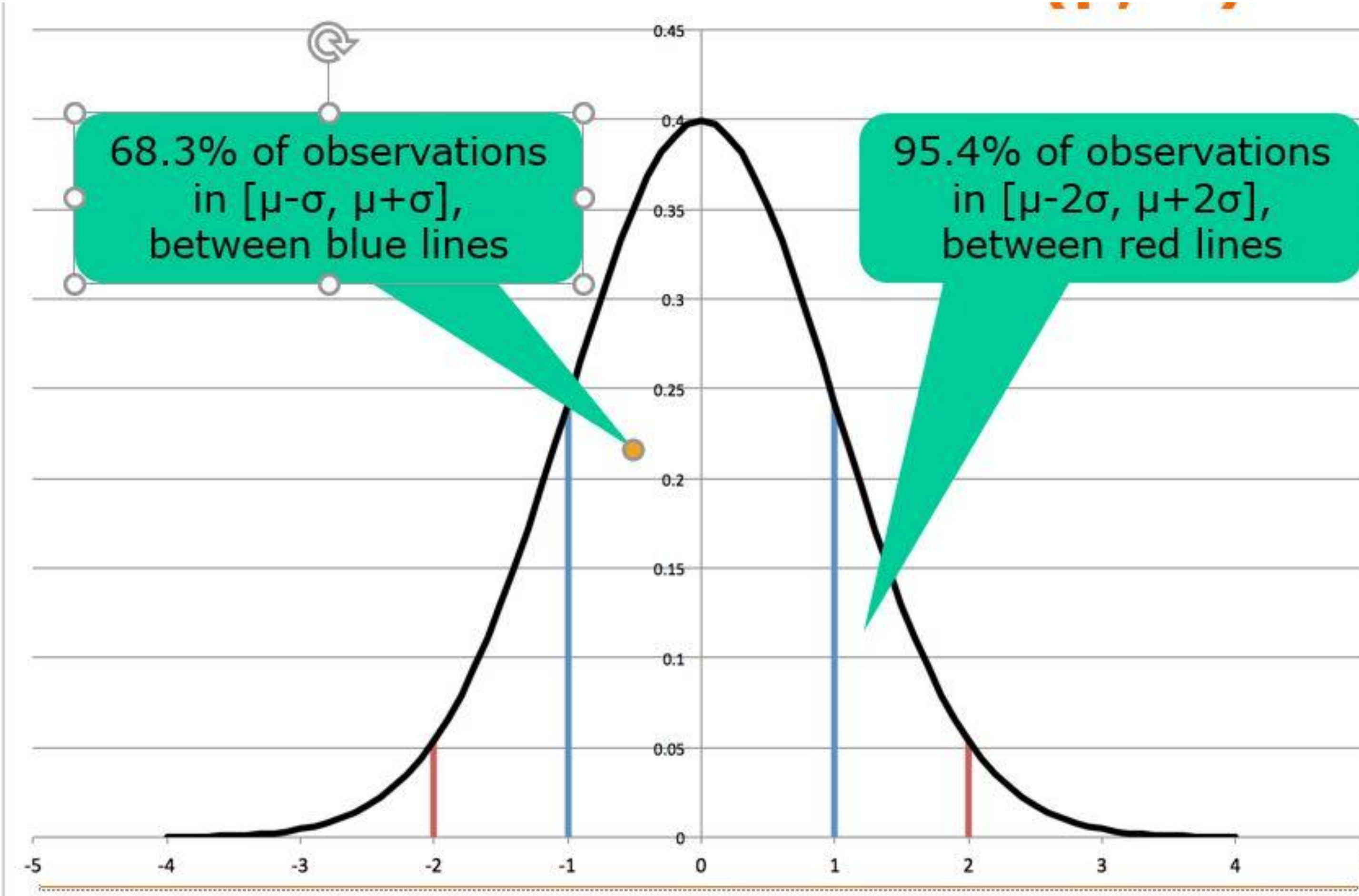
Benchmark note p6

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



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

Computing the variance

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

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

Requires two passes through the data

$$\sigma^2 \;=\; \frac{1}{n(n-1)}\left(n\sum_{j=1}^{n} t_j^2 - \left(\frac{1}{n}\sum_{j=1}^{n} t_j\right)^2\right)$$

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

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

Formula in Benchmark note

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

See exercises05.pdf

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

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:

28 significant digits

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

3 significant digits

https://blog.demofox.org/2017/11/21/floating-point-precision

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