Java Benchmarking

as easy as two timestamps

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Intro

Intro: Warming up...

«How much for instantiating a String?»

```java
long time1 = System.nanoTime();
for (int i = 0; i < 1000; i++) {
  String s = new String("");
}
long time2 = System.nanoTime();
System.out.println("Time:" + (time2 - time1));
```

Theory

Theory: Why would people benchmark?

In the name of...

1. **Holywar**: Node.js – But Java... – Node.js!
2. **Marketing**: Check we are meeting the (release) criteria
3. **Engineering**: Isolate a performance phenomena, make a reference point for improvements
4. **Science**: Understand the performance model, and predict the future behavior

Theory: In the name of Holywar

My favorite example: Computer Language Benchmarks Game:[1]

- Most comparisons are hardly fair: e.g. AOT vs. JIT
- Measures what exactly? E.g. pidigits measures the speed of FFI to GNU GMP
- Lots of disclaimers these results are misrepresentative of the real world (alas, nobody reads them or cares enough)
- People love it, since it gives you **numbers**, which you can then take as your shield and sword in Internet debates

[1] `http://benchmarksgame.alioth.debian.org/`

Theory: In the name of Marketing

My favorite example: SPEC benchmarks

- Reference benchmark suites, agreed upon by the vendors
- Provide the reference points, for which one can set the success criteria, use in adverts, tweet obnoxious competitive data, etc.
- It does not matter how representative they are – it matters they are The Benchmarks Born at the Fiery Summit of Orodruin

Theory: In the name of Engineering

«If you can't measure it, you can't optimize it»

- Need the conditions where the system is running in a predictable state, so we are able to quantify improvements
- These benchmarks usually focus on particular pieces of system, and have more resolution than «marketing» benchmarks

Theory: In the name of Science

«Science Town PD: To Explain and Predict»

- Derive the sound performance model from the results
- Use the performance model to predict the future behavior: keep calm and deploy to production
- The most sweaty, and the most reliable target for benchmarking

Theory: Why would people benchmark?

In the name of...

1. **Holywar**: Node.js – But Java... – Node.js!
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Theory: «Scientific» approach

Ultimate Question

How does a benchmark react on changing the external conditions?

Or, how far the **actual** performance model is from the **mental** one?

1. Fool-proof: do these results even make any sense?
2. Negative control: benchmark reacts on change, but shouldn't?
3. Positive control: benchmark should not react on change, but does?

Theory: «Engineering» approach

Ultimate Question

Why doesn't my benchmark run faster?

Directly observe if our experimental setup is sane:

1. Where are the bottlenecks?
2. Do we expect those things to be bottlenecks?
3. Are these benchmarks running in the same mode?

Theory: JMH

JMH is a Serious Business:
`http://openjdk.java.net/projects/code-tools/jmh/`

- When used properly, helps to mitigate VM quirks
- Aids running lots of benchmarks in different conditions
- Internal profiling to quickly triage the issues
- JVM languages support: Java, Scala, Groovy, Kotlin
- ...or anything else callable from Java (e.g. Nashorn, etc.)

Scientific

Scientific: Story

In this section, we explore some of the methodology implications when doing the benchmarks. People tend to think this story is a deal-breaker when trying to build their own benchmark harnesses.

Complete story and narrative is here:
`http://shipilev.net/blog/2014/nanotrusting-nanotime/`

Models: Model Problem

«Jessie, it's time to cook some benchmarks...»

«What is the cost of `volatile` write?»

It seems like a very easy question...
Let's measure it! Shall we?

Models: Easy...

```
public class VolatileWrite {
  int v; volatile int vv;

  @Benchmark
  int baseline1()    { return 42; }

  @Benchmark
  int incrPlain()    { return v++; }

  @Benchmark
  int incrVolatile() { return vv++; }
}
```

Models: ...does it!

```
public class VolatileWrite {
  int v; volatile int vv;

  @Benchmark
  int baseline1()     { return 42; }   // 2.0 ns

  @Benchmark
  int incrPlain()     { return v++; }  // 3.5 ns

  @Benchmark
  int incrVolatile() { return vv++; } // 15.1 ns
}
```

Models: Fatal Flaw

```
volatile int vv;

@Benchmark
int incrVolatile() { return vv++; }
```

- Measuring in very unfavorable case, when benchmark is choked by volatiles. We are pushing the system to its «edge» condition. This almost never happens in production.
- What do we really need to know is:
  «What is the volatile cost in realistic conditions?»

Models: Backoffs

```
@Param int tokens;

volatile int vv;

@Benchmark
int incrVolatile() {
  Blackhole.consumeCPU(tokens); // burn time
  return vv++;
}
```

- «Burn off» a few cycles before doing heavy-weight op
- Juggle `tokens` ⇒ juggle operation mix

Models: Backoffs

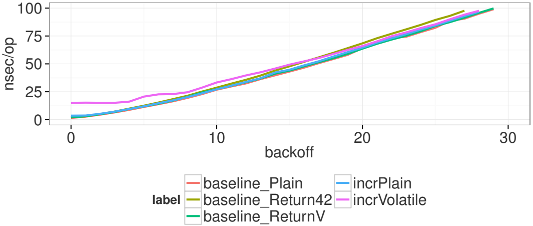
- Take a few baselines while we are at it: which one is correct?

```
@Benchmark
void baseline_Plain()
   { BH.consumeCPU(tokens); }

@Benchmark
int baseline_Return42()
   { BH.consumeCPU(tokens); return 42; }

@Benchmark
int baseline_ReturnPlain()
   { BH.consumeCPU(tokens); return v; }
```

Models: Measuring...

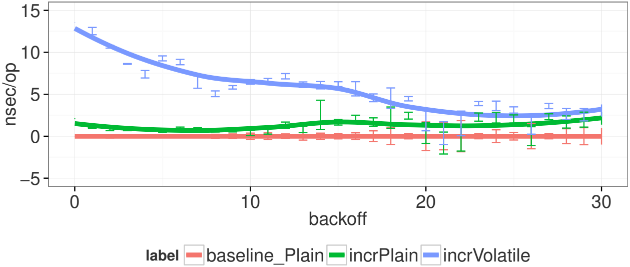
A picture with two robots
in a very hot environment,
one deeply frustrated by
its own actions,
which benefits another
(trickier) robot

«Bender B. Rodriguez regrets using Excel to draw the charts»



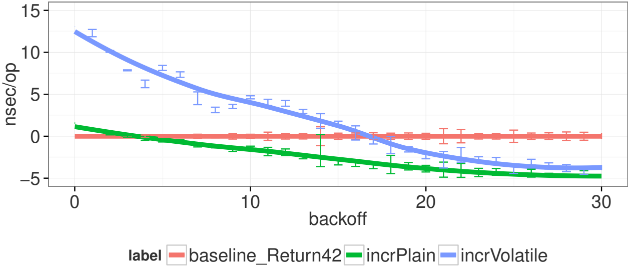
Models: Subtracting `baselinePlain`

- Absolute `volatile` cost gets compensated very well!
- Can we really subtract the baselines?

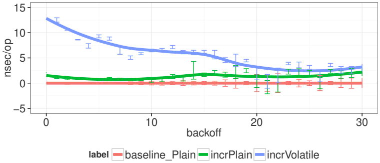


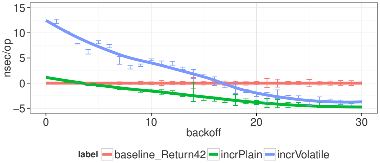
Models: Subtracting `baseline_Return42`

- We added some code in the baseline, and it runs **faster**?
- Nothing surprising: *performance is not usually composable*



Models: WTF is different?

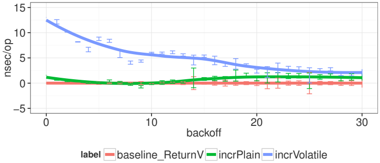


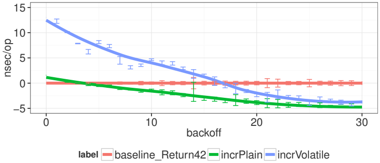


```
@Benchmark
void base_Plain() {
  BH.consumeCPU(tkns);
}
.
```

```
@Benchmark
int base_Ret42() {
  BH.consumeCPU(tkns);
  return 42;
}
```

Models: WTF is different?



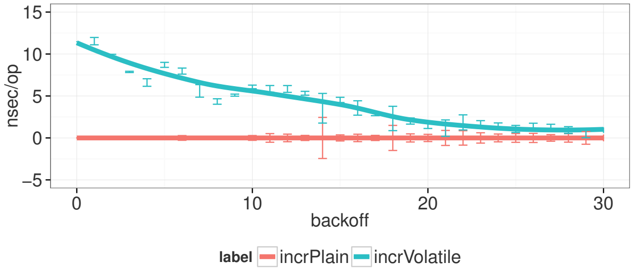


```
@Benchmark
int base_RetV() {
  BH.consumeCPU(tkns);
  return v;
}
```

```
@Benchmark
int base_Ret42() {
  BH.consumeCPU(tkns);
  return 42;
}
```

Models: Bottom Line

- Different baselines act differently: they are **tests** themselves!
- Therefore, we can just compare `plain` and `volatile`:



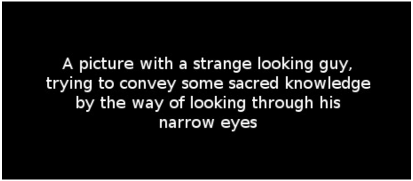
Models: Conclusion

This is what models are for!

- Explore the system behavior outside the (randomly) chosen configuration points
- Allow to predict the system behavior in future conditions
- Catch the experimental setup problems (control!)
- Combinatorial experiments help to create different operation mixes, and derive the individual op costs from their composite performance

Models: You Are Joking, Right?

«Combinatorial experiments help to create different operation mixes, and derive the individual op costs from their composite performance»



A picture with a strange looking guy, trying to convey some sacred knowledge by the way of looking through his narrow eyes

`System.nanoTime`!
Measure each part individually!

Timers: Verifying infrastructure

Why not?

```java
// call continuously
public long measure() {
  long startTime = System.nanoTime();
  work();
  return System.nanoTime() - startTime;
}
```

Timers: Measuring Latency

Latency = time to call `System.nanoTime`

```
@Benchmark
public long latency_nanotime() {
  return System.nanoTime();
}
```

Timers: Measuring Granularity

Granularity = the minimum non-zero difference between two consecutive calls

```
private long lastValue;

@Benchmark
public long granularity_nanotime() {
  long cur;
  do {
    cur = System.nanoTime();
  } while (cur == lastValue);
  lastValue = cur;
  return cur;
}
```

Timers: Typical Case [Linux]

```
Java(TM) SE Runtime Environment, 1.7.0_45-b18
Java HotSpot(TM) 64-Bit Server VM, 24.45-b08
Linux, 3.13.8-1-ARCH, amd64

Running with 1 threads and [-client]:
  granularity_nanotime: 26.300 +- 0.205 ns
      latency_nanotime: 25.542 +- 0.024 ns

Running with 1 threads and [-server]:
  granularity_nanotime: 26.432 +- 0.191 ns
      latency_nanotime: 26.276 +- 0.538 ns
```

Timers: Typical Case [Solaris]

```
Java(TM) SE Runtime Environment, 1.8.0-b132
Java HotSpot(TM) 64-Bit Server VM, 25.0-b70
SunOS, 5.11, amd64

Running with 1 threads and [-client]:
   granularity_nanotime: 29.322 +- 1.293 ns
       latency_nanotime: 29.910 +- 1.626 ns

Running with 1 threads and [-server]:
   granularity_nanotime: 28.990 +- 0.019 ns
       latency_nanotime: 30.862 +- 6.622 ns
```

Timers: Typical Case [Windows]

```
Java(TM) SE Runtime Environment, 1.7.0_51-b13
Java HotSpot(TM) 64-Bit Server VM, 24.51-b03
Windows 7, 6.1, amd64

Running with 1 threads and [-client]:
   granularity_nanotime: 371,419 +- 1,541 ns
       latency_nanotime: 14,415 +- 0,389 ns

Running with 1 threads and [-server]:
   granularity_nanotime: 371,237 +- 1,239 ns
       latency_nanotime: 14,326 +- 0,308 ns
```

Timers: Epic Case [Windows]

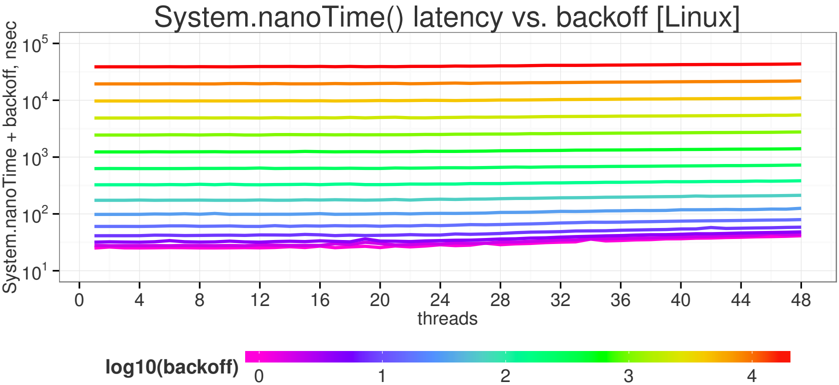
```
Java(TM) SE Runtime Environment, 1.8.0-b132
Java HotSpot(TM) 64-Bit Server VM, 25.0-b70
Windows Server 2008, 6.0, amd64

Running with 32 threads and [-client]:
   granularity_nanotime: 15137.504 +-   97.132 ns
       latency_nanotime: 15190.080 +- 1760.500 ns

Running with 32 threads and [-server]:
   granularity_nanotime: 15118.159 +-  121.671 ns
       latency_nanotime: 15176.690 +- 1504.406 ns
```

Timers: Model Experiment

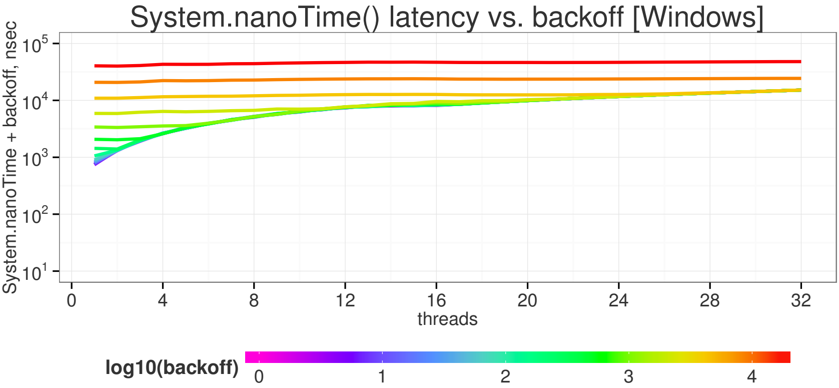
- But if `System.nanoTime()` is heavy and potentially non-scaling, then we run the system into oblivion?
- Let's figure out when it starts to Detroit:

```
@Param
int backoff;

@Benchmark
public long nanotime() {
  Blackhole.consumeCPU(backoff);
  return System.nanoTime();
}
```

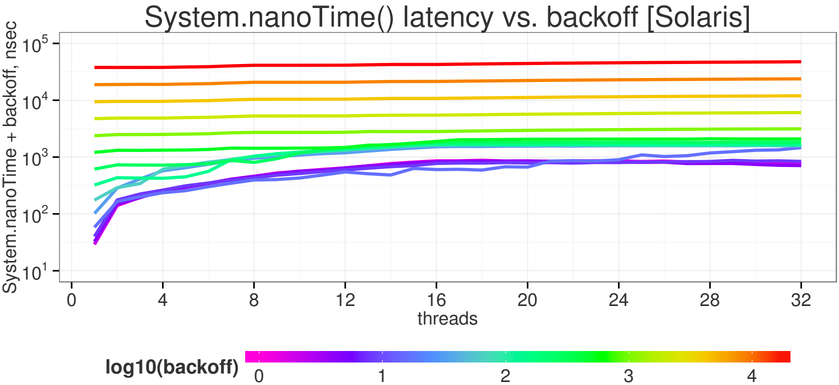
Timers: Seems OK [Linux]



Timers: Double U. Tee. Eff. [Windows]



Timers: Paying for Monotonicity [Solaris]



Timers: Typical Case [Mac OS X]

```
Java(TM) SE Runtime Environment, 1.8.0-b132
Java HotSpot(TM) 64-Bit Server VM, 25.0-b70
Mac OS X, 10.9.2, x86_64

Running with 1 threads and [-server]:
   granularity_nanotime: 1009.623 +-  2.140 ns
       latency_nanotime: 44.145 +-  1.449 ns

Running with 4 threads and [-server]:
   granularity_nanotime: 1044.703 +- 32.103 ns
       latency_nanotime: 56.111 +-  3.397 ns
```

Timers: Summing Up

`System.nanoTime` – is a new `String.intern`!

- Giving users the `nanoTime` is handing over a loaded gun
- `nanoTime` is may and should be used in selected cases, when you can foresee all disadvantages
- Most frequently, the direct measurement is not available, and we have to derive the models from the collateral evidence

Timers: Stop Kidding Already?

A picture of the dog that is derp-high on butterscotch, but still feeling OK

Our code blocks are heavy enough to keep `nanoTime()` granularity and latency at bay!

Omission: Heavy Benchmark is Heavy

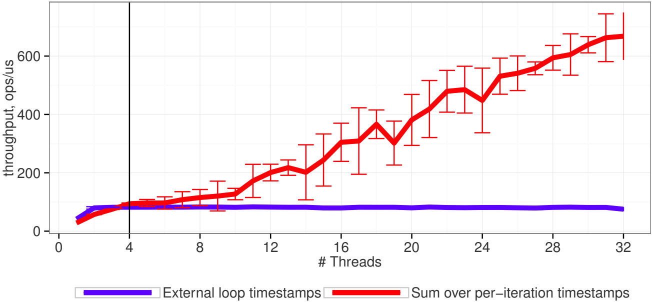
```
public long measure() {
  long ops = 0;
  long startTime = System.nanoTime();
  while(!isDone) {
    setup(); // want to skip this
    work();
    ops++;
  }
  return ops / (System.nanoTime() - startTime);
}
```

Omission: Measuring the Separate Block

```
public long measure() {
  long ops = 0;
  long realTime = 0;
  while(!isDone) {
    setup(); // skip this
    long time = System.nanoTime();
      work();
    realTime += (System.nanoTime() - time);
    ops++;
  }
  return ops / realTime;
}
```

Omission: Checking Empty setup()...

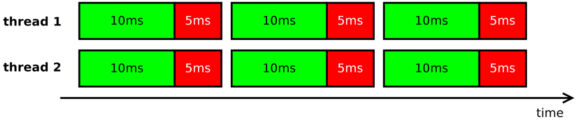
Measuring the throughput... it grows past the CPU count?!



Omission: Hint

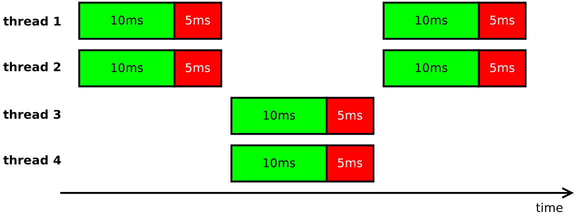
```
public long measure() {
  long ops = 0;
  long realTime = 0;
  while(!isDone) {
    setup(); // skip this
    long time = System.nanoTime();
      work();
    realTime += (System.nanoTime() - time);
    ops++;
    ...WHOOPS, WE DE-SCHEDULE HERE...
  }
  return ops / realTime;
}
```

Omission: Basic Example



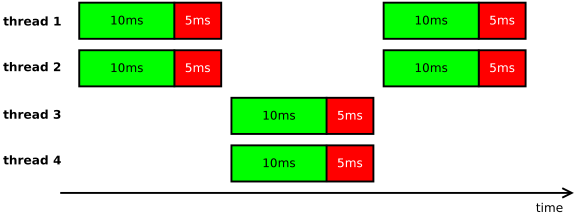
- Measuring the operation time, 10 ms/op on average ⇒ each i-th thread thinks its individual throughput is $\lambda_i =$ 100 ops/sec
- We have two threads, and therefore $\sum_{i=1}^{N} \lambda_i =$ 200 ops/sec

Omission: A Fistful of Threads More



- Each thread still believes $\lambda_i = 100$ ops/sec!
- Now we have four threads $\Rightarrow \sum_{i=1}^{N} \lambda_i = 400$ ops/sec

Omission: A Fistful of Threads More



- Each thread still believes $\lambda_i = 100$ ops/sec!
- Now we have four threads $\Rightarrow \sum_{i=1}^{N} \lambda_i =$ 400 ops/sec

Omission: Conclusion

A picture with a guy in a freezer,
waiting for beer to thaw,
while the alien spaceships
destroy the city around.

"Phillip J. Fry is experiencing the major safepoint event"

Timers skip the beats, and may grossly under/overestimate the durations.

- Every performance metric that includes time is at fault
- Very easy to blow up on overloaded systems
- Very easy to blow up when measurers coordinate with workload

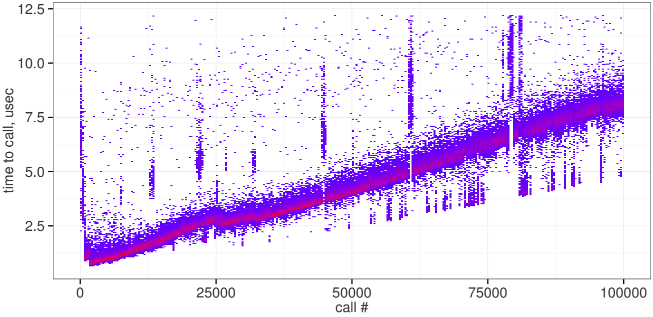
S.S.: (TGIF) Thank God It's Fibonacci

Is there a problem, officer?

```java
public class FibonacciGen {
  BigInteger n1 = ONE; BigInteger n2 = ZERO;

  @Benchmark
  public BigInteger next() {
    BigInteger cur = n1.add(n2);
    n2 = n1; n1 = cur;
    return cur;
  }
}
```

S.S.: Timing Each Call...

Whoops, this benchmark has no steady state, indeed:



S.S.: Pitfalls

No steady state – can **not** use the time-based benchmarks!
The longer we measure, the «slower» the result appears:

duration, sec	throughput, us/op
1	5.013 ± 0.006
2	7.087 ± 0.009
4	10.021 ± 0.017
8	14.159 ± 0.010

S.S.: Pick Your Poison

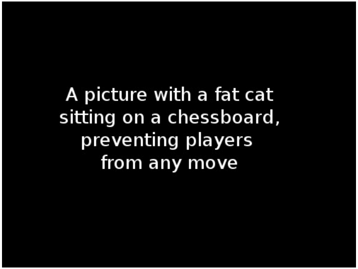
Time-based benchmarks:

- Measuring in God knows what conditions
- How should one compare two implementations?
  (if you are lucky, and your performance model is linear...)

Work-based benchmarks:

- Burning ourselves with timers latency/granularity
- Burning ourselves with omission
- Burning ourselves with transients

S.S.: Conclusion



«The only winning move is not to play at all»

Non-steady state benchmarks force you to choose between all the bad options.

Non-steady state benchmarks are the large P.I.T.A!

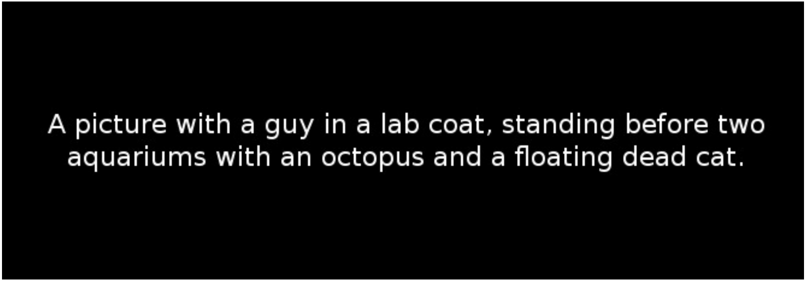
S.S.: Palliative Relief

Measure in large batches!

```
@Setup(Level.Iteration)
public void setup() {
  n1 = BigInteger.ZERO; n2 = BigInteger.ONE;
}

@Benchmark
@Measurement(batchSize = 5000)
public BigInteger next() {
  BigInteger cur = n1.add(n2);
  n2 = n1; n1 = cur;
  return cur;
}
```

Engineering

Engineering: Comparisons



A picture with a guy in a lab coat, standing before two aquariums with an octopus and a floating dead cat.

You want your results to be comparable.

- Every tiny little uncontrolled detail is a free variable
- Libraries are the large complexes of tiny details
- Language runtimes are **galaxies** of tiny details

Engineering: Story

This is a weird story of Java vs. Scala comparison coming from StackOverflow, where people are bound to that believe tail-recursion optimization is the best thing that happened in computer science since the sliced bread.

Complete story and narrative is here:

`http://shipilev.net/blog/2014/java-scala-divided-we-fail/`

Engineering: Scala's @tailrec

```
@tailrec private def
isDivisible(v: Int, d: Int, l: Int): Boolean = {
  if (d > l) true
  else (v % d == 0) && isDivisible(v, d + 1, l)
}

@Benchmark
def test(): Int = {
  var v = 10
  while(!isDivisible(v, 2, l))
    v += 2
  v
}
```

Engineering: Java's absence-of-tailrec

```
private boolean isDivisible(int v, int d, int l)
  if (d > l) return true;
  else
    return (v % d == 0) && isDivisible(v, d+1, l)
}

@Benchmark
public int test() {
  int v = 10;
  while(!isDivisible(v, 2, l))
    v += 2;
  return val;
}
```

Engineering: Measuring

```
 Benchmark      lim         Score  Score error   Units
-----------------------------------------------------
 ScalaBench      1         0.002        0.000   us/op
 ScalaBench      5         0.494        0.005   us/op
 ScalaBench     10        24.228        0.268   us/op
 ScalaBench     15      3457.733       33.070   us/op
 ScalaBench     20   2505634.259    15366.665   us/op
 JavaBench       1         0.002        0.000   us/op
 JavaBench       5         0.252        0.001   us/op
 JavaBench      10        12.782        0.325   us/op
 JavaBench      15      1615.890        7.647   us/op
 JavaBench      20   1053187.731    20502.217   us/op
```

Engineering: Profiling Java

```
Result: 12.719 +-(99.9%) 0.284 us/op [Average]

....[Thread state distributions].......................
 91.3%        RUNNABLE
  8.7%        WAITING

....[Thread state: RUNNABLE]...........................
 58.0%  63.5% n.s.JavaBench.isDivisible
 32.9%  36.1% n.s.JavaBench.test

....[Thread state: WAITING]............................
  8.7% 100.0% <irrelevant>
```

Engineering: Profiling Scala

```
Result: 24.076 +-(99.9%) 0.728 us/op [Average]

....[Thread state distributions]......................
 91.4%        RUNNABLE
  8.6%        WAITING

....[Thread state: RUNNABLE]..........................
 90.6%  99.1% n.s.ScalaBench.test
  0.9%   0.9% n.s.generated.ScalaBench_test.test_avgt_jmhLo

....[Thread state: WAITING]...........................
  8.6% 100.0% <irrelevant>
```

Engineering: Coarse-grained profilers

Coarse-grained (method-level) profilers are useless in diagnosing the problems in nano- and micro-benchmarks.

Additional penalty points if they are sampling at safepoints.

Engineering: JMH perfasm

```
java -jar benchmarks.jar ... -prof perfasm
```

Surprisingly easy to marry these three things:

1. Linux `perf` provides light-weight PMU sampling
2. JVM debug info maps events back to VM methods
3. `-XX:+PrintAssembly` maps events back to Java code

Actually, there are lots of good profilers already, but most of the time you don't need «big guns» to quickly analyze benchmarks.

Engineering: Hottest thing in Scala

One true and solid x86 division:

```
 clocks    insns    code
-------------------------------------------------------
; n.s.g.ScalaBench_test::test_avgt_jmhLoop
...
  0.27%     0.17%   cltd
  2.24%    17.26%   idiv    %ecx
 77.99%    66.44%   test    %edx,%edx
...
```

How can you possibly be 2x faster than this?

Engineering: Hottest thing in Java

```
 clocks    insns   code
-------------------------------------------------------
; n.s.JavaBench::isDivisible
...
  1.68%     2.76%  cltd
  0.06%     0.16%  idiv    %ecx
 27.59%    36.37%  test    %edx,%edx
 ...
  0.04%            cltd
                   idiv    %r10d
 12.24%     1.54%  test    %edx,%edx
 ...
  0.01%            callq   <recursive-call>
```

Engineering: Second hottest thing in Java

```
 clocks    insns    code
------------------------------------------------------
; n.s.g.JavaBench_test::test_avgt_jmhLoop
 ...
  1.34%    0.21%    imul   $0x55555556,%rdx,%rdx
  1.25%    0.20%    sar    $0x20,%rdx
  1.15%    2.36%    mov    %edx,%esi
  0.95%    1.51%    sub    %r10d,%esi            ; irem
 ...
```

[2] http://www.hackersdelight.org/divcMore.pdf

Engineering: Second hottest thing in Java

```
 clocks    insns    code
------------------------------------------------------
; n.s.g.JavaBench_test::test_avgt_jmhLoop
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  1.34%    0.21%    imul    $0x55555556,%rdx,%rdx
  1.25%    0.20%    sar     $0x20,%rdx
  1.15%    2.36%    mov     %edx,%esi
  0.95%    1.51%    sub     %r10d,%esi            ; irem
 ...
```

Beautiful trick of substituting the remainder with constant multiplication and binary shift! [2]

[2] http://www.hackersdelight.org/divcMore.pdf

Engineering: Quick Explanation

```
// inlines twice, specializes for d={2,3}
private boolean isDivisble(int v, int d, int l) {
  ...
  return (v % d == 0) && isDivisble(v, d+1, l);
}

@Benchmark
public int test() {
  int v = 10;
  while(!isDivisble(v, 2, l))
    v += 2;
  return val;
}
```

Engineering: Make «d» unpredictable

```
 Benchmark      lim         Score  Score error  Units
-----------------------------------------------------
 ScalaBench       1         0.002        0.000  us/op
 ScalaBench       5         0.489        0.002  us/op
 ScalaBench      10        23.777        0.116  us/op
 ScalaBench      15      3379.870        5.737  us/op
 ScalaBench      20   2468845.944     2413.573  us/op
 JavaBench        1         0.003        0.000  us/op
 JavaBench        5         0.465        0.001  us/op
 JavaBench       10        22.989        0.095  us/op
 JavaBench       15      3453.116       16.390  us/op
 JavaBench       20   2518726.451     4374.482  us/op
```

Engineering: Conclusion

«Days since the last benchmarking accident: 0» (@gvsmirnov)

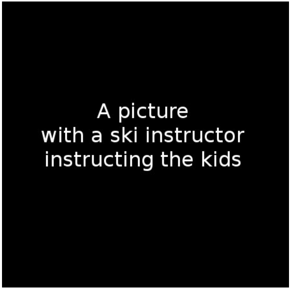
Benchmarks without analysis make me a really sad panda.

You show me nice charts: Language A vs. Language B, Nashorn vs. Rhino, Graal vs. C2, etc, and all I see is

BAYESIAN NOISE

Fin

Fin: Conclusion



«If you don't analyze the benchmarks, you've gonna waste a good time»

The superficial conclusions almost always feed on existing biases, and are almost always wrong.

Benchmarks are for understanding the Reality, not for reinforcing your prejudices about the Universe.