(The Art of) (Java) Benchmarking

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Agenda

Introduction

Basic Theory

Java Benchmarking

Tools
Introduction

• Computer Science → Software Engineering
  – Way to construct software to meet functional requirements
  – Usually don't care about HW and data specifics
  – Abstract and composable, “formal science”

• Software Performance Engineering
  – “Real world strikes back!”
  – Researching complex interactions between hardware, software, and data
    • Unable to predict performance, can only measure it
  – Based on empirical evidence, i.e. “natural science”
    • Characterization → Hypotheses → Predictions → Experiments
    • Benchmarks are ultimate tools for conducting experiments
Benchmarks

• What’s the benchmark anyway?
  – Def.: “Benchmark is the application used to measure performance”
    • Take an application, get two timestamps, now you have a benchmark
    – Every benchmark run is computational experiment

• Correct benchmark is tricky to get right
  – It has a metric: each run yields metric value (ops/sec, sec, ops/W)
  – Reliable: reproducible results, reacts correctly to changing environment
  – Objective: Tests the Right Thing™
  – Easy to run
  – Self-checking
Benchmark Taxonomy

• Real-World Applications
  – Launch manually
  – Measure with stopwatch, voltmeter, oscillograph

• Automated Scenarios of Real-World Applications
  – Record the trace through the application, feed the trace to the robot
  – Let other robots to measure time, power, traffic, etc.

• Synthetic (Macro-)Benchmarks
  – Develop golden application along with all the testing infrastructure
  – Hard to develop, lots of code, huge investment

• Microbenchmarks
  – Focus on one specific part of the code, throwing everything else out
  – Easy to develop, (everyone tends to think of it as) small investment
How Could This Go Wrong?

• Good design of experiment requires one to know the field
  – Anyone to perform heart surgery without 10+ years surgeon's experience?

• Running the benchmark is NOT the final step
  – Asking the right question is the first step
  – Interpreting the results is hard
  – Detecting Type III Errors is hard
  – Convincing yourself to fix something and run again is the hardest part

• Being effective at benchmarking means having less retries
  – Translation: don't do silly things → learn what NOT to do
  – Catch mistakes early and eagerly
  – Too many retries? Learn to give up.
You're Not Alone

• **Transaction Processing Performance Council**
  – Design documents for standard benchmarks
  – Resolve a lot of benchmark design problems

• **Standard Performance Evaluation Corporation**
  – Industry-standard performance benchmarks
    • SPECcpu, SPECvirt_sc, SPECjbb, SPECjvm, SPECjEnterprise
    • Ready-to-run implementations:
      – Download/Buy → Deploy → Run → ??? → PROFIT!
      – Updated to match newer trends in hardware and software

• **Performance teams**

• **Peer reviews**
Agenda

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Metrics

• Performance metrics have two major manifestations
  – How many operations per unit of time? (λ, throughput, bandwidth)
  – How long one operation takes? (τ, response time, latency)
  – “Bandwidth only tells parts of the story” © pingtest.net

• It turns out, λ is much easier to improve
  – DDR2 PC2-3200: 3200 Mb/sec, CL 4
  – DDR3 PC3-17000: 17000 Mb/sec, CL 15

• In most queued systems, τ is at the mercy of λ
  – “Nine women can't make a baby in one month”
    • If you pipeline them, you might have a baby each month, each day, each second
    • Now what if you have the bounded queue of available midwives?
Metrics

- Wider you go, slower you get: "hockey stick"
Composability

• Assume you have two code blocks, A and B
  – Any difference with A and B running exclusively (…) or concurrently ( || )?

• Functionality:
  – \( \text{Functionality}(A \ldots B) = \text{Functionality}(A || B) \)
  – “Black box abstraction”: behavior is the same, unless you want otherwise

• Performance:
  – \( \text{Performance}(A \ldots B) \neq \text{Performance}(A || B) \)
  – Who can bet?
    • A and B are competing for processing resources
    • It could be >, e.g. blocks are fighting for the cache
    • It could be <, e.g. single-threaded blocks on multicore machine
    • It could be even =, e.g. for perfectly multi-threaded CPU-bound tasks
Composability

• Lesson: “Black Box Abstraction does not work for performance”
  – In the real world, processes and threads are competing for resources
  – How to estimate performance then?
  – True even for uniprocessor machines: thread preemption

• Very important for manycore world
  – Virtually all the code is executed concurrently with something else
  – Single-threaded benchmarks are then useless to predict real performance
    • Unless you can expect your code is the One Mega Application

• Should I test all the juxtapositions with every other program?
  – Exponential explosion of test configuration space
  – There's good approximation: run the same code in multiple threads
God Does Play Dice

- Empirical data is subject to variance
  - Replication is your friend
    - Many runs, many iterations, statistics
    - Runs on different machines under different conditions
- Scientific Control
  - Positive: expect the phenomenon to appear
  - Negative: expect the phenomenon to not appear
- Statistical Inference
  - System A runs \(50\) ops/sec, System B runs \(40\) ops/sec, is System A faster?

"Piled Higher and Deeper" by Jorge Cham
www.phdcomics.com
God Does Play Dice

- Empirical data is subject to variance
  - Replication is your friend
    - Many runs, many iterations, statistics
    - Runs on different machines under different conditions

- Scientific Control
  - Positive: expect the phenomenon to appear
  - Negative: expect the phenomenon to not appear

- Statistical Inference
  - System A runs 50 ops/sec, System B runs 40 ops/sec, is System A faster?
    - Case 1. $A = 50 \pm 12$ ops/sec, $B = 40 \pm 24$ ops/sec (not really)
    - Case 2. $A = 50 \pm 3$ ops/sec, $B = 40 \pm 2$ ops/sec (probably, yes)
David Brent, “The Office”

“There are those of you who think you know everything are annoying to those of us who do.”
“Imperial Examination” in performance

- HW specifics
  - cpu/memory layout, cache sizes and associativity, power states, etc.

- OS specifics
  - threading model, thread scheduling and affinity, system calls performance, etc.

- Libraries specifics
  - algorithms, tips and tricks for better performance, etc.

- Compilers specifics
  - high-level and low-level optimizations, tips and tricks, etc.

- Algos specifics
  - algorithmic complexity, data access patterns, etc.

- Data specifics
  - representative sizes and values, operation mix, etc.
Why do I need to know that?

• The Ultimate Question:

How does my benchmark perform?
Why do I need to know that?

• The Ultimate Question:

How does my benchmark perform?

Why doesn't my benchmark perform better?
Why do I need to know that?

• The Ultimate Question:

  How does my benchmark perform?

  Why doesn't my benchmark perform better?

• The answer tells many things about quality of your experiment
  – What are we really stressing?
  – Are we stressing the part we want to stress?
  – What needs to be changed in benchmark to make it right?
Agenda

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Java Benchmarking

Tools
Dynamic Runtimes? Bring It On!

• Also need to know about:
  – Virtual Machines
    • Class loading, class verification, class lifecycle
  – JIT
    • Code lifecycle
    • Profiling, compile plans, OSR
    • Aggressive optimizations
    • Usual and pathological work modes
  – GC
    • Types, algos used, throughput vs. response time
    • Usual and pathological work modes
Typical Java Runtime Lifecycle (Not to scale!)

- **VM init**: JVM invoked
- **App init**: Java main() invoked
- **App active (warmup)**: First conscious action from application
- **App active (steady)**: Reached semi-optimal performance
- **Shutdown requested**: Shutdown requested

**Utilization** vs **Time**

- **Application (compiled)**
- **GC**
- **CL**
- **JIT**
- **VM**

**Max**
“Micro-benchmarks are like a microscope. Magnification is high, but what the heck are you looking at?”
Pitfall #0. Type III Errors

- **PiDigits** subtest from Computer Language Benchmarks Game
  - Computes first N digits in decimal form of π
    - Requires arbitrary precision for series coefficients
  - So, this is what you call Java benchmark?
    - Uses native GNU MP for computation
  - Java is used to arrange native calls
    - ...so up to 90% of time is spent in GNU MP
  - This code will never pass sensible code review
    - Do you really want to measure it?

```java
public void _run() {
    // ...
    acquire(sema[op1], 1);
    sema[op1].release();
    acquire(sema[op2], 1);
    sema[op2].release();

    if (instr == MUL) {
        GmpUtil.mpz_mul_si(...);
    } else if (instr == ADD) {
        GmpUtil.mpz_add(...);
    } else if (instr == DIV_Q_R) {
        GmpUtil.mpz_tdiv_qr(...);
        sema[op3].release();
    }
    sema[dest].release();
}
```
Pitfall #0. Type III Errors

Lessons Learned:

Choose what you want to measure.
Assess what you had really measured.
Fix it.
Repeat.
Pitfall #1. Improper Warmup

• CLBG has two major metrics
  – Execution time
    • Measured in scripting equivalent of “time java $*”
  – Memory footprint

• Any dynamic runtime is penalized
  – Includes time to initialize, aggressive optimizations, adaptive algos
    • Shorter the test, more the overheads
  – So then, if you're competing with static compilers
    • Gotta watch for init time!
      – Don't use complex APIs
      – Move everything in native code?
Pitfall #1. Improper Warmup

• There are some “steady state” tests:

    pidigits.javasteady:
    public static void main(String[] args){
        pidigits m = new pidigits(Integer.parseInt(args[0]));
        for (int i=0; i<65; ++i) m.pidigits(false);
        m.pidigits(true);
    }

• Now compare to the “standard” test:

    pidigits.java:
    public static void main(String[] args){
        pidigits m = new pidigits(Integer.parseInt(args[0]));
        // for (int i=0; i<19; ++i) m.pidigits(false);
        m.pidigits(true);
    }
Pitfall #1. Improper Warmup

• There are some “steady state” tests:

```java
pidigits.javasteady:
    public static void main(String[] args){
        pidigits m = new pidigits(Integer.parseInt(args[0]));
        for (int i=0; i<65; ++i) m.pidigits(false);
        m.pidigits(true);
    }
```

• CLBG maintainer furiously defended:
  – “... The JavaOne Moscow presenter's slides fail to show that combined time measurement was correctly divided by 65 to give the average.”
Pitfall #1. Improper Warmup

• There are some “steady state” tests:

```java
import java.util.*;
public class pidigits {
    public String pidigits() {
        String s = new String();
        for (int i=0; i<65; ++i) s += (char)(i+48);
        return s;
    }
}
```

• CLBG maintainer furiously defended:
  – “... The JavaOne Moscow presenter's slides fail to show that combined time measurement was **correctly divided by 65 to give the average**.”
    • Yes, right, however:
      – Warmup iterations skip I/O, hitting deopt on “real” iteration
      – If, say, first iteration takes 20x longer, then average is skewed >13%
    • Averaging scores from different modes makes **little** sense
Pitfall #1. Improper Warmup

Lessons Learned:

Warmup the code.
Embrace warmup as distinguished lifecycle phase.
Warmup on the same code and data paths.
Pitfall #2. Observing Unrelated Effect

- Found in EclipseLink tests
  - One of the tests which measures synchronized method performance in uncontended scenario

- Published data
  - Negative scientific control **FAIL**:
    - block: 8244087 usec
    - method: 13383707 usec
  - Published conclusion:
    - "synchronized(this) { } is better"
  - JVM engineers:
    - "WTF, those two are equivalent"

```java
public class SynchTest {
    int i;

    @GenerateMicroBenchmark
    void testSynchInner() {
        synchronized (this) {
            i++;
        }
    }

    @GenerateMicroBenchmark
    synchronized void testSynchOuter() {
        i++;
    }
}
```

This code is the mock. Do Try This At Home.
Pitfall #2. Observing Unrelated Effect

• Trying to reproduce
  – Calling each method many times
    • First, call synchInner() for 10 secs
    • Then, call synchOuter() for 10 secs
    • 1 thread, monitor is always uncontended
  – Results:
    • synchInner: 40988 ± 218 ops/sec
    • synchOuter: 261602 ± 11511 ops/sec

public class SynchTest {

  int i;

  @GenerateMicroBenchmark
  void testSynchInner() {
    synchronized (this) {
      i++;
    }
  }

  @GenerateMicroBenchmark
  synchronized void testSynchOuter() {
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Pitfall #2. Observing Unrelated Effect

• Solution
  – BiasedLocking is not enabled at once
    • By default, late 5000 msec after start
    • First test uses thin syncs
    • Second test uses biased syncs
  – Re-measuring with
    -XX:BiasedLockingStartupDelay=0
    • synchInner: 287905 ± 12298 ops/sec
    • synchOuter: 286962 ± 10114 ops/sec

```java
public class SynchTest {
    int i;

    @GenerateMicroBenchmark
    synchronized void testSynchInner() {
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    synchronized void testSynchOuter() {
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}
```

This code is the mock. Do Try This At Home.
Pitfall #2. Observing Unrelated Effect

Lessons Learned:

Every result needs an explanation.
Surprising results can warn you about bad design.
Let more eyeballs to look over your data.
Not so long ago in some blog:

```
Today I want to show how you could compare e.g. different algorithms. You could simply do:

```java
int COUNT = 1000000;
long firstMillis = System.currentTimeMillis();
for(int i = 0; i < COUNT; i++) {
    runAlgorithm();
}
System.out.println(System.currentTimeMillis()-firstMillis) / 1000.0 / COUNT);
```

There are several problems with this approach, which results in very unpredictable results: [...] 
You should turn off the JIT-compiler with specifying -Xint as a JVM option, otherwise your outcome could depend on the (unpredictable) JIT and not on your algorithm. You should start with enough memory, so specify e.g.-Xms64m -Xmx64m, because JVM memory allocation could get time consuming. Avoid that the garbage collector runs while your measurement: -Xnoclassgc
Pitfall #3. Weird Modes

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"Today I want to show how you could compare e.g. different algorithms. You could simply do:

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Pitfall #3. Weird Modes

• Run multiple doIteration()-s
  – On each iteration BitSet is expanding
  – Throughput goes down, and down, and down
  – Suspected “JIT variability”

• Let's turn off JIT!
  – Overall throughput plummeted
  – Relative BitSet-induced degradation is lower, given overall decrease
  – “Who-hoo, interpreter is more predictable!”

• Time to spread the word
  – But finally, took a look in the profiler, and realized BitSet is the culprit

```java
public class Test {
    private static BitSet bitset;

    private void doWork() {
        // do work
        bitset.set(n, r);
        // do more work
    }

    public void doIteration() {
        doWork();
    }
}
```

This code is the mock. Do Try This At Home.
Pitfall #3. Weird Modes

Lessons Learned:

Run with the same options you would expect in production.
Have a strong evidence additional options are needed for test.
Understand what different options actually affect.
Pitfall #4. Dead-code elimination

• Modern JIT compilers are so modern...
  – ...they do automatic constant propagation and dead-code elimination
  – That means smart compiler can detect “useless” blocks of code, and optimize out
    • The result of computation is not used? No other side effects? Eliminate!
    • What if that was our benchmarked code?

• Rather easy to fight
  – Consume the result or provide another side-effect
    • Print the result out
    • Store in field of always reachable object
    • Compare with non-trivial, but impossible value, and throw exception otherwise
    • (I would really like to see some compiler hint, i.e. “Unsafe.sideEffect(Object o)”)
Pitfall #4. Dead-code elimination

• Typical example
  – Found in Apache Commons Math tests

• Typical result
  – StrictMath: 71 msecs
  – FastMath: 39 msecs
  – Math: 0 msecs

• That's one super-fast java.util.Math!

```java
@Test
class LogTest {

    public void testLog() {
        double x = 0;
        long time = System.nanoTime();
        for (int i = 0; i < RUNS; i++)
            x += StrictMath.log(Math.PI + i);
        long strictMath = System.nanoTime() - time;

        x = 0;
        time = System.nanoTime();
        for (int i = 0; i < RUNS; i++)
            x += FastMath.log(Math.PI + i);
        long fastTime = System.nanoTime() - time;

        x = 0;
        time = System.nanoTime();
        for (int i = 0; i < RUNS; i++)
            x += Math.log(Math.PI + i);
        long mathTime = System.nanoTime() - time;

        report("log", strictMath, fastTime, mathTime);
    }
}
```
Pitfall #4. Dead-code elimination

• Typical example
  – Found in Apache Commons Math tests

• Typical result
  – StrictMath: 71 msecs
  – FastMath: 39 msecs
  – Math: 0 msecs

• What's going on?
  – “x” is not used, smart JIT deduced there are no side effects in Math.log(...) call → BOOM!
  – Printing out “x” resolves the issue
  – Math: 23 msecs

```java
@Test
public void testLog() {
    double x = 0;
    long time = System.nanoTime();
    for (int i = 0; i < RUNS; i++)
        x += StrictMath.log(Math.PI + i);
    long strictMath = System.nanoTime() - time;

    x = 0;
    time = System.nanoTime();
    for (int i = 0; i < RUNS; i++)
        x += FastMath.log(Math.PI + i);
    long fastTime = System.nanoTime() - time;

    x = 0;
    time = System.nanoTime();
    for (int i = 0; i < RUNS; i++)
        x += Math.log(Math.PI + i);
    long mathTime = System.nanoTime() - time;

    report("log", strictMath, fastTime, mathTime);
}
```
Pitfall #4. Dead-code elimination

Lessons Learned:

Computers are lazy.
Runtime may not bother computing, if result is not claimed.
Pitfall #5. Incomparable Results

• Bob (pun intended) had developed a new fancy Java collection
  – Bob claims it's uber-fast and thread-safe

• Alice is trying to get performance data with two tests
  – Test scalability for shared accesses
    • One collection instance for all the threads, #Threads = #CPUs
  – Test scalability for exclusive accesses
    • One collection per each thread, #Threads = #CPU

• Why not one collection instance for single thread?
  – Obviously not fair – system load will differ drastically
  – Note both two tests should saturate the system
Pitfall #5. Incomparable Results

• Alice's first measurement:
  – 4 threads, 4 logical cores
  – Exclusive access
    615 ± 12 ops/sec
  – Shared access
    828 ± 21 ops/sec

• Bob: “Say what?”
  – Shared access is faster?
  – This can't be happening!

```java
public class AliceBobMakerTest {
    List<String> keys = new ArrayList<>();
    Map<String, String> map = BobMaker.newMap();

    @GenerateMicroBenchmark
    public void test() {
        for(String key : keys) {
            String value = map.get(key);
            if (!value.equals(key)) {
                // make side effect
                throw new ISE("Violated");
            }
        }
    }
}
```

This code is the mock. Do Try This At Home.
Pitfall #5. Incomparable Results

• Memory footprint
  – It happens, one collection takes ~250 Kb
  – L2 cache = 256 Kb
  – L3 cache = 3072 Kb

• These two tests are incomparable:
  – Exclusive mode:
    • 4 instances x 250 Kb = 1000 Kb
  – Shared mode:
    • 1 instances x 250 Kb = 250 Kb

• Might be other non-obvious differences

<table>
<thead>
<tr>
<th></th>
<th>Exclusive</th>
<th>Shared</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 thread</td>
<td>314 ± 14</td>
<td>296 ± 11</td>
</tr>
<tr>
<td>2 threads</td>
<td>561 ± 21</td>
<td>554 ± 12</td>
</tr>
<tr>
<td>4 threads</td>
<td>615 ± 12</td>
<td>828 ± 21</td>
</tr>
<tr>
<td>8 threads</td>
<td>598 ± 15</td>
<td>815 ± 15</td>
</tr>
<tr>
<td>16 threads</td>
<td>595 ± 12</td>
<td>829 ± 16</td>
</tr>
<tr>
<td>32 threads</td>
<td>644 ± 43</td>
<td>915 ± 34</td>
</tr>
</tbody>
</table>
Pitfall #5. Incomparable Results

Lessons Learned:

Carefully assess what results you can compare.
(Turns out comparable results are rare exceptions)
Pitfall #6. Cross-Language Benchmarks

• Larger the platforms you're comparing, more the subtle differences
  – Used concepts, algorithms, libraries, default settings, hardware support
  – Comparing several large platforms is Mammoth task
    • It’s nearly impossible to create useful cross-language benchmark

• Comparing $lang1 vs. $lang2
  – Probably the easiest kickoff for never-ending holy war
    • All about wrong question: “Is $lang1 faster/slower than $lang2?”
    • Tons of troll food expected
  – Smart people see the educational opportunity here:
    • Valid question: “WHY $program1 running with $impl1 of $lang1 performs different from $program2 running with $impl2 of $lang2 on $hardware?”
    • Most of the time requires deep knowledge of both $impl1 and $impl2
Pitfall #6. Cross-Language Benchmarks

Lessons Learned:

Don't do it.

Do that *only* to answer "Why performance is different?"
Pitfall #7. Infrastructure Overheads

• Service code is executed within the same benchmark
  – In case of micros, the impact of service code is comparable with tested code itself
  – Very, very, VERY easy to shoot oneself in the foot

• Usual overheads
  – Counters
    • Useless contentions, redundant dereferences, etc.
    • (example follows)
  – Timers
    • It's OK to take the timestamp every now and then
    • “Mad Hatter” syndrome: some benchmarks do that millions times each second
  – I/O
    • Are you synchronously writing the logs to disk?
Pitfall #7. Infrastructure Overheads

• Mind the simple test
  – Measuring *something*
  – Metric: computations/sec

• How to count successful operations?
  – Sometimes you don't know the thread context
  – ...so the counter should be thread-safe anyway

• Our options are:
  1. Naked counter
  2. Atomic counter
  3. jsr166e-ish LongAdder
  4. ThreadLocal “counter”

```java
public class MyBrokenBenchmark {
    private long counter;
    private AtomicLong atomicCounter;
    private LongAdder longAdderCounter;
    private ThreadLocal<Long> tlCounter = new ThreadLocal<Long>();

    public void test() {
        // { increment counter here }
        // do work here
    }
}
```

This code is the mock. Do Try This At Home.
Pitfall #7. Infrastructure Overheads

Intel Westmere-EX (E7-4860) 2.27Ghz, 4x10x2 = 80 HW threads, RHEL 5.5, JDK 7b148. High/low whiskers are (-2σ, +2σ) for 5 samples.
Pitfall #7. Infrastructure Overheads

Lessons Learned:

Your test infrastructure is your best friend.
Your test infrastructure can turn out to be your worst enemy.
Always suspect it's faulty, unless proven otherwise.
Pitfall #8. Thread Scheduling

• Thread scheduling is not always deterministic
  – (Unless you are running real-time OS)
  – Thread start/stop times are then non-deterministic
  – Even if you park threads on locks, and let go at once

• Mind N threads doing the same work
  – Do they finish at the same time? Nope.
    • Some thread can finish prematurely
    • Then, other threads are free to proceed in better conditions
      – Distorts the measurement
      – Gives unreasonably high throughput
    • One of the most frequent jitter sources
Pitfall #8. Thread Scheduling

• Need to insert bogus iterations
  – Measured parts are always executing as if all the threads are busy

• Simple test
  – Running 24 threads on a 24-way host
  – Doing something quite heavy
  – Without bogus iterations
    957 \( \pm \) 32 ops/min
  – With bogus iterations
    821 \( \pm \) 5 ops/min
Pitfall #8. Thread Scheduling

Lessons Learned:

High benchmark variance is telling you something. Usually it means someone is making critical decisions behind your back.
Pitfall #9. Compile Plans

• Runtime is able to adapt to profile
  – Benefits (lots of) real applications
  – Subtle trouble for benchmarking

• Profile might be conservative
  – Running test T1: runtime gathers profile \( P(T1) \), compiles for it
  – Running another test T2, runtime gathers additional profile \( P(T2) \), so new profile is \( P(T1+T2) \)
  – Runtime has no hints to indicate “now everything had changed, scrap all you have”

```java
public class CompilePlanTest {
    Counter counter1 = new CounterImpl1();
    Counter counter2 = new CounterImpl2();

    @GenerateMicroBenchmark
    public void testM1() {
        test(counter1);
    }

    @GenerateMicroBenchmark
    public void testM2() {
        test(counter2);
    }

    public void test(Counter counter) {
        for(int c = 0; c < LIMIT; c++) {
            counter.inc();
        }
    }
}
```

This code is the mock. Do Try This At Home.
Pitfall #9. Compile Plans

- Executing one-by-one in single JVM
  - testM1: 394 ± 7 ops/msec
  - testM2: 11 ± 1 ops/msec

- Executing each one in fresh JVM
  - testM1: 396 ± 3 ops/msec
  - testM2: 381 ± 16 ops/msec

- Single test is aggressively optimized
  - JVM is able to inline inc() { i++; }, unroll the loop, figure out bunch of increments is actually { i += $unroll_limit; }, furiously faster!

```java
public class CompilePlanTest {
    Counter counter1 = new CounterImpl1();
    Counter counter2 = new CounterImpl2();

    @GenerateMicroBenchmark
    public void testM1() {
        test(counter1);
    }

    @GenerateMicroBenchmark
    public void testM2() {
        test(counter2);
    }

    public void test(Counter counter) {
        for(int c = 0; c < LIMIT; c++) {
            counter.inc();
        }
    }
}
```

This code is the mock. **Do Try This At Home.**
Pitfall #9. Compile Plans

Lessons Learned:

Profiles are usually to be “shaken, not stirred”
When measuring multi-method performance, warm up everything.
When measuring single-method performance, better start fresh VM.
Agenda

Introduction

Basic Theory

Java Benchmarking

Tools
Essential Tools

• Your Brain, equipped with some plug-ins*
  – “WTFISGOINGON” for doubting and rechecking facts
  – “LETMETHINK” for building hypotheses, and appropriate tests
  – “THISCANTBEHAPPENNING” for checking data consistency
  – “THATWASSTUPID” for painless rejection of results

• Your Hands
  – Accurate, for making neat experiments
  – Strong and powerful, for processing tons of experimental data

• Your Peripheral I/O Devices
  – Exchanging the results with fellow researchers, and conducting peer review
  – Accessing experiment history

* these plug-ins do not come with basic package
Collateral Tools

• Application Profilers
  – VisualVM, JRockit Mission Control, Oracle Solaris Studio Performance Analyzer

• Whole-System Profilers
  – top, vmstat, mpstat, iostat, dtrace, strace, etc.

• JRE profiling and debug information
  – -XX:+PrintCompilation, -verbose:gc, -verbose:class, -Xprintflags

• Disassemblers
  – http://wikis.sun.com/display/HotSpotInternals/PrintAssembly

• Hardware Counters
  – Sun Studio Performance Analyzer, oprofile, VTune, etc.
Q & A
Q & A Ultimate Answer: “It Depends”