MOVING JAVA FORWARD

(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

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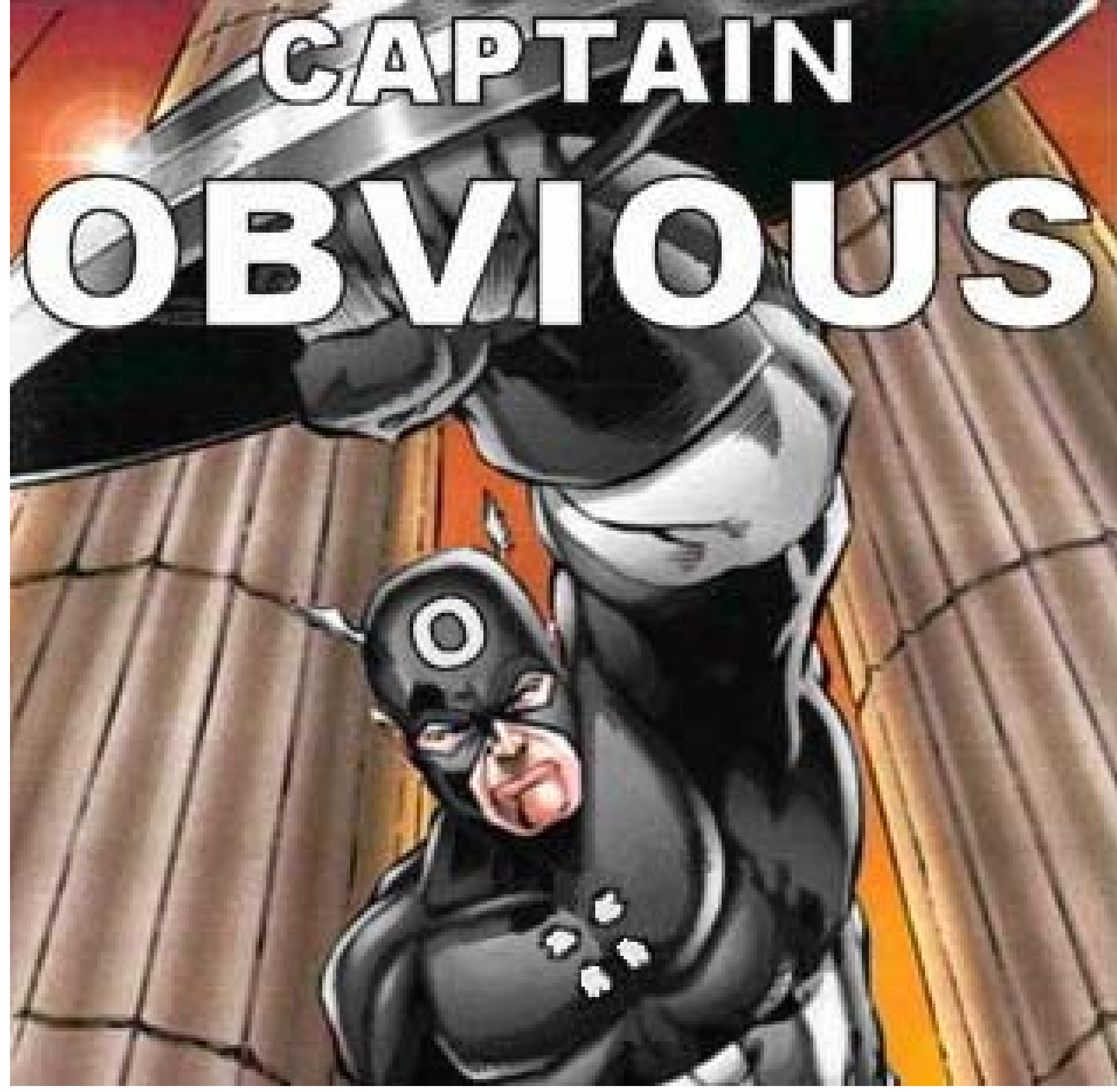
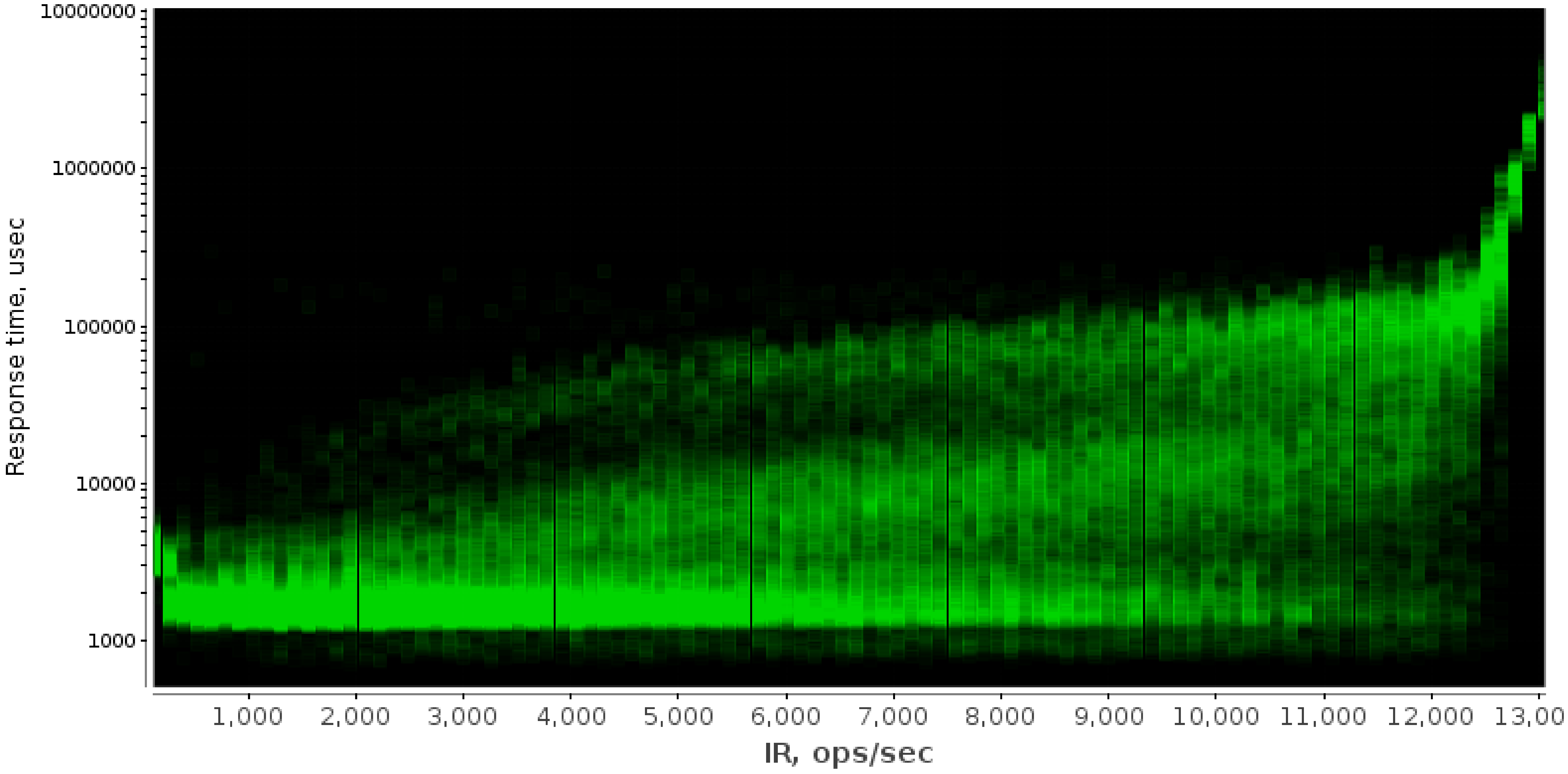
Metrics



- 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:
  - *Functionality(A ... B) = Functionality(A || B)*
  - “Black box abstraction”: behavior is the same, unless you want otherwise
- Performance:
  - *Performance(A … B)* ***?*** *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

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- Statistical Inference
  - System A runs **50** ops/sec, System B runs **40** ops/sec, is System A faster?
    - Case 1. A = **50** ± 12 ops/sec, B = **40** ± 24 ops/sec (not really)
    - Case 2. A = **50** ± 3 ops/sec, B = **40** ± 2 ops/sec (*probably*, yes)

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David Brent, “The Office”

“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?

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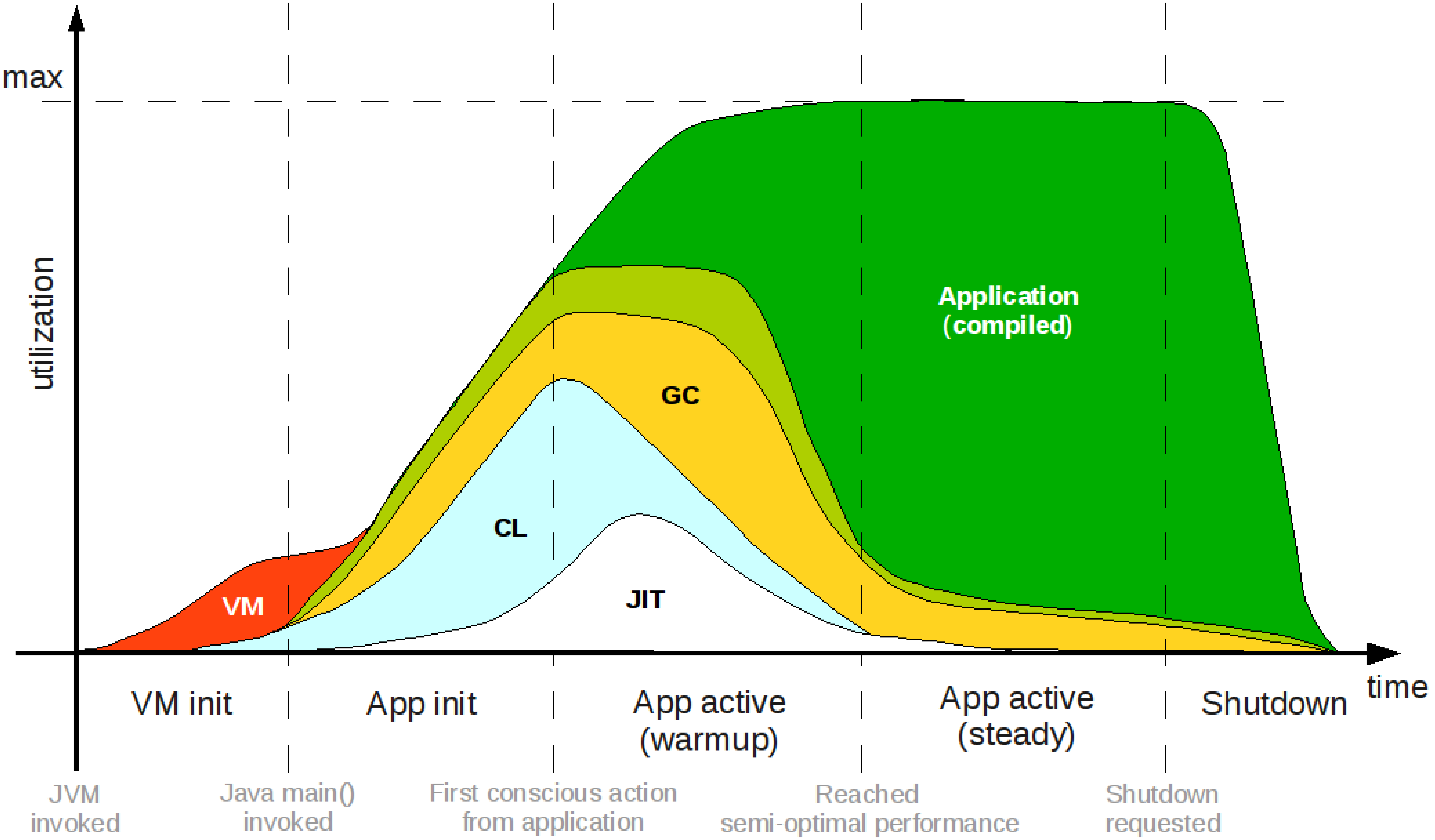
Dynamic Runtimes? Bring It On!

- 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!)



Dr. Cliff Click

“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?

```
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:

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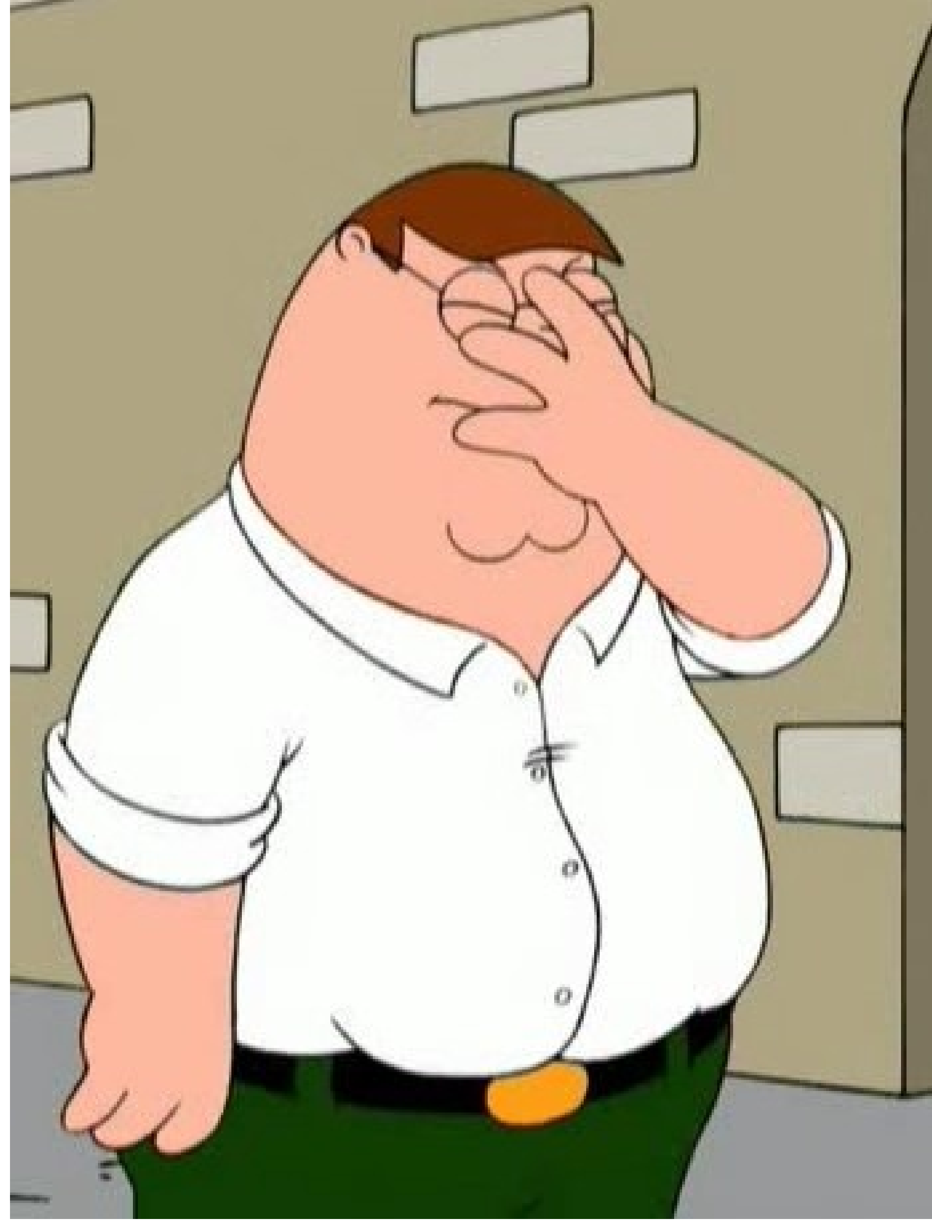
- CLBG maintainer furiously defended:
  - “... *The JavaOne Moscow presenter's slides fail to show that combined time measurement was* ***correctly divided by 65 to give the average.***”

Pitfall #1. Improper Warmup



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- 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”

```
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

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public class SynchTest {

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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

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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.

Pitfall #3. Weird Modes

- Not so long ago in some blog:

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

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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

```
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!

```
@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

- 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

```
@Test
public void testLog() {
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    for (int i = 0; i < RUNS; i++)
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    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!

```
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

	Exclusive	**Shared**
1 thread	314 ± 14	296 ± 11
2 threads	561 ± 21	554 ± 12
4 threads	615 ± 12	828 ± 21
8 threads	598 ± 15	815 ± 15
16 threads	595 ± 12	829 ± 16
32 threads	644 ± 43	915 ± 34

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?

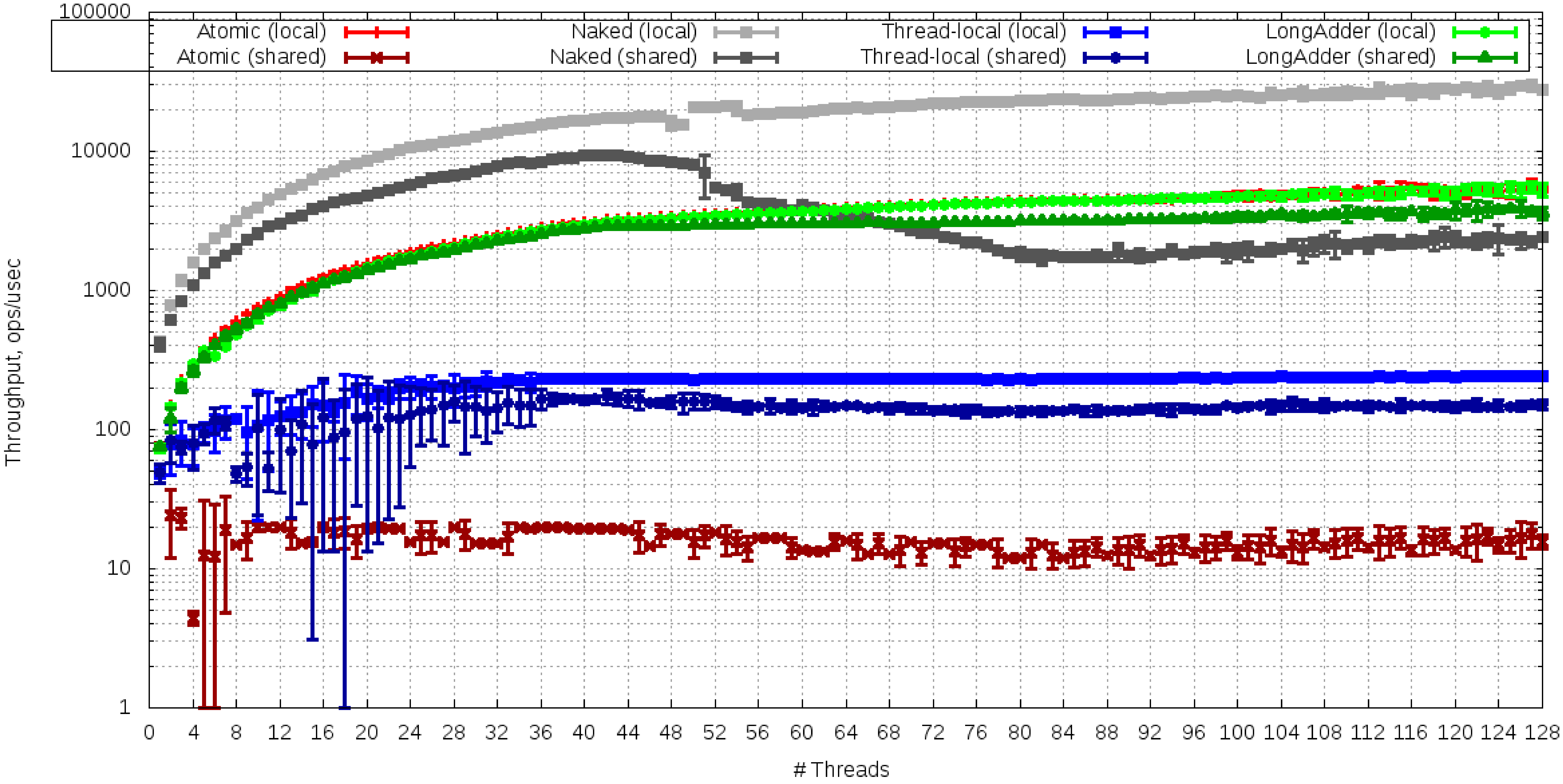
Pitfall #7. Infrastructure Overheads

- 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”

```
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:

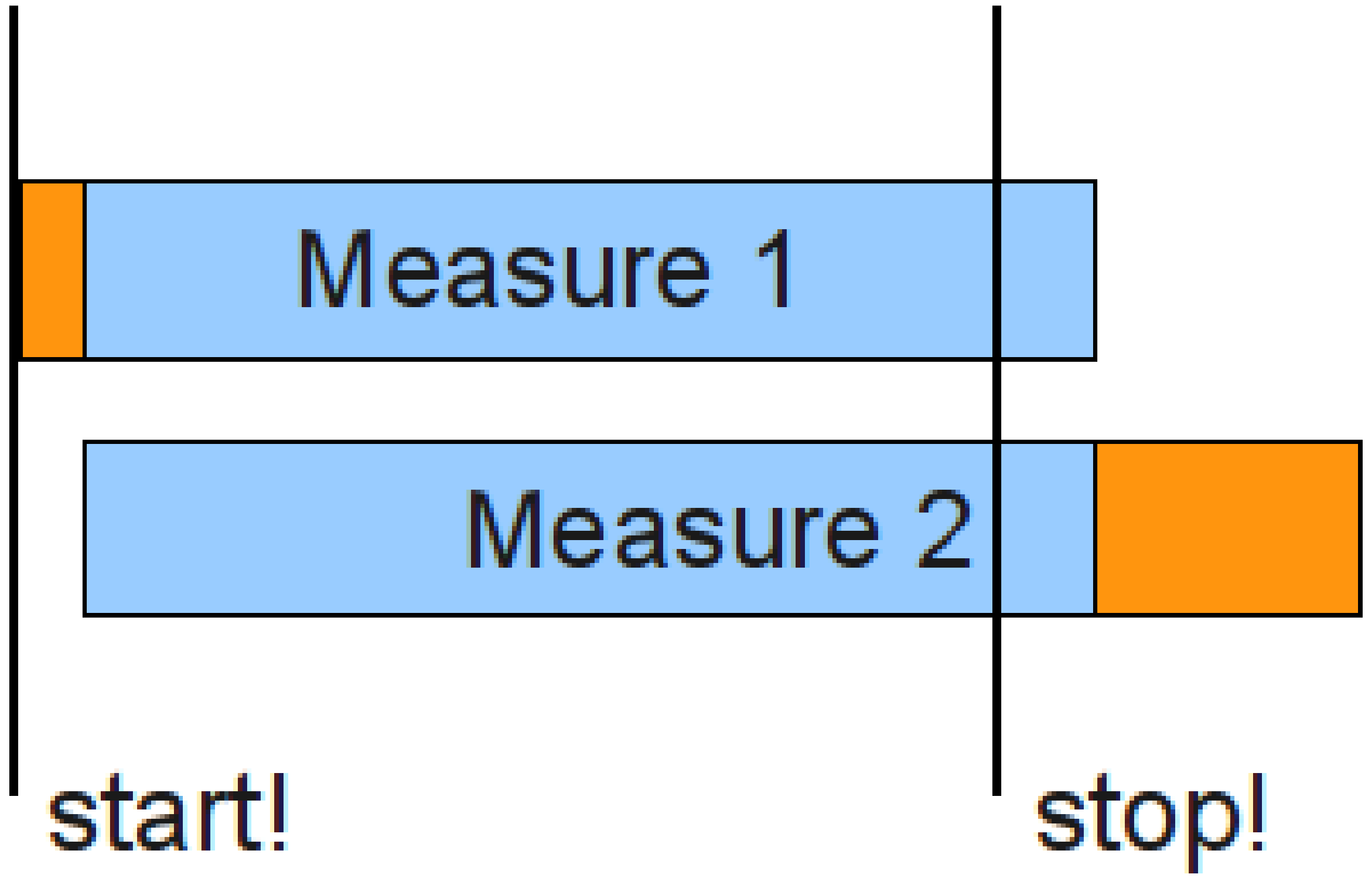
Your test infrastructure is your best friend.

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 realtime 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

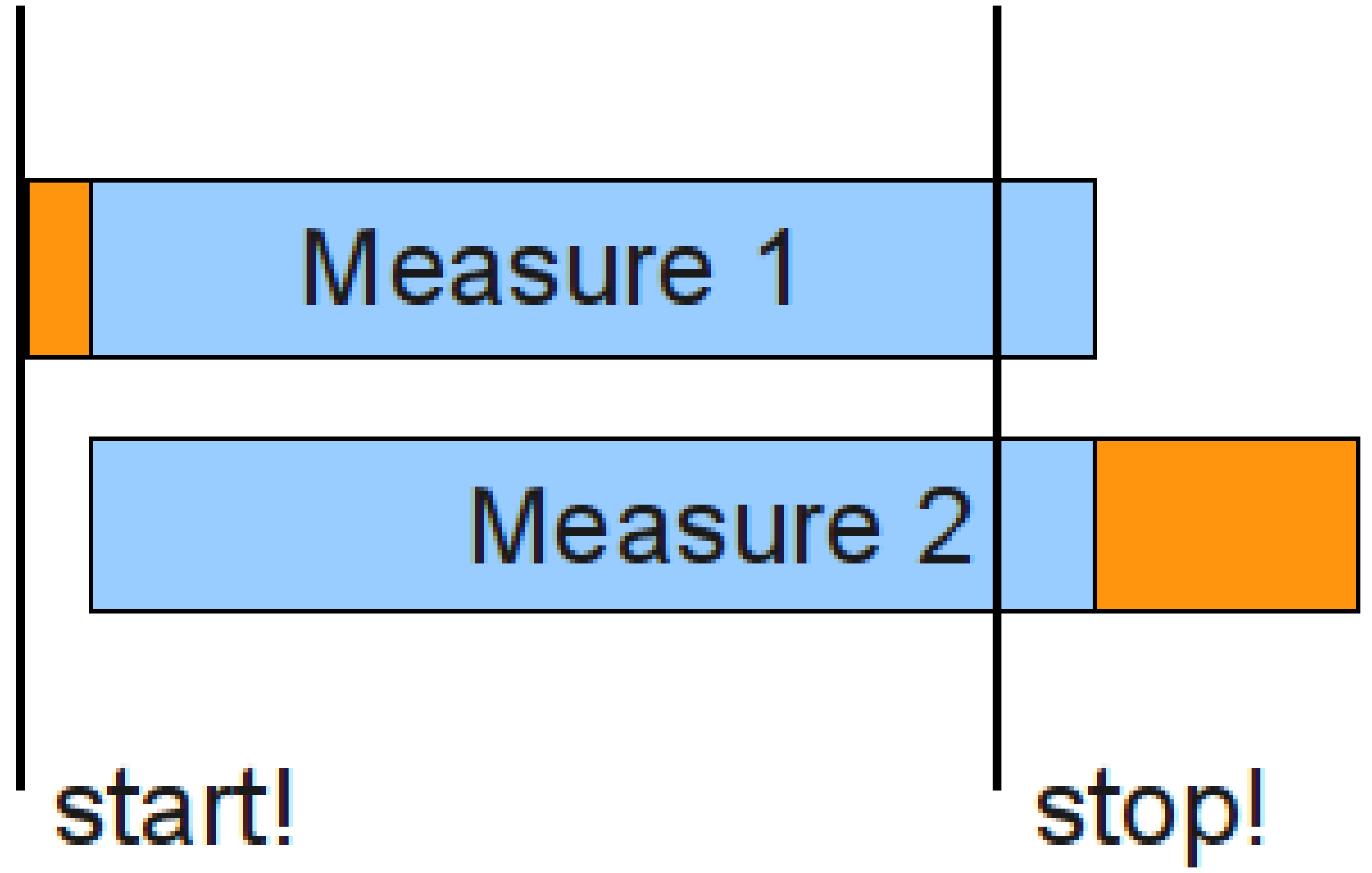


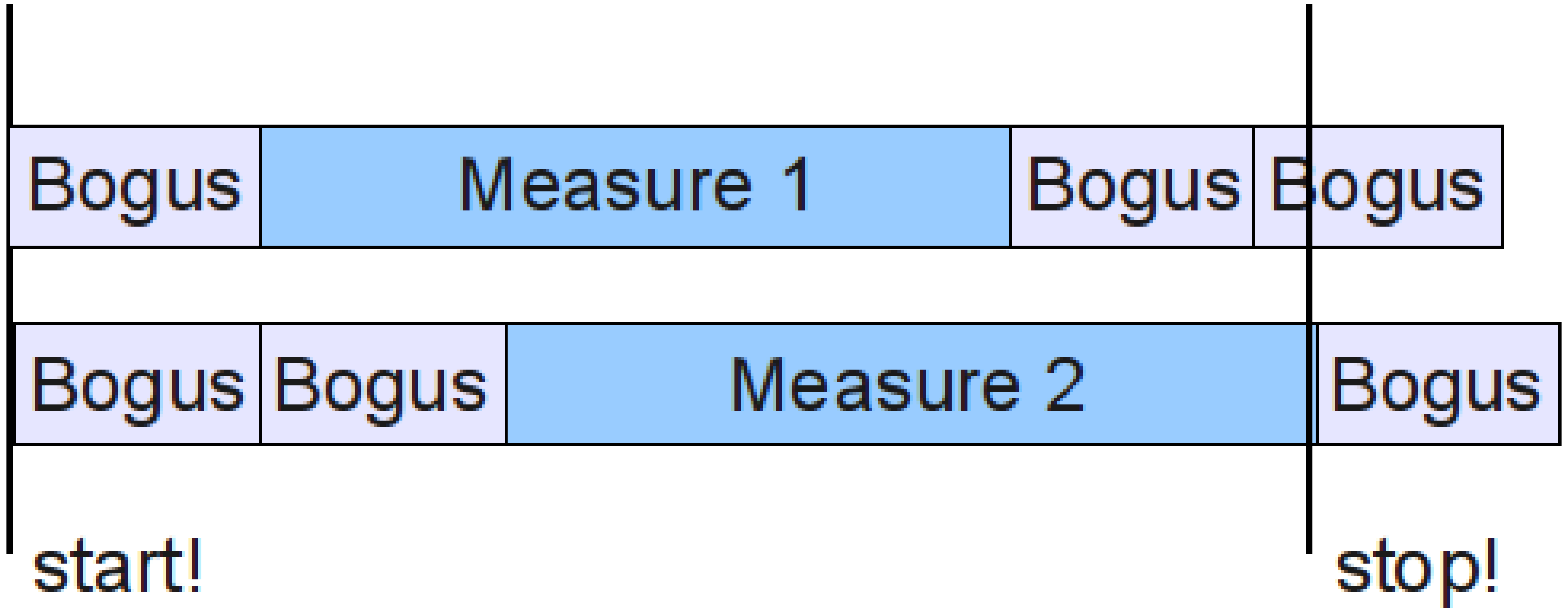
Pitfall #8. Thread Scheduling

- Need to insert bogus iterations
  - Measured parts are always executing as if all the threads are busy
- Simple test
  - Running 24 threads on 24-way host
  - Doing something quite heavy
  - Without bogus iterations

    957 ± 32 ops/min
  - With bogus iterations

    821 ± 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”

```
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!

```
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”

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