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Java Microbenchmark Harness
(the lesser of two evils)

Aleksey Shipilev
aleksey.shipilev@oracle.com, @shipilev

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Intro

Intro: Why would we even listen to this guy?

- ex-«Intel, Apache Harmony performance geek»
- ex-«SPEC tech. representative for Oracle»
- in-«Oracle/OpenJDK performance geek»
- Guilty of:
  1. Lots of shameful internal stuff
  2. SPECjbb2013
  3. Concurrency improvements (e.g. `@Contended`)
  4. Java Concurrency Stress Tests (jcstress)
  5. Java Microbenchmark Harness (jmh)

Intro: Obligatory JVMLS reference

This talk was also well received at JVMLS 2013.

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Basics

Basics: Benchmarks are experiments

- Computer Science $\rightarrow$ Software Engineering
  - Build software to meet functional requirements
  - Mostly don't care about HW and data specifics
  - Abstract and composable, «formal science»
- Software Performance Engineering
  - «Real world strikes back!»
  - Exploring complex interactions between hardware, software, and data
  - Based on empirical evidence, i.e. «natural science»

Basics: Experimental Control

Any experiment requires the control

- Sometimes, just a few baseline measurements
- Sometimes, vast web of support experiments

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- Software-specific: peek under the hood!

Experiments assume the hypothesis (model), against which we do the control

Basics: Common Wisdom

Microbenchmarks are bad

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~~Microbenchmarks are bad~~

Basics: The Root Cause

«Premature optimization
is the root of all evil»
(Khuth, 1974)

Basics: The Root Cause

«~~Premature~~ Optimization
is the root of all evil»
(Shipilev, 2013)

Basics: Evil Optimizations

Optimizations distort the performance models!

- Applied in «common» (>50%) cases
- Unclear interdependencies
- «Black box» abstraction fails big time

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Examples:

- «`new MyObject()`»

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Optimizations distort the performance models!

- Applied in «common» (>50%) cases
- Unclear interdependencies
- «Black box» abstraction fails big time

Examples:

- «`new MyObject()`»: allocated in TLAB? allocated in LOB? scalarized? eliminated?

Basics: Know Thy Optimizations

Understanding the performance model
is the road to awe

- This is the endgame result for benchmarking
- Benchmarking is for exploring the performance models (which also helps to get better at benchmarking)
- Every new optimization $\Rightarrow$ new hassle for everyone

Basics: Benchmarks vs. Optimization

Ground Rule

Benchmarking is the (endless) fight against the optimizations

Collorary

Benchmarking harness #1 priority: managing the optimizations

Basics: JMH

Java Microbenchmark Harness:
`http://openjdk.java.net/projects/code-tools/jmh/`

- Works around pitfalls common to HotSpot/OpenJDK
- Bugs are fixed as VM evolves, or we discover more
- We (perfteam) validate benches by rewriting them with JMH
- Facilitates peer review

Basics: JMH API Sneak Peek

Let users declare the benchmark body:

```
@GenerateMicroBenchmark
public void helloWorld() {
    // do something here
}
```

...then generate lots of supporting synthetic code around that body.

(At this point, simply generating the auxiliary subclass works fine, but it is limiting for some cases)

Basics: Getting the units right

*Benchmarks:

- micro:

Basics: Getting the units right

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- micro: 1...1000 us, single webapp request

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- micro: 1...1000 us, single webapp request
- nano: 1...1000 ns, single operations

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- milli: 1...1000 ms, SPECjvm98, SPECjbb2005
- micro: 1...1000 us, single webapp request
- nano: 1...1000 ns, single operations

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*Benchmarks:

- kilo: > 1000 s, Linpack
- ______: 1...1000 s, SPECjvm2008, SPECjbb2013
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- micro: 1...1000 us, single webapp request
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- micro: 1...1000 us, single webapp request
- nano: 1...1000 ns, single operations
- pico: 1...1000 ps, pipelining

Basics: ...increaseth sorrow

Benchmarks amplify all the effects
visible at the same scale.

- Millibenchmarks are not really hard
- Microbenchmarks are challenging, but OK
- Nanobenchmarks are the damned beasts!
- Picobenchmarks...

Basics: Warmup

Definition

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«Warmup» = waiting for the transient responses to settle down

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- Every online optimization requires warmup

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- JIT compilation is **NOT** the only online optimization

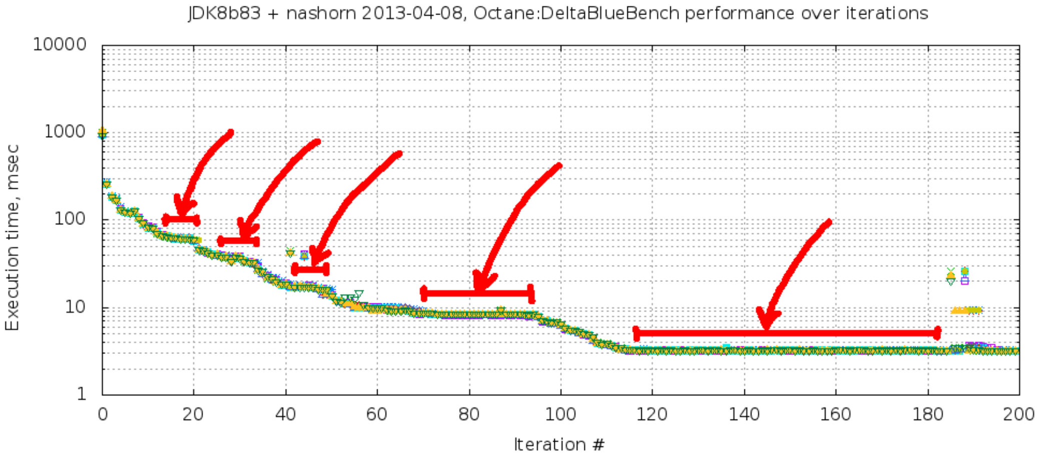
Basics: Warmup

Definition

«Warmup» = waiting for the transient responses to settle down

- Every online optimization requires warmup
- JIT compilation is **NOT** the only online optimization
- Ok, «Watch -XX:+PrintCompilation»?

Basics: Warmup plateaus



Major pitfalls

Major pitfalls: The Goal

The goal for this section is
to scare you away from:

- (blindly) building the benchmark harnesses
- (blindly) trusting the benchmark harnesses
- (blindly) trusting the benchmarks
- (blindly) being generally blind about benchmarks

System: Optimization Quiz (A)

Let us run the empty benchmark.
System reports 4 online CPUs.

Threads	Ops/nsec	Scale
1	3.06 ± 0.10	
2	5.72 ± 0.10	1.87 ± 0.03
4	5.87 ± 0.02	1.91 ± 0.03

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- Question 1: Why no change for $2 \rightarrow 4$ threads?

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- Question 1: Why no change for 2 $\rightarrow$ 4 threads?
- Question 2: Why only 1.87x change for 1 $\rightarrow$ 2 threads?

System: Power management

Running dummy benchmark,
+ Down-clocking to 2.0 GHz

Threads	Ops/nsec	Scale
1	1.97 ± 0.02	
2	3.94 ± 0.05	2.00 ± 0.02
4	4.03 ± 0.04	2.04 ± 0.02

System: Power management

Many subsystems balance power-vs-performance

(Ex.: cpufreq, SpeedStep, Cool&Quiet, TurboBoost)

- **Downside**: breaks the homogeneity of time
- **Remedy**: disable power management, fix CPU clock frequency
- **JMH Remedy**: run longer, do not park threads

System: OS Schedulers

OS schedulers balance affinity-vs-power

(Ex.: Solaris schedulers, Linux power-efficient taskqueues)

- **Downside**: breaks the processing symmetry
- **Remedy**: tight up scheduling policies
- **JMH Remedy**: run longer, do not park threads

System: Time Sharing

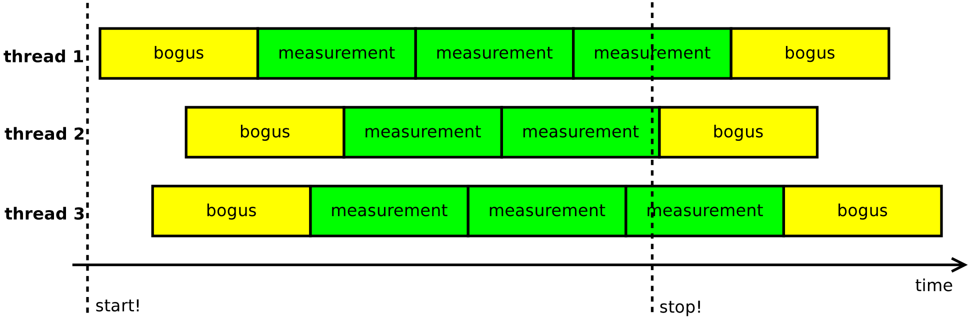
Time sharing systems balance utilization

(Ex.: everywhere)

- **Downside**: thread start/stop is not instantaneous, thread run time is non-deterministic, the load is non-uniform
- **Remedy**: make sure everything runs before measuring
- **JMH Remedy**: «bogus iterations»

System: Time Sharing, #2

JMH provides the remedy – bogus iterations:



System: Time Sharing, Quiz (B)

```
public void measure() {
    long startTime = System.nanoTime();
    while(!isDone) {
        work();
    }
    println(System.nanoTime() - startTime);
}
```

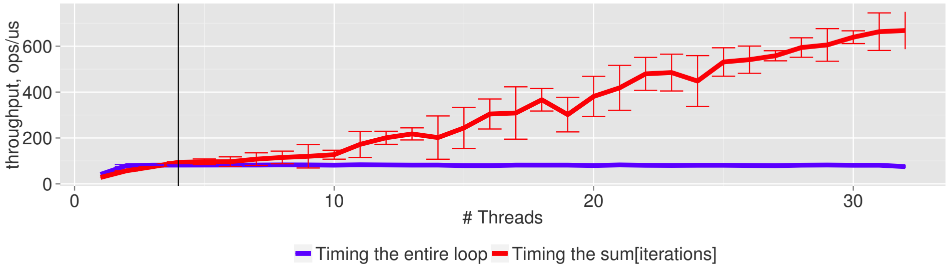

System: Time Sharing, Quiz (B)

«Is there a problem, officer?»

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


System: Time Sharing, Quiz (B)

Measuring the reciprocal throughput via total/iteration time:



The throughput grows past the CPU count – WTF?!

System: Time Sharing, Quiz (B)

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


System: Time Sharing

Time sharing gives the illusion of running multiple threads simultaneously

- **Downside**: this illusion is broken for performance
- **Remedy**: do **NOT** overload the system!
- **JMH Remedy**: big red warning sign

VM: Optimization Quiz (C)

```
@GenerateMicroBenchmark
public void baseline() {
}
```

0.5 ± 0.1 ns

```
@GenerateMicroBenchmark
public void measureWrong() {
    Math.log(x);
}
```

0.5 ± 0.1 ns

```
@GenerateMicroBenchmark
public double measureRight() {
    return Math.log(x);
}
```

34.0 ± 1.0 ns

VM: Dead-code elimination

Compilers are good at eliminating the redundant code.

- **Downside**: can remove (parts of) the benchmarked code
- **Remedy**: consume the results, depend on the results, provide the side effect
- **JMH Remedy**: API support

VM: Avoiding dead-code elimination

DCE is somewhat easy to avoid for primitives:

- Primitives have binary combinators!
- Caveat #1: Combinator cost?
- Caveat #2: Low-range primitives enable speculation (`boolean`)

```
int sum = 0;
for (int i = 0; i < 100; i++) {
    sum += op(i);
}
return sum; // consume in caller
```


VM: Avoiding dead-code elimination

DCE is hard to avoid for references:

- Caveat #1: Fast object combinator, anyone?
- Caveat #2: Need to escape object to limit thread-local optimizations.
- Caveat #3: Publishing the object $\Rightarrow$ reference heap write $\Rightarrow$ store barrier

VM: DCE, Blackholes

JMH provides «Blackholes».
Blackhole consumes the value.

```
class Blackhole {
  void consume(int v) { doMagic(v); }
  void consume(Object o) { doMagic(o); }
}
```

- Returns are implicitly fed into the blackhole
- User can request additional blackhole ⇒ heap writes again, dammit!

VM: Avoiding dead-code elimination, Blackholes

Relatively easy for primitives:

```
class Blackhole {
  static volatile Wrapper NULL;
  volatile int g1 = 1, g2 = 2;

  void consume(int v) {
    if (v == g1 & v == g2) {
      NULL.field = 0; // implicit NPE
    }
  }
}
```


VM: DCE, Blackholes

Harder for references:

```
class Blackhole {
  Object sink;
  int prngState;
  int prngMask;

  void consume(Object v) {
    if ((next(prngState) & prngMask) == 0) {
      sink = v; // store barrier here
      prngMask = (prngMask << 1) + 1;
    }
  }
}
```


VM: Optimization Quiz (D)

```
@GenerateMicroBenchmark
public void baseline() {
}
```

0.5 ± 0.1 ns

```
@GenerateMicroBenchmark
public double measureWrong() {
    return Math.log(42);
}
```

1.0 ± 0.1 ns

```
private double x = 42;
@GenerateMicroBenchmark
public double measureRight() {
    return Math.log(x);
}
```

34.0 ± 1.0 ns

VM: Constant folding, etc.

Compilers are good at partial evaluation[1]

- **Downside**: can remove (parts of) the benchmarked code
- **Remedy**: make the sources unpredictable
- **JMH Remedy**: API support

[1] All right, all right! It is not really *the* PE.

VM: CSE

JMH prevents load commoning across @GMB calls

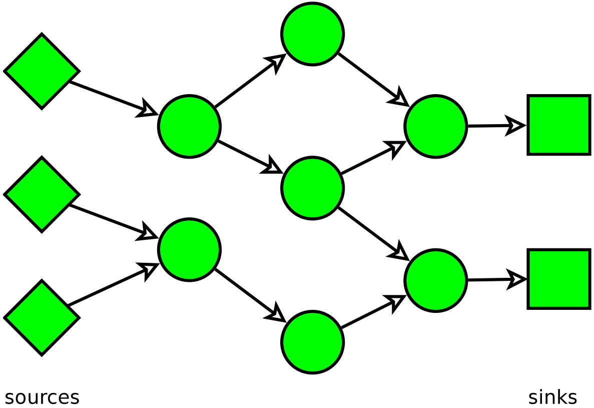
```
double x;

@GenerateMicroBenchmark
double doWork() {
  doStuff(x);
}
```

```
volatile boolean done;
void doMeasure() {
  while (!done) {
    doWork();
  }
}
```

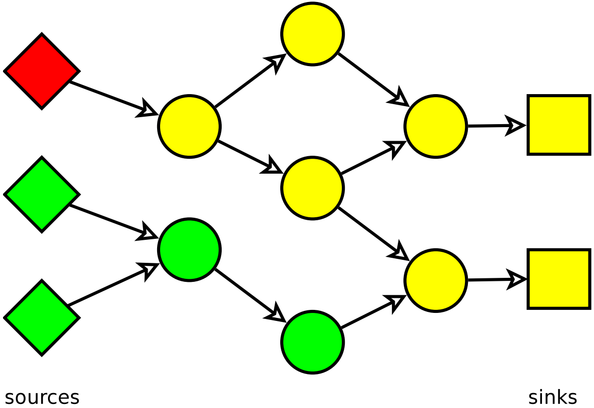
(i.e. read everything from heap $\Rightarrow$ you are good!)

VM: DCE, CSE... Same thing!



Losing either a source or a sink loses the part of the benchmark.
Silently.

VM: DCE, CSE... Same thing!



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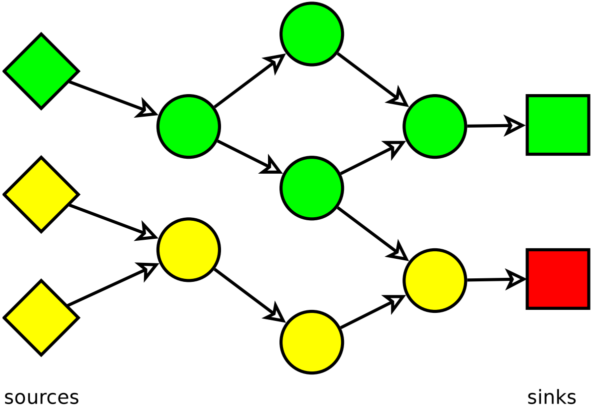


Losing either a source or a sink loses the part of the benchmark.
Silently.

VM: Optimization Quiz (E)

```
// changing N, will performance differ?
static int N = 100;

@GenerateMicroBenchmark
public int test() { return doWork(N); }

int x = 1, y = 2;

private int doWork(int reps) {
  int s = 0;
  for (int i = 0; i < reps; i++)
    s += (x + y);
  return s;
}
```


VM: Optimization Quiz (E), #2

N	ns/call		ns/add	
1	1.5	± 0.1	1.5	± 0.1
10	2.0	± 0.1	0.1	± 0.01
100	2.7	± 0.2	0.05	± 0.02
1000	68.8	± 0.9	0.07	± 0.01
10000	410.3	± 2.1	0.04	± 0.01
100000	3836.1	± 40.6	0.04	± 0.01

VM: Optimization Quiz (E), #2

N	ns/call	ns/add
1	1.5 ± 0.1	1.5 ± 0.1
10	2.0 ± 0.1	0.1 ± 0.01
100	2.7 ± 0.2	0.05 ± 0.02
1000	68.8 ± 0.9	0.07 ± 0.01
10000	410.3 ± 2.1	0.04 ± 0.01
100000	3836.1 ± 40.6	0.04 ± 0.01

Which one to believe?

0.04 ns/add $\Rightarrow$ 25 adds/ns $\Rightarrow$ GTFO!

VM: Loop unrolling

Loop unrolling greatly expands
the scope of optimizations

- **Downside**: assume the single loop iteration is M ns. After unrolling the effective cost is αM ns, where $\alpha \in [0; +\infty)$
- **Remedy**: avoid unrollable loops, limit the effect of unrolling
- **JMH Remedy**: proper handling for CSE/DCE nils loop unrolling effects

VM: Optimization Quiz (F)

```
interface M {
  void inc();
}

abstract class AM implements M {
  int c;
  void inc() {
    c++;
  }
}

class M1 extends AM {}
class M2 extends AM {}
```


VM: Optimization Quiz (F), #2

```
M m1 = new M1();
M m2 = new M2();

@GenerateMicroBenchmark
public void testM1() { test(m1); }

@GenerateMicroBenchmark
public void testM2() { test(m2); }

void test(M m) {
    for (int i = 0; i < 100; i++)
        m.inc();
}
```


VM: Optimization Quiz (F), #3

test	ns/op
testM1	4.6 ± 0.1
testM2	36.0 ± 0.4

VM: Optimization Quiz (F), #3

test	ns/op
`testM1`	4.6 ± 0.1
`testM2`	36.0 ± 0.4
repeat `testM1`	35.8 ± 0.4

VM: Optimization Quiz (F), #3

test	ns/op
`testM1`	4.6 ± 0.1
`testM2`	36.0 ± 0.4
repeat `testM1`	35.8 ± 0.4
forked `testM1`	4.5 ± 0.1
forked `testM2`	4.5 ± 0.1

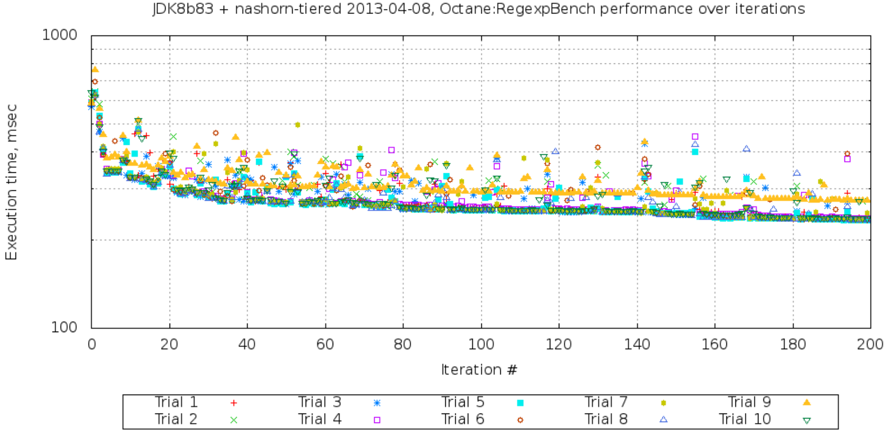
VM: Profile feedback

Dynamic optimizations
can use runtime information

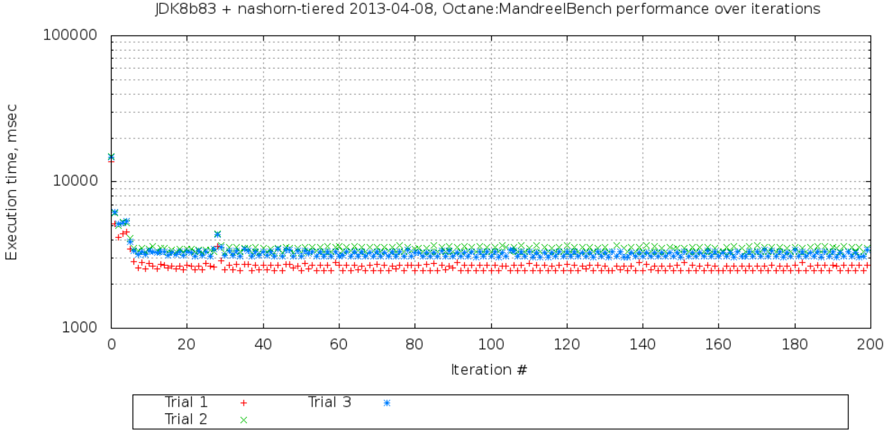
(Ex.: call profile, type profile, CHA info)

- **Downside**: Big difference in running multiple benchmarks, or a single benchmark in the VM
- **Remedy**: Warmup all benchmarks together; OR fork the JVMs
- **JMH Remedy**: Bulk warmup support; forking

VM: Optimization Quiz (G)



VM: Optimization Quiz (G), #2



VM: Run-to-run variance

Many scalable algos are inherently non-deterministic!

(Ex.: memory allocators, profiler counters, non-fair locks, concurrent data structures, some other intelligent tricks up our sleeve...)

- **Downside**: (potentially) (devastatingly) large run-to-run variance
- **Remedy**: replays withing every subsystem, multiple JVM runs
- **JMH Remedy**: multiple forks

VM: Inlining budgets

Inlining is the über-optimization

- **Downside**: You can not inline everything ⇒ subtle inlining budget considerations
- **Remedy**: Smaller methods, smaller loops, examining -XX:+PrintInlining, forcing inlining
- **JMH Remedy**: Generated code peels potentially hot loops, user-friendly `@CompileControl`

VM: Inlining example

Small hot method: inlining budget starts here.

```
public void testLong_loop
    (Loop loop, Result r, MyBenchmark bench) {
  long ops = 0;
  r.start = System.nanoTime();
  do {
    bench.testLong(); // @GenerateMicroBenchmark
    ops++;
  } while(!loop.isDone);
  r.end = System.nanoTime();
  r.ops = ops;
}
```


CPU: Optimization Quiz (H)

```
@State
public class TreeMapBench {
  Map<String, String> map = new TreeMap<>();

  @Setup
  public void setup() { populate(map); }

  @GenerateMicroBenchmark
  public void test(BlackHole bh) {
    for(String key : map.keySet()) {
      String value = map.get(key);
      bh.consume(value);
    }
  }
}
```


CPU: Optimization Quiz (H), #2

```
@GenerateMicroBenchmark
public void test(BlackHole bh) {
  for(String key : map.keySet()) {
    String value = map.get(key);
    bh.consume(value);
  }
}
```

	Exclusive	Shared
Throughput, op/sec	615 ± 12	828 ± 21

CPU: Optimization Quiz (H), #2

```
@GenerateMicroBenchmark
public void test(BlackHole bh) {
  for(String key : map.keySet()) {
    String value = map.get(key);
    bh.consume(value);
  }
}
```

	Exclusive	Shared
Throughput, op/sec	615 ± 12	828 ± 21
Threads	4	4

CPU: Optimization Quiz (H), #2

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public void test(BlackHole bh) {
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Throughput, op/sec	615 ± 12	828 ± 21
Threads	4	4
Maps	4	1

CPU: Optimization Quiz (H), #2

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@GenerateMicroBenchmark
public void test(BlackHole bh) {
    for(String key : map.keySet()) {
        String value = map.get(key);
        bh.consume(value);
    }
}
```

	Exclusive	Shared
Throughput, op/sec	615 ± 12	828 ± 21
Threads	4	4
Maps	4	1
Footprint, Kb	1024	256

CPU: Cache capacity

DRAM memory is too far and too slow.
Cache the hottest stuff on-die SRAM cache!

- **Downside**: Remarkably different performance for memory accesses, depending on your luck
- **Remedy**: Track the memory footprint; multiple experiments with different problem sizes; shared/distinct data for the worker threads
- **JMH Remedy**: `@State` scopes

CPU: Optimization Quiz (I)

How scalable is this?

```
@State(Scope.Benchmark) class Shared {
  final int[] c = new int[64];
}

@State(Scope.Thread) class Local {
  static final AtomicInteger COUNTER = ...;
  final int index = COUNTER.incrementAndGet();
}

@GenerateMicroBenchmark
void work(Shared s, Local l) {
  s.c[l.index]++;
}
```


CPU: Optimization Quiz (I), #2

Threads	Average ns/call	Hit
1	2.0 ± 0.1	
2	18.5 ± 2.4	9x
4	32.9 ± 6.2	16x
8	85.4 ± 13.4	42x
16	208.9 ± 52.1	104x
32	464.2 ± 46.1	232x

Why?

CPU: Bulk method transfers

Memory subsystem tracks data in cache-line quantums.
Cache lines are 32, 64, 128 bytes long.

- **Downside**: the dense inter-thread accesses are hard on memory subsystem (false sharing)
- **Remedy**: padding, subclass juggling, `@Contended`
- **JMH Remedy**: control structures are heavily padded, auto-padding for `@State`

CPU: Optimization Quiz (J)[2]

Exhibit B.	Exhibit P.

<pre>int sum = 0;
for (int x : a) {
   if (x < 0) {
      sum -= x;
   } else {
      sum += x;
   }
}
return sum;</pre>
	<pre>int sum = 0;
	for (int x : a) {
	   sum += Math.abs(x);
	}
	return sum;</pre>

Which one is faster?

[2]Credits: Sergey Kuksenko (@kuksenk0)

CPU: Optimization Quiz (J)

E. Branched	E. Predicated

<pre>L0: mov   0xc(%ecx,%ebp,4),%ebx
    test %ebx,%ebx
    jl   L1
    add   %ebx,%eax
    jmp   L2
L1: sub   %ebx,%eax
L2: inc   %ebp
    cmp   %edx,%ebp
    jl   L0</pre>
	<pre>L0: mov 0xc(%ecx,%ebp,4),%ebx
	    mov %ebx,%esi
	    neg %esi
	    test %ebx,%ebx
	    cmovl %esi,%ebx
	    add %ebx,%eax
	    inc %ebp
	    cmp %edx,%ebp
	    jl Loop</pre>

Which one is faster?

CPU: Optimization Quiz (J)

Regular Pattern = (+, −)*

	NHM	Bldzr	C-A9[3]	SNB
branch_regular	0.9	0.8	5.0	0.5
branch_shuffled	6.2	2.8	9.4	1.0
branch_sorted	0.9	1.0	5.0	0.6
predicated_regular	2.0	1.0	5.3	0.8
predicated_shuffled	2.0	1.0	9.3	0.8
predicated_sorted	2.0	1.0	5.7	0.8

time, nsec/op

[3] Using client compiler

CPU: Branch Prediction

Out-of-Order engines speculate a lot.
Most of the time (99%+) correct!

- **Downside**: Vastly different performance when speculation fails
- **Remedy**: Realistic data! Multiple diverse datasets

Conclusion

Conclusion: not as simple as it sounds

You should be scared by now!

Resist the urge to:

- believe the pleasant results
- reject the unpleasant results
- write the throw-away benchmarks
- write the «generic» benchmark harnesses
- believe the fancy reports and beautiful APIs
- trust the code

Conclusion: Benchmarking is serious

More rigor is never a bad thing!

- The intuition is almost always wrong (unless you rock)
- Never trust anything (unless checked before)
- Ever challenge everything (especially these slides)
- Embrace failure (especially your failures)
- Grind your teeth, and redo the tests (especially yours)

Conclusion: Things on list to do

JMH does one thing and does it right:
gets you less «back to square one» moments

Other things to improve usability:

- Java API (in progress)
- Bindings to reporters (in progress)
- Bindings to the other JVM languages
- `@Param`-eters

Thanks!

Conclusion: But wait...

Conclusion: Alternative Evil

Don't do any performance assessments at all

You should already know why it is far worse.
...right?

Thanks!

