Microbenchmarking on the JVM with JMH

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Agenda

- Definitions
  How to measure performance? What is benchmarking?
- Problem
  Why are benchmarks on the JVM hard?
- Solution
  Introduction to the Java Microbenchmarking Harness (JMH)

How to Determine Performance?

Lots of approaches, for example:

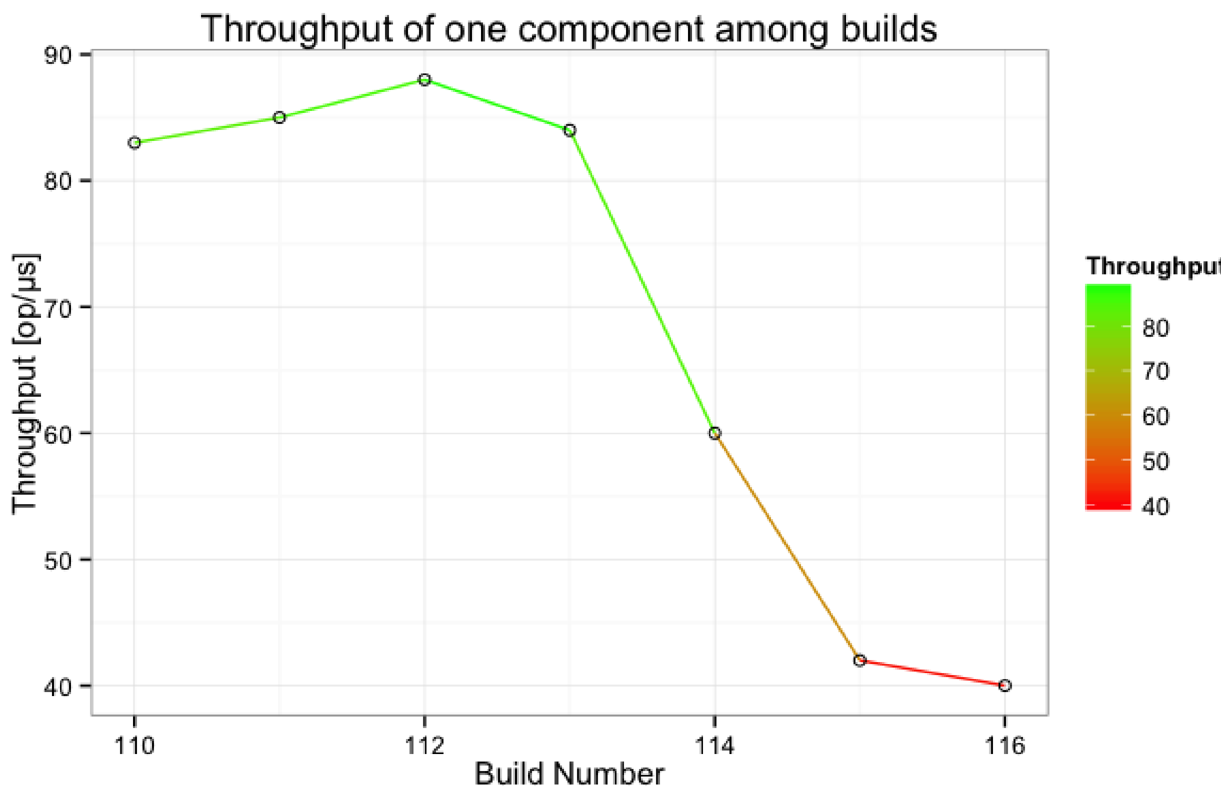
- Analysis
  to determine performance characteristics of a system upfront (e.g. Big-O notation)
- Profiling
  to find bottlenecks in a system
- Benchmarking
  to compare the relative performance of systems

Benchmark Scopes

- Macrobenchmark
  An entire system (application level)
- Microbenchmark
  A single component
- (Mesobenchmark)

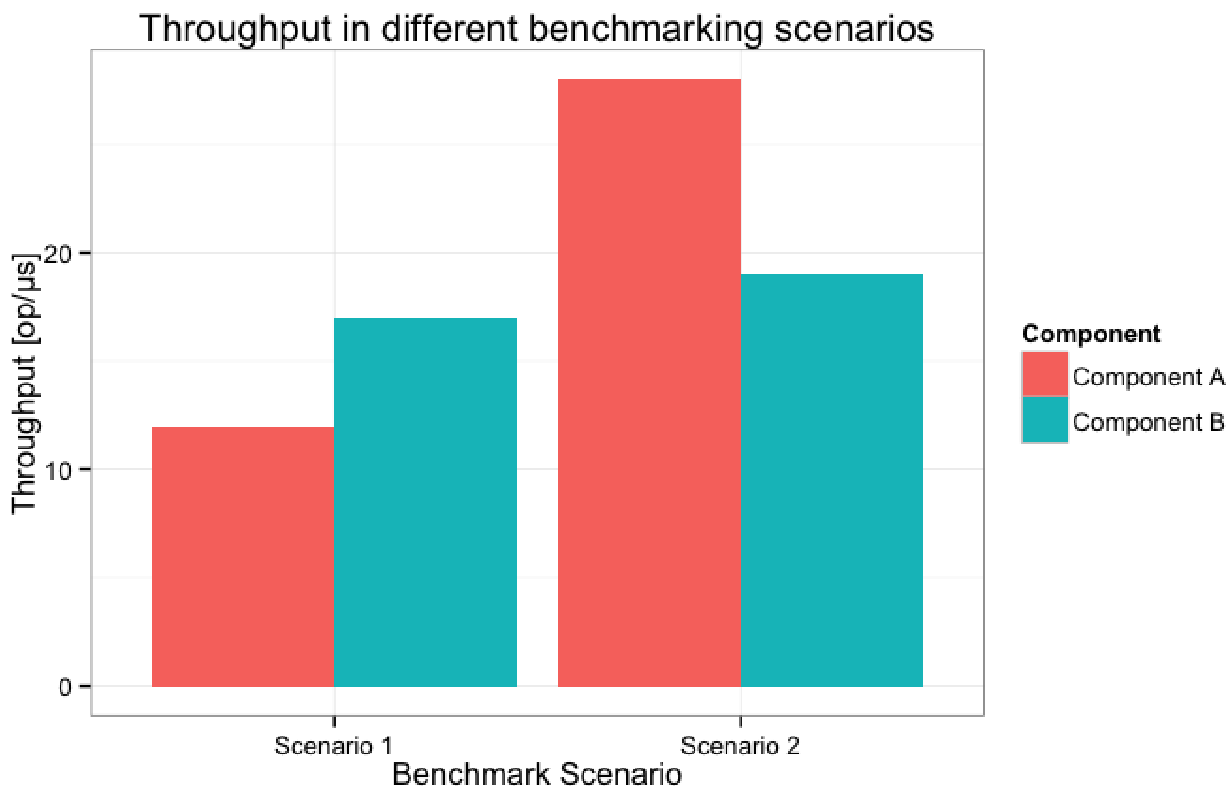
Purpose of Benchmarking

Find performance regressions in *critical* components.



Purpose of Benchmarking

Compare alternative implementations or system configurations



Purpose of Benchmarking

Ultimate purpose: Derive a performance model for a component

- Understand why a component behaves performance-wise in certain way
- Understand which "knobs" you can turn

Writing Benchmarks is Easy...

Example: How long does it take to calculate the sum of an array?

```java
public class SumBenchmark {
  public static double sum(double[] array) {
    double total = 0.0d;
    for (int i = 0; i < array.length; i++) {
      total += array[i];
    }
    return total;
  }
}
```

Writing Benchmarks is Easy...

```java
public class SumBenchmark {
  private static final int BATCH_SIZE = 15000;

  public static double sum(double[] array) { /* ... */ }

  private static void benchmarkSum(double[] array) {
    long start = System.nanoTime();
    for (int j = 0; j < BATCH_SIZE; j++) {
      sum(array);
    }
    long stop = System.nanoTime();
    System.out.printf("Computation finished in %d ns.%n",
                                      ((stop - start) / BATCH_SIZE));
  }

  public static void main(String[] args) { /* ... */ }
}
```

Writing Benchmarks is Easy...

Benchmarking Scenario: Benchmark with 10.000 array elements

```
public class SumBenchmark {
  private static final int BATCH_SIZE = 15000;

  public static double sum(double[] array) { /* ... */ }

  private static void benchmarkSum(double[] array) { /* ... */ }

  public static void main(String[] args) {
    double[] array = new double[10000];
    // initialize array with some values
    for (int i = 0; i < array.length; i++) {
      array[i] = (double)i;
    }
    // perform actual benchmark
    for (int iteration = 0; iteration < 10; iteration++) {
      benchmarkSum(array);
    }
  }
```

Writing Benchmarks is Easy…
… except when it's not

```
Computation finished in 11561 ns.
Computation finished in 447 ns.
Computation finished in 0 ns.
Computation finished in 0 ns.
[...]
Computation finished in 0 ns.
```

0 ns? Really?

What happened?

Rerun with `-XX:+PrintCompilation`

```
[...]
123     7     name.mit[...].SumBenchmark::sum (24 bytes)
127     1 %   name.mit[...].SumBenchmark::sum @ 4 (24 bytes)
293     2 %   name.mit[...].SumBenchmark::benchmarkSum @ 6 (51 bytes)
306     8     java.lang.String::indexOf (166 bytes)
Computation finished in 11561 ns.
313     9     name.mit[...].SumBenchmark::benchmarkSum (51 bytes)
319     2 %   name.mit[...].SumBenchmark::benchmarkSum @ -2 (51 bytes) made not entrant
Computation finished in 447 ns.
Computation finished in 0 ns.
Computation finished in 0 ns.
[...]
Computation finished in 0 ns.
```

The JIT compiler kicks in and eliminates the benchmark loop

Dead Code Elimination - A Closer Look

```
private static void benchmarkSum(double[] array) {
  long start = System.nanoTime();
  for (int j = 0; j < BATCH_SIZE; j++) {
    // (1) The return value is never used, let's eliminate the call
    sum(array);
  }
  long stop = System.nanoTime();
  System.out.printf("Computation finished in %d ns.%n",
                                   ((stop - start) / BATCH_SIZE));
}
```

Only illustrative: HotSpot may implement this differently

Dead Code Elimination - A Closer Look

```
private static void benchmarkSum(double[] array) {
  long start = System.nanoTime();
  for (int j = 0; j < BATCH_SIZE; j++) {
  // (2) The loop body is empty, let's eliminate the loop
  }
  long stop = System.nanoTime();
  System.out.printf("Computation finished in %d ns.%n",
                                  ((stop - start) / BATCH_SIZE));
}
```

Only illustrative: HotSpot may implement this differently

Dead Code Elimination - A Closer Look

```
private static void benchmarkSum(double[] array) {
  long start = System.nanoTime();
  //(3) Huh, were is the benchmark?
  long stop = System.nanoTime();
  System.out.printf("Computation finished in %d ns.%n",
                                  ((stop - start) / BATCH_SIZE));
}
```

Some Sources of Pitfalls

- JIT-Compiler
  Implements dozens of optimizations
- Garbage Collector
  Runs at unpredictable times
- Operating System/JVM
  Different implementations will have different performance characteristics
- CPU
  Singlecore vs. Multicore
- Tons of problems you haven't even considered
  False sharing and other cache effects, timer accuracy, CPU's C-states, branch prediction and many more

Haunted by Cliff Click

“Without exception every microbenchmark I've seen has had serious flaws. Except those I've had a hand in correcting.”

Java Microbenchmarking Harness

- Best practices are baked in
  Avoids lots of flaws of handwritten microbenchmarks; still no silver bullet
- Batteries included
  Supports different metrics (called "benchmark modes"), multithreaded tests, parameterized benchmarks, multiple language bindings (Scala, Groovy, Kotlin), etc.
- Open source; developed by experts
  OpenJDK subproject (maintainers: Aleksey Shipilëv and Sergey Kuksenko from Oracle)
- De-facto standard
  Used by JDK developers, growing user base outside of Oracle (e.g. Netty, Reactor, Azul)

Microbenchmarking Best Practices

- Warmup
  JMH performs multiple warmup iterations before actual measurement iterations
- Mitigate Energy Saving Settings
  JMH benchmarks run multiple iterations and do not park benchmarking threads to keep the CPU busy
- Compiler optimizations
  JMH provides support to avoid or control compiler optimizations
- Run-to-run variance
  JMH creates multiple JVM forks; variance is reported ("score error")

Hello JMH

```
import org.openjdk.jmh.annotations.Benchmark;

public class HelloJMHMicroBenchmark {
  @Benchmark
  public void benchmarkRuntimeOverhead() {
    //intentionally left blank
  }
}
```

Generating HelloJMHMicroBenchmark

- Run `mvn clean install` or `gradle shadow`
- JMH generates a benchmark class for each method annotated with `@Benchmark` using its annotation processors
- Run the self-contained JAR

Running HelloJMHMicroBenchmark

```
# Run progress: 0,00% complete, ETA 00:06:40
[...]
# Fork: 1 of 10
# Warmup Iteration   1: 1442257053,080 ops/s
[...]
# Warmup Iteration  20: 436917769,398 ops/s
Iteration   1: 1462176825,349 ops/s
Iteration   2: 1431427218,067 ops/s
[...]

# Run complete. Total time: 00:08:06

Benchmark                                 Mode   Samples          Score  Score error    Un
n.m.b.j.H.benchmarkRuntimeOverhead       thrpt       200 1450534078,416 29308551,722    op
```

Benchmarking Array Sum with JMH

```java
import org.openjdk.jmh.annotations.*;

@State(Scope.Benchmark)
public class SumBenchmark {
  private double[] values;

  @Setup
  public void setup() {
    this.values = new double[10000];
    for (int i = 0; i < values.length; i++) {
      values[i] = (double)i;
    }
  }

  @Benchmark
  public double calculateSum() {
    return sum(values);
  }
}
```

Running SumBenchmark

```
# Run progress: 0,00% complete, ETA 00:06:40
# Warmup: 20 iterations, 1 s each
# Measurement: 20 iterations, 1 s each
# Threads: 1 thread, will synchronize iterations
# Benchmark mode: Throughput, ops/time
# Benchmark: name.mitterdorfer.benchmark.jmh.SumBenchmark.calculateSum
[...]
# Fork: 1 of 10
# Warmup Iteration   1: 89162,938 ops/s
# Warmup Iteration   2: 91655,330 ops/s
[...]
# Run complete. Total time: 00:08:04

Benchmark                                Mode  Samples      Score  Score error  Units
n.m.b.j.SumBenchmark.calculateSum       thrpt      200  92684,491      395,882  ops/s
```

Score based on array size (10.000 elements). Use `@OperationsPerInvocation` to normalize the reported throughput if needed.

Complex Microbenchmarks with JMH

- `@State`
  Annotate benchmark state scoped to the benchmark, a single benchmark thread or a benchmark group
- `@Threads`
  Execute multithreaded microbenchmarks
- `@CompilerControl`
  Offers limited control over the JIT compiler's behavior (e.g. inlining of a specific method)
- Profilers
  Pluggable profilers to observe microbenchmark behavior, e.g. gc, comp, perf

For more information please study the official JMH samples.

Microbenchmark Limitations

Microbenchmarks are not the solution to every performance problem:

- Don't generalize the results of a microbenchmark
  Measure different workloads; Measure in an environment as close as possible to production
- Don't optimize a component blindly based on a microbenchmark result
  You might be looking in the wrong spot; use profilers to determine bottlenecks

Summary

- Microbenchmarks are hard
  The JIT compiler, the OS and the CPU are trying to fool you
- JMH helps a lot
  JMH has the hard problems covered but you can still screw things up. Think whether the results are plausible.
- Microbenchmarks have their limitations
  Think in a broader context: Are the results are applicable at all in your situation?

More Information

- JMH project page: http://openjdk.java.net/projects/code-tools/jmh
- Aleksey Shipilëv's Blog: http://shipilev.net/

- My Blog: http://daniel.mitterdorfer.name
- Code: https://github.com/danielmitterdorfer/benchmarking-talk

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