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?

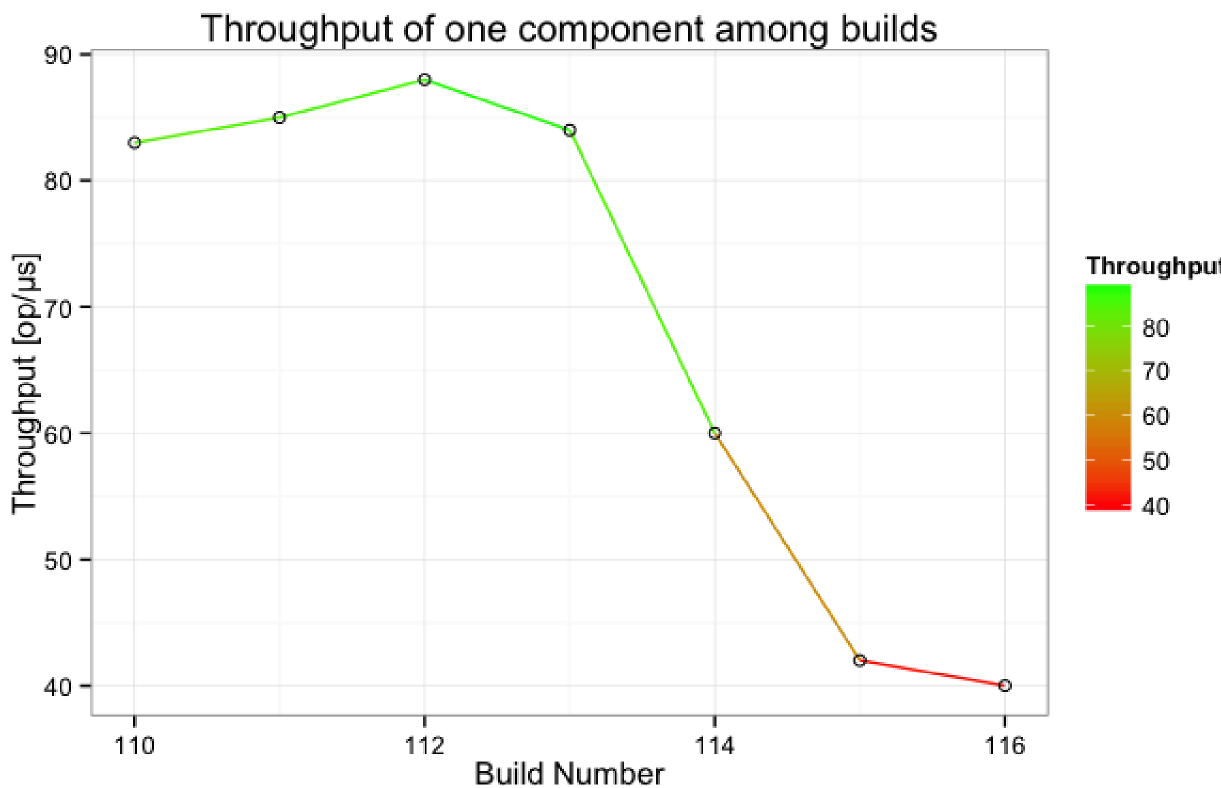
- Analysis
  to determine performance characteristics of a system upfront (e.g. Big-O notation)
- Profiling
  to find bottlenecks in a system
- Benchmarking
  to compare the relative performance of systems

Benchmark Scopes

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

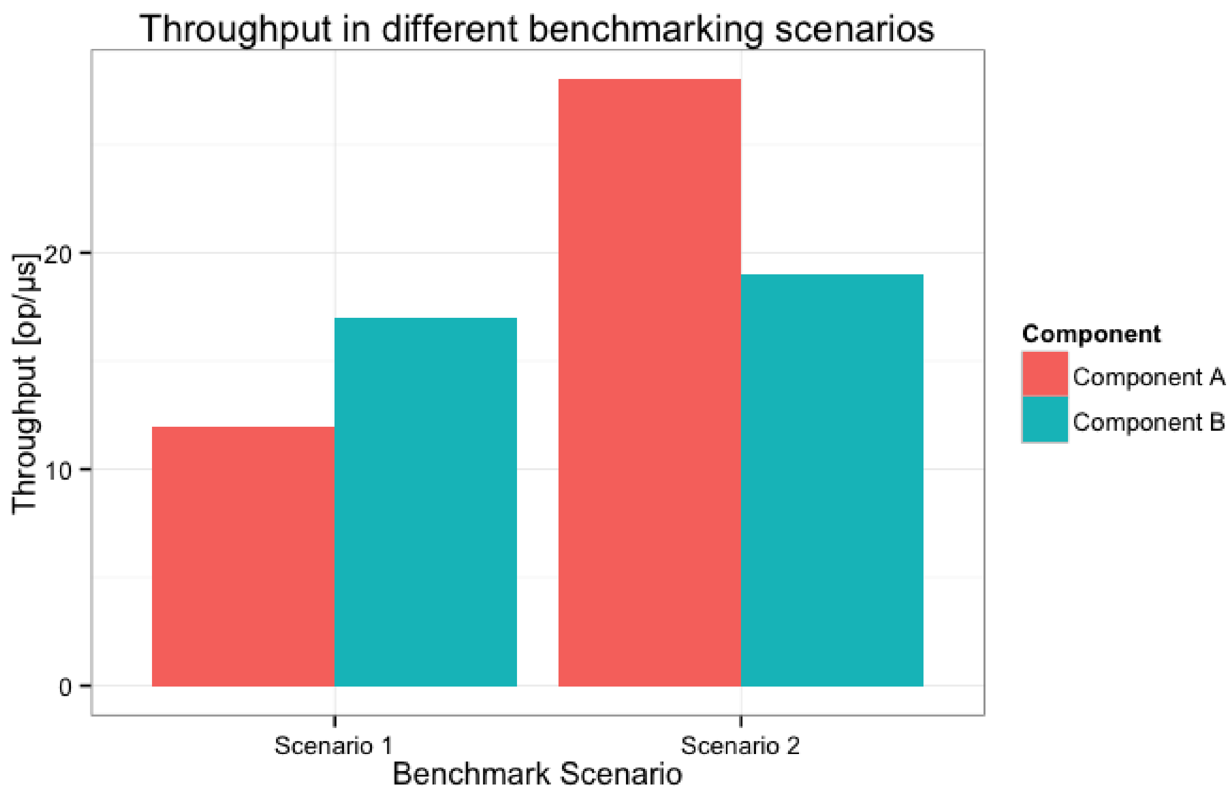
Purpose of Benchmarking

Find performance regressions in *critical* components.



Purpose of Benchmarking

Compare alternative implementations or system configurations



Purpose of Benchmarking

Understand the low-level behavior of system components

Purpose of Benchmarking

Ultimate purpose: Derive a performance model for a component

Writing Benchmarks is Easy...

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

```
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...

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

  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_SIZ
  }
}
```

Writing Benchmarks is Easy...

Benchmarking Scenario: Benchmark with 10.000 array elements

```
public class SumBenchmark {
  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);
    }
  }
}
```

… 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 byt
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 by
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
    sum(array);
  }
  long stop = System.nanoTime();
  System.out.printf("Computation finished in %d ns.%n",
                                ((stop - start) / BATCH_SIZ
}
```

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_SIZ
}
```

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_SIZ
}
```

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 hello() {
    //intentionally left blank
  }
}
```

Generating HelloJMHMicroBenchmark

- `mvn clean install`
- `@Benchmark` annotated method => one benchmark class
- 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
n.m.b.j.H.hello       thrpt       200 1450534078,416 29308551,722
```

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 calcSum() {
    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.calcSu
[...]
# 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 e
n.m.b.j.SumBenchmark.calcSum   thrpt      200  92684,491       395
```

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

Complex Microbenchmarks with JMH

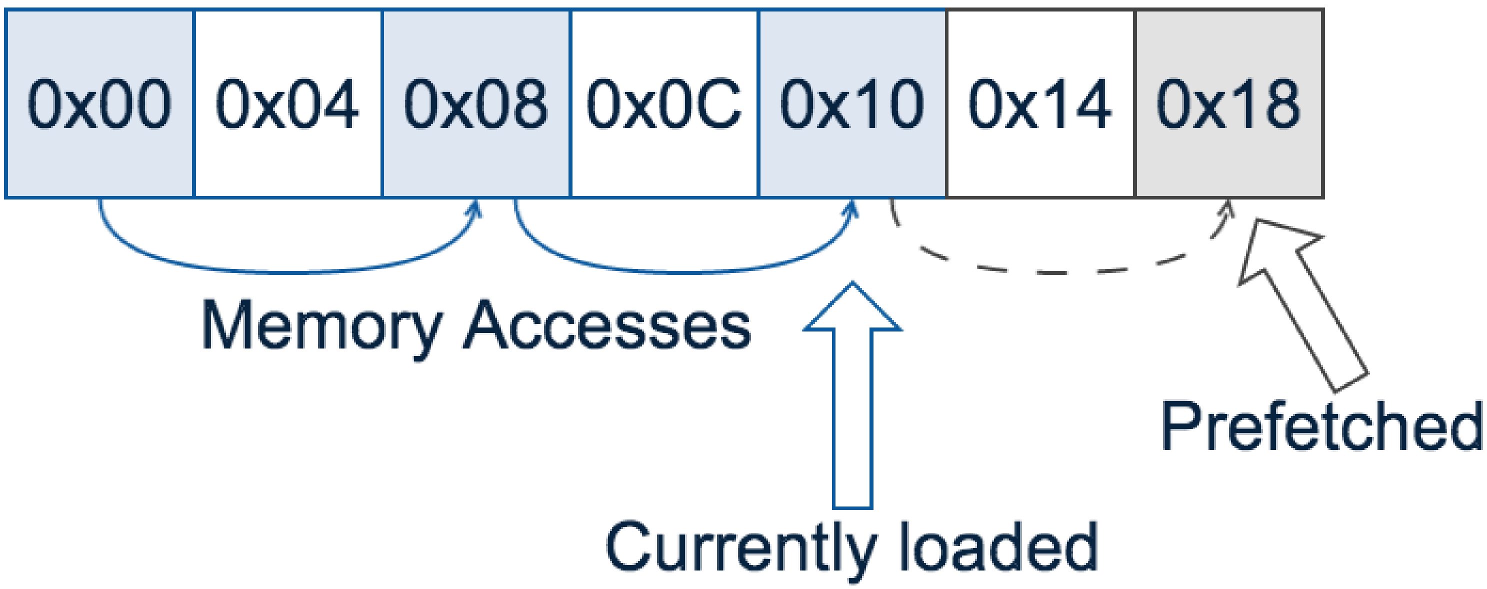
- `@State`
  Annotate benchmark state scoped to the benchmark, a single benchmark thread or a benchmark group
- `@Threads`
  Execute multithreaded microbenchmarks
- `@CompilerControl`
  Offers limited control over the JIT compiler's behavior (e.g. inlining of a specific method)
- Profilers
  Pluggable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

For more information please study the official JMH samples.

Case Study: JMH `perf` profiler

Prefetching Unit

CPU speculatively loads data based on memory access patterns

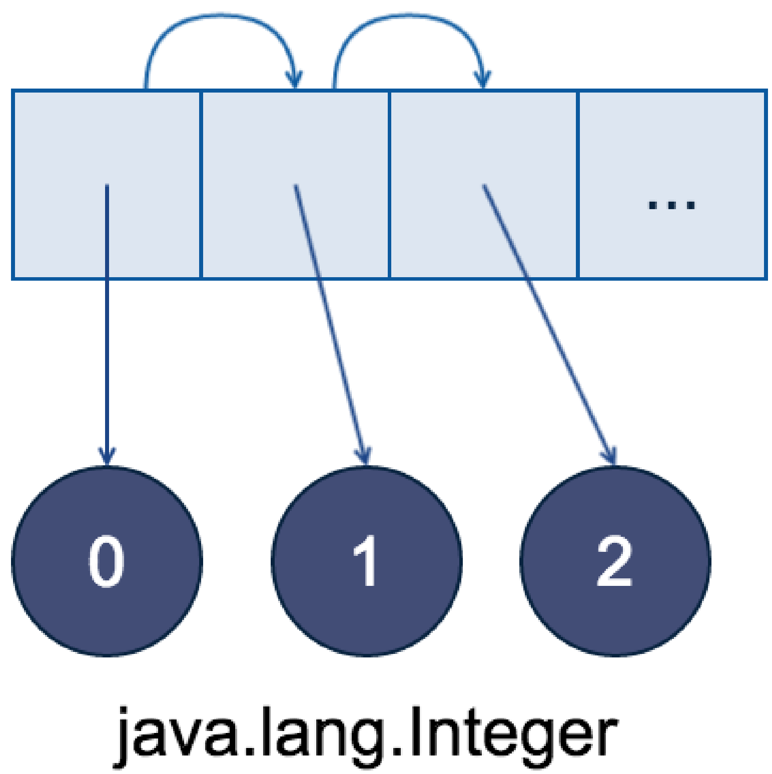


Contenders: `int[]`

Contiguous array: Linear memory access pattern for traversal:

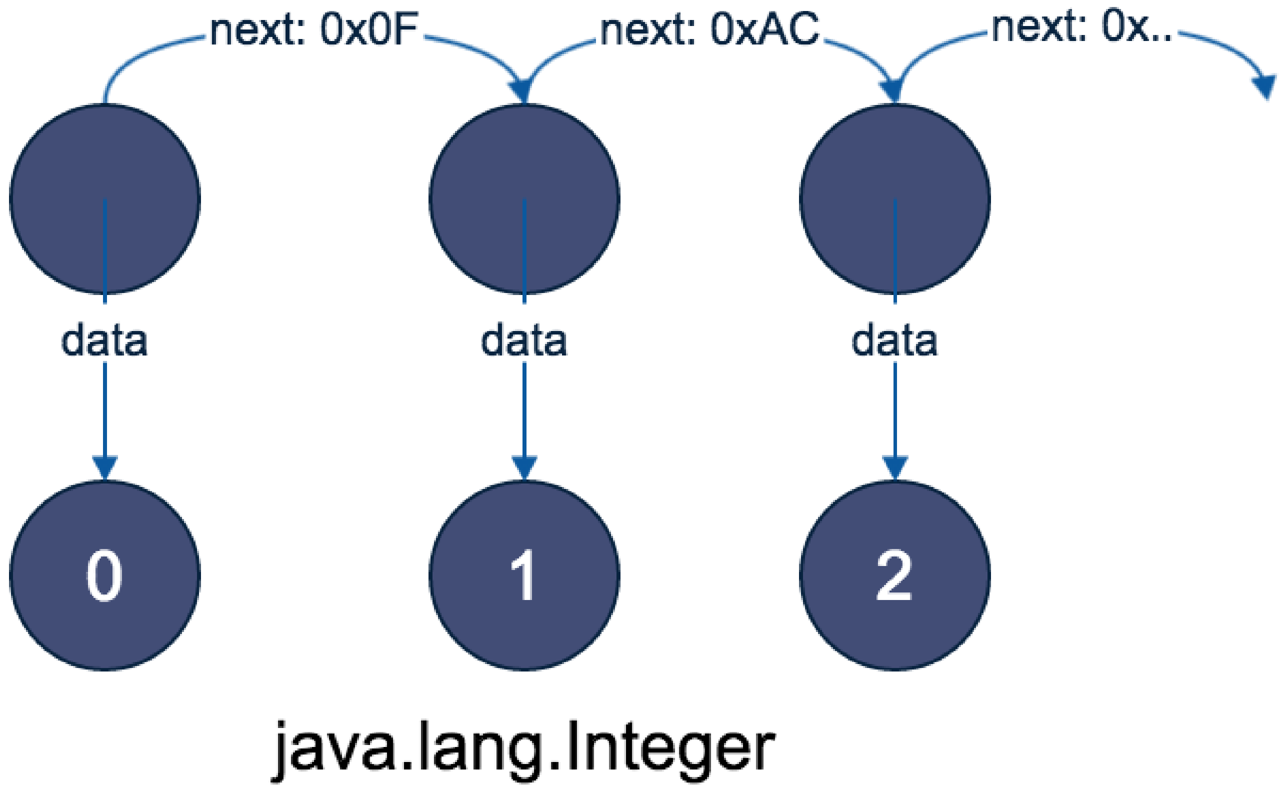
Contenders: `ArrayList`

Linear memory access pattern for array traversal; pointer chasing for elements:



Contenders: `LinkedList`

Nonlinear memory access pattern for traversal and elements:



Experiment Setup

- Task: Calculate the sum of all elements

Benchmark: Setup
`LinkedList`

```java
@State(Scope.Benchmark)
public class PointerChasingBenchmark {
  @Param({"1024", "2048", "4096", "8192", "16384", "32768"})
  public int problemSize;

  private final List<Integer> linkedList = new LinkedList<>();

  @Setup
  public void setUp() {
      for (int idx = 0; idx < problemSize; idx++) {
          linkedList.add(idx);
      }
  }
  // ...
}
```

Note: the other setup methods are identical except for their type

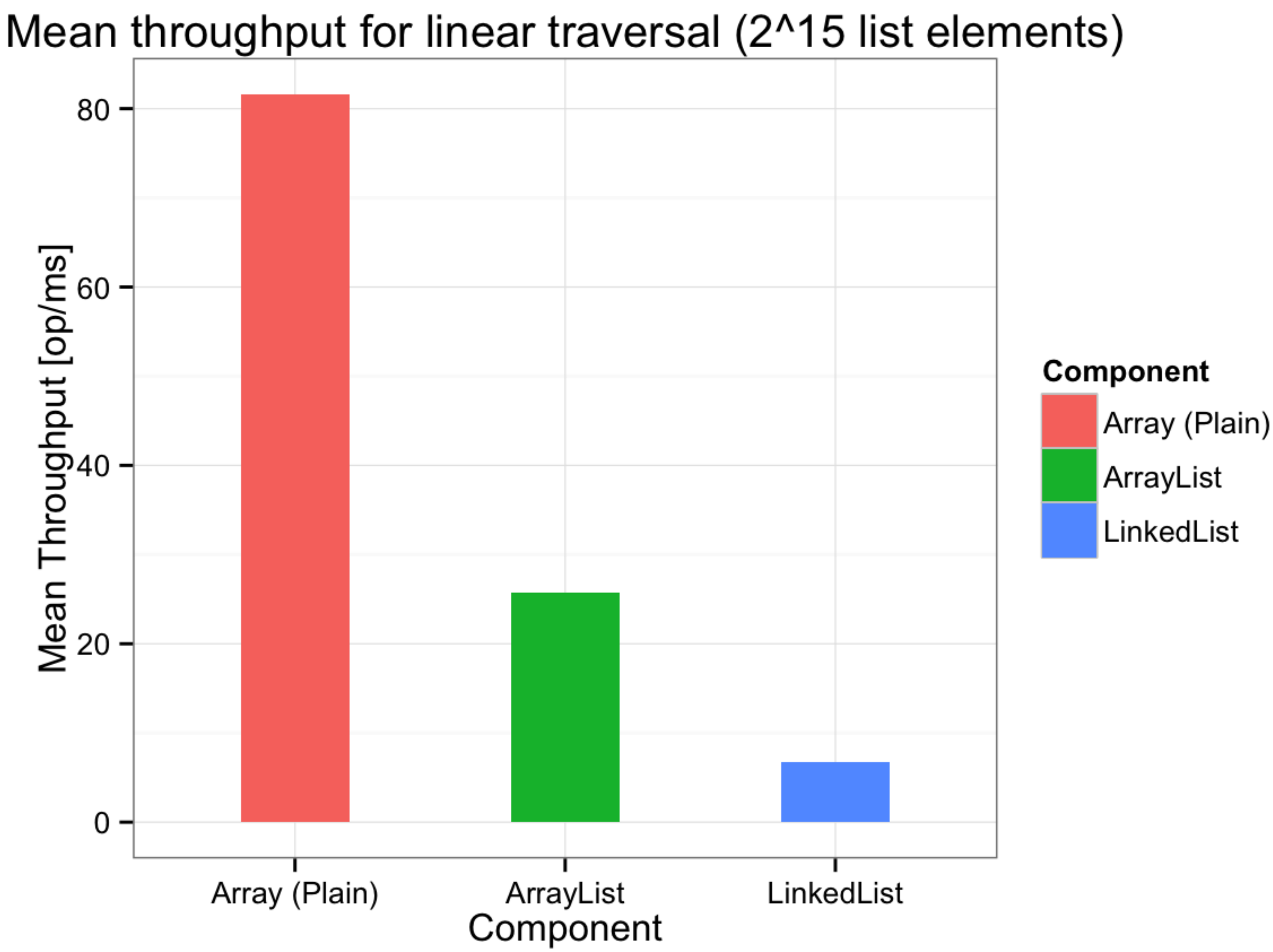
Benchmark: `LinkedList`

```
@State(Scope.Benchmark)
public class PointerChasingBenchmark {
  // .. Setup ..

  @Benchmark
  public long sumLinkedList() {
    long sum = 0;
    for (int val : linkedList) {
      sum += val;
    }
    return sum;
  }
}
```

Note: the other benchmark methods are identical except for their type

Results


Mean throughput for linear traversal (2^15 list elements)
Mean Throughput [op/ms]
80
60
40
20
0
Array (Plain)
ArrayList
LinkedList
Component
Component
Array (Plain)
ArrayList
LinkedList

Why the difference?

Read CPU performance monitoring data with JMH's `perf` profiler

Metric	`int[]`	`ArrayList`	`LinkedList`
L1-dcache-loads	$61 * 10^9$	$58 * 10^9$	$21 * 10^9$
L1-dcache-load-misses (relative to L1 cache hits)	6 %	10 %	22 %

Conclusion

Pointer indirection renders prefetching ineffective

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 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

Slides

http://bit.ly/javaland-benchmarking

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