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# "Quantum" Performance Effects

*v 2.0; November 2013*


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MAKE THE FUTURE JAVA

Java

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# Intro

# Intro: performance engineering

1. 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"

2. Performance Engineering
   - "Real world strikes back!"
   - Exploring complex interactions between hardware, software, and data
   - Based on empirical evidence, i.e. «natural science»

# Intro: what's the difference?

architecture vs microarchitecture

# Intro: what's the difference?

## architecture vs microarchitecture

x86
AMD64(x86-64/Intel64)
ARMv7
....

Nehalem
Sandy Bridge
Bulldozer
Bobcat
Cortex-A9

# Intro: SUTs[1]

- Intel® Core™ i5-520M (Westmere) [↓2.0 GHz] 1x2x2
  - Ubuntu 10.04 (32-bit)
  - Xubuntu 12.04 (64-bit)

[1] System Under Test


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# Intro: SUTs[1]

- Intel® Core™ i5-520M (Westmere) [↓2.0 GHz] 1x2x2
  - Ubuntu 10.04 (32-bit)
  - Xubuntu 12.04 (64-bit)

- Intel® Core™ i5-3320M (Ivy Bridge) [↓2.0 GHz] 1x2x2
  - Ubuntu 13.10 (64-bit)

- Samsung Exynos 4412, ARMv7 (Cortex-A9) [1.6 GHz] 1x4x1
  - Linaro 12.11

[1] System Under Test


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# Intro: SUTs (cont.)

- AMD Opteron™ 4274HE (Bulldozer/Valencia) [2.5 GHz] 2x8x1
  - Oracle Linux Server release 6.0 (64-bit)

- Intel® Xeon® CPU E5-2680 (Sandy Bridge) [2.70 GHz] 2x8x2
  - Oracle Linux Server release 6.3 (64-bit)

# Intro: JVM

- OpenJDK version "1.8.0-ea-lambda" build 83, 32-bits
- OpenJDK version "1.8.0-ea-lambda" build 83, 64-bits
- OpenJDK version "1.8.0-ea" build 116, 64-bits
- Java HotSpot(tm) Embedded "1.8.0-ea-b79"

https://jdk8.java.net/download.html

# Intro: Demo code

`https://github.com/kuksenko/quantum`



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# Intro: Required

JMH (Java Microbenchmark Harness)

- http://openjdk.java.net/projects/code-tools/jmh/
- Shipilëv A., “JMH: The Lesser of Two Evils”
- http://shipilev.net/pub/#benchmarking


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# Core

# demo1: double sum

```
private double[] A = new double[2048];

@GenerateMicroBenchmark
public double test1() {
    double sum = 0.0;
    for (int i = 0; i < A.length; i++) {
        sum += A[i];
    }
    return sum;
}

@GenerateMicroBenchmark
public double testManualUnroll() {
    double sum = 0.0;
    for (int i = 0; i < A.length; i += 4) {
        sum += A[i] + A[i + 1] + A[i + 2] + A[i + 3];
    }
    return sum;
}
```


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# demo1: double sum

```java
private double[] A = new double[2048];

@GenerateMicroBenchmark
public double test1() {
    double sum = 0.0;
    for (int i = 0; i < A.length; i++) {
        sum += A[i];
    }
    return sum;
}

@GenerateMicroBenchmark
public double testManualUnroll() {
    double sum = 0.0;
    for (int i = 0; i < A.length; i += 4) {
        sum += A[i] + A[i + 1] + A[i + 2] + A[i + 3];
    }
    return sum;
}
```

327 ops/msec

699 ops/msec



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# demo1: looking into asm, test1

```
loop: addsd   0x10(%edi,%eax,8),%xmm0
      addsd   0x18(%edi,%eax,8),%xmm0
      addsd   0x20(%edi,%eax,8),%xmm0
      addsd   0x28(%edi,%eax,8),%xmm0
      addsd   0x30(%edi,%eax,8),%xmm0
      addsd   0x38(%edi,%eax,8),%xmm0
      addsd   0x40(%edi,%eax,8),%xmm0
      addsd   0x48(%edi,%eax,8),%xmm0
      addsd   0x50(%edi,%eax,8),%xmm0
      addsd   0x58(%edi,%eax,8),%xmm0
      addsd   0x60(%edi,%eax,8),%xmm0
      addsd   0x68(%edi,%eax,8),%xmm0
      addsd   0x70(%edi,%eax,8),%xmm0
      addsd   0x78(%edi,%eax,8),%xmm0
      addsd   0x80(%edi,%eax,8),%xmm0
      addsd   0x88(%edi,%eax,8),%xmm0
      add     $0x10,%eax
      cmp     %ebx,%eax
      jl      loop:
```


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# demo1: looking into asm, testManualUnroll

```
loop: movsd   %xmm0,0x20(%esp)
      movsd   0x48(%eax,%edx,8),%xmm0
      movsd   %xmm0,(%esp)
      movsd   0x40(%eax,%edx,8),%xmm0
      movsd   %xmm0,0x8(%esp)
      movsd   0x78(%eax,%edx,8),%xmm0
      addsd   0x70(%eax,%edx,8),%xmm0
      movsd   0x80(%eax,%edx,8),%xmm1
      movsd   %xmm1,0x10(%esp)
      movsd   0x88(%eax,%edx,8),%xmm1
      movsd   %xmm1,0x18(%esp)
      movsd   0x38(%eax,%edx,8),%xmm4
      addsd   0x30(%eax,%edx,8),%xmm4
      movsd   0x58(%eax,%edx,8),%xmm5
      addsd   0x50(%eax,%edx,8),%xmm5
      movsd   0x28(%eax,%edx,8),%xmm1
      movsd   0x60(%eax,%edx,8),%xmm2
```

```
movsd   0x68(%eax,%edx,8),%xmm3
movsd   0x20(%eax,%edx,8),%xmm7
movsd   0x18(%eax,%edx,8),%xmm6
addsd   0x10(%eax,%edx,8),%xmm6
addsd   0x10(%esp),%xmm0
addsd   %xmm7,%xmm6
addsd   0x18(%esp),%xmm0
addsd   %xmm1,%xmm6
addsd   %xmm2,%xmm5
addsd   0x20(%esp),%xmm6
addsd   %xmm3,%xmm5
addsd   0x8(%esp),%xmm4
addsd   (%esp),%xmm4
addsd   %xmm4,%xmm6
addsd   %xmm6,%xmm5
addsd   %xmm5,%xmm0
add     $0x10,%edx
cmp     %ebx,%edx
jl      loop:
```



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# demo1: measure time

```
private double[] A = new double[2048];
@GenerateMicroBenchmark
@BenchmarkMode(Mode.AverageTime)
@OperationsPerInvocation(2048)
public double test1() {
    double sum = 0.0;
    for (int i = 0; i < A.length; i++) {
        sum += A[i];
    }
    return sum;
}
@GenerateMicroBenchmark
@BenchmarkMode(Mode.AverageTime)
@OperationsPerInvocation(2048)
public double testManualUnroll() {
    double sum = 0.0;
    for (int i = 0; i < A.length; i += 4) {
        sum += A[i] + A[i + 1] + A[i + 2] + A[i + 3];
    }
    return sum;
}
```



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# demo1: measure time

```
private double[] A = new double[2048];
@GenerateMicroBenchmark
@BenchmarkMode(Mode.AverageTime)
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public double test1() {
    double sum = 0.0;
    for (int i = 0; i < A.length; i++) {
        sum += A[i];
    }
    return sum;
}
@GenerateMicroBenchmark
@BenchmarkMode(Mode.AverageTime)
@OperationsPerInvocation(2048)
public double testManualUnroll() {
    double sum = 0.0;
    for (int i = 0; i < A.length; i += 4) {
        sum += A[i] + A[i + 1] + A[i + 2] + A[i + 3];
    }
    return sum;
}
```

1.5 nsec/op

0.7 nsec/op



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# demo1: measure time

```
private double[] A = new double[2048];
@GenerateMicroBenchmark
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public double test1() {
    double sum = 0.0;
    for (int i = 0; i < A.length; i++) {
        sum += A[i];
    }
    return sum;
}
@GenerateMicroBenchmark
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public double testManualUnroll() {
    double sum = 0.0;
    for (int i = 0; i < A.length; i += 4) {
        sum += A[i] + A[i + 1] + A[i + 2] + A[i + 3];
    }
    return sum;
}
```

1.5 nsec/op

CPI = ~2.5

0.7 nsec/op

CPI = ~0.6



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# $\mu$Arch: x86

## CISC vs RISC

# $\mu$Arch: x86

## CISC and RISC

**modern x86 CPU is not what it seems**

All instructions (CISC) are dynamically translated into RISC-like microoperations ($\mu$ops).



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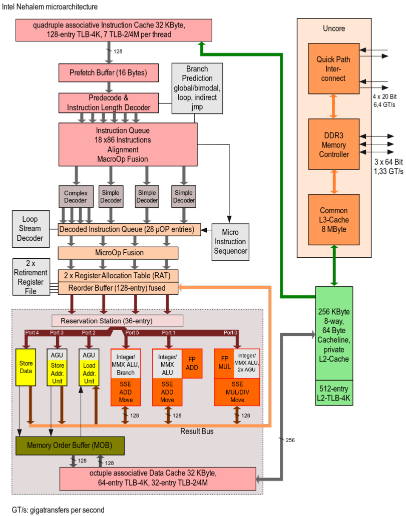
# μArch: Nehalem internals



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# $\mu$Arch: simplified scheme




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# $\mu$Arch: looking into instruction tables

| Instrustion | Latency | $\frac{1}{Throughput}$ |
|---|---|---|
| ADDSP r,r | 3 | 1 |
| MULSD r,r | 5 | 1 |
| ADD/SUB r,r | 1 | 0.33 |
| MUL/IMUL r,r | 3 | 1 |

# demo1: test1, looking into asm again

```
loop: addsd   0x10(%edi,%eax,8),%xmm0
      addsd   0x18(%edi,%eax,8),%xmm0
      addsd   0x20(%edi,%eax,8),%xmm0
      addsd   0x28(%edi,%eax,8),%xmm0
      addsd   0x30(%edi,%eax,8),%xmm0
      addsd   0x38(%edi,%eax,8),%xmm0
      addsd   0x40(%edi,%eax,8),%xmm0
      addsd   0x48(%edi,%eax,8),%xmm0
      addsd   0x50(%edi,%eax,8),%xmm0
      addsd   0x58(%edi,%eax,8),%xmm0
      addsd   0x60(%edi,%eax,8),%xmm0
      addsd   0x68(%edi,%eax,8),%xmm0
      addsd   0x70(%edi,%eax,8),%xmm0
      addsd   0x78(%edi,%eax,8),%xmm0
      addsd   0x80(%edi,%eax,8),%xmm0
      addsd   0x88(%edi,%eax,8),%xmm0
      add     $0x10,%eax
      cmp     %ebx,%eax
      jl      loop:
```

**1.5 nsec/op**
**$\sim$ 3 clk/op**
**unroll by 16**
**19 insts**
**CPI $\sim$ 2.5**


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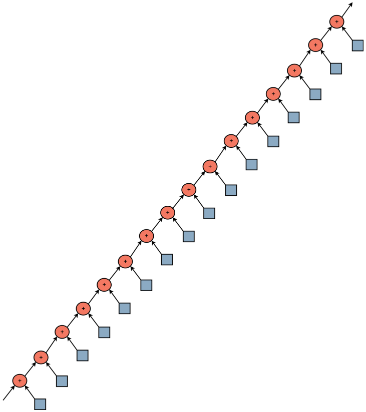
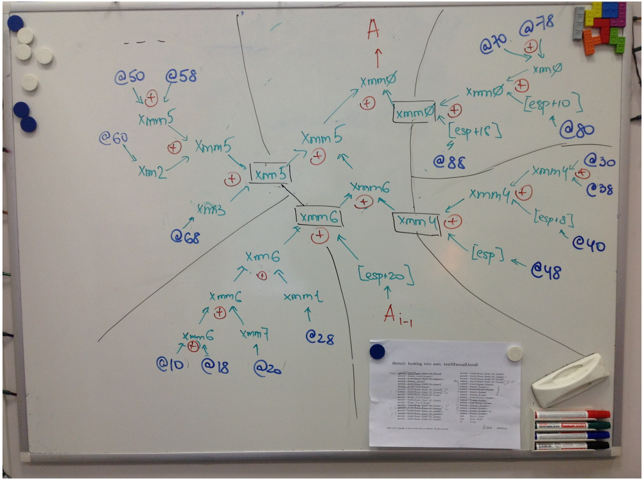
# demo1: test1, other view

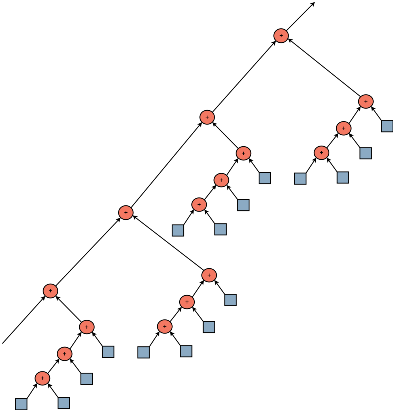


1.5 nsec/op
$\sim$ 3 clk/op
unroll by 16
19 insts
CPI $\sim$ 2.5

# demo1: testManualUnroll



# demo1: testManualUnroll, other view




0.7 nsec/op
$\sim$ 1.4 clk/op
unroll by 4x4
36 insts
CPI $\sim$ 0.6



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# $\mu$Arch: Dependencies

~~Performance~~ ILP[1] of many programs is limited by natural data dependencies.

[1] Instruction Level Parallelism

# $\mu$Arch: Dependencies

~~Performance~~ ILP[1] of many programs is limited by natural data dependencies.

**What to do?**

Break the Dependency Chains!

[1] Instruction Level Parallelism



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# demo1 back: breaking chains in a “right” way

# demo1 back: breaking chains in a “right” way

```
...
for (int i = 0; i < A.length; i++) {
    sum += A[i];
}
return sum;
```

# demo1 back: breaking chains in a “right” way

```
...
for (int i = 0; i < A.length; i++) {
    sum += A[i];
}
return sum;

...
for (int i = 0; i < A.length; i += 2) {
    sum0 += A[i];
    sum1 += A[i + 1];
}
return sum0 + sum1;
```

# demo1 back: breaking chains in a “right” way

```
...
for (int i = 0; i < A.length; i++) {
    sum += A[i];
}
return sum;

...
for (int i = 0; i < A.length; i += 2) {
    sum0 += A[i];
    sum1 += A[i + 1];
}
return sum0 + sum1;

...
for (int i = 0; i < array.length; i += 4) {
    sum0 += A[i];
    sum1 += A[i + 1];
    sum2 += A[i + 2];
    sum3 += A[i + 3];
}
return (sum0 + sum1) + (sum2 + sum3);
```

# demo1 back: double sum final results

| | Nehalem | AMD | ARM |
|---|---|---|---|
| testManualUnroll | 0.70 | 0.45 | 3.31 |
| test1 | 1.49 | 1.50 | 6.60 |
| test2 | 0.75 | 0.79 | 4.25 |
| test4 | 0.51 | 0.43 | 4.25 |
| test8 | 0.51 | 0.25 | 2.55 |

time, nsec/op

# demo2: results

| | Nehalem | AMD | ARM |
|---|---|---|---|
| DoubleMul.test1 | 3.89 | 2.52 | 8.17 |
| DoubleMul.test2 | 3.59 | 2.37 | 4.25 |
| DoubleMul.test4 | 0.73 | 0.49 | 3.15 |
| DoubleMul.test8 | 0.61 | 0.30 | 2.53 |
| IntMul.test1 | 1.49 | 1.16 | 10.04 |
| IntMul.test2 | 0.75 | 0.75 | 7.38 |
| IntMul.test4 | 0.57 | 0.67 | 4.64 |
| IntSum.test1 | 0.51 | 0.32 | 8.92 |
| IntSum.test2 | 0.51 | 0.48 | 6.12 |

time, nsec/op

# Branches: to jump or not to jump

```java
public int absSumBranch(int a[]) {
    int sum = 0;
    for (int x : a) {
        if (x < 0) {
            sum -= x;
        } else {
            sum += x;
        }
    }
    return sum;
}
```

```
loop:   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      loop
```

# Branches: to jump or not to jump

```java
public int absSumPredicated(int a[]) {
    int sum = 0;
    for (int x : a) {
        sum += Math.abs(x);
    }
    return sum;
}
```

```
loop:  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
```



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# demo3: results

Regular Pattern = $(+, -)^*$

| | Nehalem | Ivy Bridge | Bulldozer | Cortex-A9 |
|---|---|---|---|---|
| branch_regular | 0.88 | 0.88 | 0.82 | 5.02 |
| branch_shuffled | 6.42 | 1.29 | 2.84 | 9.44 |
| branch_sorted | 0.90 | 0.95 | 0.99 | 5.02 |
| predicated_regular | 1.33 | 1.16 | 0.92 | 5.33 |
| predicated_shuffled | 1.33 | 1.16 | 0.96 | 9.3 |
| predicated_sorted | 1.33 | 1.16 | 0.96 | 5.65 |

time, nsec/op

# demo3: results

Regular Pattern $= (+, +, -, +, -, -, +, -, -, +)^*$

| | Nehalem | Ivy Bridge | Bulldozer | Cortex-A9 |
|---|---|---|---|---|
| branch_regular | 1.55 | 1.14 | 0.98 | 5.02 |
| branch_shuffled | 6.38 | 1.33 | 2.33 | 9.53 |
| branch_sorted | 0.90 | 0.95 | 0.95 | 5.03 |
| predicated_regular | 1.33 | 1.16 | 0.95 | 5.33 |
| predicated_shuffled | 1.33 | 1.16 | 0.94 | 9.38 |
| predicated_sorted | 1.33 | 1.16 | 0.91 | 5.65 |

time, nsec/op

# demo4: && vs &

```
public int countConditional(boolean[] f0, boolean[] f1) {
    int cnt = 0;
    for (int j = 0; j < SIZE; j++) {
        for (int i = 0; i < SIZE; i++) {
            if (f0[i] && f1[j]) {
                cnt++;
            }
        }
    }
    return cnt;
}
```

| && | |
|---|---|
| shuffled | 4.4 nsec/op |
| sorted | 1.5 nsec/op |



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# demo4: && vs &

```java
public int countLogical(boolean[] f0, boolean[] f1) {
    int cnt = 0;
    for (int j = 0; j < SIZE; j++) {
        for (int i = 0; i < SIZE; i++) {
            if (f0[i] & f1[j]) {
                cnt++;
            }
        }
    }
    return cnt;
}
```

**&&**

| | |
|---|---|
| shuffled | 4.4 nsec/op |
| sorted | 1.5 nsec/op |

**&**

| | |
|---|---|
| shuffled | 2.0 nsec/op |
| sorted | 2.0 nsec/op |

# demo5: interface invocation cost

```
public interface I             { public int amount(); }
...
public class C0 implements I { public int amount(){ return 0; } }
public class C1 implements I { public int amount(){ return 1; } }
public class C2 implements I { public int amount(){ return 2; } }
public class C3 implements I { public int amount(){ return 3; } }
...
@GenerateMicroBenchmark
@BenchmarkMode(Mode.AverageTime)
@OperationsPerInvocation(SIZE)
public int sum(I[] a) {
    int s = 0;
    for (I i : a) {
        s += i.amount();
    }
    return s;
}
```

# demo5: results

| | 1 target | 2 targets | 3 targets | 4 targets |
|---|---|---|---|---|
| sorted | 1.0 | 1.1 | 7.7 | 7.8 |
| regular | | 1.0 | 7.7 | 19.0 |
| shuffled | | 7.4 | 22.7 | 24.8 |

time, nsec/op

# Not-a-Core

# Not-a-Core: HW Multithreading

- Simultaneous multithreading, SMT
  e.g. Intel® Hyper-Threading Technology

- Fine-grained temporal multithreading
  e.g. CMT, Sun/Oracle ULTRASparc T1, T2, T3, T4, T5 ...

# back to demo1: Execution Units Saturation

| | 1 thread | 2 threads | 4 threads |
|---|---|---|---|
| DoubleSum.test1 | 327 | 654 | 1279 |
| DoubleSum.test2 | 647 | 1293 | 1865 |
| DoubleSum.test4 | 957 | 1916 | 1866 |
| DoubleSum.testManualUnroll | 699 | 1398 | 1432 |

overall throughput, ops/msec

# demo6: show

All eyes on the the screen!



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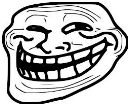
# demo6: show

All eyes on the the screen!



# demo6: HDivs.heavy* results on Nehalem

1 thread

| | |
|---|---|
| int | 180 |
| double | 90 |

throughput, ops/$\mu$sec

2 threads

| | -cpu 1,3 | -cpu 2,3 | -cpu 3 |
|---|---|---|---|
| (int, int) | (180, 180) | (90, 90) | (90, 90) |
| (double, double) | (90, 90) | (45, 45) | (45, 45) |
| (double, int) | (90, 180) | (81, 18) | (90, 45) |

throughput, ops/$\mu$sec

# demo6: HDivs.heavy* results on AMD

1 thread

| | |
|---|---|
| int | 128 |
| double | 306 |

throughput, ops/$\mu$sec

2 threads

| | -cpu 0,1 | -cpu 0,2 | -cpu 0,8 | -cpu 0 |
|---|---|---|---|---|
| (int, int) | (92, 92) | (127, 127) | (128, 132) | (63, 63) |
| (double, double) | (151, 153) | (304, 304) | (313, 314) | (154, 155) |
| (double, int) | (278, 119) | (290, 127) | (313, 129) | (122, 64) |

throughput, ops/$\mu$sec

# Conclusion

# Enlarge your knowledge with these simple tricks!

## Reading list:

- "Computer Architecture: A Quantitative Approach"
  John L. Hennessy, David A. Patterson
- `http://www.agner.org/optimize/`

# Thanks!

# Q & A