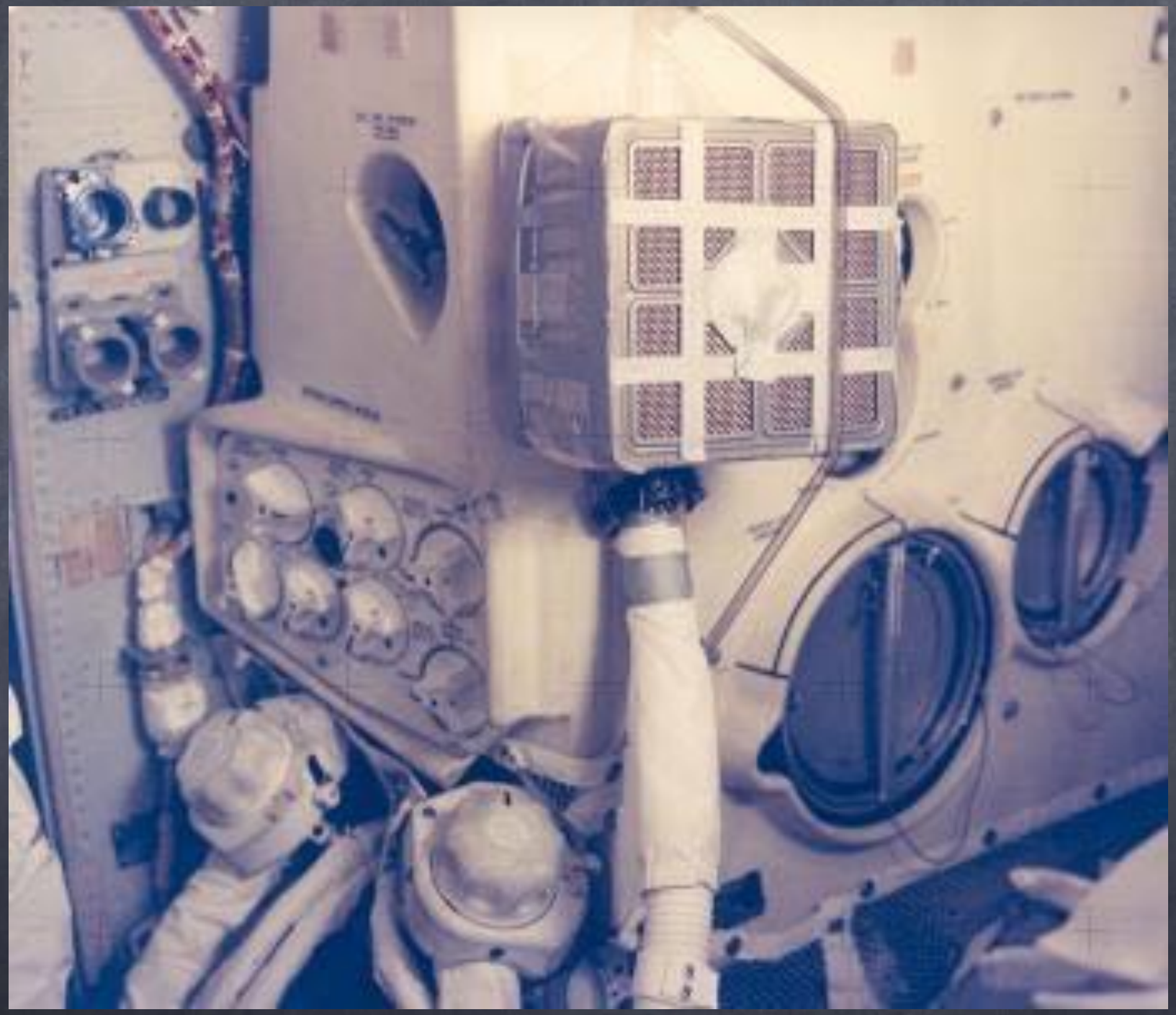

AZUL SYSTEMS

Java at Speed

getting the most out of modern hardware

Gil Tene, CTO & co-Founder, Azul Systems

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High level agenda

- Intro & Motivation
- Some hardware trends and new features
- Some compiler stuff
- A microbenchmark detour
- Some more compiler stuff
- Warmup, and what we can do about it
- Putting it all together (and maybe some bragging)

About me: Gil Tene

- co-founder, CTO @Azul Systems
- Have been working on "think different" GC and runtime approaches since 2002
- A Long history building Virtual & Physical Machines, Operating Systems, Enterprise apps, etc…
- At Azul we make JVMs that dramatically improve response time and latency behaviors
- I also depress people by demonstrating how terribly wrong their latency measurements are…

* working on real-world trash compaction issues, circa 2004

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Speed

What is it good for?

?

?

Are you fast?

?

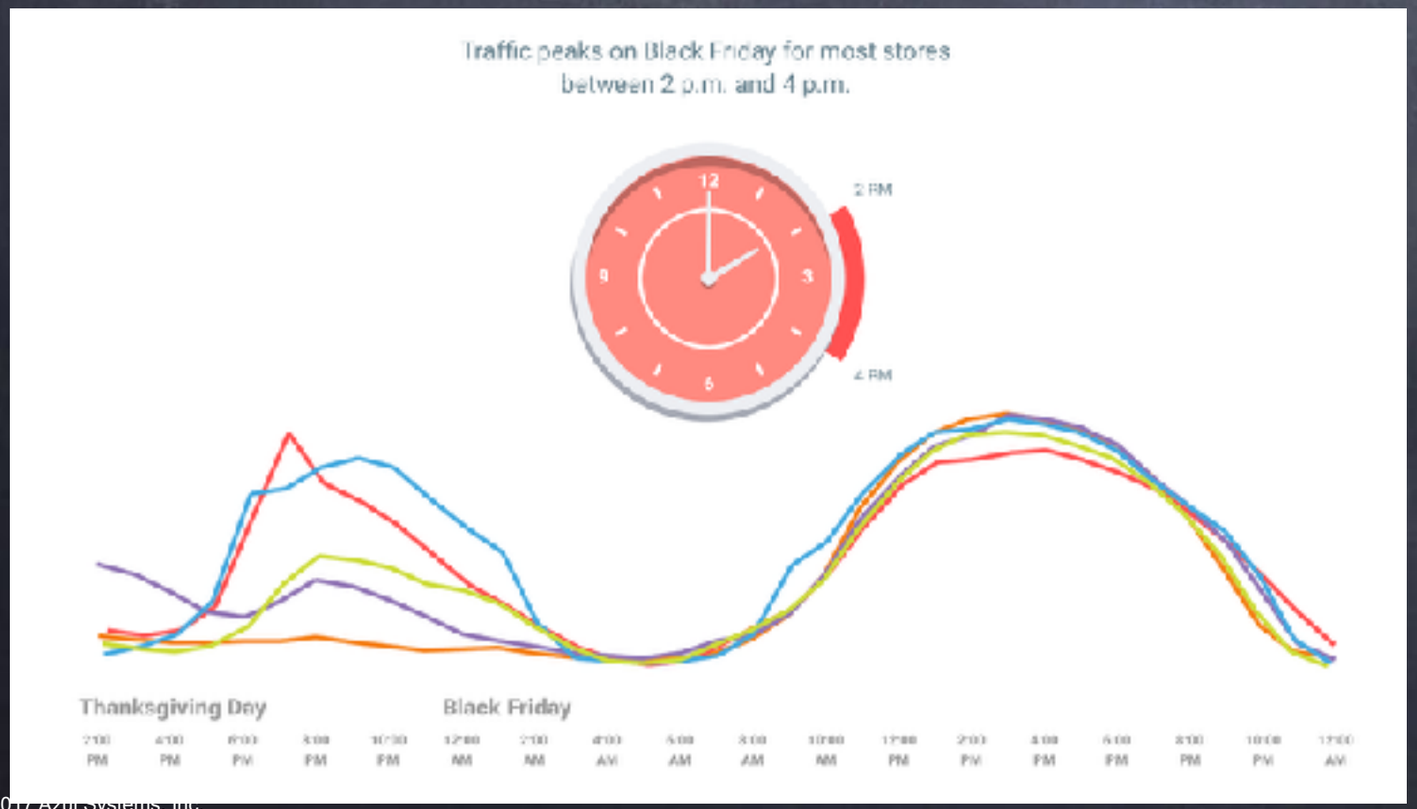
?

Are you fast when new code rolls out?

?

?

Are you fast when it matters?



?

?

Are you fast at Market Open?

?

?

Are you fast when you actually trade?

?

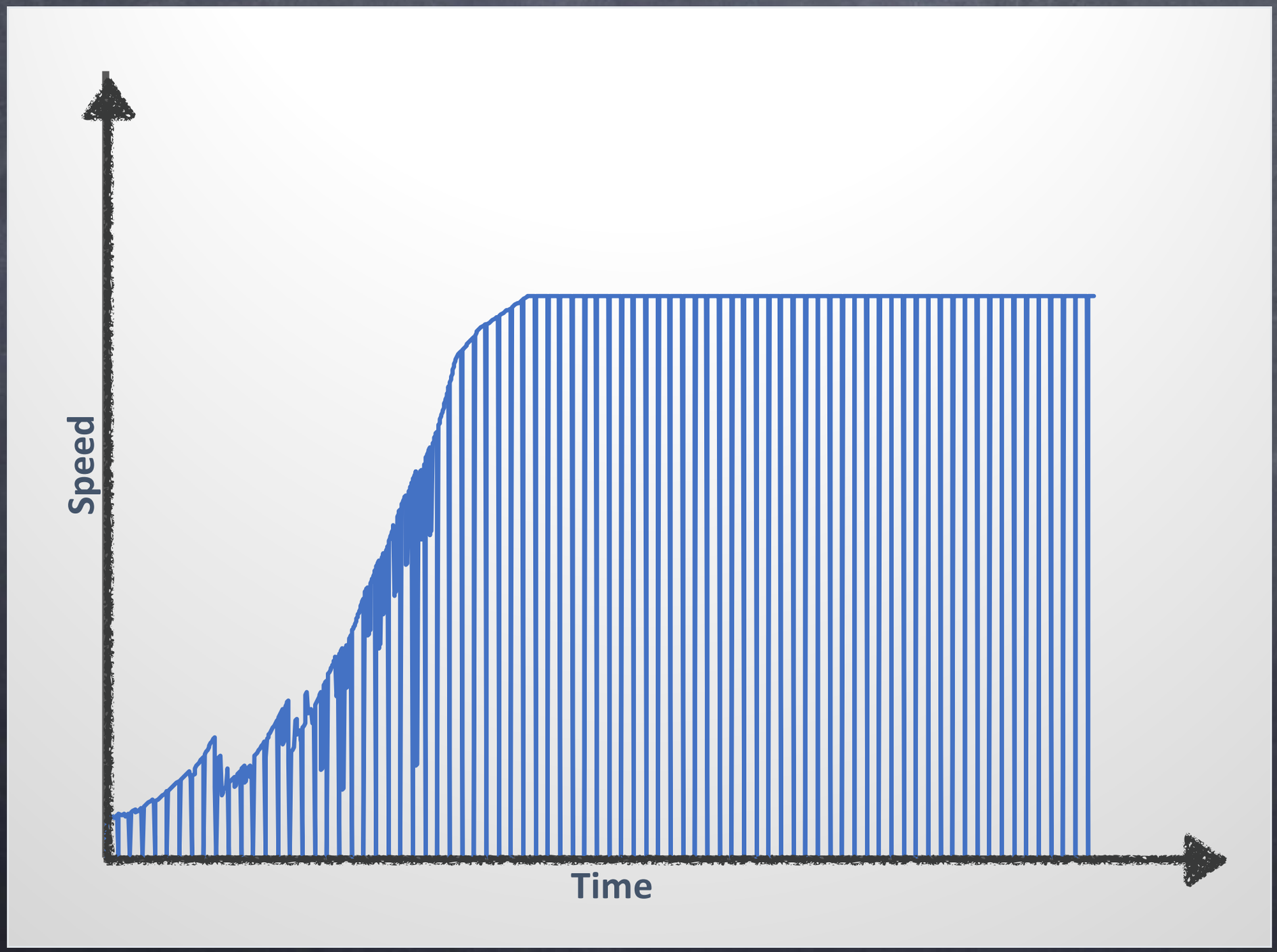
?

Are you reliably fast?

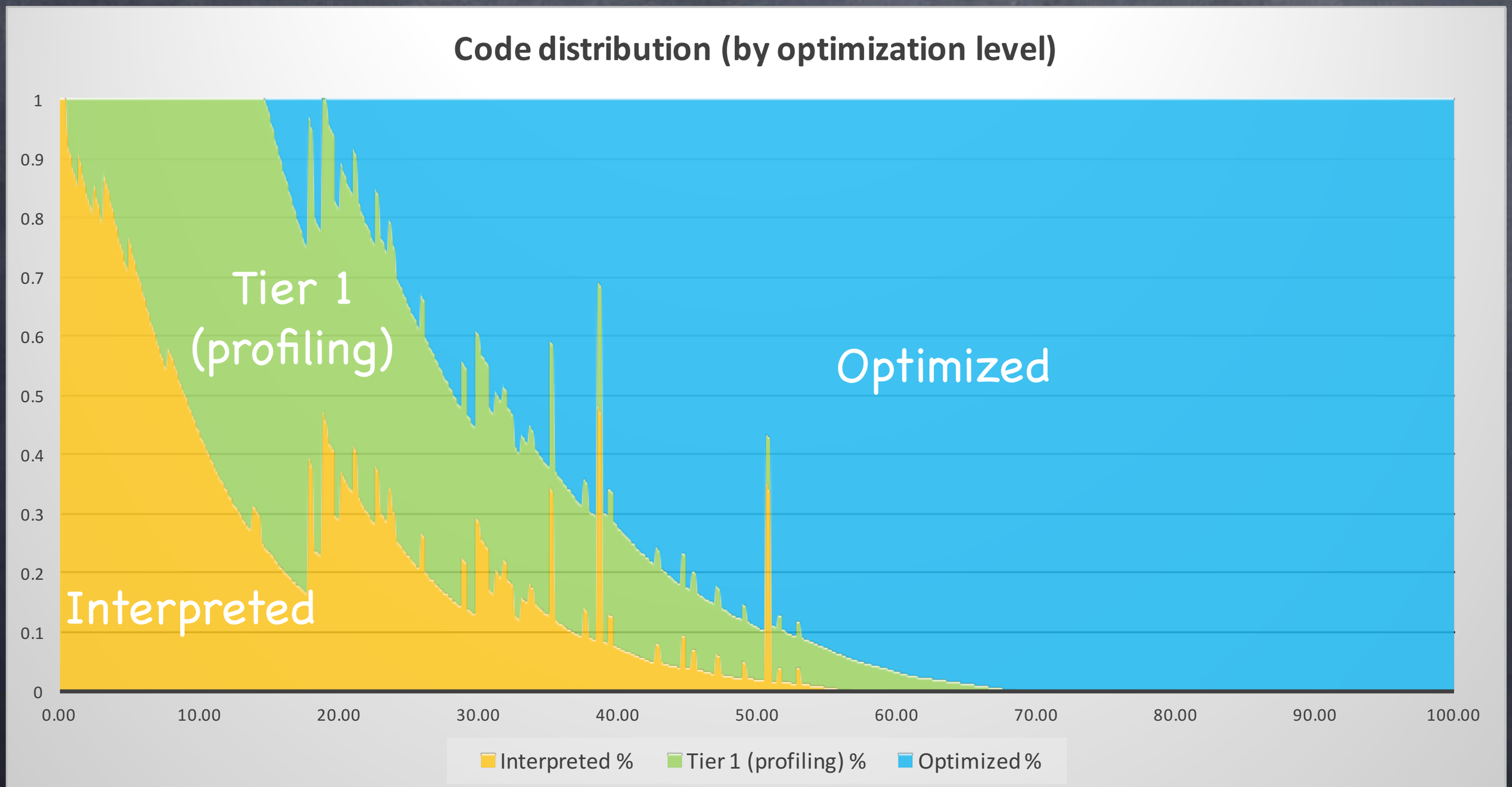
What do you mean by “fast”?

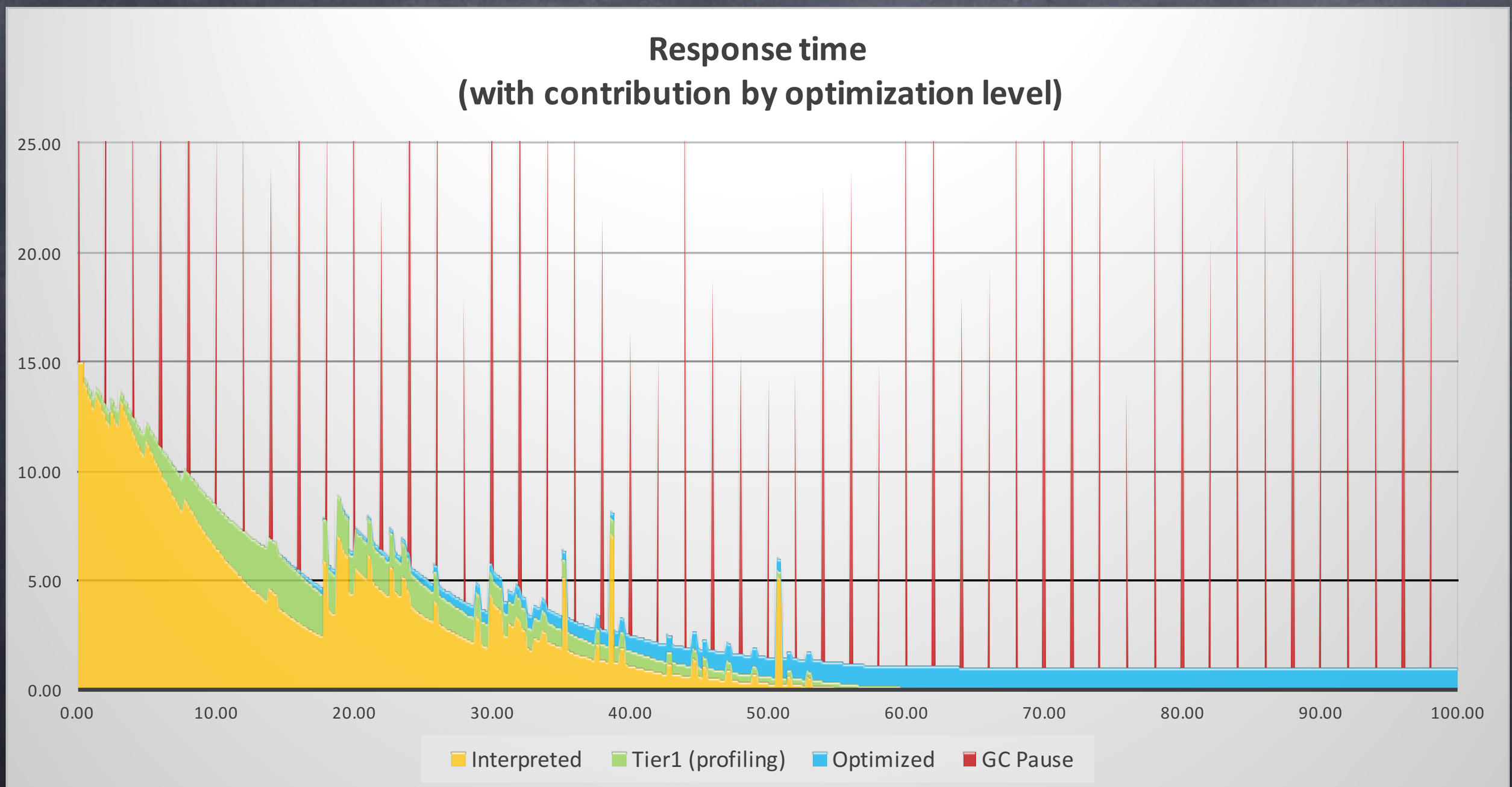
??

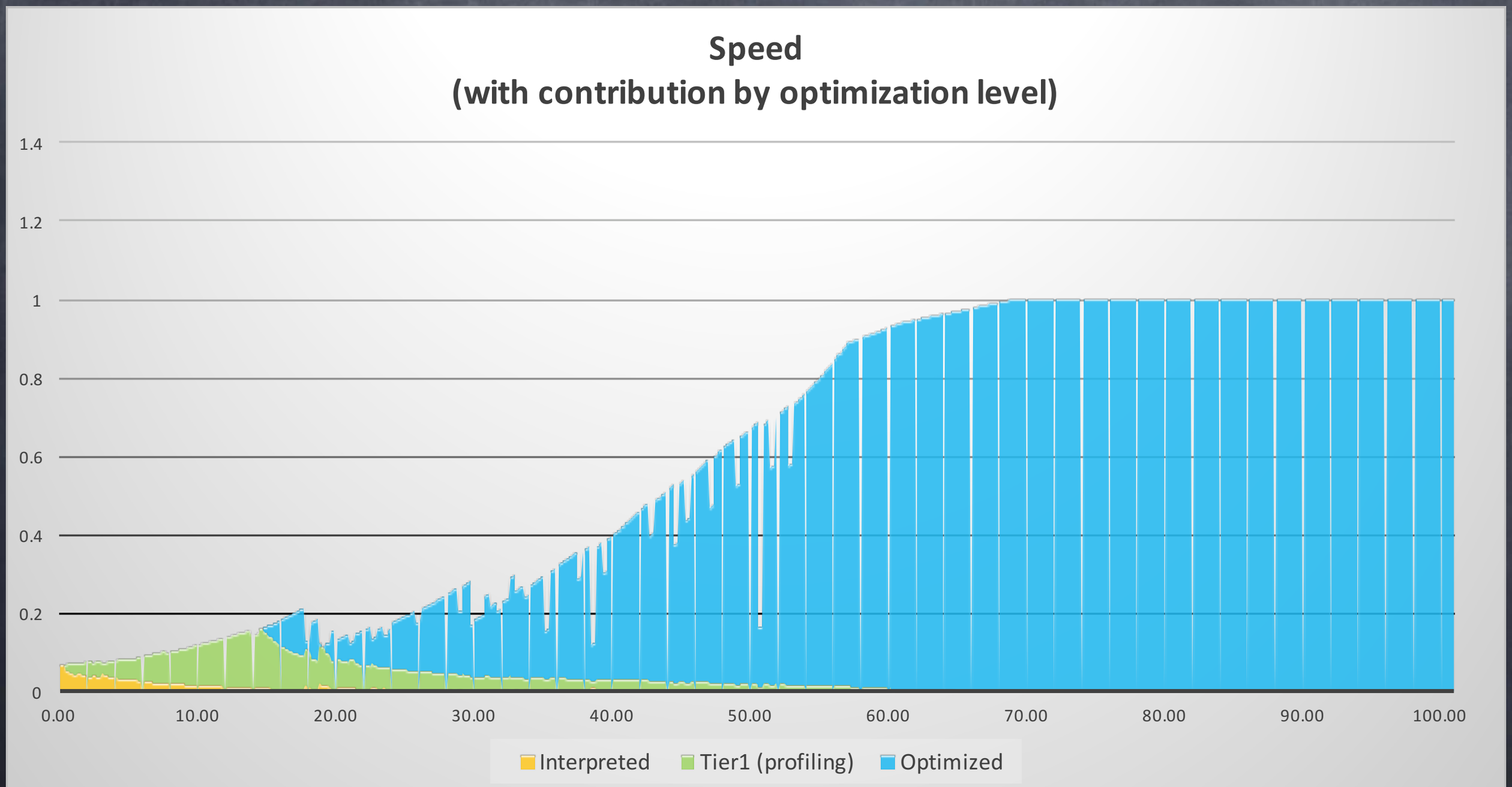
What do you mean by “fast”?



Speed in the Java world…







Some notes on modern servers

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Code name	Model	Intro Date		cores/chip
Nehalem EP	Xeon 5500	March 2009		4
Westemere EP	Xeon 5600	June 2010		6
Sandy Bridge EP	E5-2600	March 2012	AVX	8
Ivy Bridge EP	E5-2600 V2	Sep. 2013		12
Haswell EP	E5-2600 V3	Sep. 2014	AVX2, BMI, BMI2	18
Broadwell EP	E5-2600 V4	March 2016	TSX, HLE	22
Skylake SP	Silver/Gold/…	July 2017	AVX512	32

Instruction Window Keeps Increasing

	Sandy Bridge	Haswell	SkyLake
Out-of-order Window	168	192	224 ↑
In-flight Loads	64	72	72
In-flight Stores	36	42	56 ↑
Scheduler Entries	54	60	97 ↑
Integer Register File	160	168	180 ↑
FP Register File	144	168	168
Allocation Queue	28/thread	56	64/thread ↑

Extract more parallelism in every generation

Intel Next Generation Microarchitecture Code Name Skylake

IDF15

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Some machine code zoom-in

AZUL SYSTEMS — Azul ZVision

User: gil Host: cperf2 / 47781 Version: 1.8.0-zing_99.99.99.99.dev-b1686
Uptime: 00:21:51

Overview | Azul Support | Threads | CPU | Memory | Compilers | Applications

Tick Profile | Metaticks | Event Tracker

Pause The Tick Collection | Reset Tick Profile | Stop Saving Ticks To Disk

Timer Tick Profile

Cutoff: .1 Threads (comma separated list): None JVM All Submit

Note: Functions that could not be resolved to a name string are displayed as an address followed by "<-" and the first calling function (in their stack) that can.

Percent	Ticks	Source
41.8%	11,459	bench.CodeGenExampleBench.trueIfMaskMatched (codeblob)
18.9%	5,169	bench.CodeGenExampleBench.addArraysIfEven (codeblob)
11.2%	3,063	bench.CodeGenExampleBench.addXtoArray (codeblob)
8.3%	2,267	bench.CodeGenExampleBench.sumShifted (codeblob)
8.0%	2,190	bench.CodeGenExampleBench.sumIfEvenLoop (codeblob)
5.1%	1,405	bench.CodeGenExampleBench.sumLoop (codeblob)
0.5%	128	ElfSymbolTable::lookup(unsigned char*, int*, int*, int*, unsigned long*) (PC ref)
0.3%	93	_dl_addr (PC ref)
0.2%	64	_int_free (PC ref)
0.2%	59	libLLVM-4.0svn.so (PC ref)
0.2%	58	_int_malloc (PC ref)
0.2%	57	__libc_malloc (PC ref)
0.1%	35	syscall (PC ref)
0.1%	32	llvm::PMDataManager::findAnalysisPass(void const*, bool) (PC ref)
0.1%	16	computeKnownBits(llvm::Value const*, llvm::APInt&, llvm::APInt&, unsigned int, (anonymous namespace)::Query const&) (PC ref)
0.1%	15	llvm::PMTopLevelManager::setLastUser(llvm::ArrayRef, llvm::Pass*) (PC ref)
0.0%	12	bench.CodeGenExampleBench.doAddArraysIfEven (codeblob)
0.0%	12	ioctl (PC ref)
0.0%	12	malloc_consolidate (PC ref)
0.0%	12	llvm::InstCombiner::run() (PC ref)
0.0%	11	llvm::PMTopLevelManager::findAnalysisPass(void const*) (PC ref)
0.0%	11	llvm::Use::getImpliedUser() const (PC ref)
0.0%	10	llvm::ValueHandleBase::AddToUseList() (PC ref)
0.0%	10	mprotect (PC ref)
0.0%	10	malloc (PC ref)
0.0%	9	sysmalloc (PC ref)
0.0%	8	bench.CodeGenExampleBench.doSumShiftedLoop (codeblob)
0.0%	8	llvm::Value::getValueName() const (PC ref)

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bench.CodeGenExampleBench.sumLoop([I)I

ID: 0x3000f600

Reset Tick Profile

Assembly | Callee | Caller

Percent	Ticks	Address	Code	Opcode
		0x3000f650	pushq %rax	0xfff0
		0x3000f652	cmpl $0, %gs:104	0x65833c2568000000000
		0x3000f65b	jne 127 ; ABS: 0x3000f6dc	0x757f
		0x3000f65d	movl 8(%rsi), %ecx // NPE-> 0x3000f6f5	0x8b4e08
		0x3000f660	testq %rcx, %rcx	0x4885c9
		0x3000f663	je 115 ; ABS: 0x3000f6d8	0x7473
		0x3000f665	cmpl $7, %ecx	0x83f907
		0x3000f668	ja 20 ; ABS: 0x3000f67e	0x7714
		0x3000f66a	xorl %edx, %edx	0x31d2
		0x3000f66c	xorl %eax, %eax	0x31c0
		0x3000f66e	nop	0x6690
		0x3000f670	addl 12(%rsi,%rdx,4), %eax	0x0344960c
		0x3000f674	incq %rdx	0x48ffc2
		0x3000f677	cmpq %rcx, %rdx	0x4839ca
		0x3000f67a	jl -12 ; ABS: 0x3000f670	0x7cf4
		0x3000f67c	popq %rcx	0x59
0.05%	1	0x3000f67d	retq	0xc3
		0x3000f67e	movl %ecx, %r8d	0x4189c8
		0x3000f681	andl $7, %r8d	0x4183e007
		0x3000f685	movq %rcx, %rdx	0x4889ca
		0x3000f688	subq %r8, %rdx	0x4c29c2
0.05%	1	0x3000f68b	je -35 ; ABS: 0x3000f66a	0x74dd
		0x3000f68d	leaq 28(%rsi), %rax	0x488d461c
		0x3000f691	pxor %xmm0, %xmm0	0x660fefc0
		0x3000f695	movq %rdx, %rdi	0x4889d7
		0x3000f698	pxor %xmm1, %xmm1	0x660fefc9
		0x3000f69c	nopl (%rax)	0x0f1f4000
21.90%	418	0x3000f6a0	movdqu -16(%rax), %xmm2	0xf30f6f50f0
5.08%	97	0x3000f6a5	movdqu (%rax), %xmm3	0xf30f6f18
40.86%	780	0x3000f6a9	paddd %xmm2, %xmm0	0x660ffec2
2.72%	52	0x3000f6ad	paddd %xmm3, %xmm1	0x660ffecb
29.23%	558	0x3000f6b1	addq $32, %rax	0x4883c020
		0x3000f6b5	addq $-8, %rdi	0x4883c7f8
		0x3000f6b9	jne -27 ; ABS: 0x3000f6a0	0x75e5
		0x3000f6bb	paddd %xmm0, %xmm1	0x660ffec8
		0x3000f6bf	pshufd $78, %xmm1, %xmm0	0x660f70c14e
		0x3000f6c4	paddd %xmm1, %xmm0	0x660ffec1
		0x3000f6c8	phaddd %xmm0, %xmm0	0x660f3802c0
0.05%	1	0x3000f6cd	movd %xmm0, %eax	0x660f7ec0
0.05%	1	0x3000f6d1	testl %r8d, %r8d	0x4585c0
		0x3000f6d4	jne -102 ; ABS: 0x3000f670	0x759a
		0x3000f6d6	jmp -92 ; ABS: 0x3000f67c	0xeba4
		0x3000f6d8	xorl %eax, %eax	0x31c0
		0x3000f6da	popq %rcx	0x59
		0x3000f6db	retq	0xc3

A simple array summing loop

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

```java
private int sumLoop(int[] a) {
    int sum = 0;
    for (int i = 0; i < a.length; i++) {
        sum += a[i];
    }
    return sum;
}
```

Address	Code	Opcode
0x3000fe50	pushq %rax	0xfff0
0x3000fe52	cmpl $0, %gs:104	0x65833c256800000000
0x3000fe5b	jne 127 ; ABS: 0x3000fedc	0x757f
0x3000fe5d	movl 8(%rsi), %ecx // NPE-> 0x3000fef5	0x8b4e08
0x3000fe60	testq %rcx, %rcx	0x4885c9
0x3000fe63	je 115 ; ABS: 0x3000fed8	0x7473
0x3000fe65	cmpl $7, %ecx	0x83f907
0x3000fe68	ja 20 ; ABS: 0x3000fe7e	0x7714
0x3000fe6a	xorl %edx, %edx	0x31d2
0x3000fe6c	xorl %eax, %eax	0x31c0
0x3000fe6e	nop	0x6690
0x3000fe70	addl 12(%rsi,%rdx,4), %eax	0x0344960c
0x3000fe74	incq %rdx	0x48ffc2
0x3000fe77	cmpq %rcx, %rdx	0x4839ca
0x3000fe7a	jl -12 ; ABS: 0x3000fe70	0x7cf4
0x3000fe7c	popq %rcx	0x59
0x3000fe7d	retq	0xc3
0x3000fe7e	movl %ecx, %r8d	0x4189c8
0x3000fe81	andl $7, %r8d	0x4183e007
0x3000fe85	movq %rcx, %rdx	0x4889ca
0x3000fe88	subq %r8, %rdx	0x4c29c2
0x3000fe8b	je -35 ; ABS: 0x3000fe6a	0x74dd
0x3000fe8d	leaq 28(%rsi), %rax	0x488d461c
0x3000fe91	pxor %xmm0, %xmm0	0x660fefc0
0x3000fe95	movq %rdx, %rdi	0x4889d7
0x3000fe98	pxor %xmm1, %xmm1	0x660fefc9
0x3000fe9c	nopl (%rax)	0x0f1f4000
0x3000fea0	movdqu -16(%rax), %xmm2	0xf30f6f50f0
0x3000fea5	movdqu (%rax), %xmm3	0xf30f6f18
0x3000fea9	paddd %xmm2, %xmm0	0x660ffec2
0x3000fead	paddd %xmm3, %xmm1	0x660ffecb
0x3000feb1	addq $32, %rax	0x4883c020
0x3000feb5	addq $-8, %rdi	0x4883c7f8
0x3000feb9	jne -27 ; ABS: 0x3000fea0	0x75e5
0x3000febb	paddd %xmm0, %xmm1	0x660ffec8
0x3000febf	pshufd $78, %xmm1, %xmm0	0x660f70c14e
0x3000fec4	paddd %xmm1, %xmm0	0x660ffec1
0x3000fec8	phaddd %xmm0, %xmm0	0x660f3802c0
0x3000fecd	movd %xmm0, %eax	0x660f7ec0
0x3000fed1	testl %r8d, %r8d	0x4585c0
0x3000fed4	jne -102 ; ABS: 0x3000fe70	0x759a
0x3000fed6	jmp -92 ; ABS: 0x3000fe7c	0xeba4
0x3000fed8	xorl %eax, %eax	0x31c0
0x3000feda	popq %rcx	0x59
0x3000fedb	retq	0xc3
0x3000fedc	movq %rsi, (%rsp)	0x48893424
0x3000fee0	movabsq $805334400, %rax	0x48b8806d003000000000
0x3000feea	callq *%rax	0xffd0
0x3000feec	movq (%rsp), %rsi	0x488b3424
0x3000fef0	jmp -152 ; ABS: 0x3000fe5d	0xe968ffffff
0x3000fef5	movabsq $805319872, %rax	0x48b8c034003000000000
0x3000feff	movl $7, %edi	0xbf07000000
0x3000ff04	callq *%rax	0xffd0
0x3000ff06	addq $-8, %rsp	0x4883c4f8
0x3000ff0a	jmp -50575 ; ABS: 0x30003980 = StubRoutines::deoptimize	0xe9713affff
0x3000ff0f	int3	0xcc

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```java
private int sumLoop(int[] a) {
    int sum = 0;
    for (int i = 0; i < a.length; i++) {
        sum += a[i];
    }
    return sum;
}
```

Percent	Ticks	Address	Code	Opcode
		0x3000fe50	pushq %rax	0xfff0
		0x3000fe52	cmpl $0, %gs:104	0x65833c256800000000
		0x3000fe5b	jne 127 ; ABS: 0x3000fedc	0x757f
		0x3000fe5d	movl 8(%rsi), %ecx // NPE-> 0x3000fef5	0x8b4e08
0.06%	1	0x3000fe60	testq %rcx, %rcx	0x4885c9
		0x3000fe63	je 115 ; ABS: 0x3000fed8	0x7473
		0x3000fe65	cmpl $7, %ecx	0x83f907
		0x3000fe68	ja 20 ; ABS: 0x3000fe7e	0x7714
		0x3000fe6a	xorl %edx, %edx	0x31d2
		0x3000fe6c	xorl %eax, %eax	0x31c0
		0x3000fe6e	nop	0x6690
		0x3000fe70	addl 12(%rsi,%rdx,4), %eax	0x0344960c
		0x3000fe74	incq %rdx	0x48ffc2
		0x3000fe77	cmpq %rcx, %rdx	0x4839ca
		0x3000fe7a	jl -12 ; ABS: 0x3000fe70	0x7cf4
		0x3000fe7c	popq %rcx	0x59
		0x3000fe7d	retq	0xc3
0.06%	1	0x3000fe7e	movl %ecx, %r8d	0x4189c8
		0x3000fe81	andl $7, %r8d	0x4183e007
		0x3000fe85	movq %rcx, %rdx	0x4889ca
		0x3000fe88	subq %r8, %rdx	0x4c29c2
		0x3000fe8b	je -35 ; ABS: 0x3000fe6a	0x74dd
		0x3000fe8d	leaq 28(%rsi), %rax	0x488d461c
		0x3000fe91	pxor %xmm0, %xmm0	0x660fefc0
		0x3000fe95	movq %rdx, %rdi	0x4889d7
		0x3000fe98	pxor %xmm1, %xmm1	0x660fefc9
		0x3000fe9c	nopl (%rax)	0x0f1f4000
20.64%	327	0x3000fea0	movdqu -16(%rax), %xmm2	0xf30f6f50f0
35.42%	561	0x3000fea5	movdqu (%rax), %xmm3	0xf30f6f18
11.30%	179	0x3000fea9	paddd %xmm2, %xmm0	0x660ffec2
13.70%	217	0x3000fead	paddd %xmm3, %xmm1	0x660ffecb
18.69%	296	0x3000feb1	addq $32, %rax	0x4883c020
		0x3000feb5	addq $-8, %rdi	0x4883c7f8
		0x3000feb9	jne -27 ; ABS: 0x3000fea0	0x75e5
		0x3000febb	paddd %xmm0, %xmm1	0x660ffec8
		0x3000febf	pshufd $78, %xmm1, %xmm0	0x660f70c14e
		0x3000fec4	paddd %xmm1, %xmm0	0x660ffec1
		0x3000fec8	phaddd %xmm0, %xmm0	0x660f3802c0
0.13%	2	0x3000fecd	movd %xmm0, %eax	0x660f7ec0
		0x3000fed1	testl %r8d, %r8d	0x4585c0
		0x3000fed4	jne -102 ; ABS: 0x3000fe70	0x759a
		0x3000fed6	jmp -92 ; ABS: 0x3000fe7c	0xeba4
		0x3000fed8	xorl %eax, %eax	0x31c0
		0x3000feda	popq %rcx	0x59
		0x3000fedb	retq	0xc3
		0x3000fedc	movq %rsi, (%rsp)	0x48893424
		0x3000fee0	movabsq $805334400, %rax	0x48b8806d003000000000
		0x3000feea	callq *%rax	0xffd0
		0x3000feec	movq (%rsp), %rsi	0x488b3424
		0x3000fef0	jmp -152 ; ABS: 0x3000fe5d	0xe968ffffff
		0x3000fef5	movabsq $805319872, %rax	0x48b8c034003000000000
		0x3000feff	movl $7, %edi	0xbf07000000
		0x3000ff04	callq *%rax	0xffd0
		0x3000ff06	addq $-8, %rsp	0x4883c4f8
		0x3000ff0a	jmp -50575 ; ABS: 0x30003980 = StubRoutines::deoptimize	0xe9713affff
		0x3000ff0f	int3	0xcc

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This is on X5690 (Westmere)

Uses SSE (128bit)

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

		0x3000fe81	andl $7, %r8d
		0x3000fe85	movq %rcx, %rdx
		0x3000fe88	subq %r8, %rdx
		0x3000fe8b	je -35 ; ABS: 0x3000fe6a
		0x3000fe8d	leaq 28(%rsi), %rax
		0x3000fe91	pxor %xmm0, %xmm0
		0x3000fe95	movq %rdx, %rdi
		0x3000fe98	pxor %xmm1, %xmm1
		0x3000fe9c	nopl (%rax)
20.64%	327	0x3000fea0	movdqu -16(%rax), %xmm2
35.42%	561	0x3000fea5	movdqu (%rax), %xmm3
11.30%	179	0x3000fea9	paddd %xmm2, %xmm0
13.70%	217	0x3000fead	paddd %xmm3, %xmm1
18.69%	296	0x3000feb1	addq $32, %rax
		0x3000feb5	addq $-8, %rdi
		0x3000feb9	jne -27 ; ABS: 0x3000fea0
		0x3000febb	paddd %xmm0, %xmm1
		0x3000febf	pshufd $78, %xmm1, %xmm0
		0x3000fec4	paddd %xmm1, %xmm0
		0x3000fec8	phaddd %xmm0, %xmm0
0.13%	2	0x3000fecd	movd %xmm0, %eax
		0x3000fed1	testl %r8d, %r8d
		0x3000fed4	jne -102 ; ABS: 0x3000fe70
		0x3000fed6	jmp -92 ; ABS: 0x3000fe7c
		0x3000fed8	xorl %eax, %eax
		0x3000feda	popq %rcx
		0x3000fedb	retq
		0x3000fedc	movq %rsi, (%rsp)
		0x3000fee0	movabsq $805334400, %rax
		0x3000feea	callq *%rax
		0x3000feec	movq (%rsp), %rsi

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

This is on E5-2690 v4 (Broadwell)

Uses AVX2 (256bit)

		0x3001269c	subq %r8, %rdx
		0x3001269f	je -47 ; ABS: 0x30012672
		0x300126a1	leaq 108(%rsi), %rax
		0x300126a5	vpxor %ymm0, %ymm0, %ymm0
		0x300126a9	movq %rdx, %rdi
		0x300126ac	vpxor %ymm1, %ymm1, %ymm1
		0x300126b0	vpxor %ymm2, %ymm2, %ymm2
		0x300126b4	vpxor %ymm3, %ymm3, %ymm3
		0x300126b8	nopl (%rax,%rax)
0.06%	1	0x300126c0	vpaddd -96(%rax), %ymm0, %ymm0
37.08%	603	0x300126c5	vpaddd -64(%rax), %ymm1, %ymm1
0.92%	15	0x300126ca	vpaddd -32(%rax), %ymm2, %ymm2
54.80%	891	0x300126cf	vpaddd (%rax), %ymm3, %ymm3
0.55%	9	0x300126d3	subq $-128, %rax
5.84%	95	0x300126d7	addq $-32, %rdi
		0x300126db	jne -29 ; ABS: 0x300126c0
		0x300126dd	vpaddd %ymm0, %ymm1, %ymm0
0.12%	2	0x300126e1	vpaddd %ymm2, %ymm0, %ymm0
		0x300126e5	vpaddd %ymm3, %ymm0, %ymm0
		0x300126e9	vextracti128 $1, %ymm0, %xmm1
0.25%	4	0x300126ef	vpaddd %ymm0, %ymm1, %ymm0
		0x300126f3	vpshufd $78, %xmm0, %xmm1
0.06%	1	0x300126f8	vpaddd %ymm0, %ymm1, %ymm0
0.12%	2	0x300126fc	vphaddd %ymm0, %ymm0, %ymm0
		0x30012701	vmovd %xmm0, %eax
		0x30012705	testl %r8d, %r8d
		0x30012708	jne -142 ; ABS: 0x30012680
		0x3001270e	jmp -134 ; ABS: 0x3001268d
		0x30012713	xorl %eax, %eax
		0x30012715	popq %rcx
		0x30012716	retq
		0x30012717	movq %rsi, (%rsp)
		0x3001271b	movabsq $805344640, %rax
		0x30012725	callq *%rax
		0x30012727	movq (%rsp), %rsi
		0x3001272b	jmp -207 ; ABS: 0x30012661

A conditional array cell addition loop

```
private void addArraysIfEven(int a[], int b[]) {
    if (a.length != b.length) {
        throw new RuntimeException("length mismatch");
    }
    for (int i = 0; i < a.length; i++) {
        if ((b[i] & 0x1) == 0) {
            a[i] += b[i];
        }
    }
}
```

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```java
private void addArraysIfEven(int a[], int b[]) {
    if (a.length != b.length) {
        throw new RuntimeException("length mismatch");
    }
    for (int i = 0; i < a.length; i++) {
        if ((b[i] & 0x1) == 0) {
            a[i] += b[i];
        }
    }
}
```

Percent	Ticks	Address	Code	Opcode
		0x3(010650	subq $24, %rsp	0x4883ec18
		0x3(010654	cmpl $0, %gs:104	0x65833c256800000000
		0x3(01065d	jne 106 ; ABS: 0x300106c9	0x756a
0.01%	1	0x3(01065f	movl 8(%rsi), %eax // NPE-> 0x300106ee	0x8b4608
		0x3(010662	cmpl 8(%rdx), %eax // NPE-> 0x300106ff	0x3b4208
		0x3(010665	jne 165 ; ABS: 0x30010710	0x0f85a5000000
		0x3(01066b	testl %eax, %eax	0x85c0
		0x3(01066d	je 85 ; ABS: 0x300106c4	0x7455
		0x3(01066f	testb $1, %al	0xa801
		0x3(010671	jne 4 ; ABS: 0x30010677	0x7504
		0x3(010673	xorl %edi, %edi	0x31ff
		0x3(010675	jmp 18 ; ABS: 0x30010687	0xeb10
		0x3(010677	movl 12(%rdx), %ecx	0x8b4a0c
		0x3(01067a	testb $1, %cl	0xf6c101
		0x3(01067d	jne 3 ; ABS: 0x30010682	0x7503
		0x3(01067f	addl %ecx, 12(%rsi)	0x014e0c
		0x3(010682	movl $1, %edi	0xbf01000000
		0x3(010687	cmpl $1, %eax	0x83f801
		0x3(01068a	je 56 ; ABS: 0x300106c4	0x7438
		0x3(01068c	subq %rdi, %rax	0x4829f8
		0x3(01068f	leaq 16(%rdx,%rdi,4), %rcx	0x488d4cba10
		0x3(010694	leaq 16(%rsi,%rdi,4), %rdx	0x488d54be10
		0x3(010699	nopl (%rax)	0x0f1f8000000000
16.84%	1,286	0x3(0106a0	movl -4(%rcx), %esi	0x8b71fc
6.10%	466	0x3(0106a3	testb $1, %sil	0x40f6c601
		0x3(0106a7	jne 3 ; ABS: 0x300106ac	0x7503
7.61%	581	0x3(0106a9	addl %esi, -4(%rdx)	0x0172fc
29.41%	2,246	0x3(0106ac	movl (%rcx), %esi	0x8b31
2.25%	172	0x3(0106ae	testb $1, %sil	0x40f6c601
		0x3(0106b2	jne 2 ; ABS: 0x300106b6	0x7502
8.00%	611	0x3(0106b4	addl %esi, (%rdx)	0x0132
29.73%	2,271	0x3(0106b6	addq $8, %rcx	0x4883c108
		0x3(0106ba	addq $8, %rdx	0x4883c208
		0x3(0106be	addq $-2, %rax	0x4883c0fe
		0x3(0106c2	jne -38 ; ABS: 0x300106a0	0x75dc
0.03%	2	0x3(0106c4	addq $24, %rsp	0x4883c418
0.03%	2	0x3(0106c8	retq	0xc3
		0x3(0106c9	movq %rsi, 16(%rsp)	0x4889742410
		0x3(0106ce	movq %rdx, 8(%rsp)	0x4889542408
		0x3(0106d3	movabsq $805334400, %rax	0x48b8806d003000000000
		0x3(0106dd	callq *%rax	0xffd0
		0x3(0106df	movq 8(%rsp), %rdx	0x488b542408
		0x3(0106e4	movq 16(%rsp), %rsi	0x488b742410
		0x3(0106e9	jmp -143 ; ABS: 0x3001065f	0xe971ffffff
		0x3(0106ee	movabsq $805319872, %rax	0x48b8c034003000000000
		0x3(0106f8	movl $7, %edi	0xbf07000000
		0x3(0106fd	callq *%rax	0xffd0
		0x3(0106ff	movabsq $805319872, %rax	0x48b8c034003000000000
		0x3(010709	movl $7, %edi	0xbf07000000
		0x3(01070e	callq *%rax	0xffd0
		0x3(010710	movabsq $805319872, %rax	0x48b8c034003000000000
		0x3(01071a	movl $4294967288, %edi	0xbff8ffffff
		0x3(01071f	callq *%rax	0xffd0
		0x3(010721	addq $-8, %rsp	0x4883c4f8
		0x3(010725	jmp -52650 ; ABS: 0x30003980 = StubRoutines::deoptimize	0xe95632ffff
		0x3(01072a	int3	0xcc

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Traditional JVM JITs

per-element jumps,
2 elements per iteration

```
private void addArraysIfEven(int a[], int b[]) {
    if (a.length != b.length) {
        throw new RuntimeException("length mismatch");
    }
    for (int i = 0; i < a.length; i++) {
        if ((b[i] & 0x1) == 0) {
            a[i] += b[i];
        }
    }
}
```

		0x3001067a	testb $1, %cl
		0x3001067d	jne 3 ; ABS: 0x30010682
		0x3001067f	addl %ecx, 12(%rsi)
		0x30010682	movl $1, %edi
		0x30010687	cmpl $1, %eax
		0x3001068a	je 56 ; ABS: 0x300106c4
		0x3001068c	subq %rdi, %rax
		0x3001068f	leaq 16(%rdx,%rdi,4), %rcx
		0x30010694	leaq 16(%rsi,%rdi,4), %rdx
		0x30010699	nopl (%rax)
16.84%	1,286	0x300106a0	movl -4(%rcx), %esi
6.10%	466	0x300106a3	testb $1, %sil
		0x300106a7	jne 3 ; ABS: 0x300106ac
7.61%	581	0x300106a9	addl %esi, -4(%rdx)
29.41%	2,246	0x300106ac	movl (%rcx), %esi
2.25%	172	0x300106ae	testb $1, %sil
		0x300106b2	jne 2 ; ABS: 0x300106b6
8.00%	611	0x300106b4	addl %esi, (%rdx)
29.73%	2,271	0x300106b6	addq $8, %rcx
		0x300106ba	addq $8, %rdx
		0x300106be	addq $-2, %rax
		0x300106c2	jne -36 ; ABS: 0x300106a0
0.03%	2	0x300106c4	addq $24, %rsp
0.03%	2	0x300106c8	retq
		0x300106c9	movq %rsi, 16(%rsp)
		0x300106ce	movq %rdx, 8(%rsp)
		0x300106d3	movabsq $805334400, %rax
		0x300106dd	callq *%rax
		0x300106df	movq 8(%rsp), %rdx
		0x300106e4	movq 16(%rsp), %rsi
		0x300106e9	jmp -143 ; ABS: 0x3001065f
		0x300106ee	movabsq $805319872, %rax
		0x300106f8	movl $7, %edi

```
private void addArraysIfEven(int a[], int b[]) {
    if (a.length != b.length) {
        throw new RuntimeException("length mismatch");
    }
    for (int i = 0; i < a.length; i++) {
        if ((b[i] & 0x1) == 0) {
            a[i] += b[i];
        }
    }
}
```

This is on E5-2690 v4 (Broadwell)

Vectorized with AVX2
32 elements per iteration

		0x30014548	movabsq $805389904, %rbx
		0x30014552	vpbroadcastd (%rbx), %ymm0
		0x30014557	vpxor %ymm1, %ymm1, %ymm1
		0x3001455b	movq %rdi, %rbx
		0x3001455e	nop
0.15%	4	0x30014560	vmovdqu -96(%r11), %ymm2
12.31%	320	0x30014566	vmovdqu -64(%r11), %ymm3
0.50%	13	0x3001456c	vmovdqu -32(%r11), %ymm4
2.04%	53	0x30014572	vmovdqu (%r11), %ymm5
0.31%	8	0x30014577	vpand %ymm0, %ymm2, %ymm6
4.54%	118	0x3001457b	vpand %ymm0, %ymm3, %ymm7
0.69%	18	0x3001457f	vpand %ymm0, %ymm4, %ymm8
1.35%	35	0x30014583	vpand %ymm0, %ymm5, %ymm9
0.42%	11	0x30014587	vpcmpeqd %ymm1, %ymm6, %ymm8
2.58%	67	0x3001458b	vpmaskmovd -96(%rcx), %ymm6, %ymm10
3.58%	93	0x30014591	vpcmpeqd %ymm1, %ymm7, %ymm7
2.12%	55	0x30014595	vpmaskmovd -64(%rcx), %ymm7, %ymm11
12.12%	315	0x3001459b	vpcmpeqd %ymm1, %ymm8, %ymm8
1.50%	39	0x3001459f	vpmaskmovd -32(%rcx), %ymm8, %ymm12
3.69%	96	0x300145a5	vpcmpeqd %ymm1, %ymm9, %ymm9
1.81%	47	0x300145a9	vpmaskmovd (%rcx), %ymm9, %ymm13
12.27%	319	0x300145ae	vpaddd %ymm2, %ymm10, %ymm2
0.58%	15	0x300145b2	vpaddd %ymm3, %ymm11, %ymm3
0.19%	5	0x300145b6	vpaddd %ymm4, %ymm12, %ymm4
0.58%	15	0x300145ba	vpaddd %ymm5, %ymm13, %ymm5
3.27%	85	0x300145be	vpmaskmovd %ymm2, %ymm6, -96(%rcx)
7.15%	186	0x300145c4	vpmaskmovd %ymm3, %ymm7, -64(%rcx)
13.65%	355	0x300145ca	vpmaskmovd %ymm4, %ymm8, -32(%rcx)
4.58%	119	0x300145d0	vpmaskmovd %ymm5, %ymm9, (%rcx)
6.81%	177	0x300145d5	subq $-128, %r11
0.69%	18	0x300145d9	subq $-128, %rcx
0.31%	8	0x300145dd	addq $-32, %rbx
		0x300145e1	jne -135 ; ABS: 0x30014560
		0x300145e7	testl %r9d, %r9d
		0x300145ea	jne -356 ; ABS: 0x3001448c
		0x300145f0	jmp -233 ; ABS: 0x3001450c

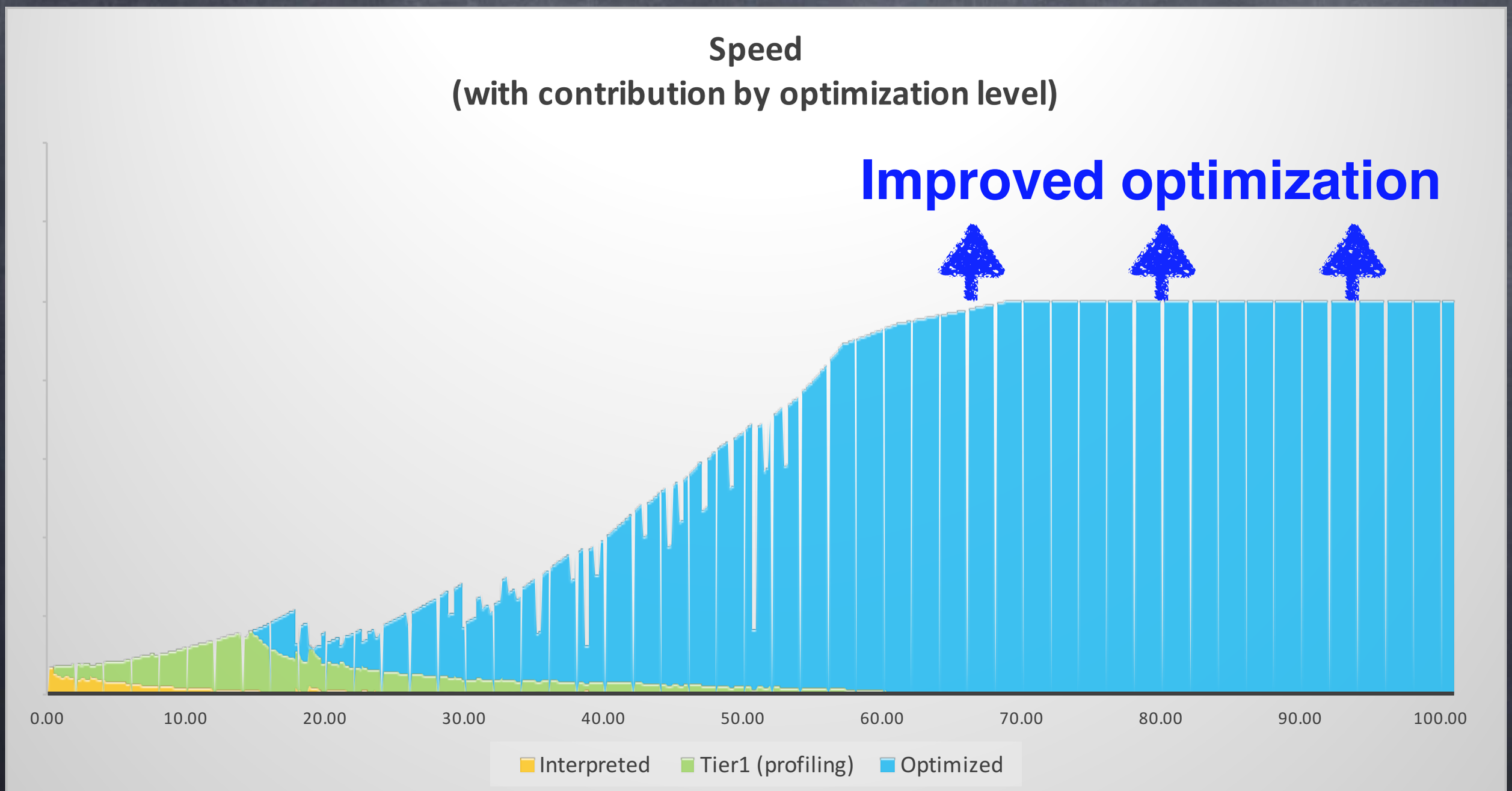
```
private void addArraysIfEven(int a[], int b[]) {
    if (a.length != b.length) {
        throw new RuntimeException("length mismatch");
    }
    for (int i = 0; i < a.length; i++) {
        if ((b[i] & 0x1) == 0) {
            a[i] += b[i];
        }
    }
}
```

This is on Skylake SP

Vectorized with AVX512
64 elements per iteration

		0x3001ab4a	jb -206 ; ABS: 0x3001aa82
		0x3001ab50	movl %eax, %ecx
		0x3001ab52	andl $2147483584, %ecx
0.02%	1	0x3001ab58	leaq 204(%rdx), %r8
		0x3001ab5f	leaq 204(%rsi), %rdi
		0x3001ab66	movabsq $805416064, %rbx
		0x3001ab70	vpbroadcastd (%rbx), %zmm0
0.04%	2	0x3001ab76	movq %rcx, %r9
		0x3001ab79	nopl (%rax)
0.46%	24	0x3001ab80	vmovdqu32 -192(%r8), %zmm1
3.46%	179	0x3001ab87	vmovdqu32 -128(%r8), %zmm2
3.52%	182	0x3001ab8e	vmovdqu32 -64(%r8), %zmm3
4.95%	256	0x3001ab95	vmovdqu32 (%r8), %zmm4
12.73%	658	0x3001ab9b	vptestnmd %zmm0, %zmm1, %k1
1.99%	103	0x3001aba1	vptestnmd %zmm0, %zmm2, %k2
1.53%	79	0x3001aba7	vptestnmd %zmm0, %zmm3, %k3
2.69%	139	0x3001abad	vmovdqu32 -192(%rdi), %zmm5 {%k1} {z}
8.38%	433	0x3001abb4	vmovdqu32 -128(%rdi), %zmm6 {%k2} {z}
11.13%	575	0x3001abbb	vmovdqu32 -64(%rdi), %zmm7 {%k3} {z}
10.51%	543	0x3001abc2	vptestnmd %zmm0, %zmm4, %k4
1.76%	91	0x3001abc8	vmovdqu32 (%rdi), %zmm8 {%k4} {z}
18.25%	943	0x3001abce	vpaddd %zmm1, %zmm5, %zmm1
0.97%	50	0x3001abd4	vpaddd %zmm2, %zmm6, %zmm2
0.91%	47	0x3001abda	vpaddd %zmm3, %zmm7, %zmm3
0.46%	24	0x3001abe0	vmovdqu32 %zmm1, -192(%rdi) {%k1}
2.26%	117	0x3001abe7	vmovdqu32 %zmm2, -128(%rdi) {%k2}
0.66%	34	0x3001abee	vmovdqu32 %zmm3, -64(%rdi) {%k3}
1.10%	57	0x3001abf5	vpaddd %zmm4, %zmm8, %zmm1
0.64%	33	0x3001abfb	vmovdqu32 %zmm1, (%rdi) {%k4}
9.85%	514	0x3001ac01	addq $256, %r8
0.64%	33	0x3001ac08	addq $256, %rdi
0.85%	44	0x3001ac0f	addq $-64, %r9
		0x3001ac13	jne -153 ; ABS: 0x3001ab80
		0x3001ac19	cmpq %rax, %rcx
		0x3001ac1c	jne -414 ; ABS: 0x3001aa84

Better JIT'ing is basically about speed



Compiler Stuff

Some simple compiler tricks

Code can be reordered…

```
int doMath(int x, int y, int z) {
  int a = x + y;
  int b = x - y;
  int c = z + x;
  return a + b;
}
```

Can be reordered to:

```
int doMath(int x, int y, int z) {
  int c = z + x;
  int b = x - y;
  int a = x + y;
  return a + b;
}
```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Dead code can be removed

```
int doMath(int x, int y, int z) {
  int a = x + y;
  int b = x - y;
  int c = z + x;
  return a + b;
}
```

Can be reduced to:

```
int doMath(int x, int y, int z) {
  int a = x + y;
  int b = x - y;
  return a + b;
}
```


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Values can be propagated

```
int doMath(int x, int y, int z) {
  int a = x + y;
  int b = x - y;
  int c = z + x;
  return a + b;
}
```

Can be reduced to:

```
int doMath(int x, int y, int z) {
  return x + y + x - y;
}
```


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Math can be simplified

```
int doMath(int x, int y, int z) {
  int a = x + y;
  int b = x - y;
  int c = z + x;
  return a + b;
}
```

Can be reduced to:

```
int doMath(int x, int y, int z) {
  return x + x;
}
```


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Some more compiler tricks

propagation can affect flow

constants can be propagated to pre-compute results:

```
int computeBias() {
  int bias, val = 5;
  if (val > 10) {
      bias = computeComplicatedBias(val);
  else {
      bias = 1;
  }
  return bias;
}
```

Can be reduced to:

```
int computeBias() {
  return 1;
}
```


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Reads can be cached

```
class Point { int x, y; }

int distanceRatio(Point a) {
   int distanceTo = a.x - start;
   int distanceAfter = end - a.x;
   return distanceTo/distanceAfter;
}
```

Is (semantically) the same as

```
int distanceRatio(Point a) {
   int x = a.x;
   int distanceTo = x - start;
   int distanceAfter = end - x;
   return distanceTo/distanceAfter;
}
```

Reads can be cached

```
class Trigger { boolean flag; }

void loopUntilFlagSet(Tigger a) {
  while (!a.flag) {
    loopcount++;
  }
}
```

Is the same as:

```
void loopUntilFlagSet(Object a) {
  boolean flagIsSet = a.flag;
  while (!flagIsSet) {
    loopcount++;
  }
}
```

That's what volatile is for...

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Writes can be eliminated

Intermediate values might never be visible

```
void updateDistance(Point a) {
  int distance = 100;
  a.x = distance;
  a.x = distance * 2;
  a.x = distance * 3;
}
```

Is the same as

```
void updateDistance(Point a) {
  a.x = 300;
}
```


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Writes can be eliminated

Intermediate values might never be visible

```
void updateDistance(SomeObject a) {
  a.visibleValue = 0;
  for (int i = 0; i < 1000000; i++) {
    a.internalValue = i;
  }
  a.visibleValue = a.internalValue;
}
```

Is the same as

```
void updateDistance(SomeObject a) {
  a.internalValue = 1000000;
  a.visibleValue = 1000000;
}
```


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Inlining…

```
public class Thing {
   private int x;
   public final int getX() { return x };
}
…
myX = thing.getX();
```

Is the same as

```
Class Thing {
   int x;
}
…
myX = thing.x;
```


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Inlining is very powerful

inlining exposes other optimizations

```
int computeBias(int val) {
  int bias;
  if (val > 10) {
      bias = computeComplicatedBias(val);
  else {
      bias = 1;
  }
  return bias;
}
...
myBias = computeBias(5);
```

Can be reduced to:

```
myBias = 1;
```


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A uBenchmark sidetrack

A simple loop uBenchmark (0)

```
public void loopUbench0(int count) {
    long sum = 0;
    for (int i = 0; i < count; i++) {
        sum++;
    }
}
```

Turns out this is "really fast"

As in: when count = 1,000,000 we complete
~500,000,000 calls per second
(for 5,000,000,000,000,000 iterations/sec)

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A simple loop uBenchmark (1)

```
public void loopUbench1(int count) {
    long sum = 0;
    for (int i = 0; i < count; i++) {
        sum += i;
    }
}
```

Still "impossibly fast"

It's all "provably dead code".
Compiler translates the method to a no-op

A simple loop uBenchmark (2)

```
public long loopUbench2(int count) {
    long sum = 0;
    for (int i = 0; i < count; i++) {
        sum++;
    }
    return sum;
}
```

Better?

No. Still "impossibly fast".

Compiler returns count. No loop.

A simple loop uBenchmark (3)

```
public long loopUbench3(int count) {
    long sum = 0;
    for (int i = 0; i < count; i++) {
        sum += i;
    }
    return sum;
}
```

Better?

Depends. On HotSpot and Zing C2, yes.

But Zing's new Falcon compiler is smart enough to recognize arithmetic series

A simple loop uBenchmark (4)

```
public long loopUbench4(int count) {
    long sum = 0;
    for (int i = 0; i < count; i++) {
        sum *= i;
    }
    return sum;
}
```

How about this?

Zing's Falcon will even figure out this one.
(it returns zero)

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A simple loop uBenchmark (5)

```
public long loopUbench5(int count) {
    long sum = 0;
    for (int i = 0; i < count; i++) {
        sum += i + ((i - 3) & 0x7);
    }
    return sum;
}
```

Seems to be complicated enough to defeat *current* compilers...

uBenchmarking Takeaways

- uBenchmarking is "hard". As in "very tricky"
- You may not be measuring what you think you are
- "Trickiness" can change over time, between versions
- Sanity check EVERYTHING
- Use jmh
- Use jmh
- Use jmh
- And even then, suspect everything

Back to compiler stuff

Speculative compiler tricks

JIT compilers can do things that static compilers can have a hard time with…

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Untaken path example

"Never taken" paths can be optimized away with benefits:

```
int computeMagnitude(int val) {
  if (val > 10) {
      bias = computeBias(val);
  else {
      bias = 1;
  }
  return Math.log10(bias + 99);
}
```

When all values so far were <= 10 , could be compiled to:

```
int computeMagnitude(int val) {
  if (val > 10) uncommonTrap();
  return 2;
}
```

Implicit Null Check example

All field and array access in Java is null checked

```
x = foo.x;
```

is (in equivalent required machine code):

```
if (foo == null)
    throw new NullPointerException();
x = foo.x;
```

But compiler can "hope" for non-nulls, and handle SEGV

```
<Point where later SEGV will appear to throw>
x = foo.x;
```

This is faster *IF* no nulls are encountered…

Class Hierarchy Analysis (CHA)

- Can perform global analysis on currently loaded code
- Deduce stuff about inheritance, method overrides, etc.
- Can make optimization decisions based on assumptions
- Re-evaluate assumptions when loading new classes
- Throw away code that conflicts with assumptions before class loading makes them invalid

Inlining works without "final"

```
public class Animal {
   private int color;
   public int getColor() { return color };
}
…
myColor = animal.getColor();
```

Is the same as

```
Class Animal {
   int color;
}
…
myColor = animal.color;
```

THIS (CHA) is why Java field accessors are free & clean

As long as only one implementer of getColor() exists

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Inlining monomorphic sites

```
public class Animal {
   private int color;
   public int getColor() { return color };
}
…
myColor = animal.getColor();
```

Can be converted to:

```
…
if (animal.type != Dog) uncommonTrap();
myColor = animal.color;
```

Even if we have multiple conflicting implementors…

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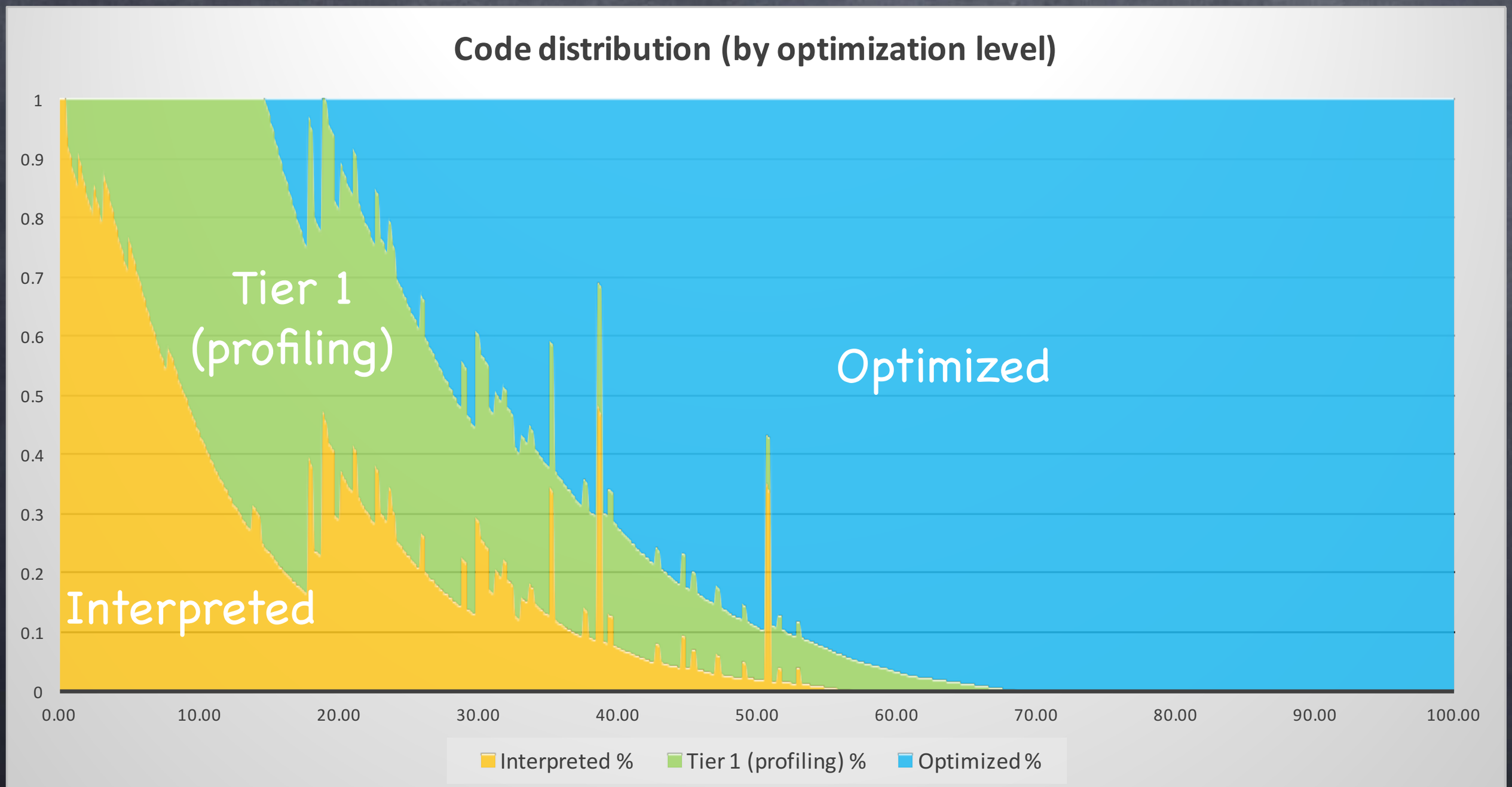
Deoptimization



Deoptimization: Adaptive compilation is... adaptive

- Micro-benchmarking is a black art
- So is the art of the Warmup
  - Running code long enough to compile is just the start...
- Deoptimizations can occur at any time
  - often occur after you *think* the code is warmed up.
- Many potential causes

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Warmup often doesn't cut it...

- Common Example:
  - Trading system wants to have the first trade be fast
  - So run 20,000 "fake" messages through the system to warm up
  - let JIT compilers optimize, learn, and deopt before actual trades
- But...
  - Code is written to do different things "if this is a fake message"
  - e.g. "Don't send to the exchange if this is a fake message"
- What really happens
  - JITs optimize for fake path, including speculatively assuming "fake"
  - First real message through causes a deopt...

Market Open

Java at Market Open

Java's "Just In Time" Reality

- Starts slow, learns fast
- Lazy loading & initialization
- Aggressively optimized for the common case
- (temporarily) Reverts to slower execution to adapt

Warmup

Deoptimization

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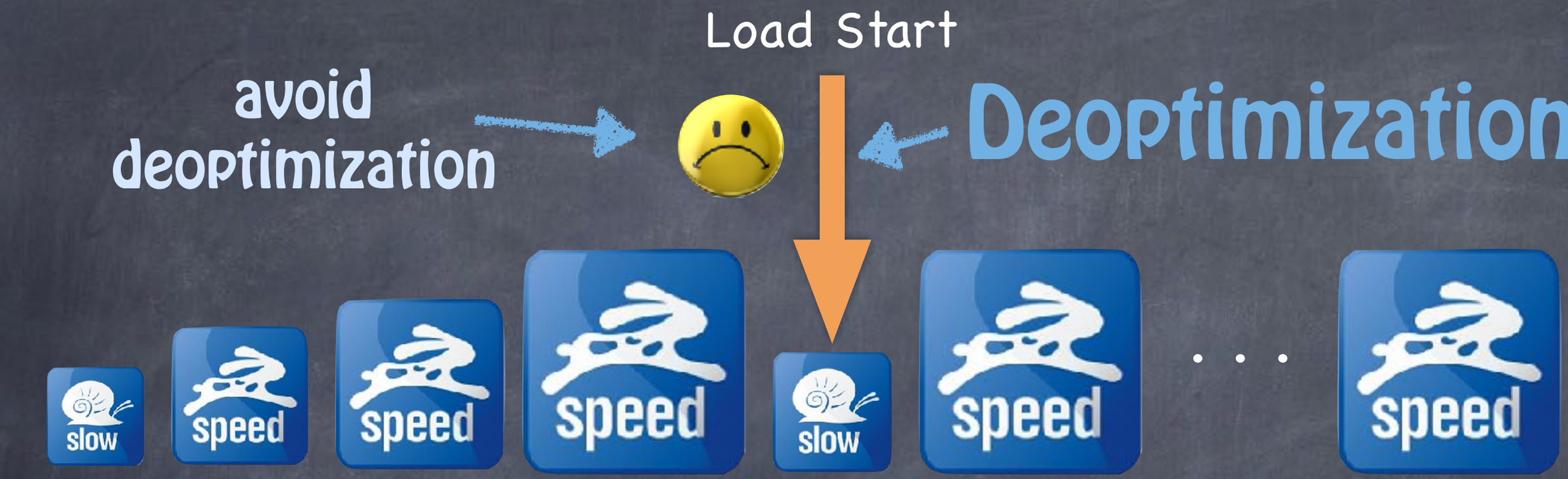
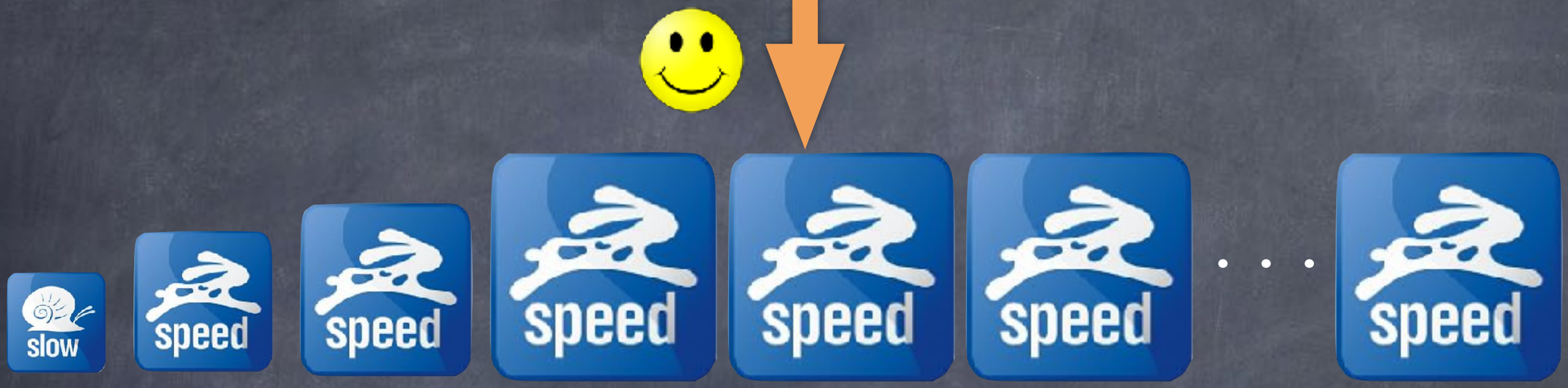
Logging and "replaying" optimizations

- Log optimization information
  - Record ongoing optimization decisions and stats
  - Record optimization dependencies
  - Establish "stable optimization state" at end of previous run
- Read prior logs at startup
  - "Prime" JVM with knowledge of prior stable optimizations
  - Apply optimizations as their dependencies get resolved
- Build workflow to promote confidence
  - Let you know if/when all optimizations have been applied
  - If some optimization haven't been applied, let you know why...



Java at "Load Start"

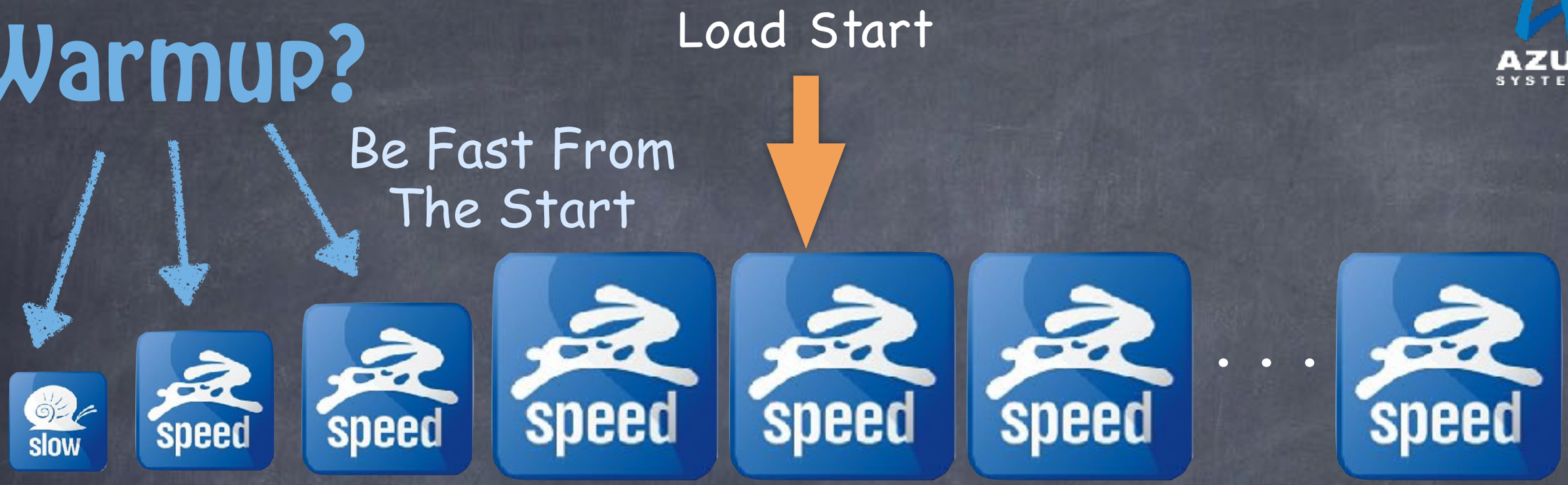
Load Start



Java at "Load Start"

With de-optimization avoided

Warmup?



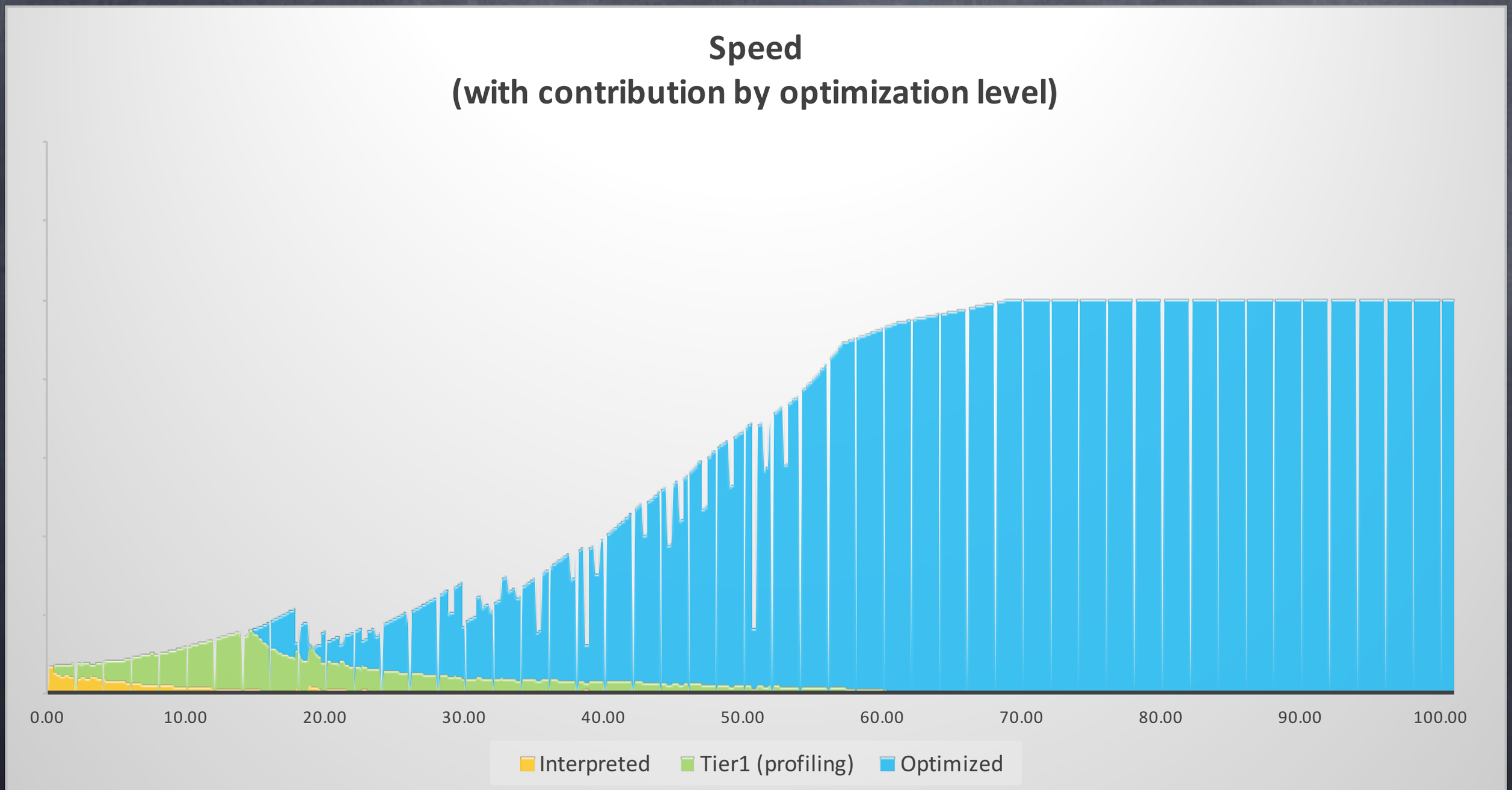
Java at "Load Start"

Load Start

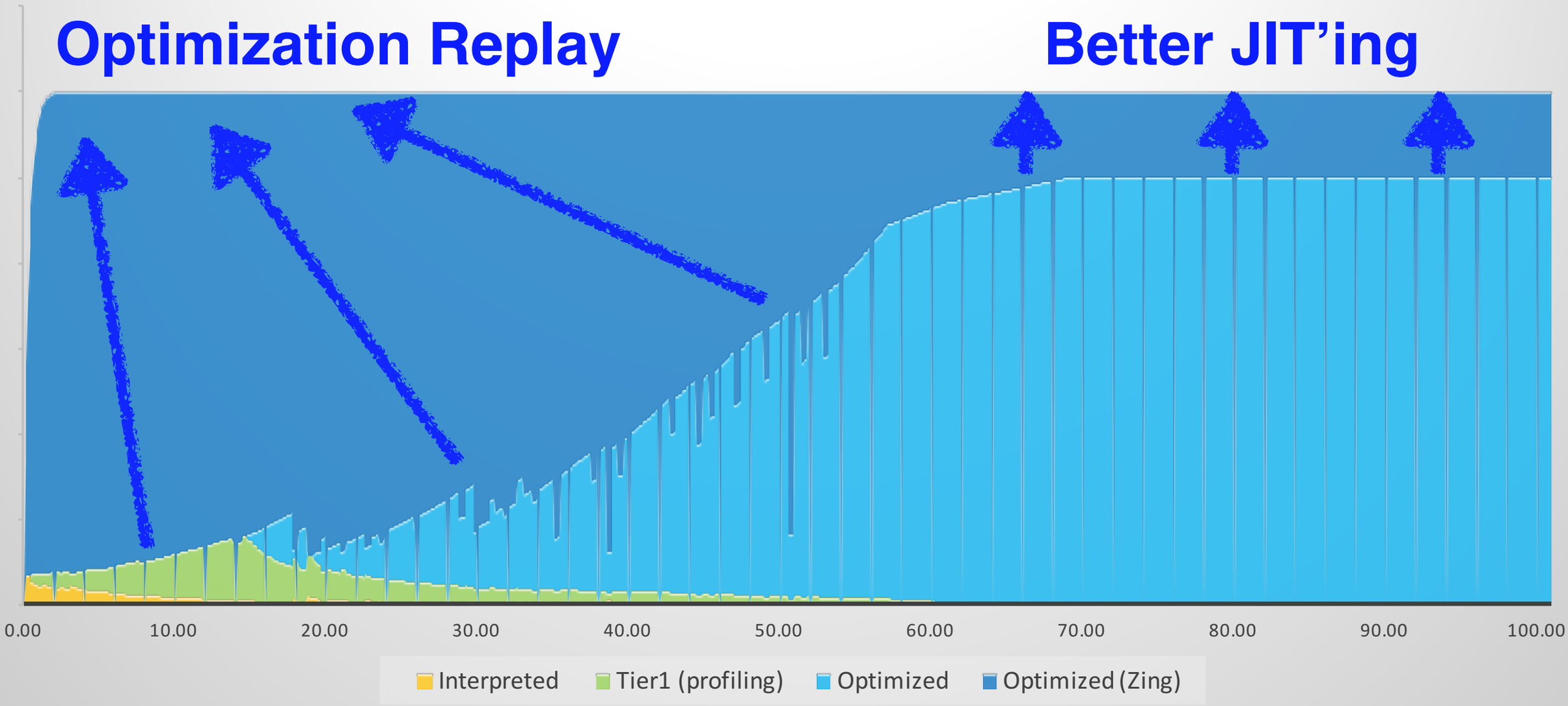
Java at "Load Start"

With pre-loading of prior optimizations

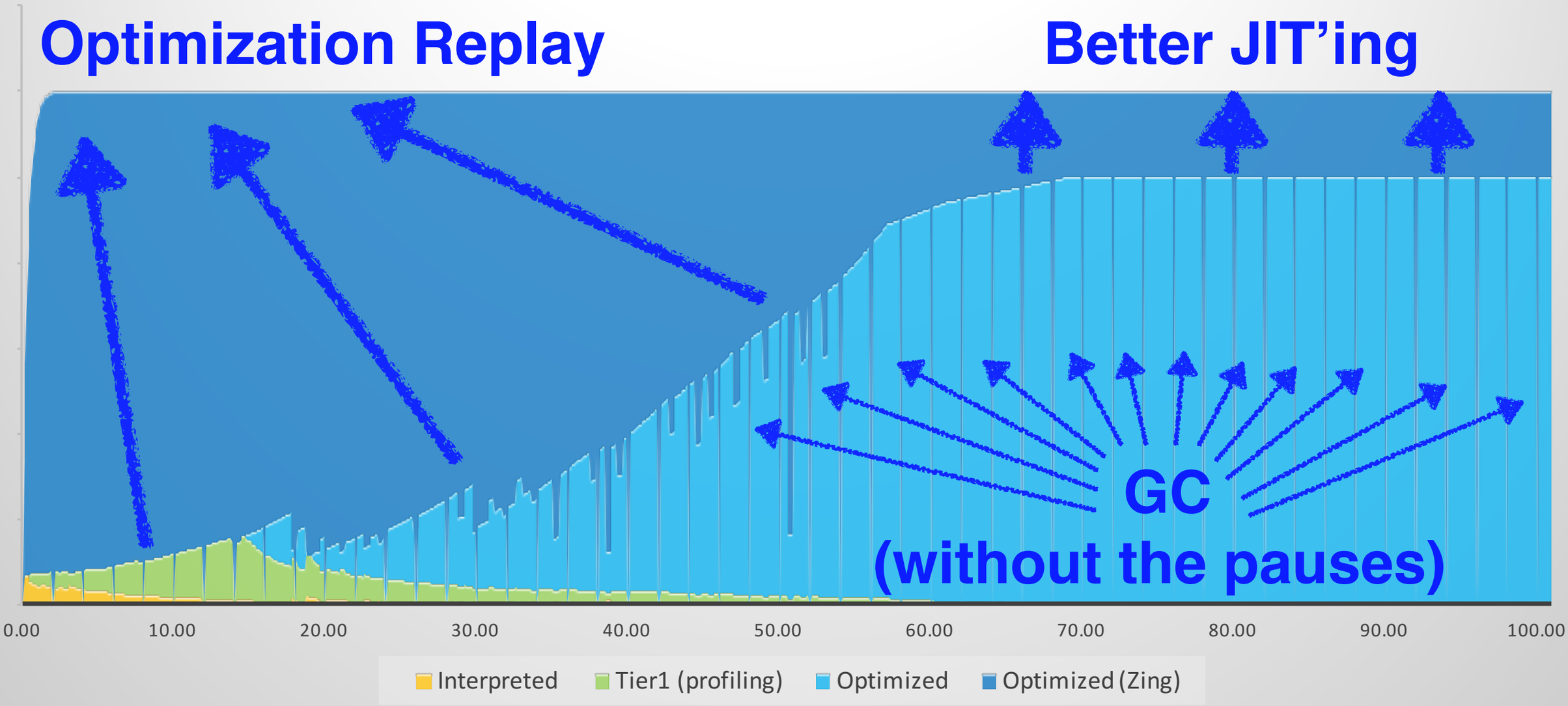
Speed improvements



Speed
(with contribution by optimization level)



Speed
(with contribution by optimization level)

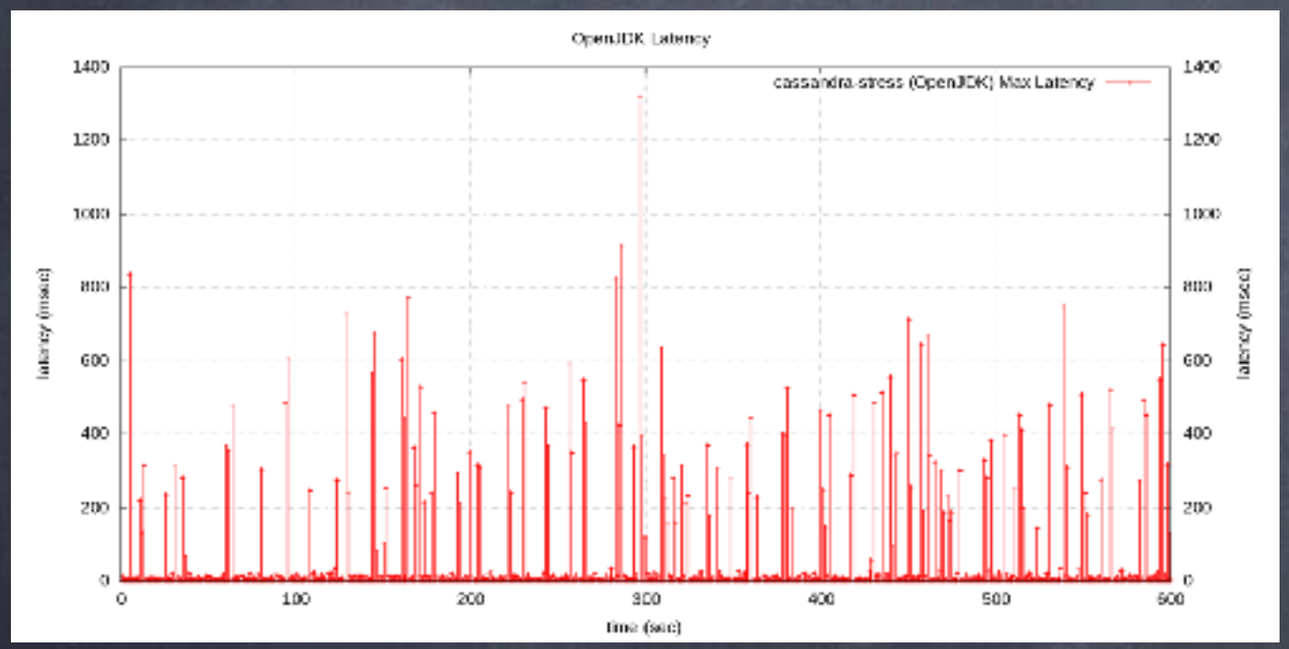


C4 Garbage Collector

ELIMINATES Garbage Collection as a concern for enterprise applications

A simple visual summary

This is <Your App> on HotSpot



This is <Your App> on Zing

Any Questions?

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GC Tuning

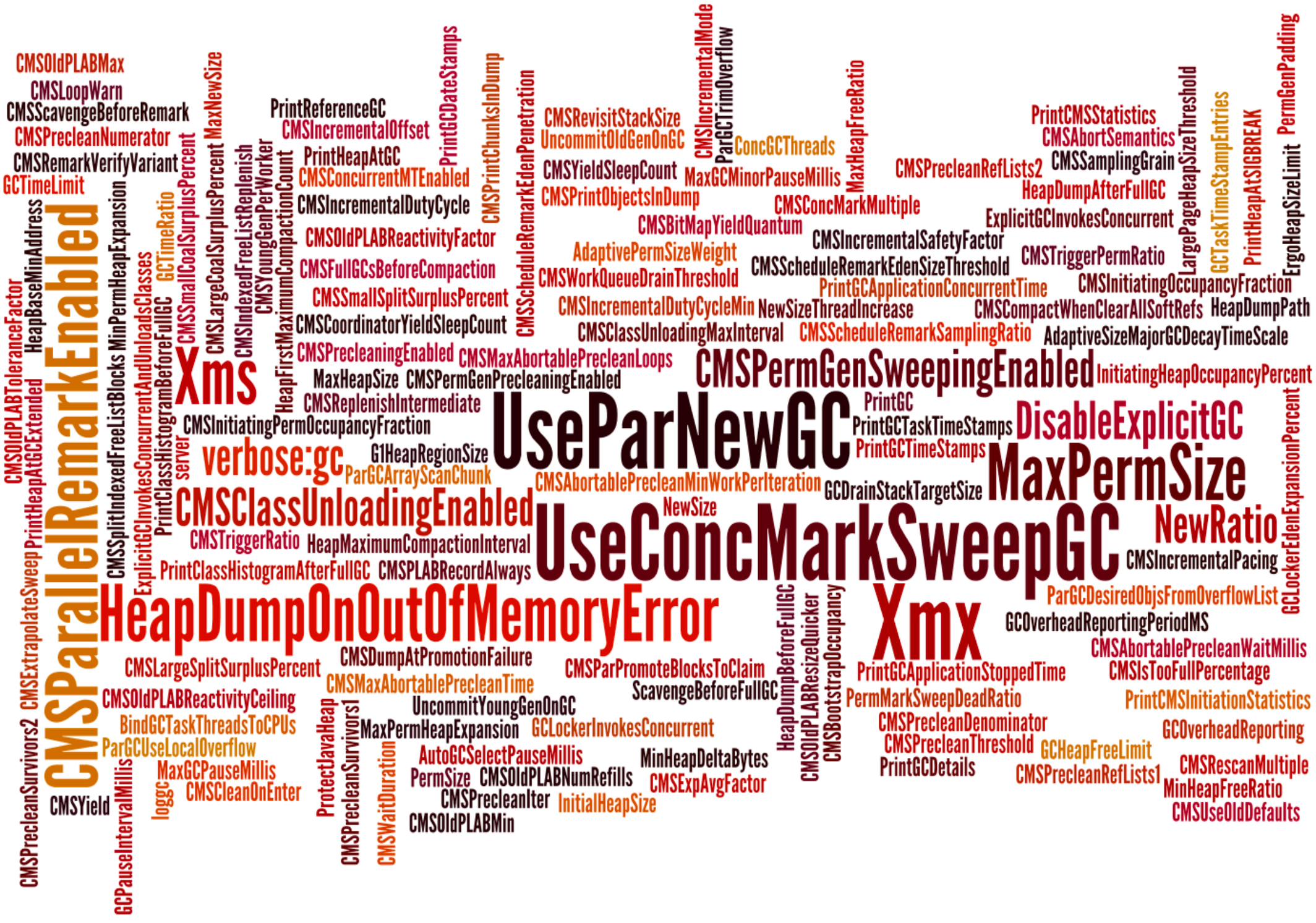
Java GC tuning is "hard"...

Examples of actual command line GC tuning parameters:

```
Java -Xmx12g -XX:MaxPermSize=64M -XX:PermSize=32M -XX:MaxNewSize=2g
        -XX:NewSize=1g -XX:SurvivorRatio=128 -XX:+UseParNewGC
        -XX:+UseConcMarkSweepGC -XX:MaxTenuringThreshold=0
        -XX:CMSInitiatingOccupancyFraction=60 -XX:+CMSParallelRemarkEnabled
        -XX:+UseCMSInitiatingOccupancyOnly -XX:ParallelGCThreads=12
        -XX:LargePageSizeInBytes=256m ...

Java -Xms8g -Xmx8g -Xmn2g -XX:PermSize=64M -XX:MaxPermSize=256M
        -XX:-OmitStackTraceInFastThrow -XX:SurvivorRatio=2 -XX:-UseAdaptiveSizePolicy
        -XX:+UseConcMarkSweepGC -XX:+CMSConcurrentMTEnabled
        -XX:+CMSParallelRemarkEnabled -XX:+CMSParallelSurvivorRemarkEnabled
        -XX:CMSMaxAbortablePrecleanTime=10000 -XX:+UseCMSInitiatingOccupancyOnly
        -XX:CMSInitiatingOccupancyFraction=63 -XX:+UseParNewGC -Xnoclassgc ...
```

A few more GC tuning flags



Source: Word Cloud created by Frank Pavageau in his Devoxx FR 2012 presentation titled “Death by Pauses”

The complete guide to modern GC tuning

java -Xmx40g

java -Xmx20g

java -Xmx10g

java -Xmx5g

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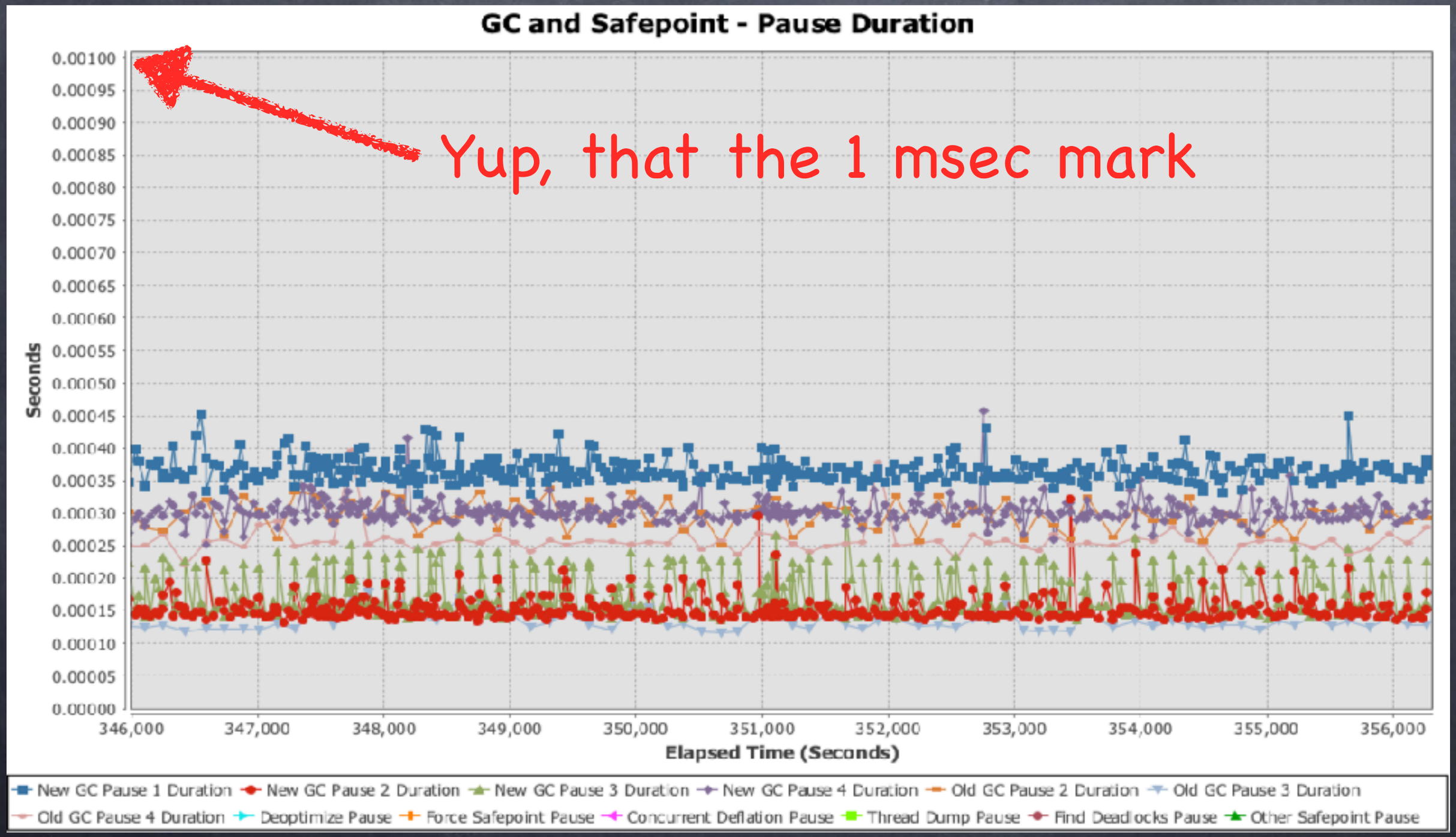
Cassandra under heavy load, Intel E5-2690 v4 server



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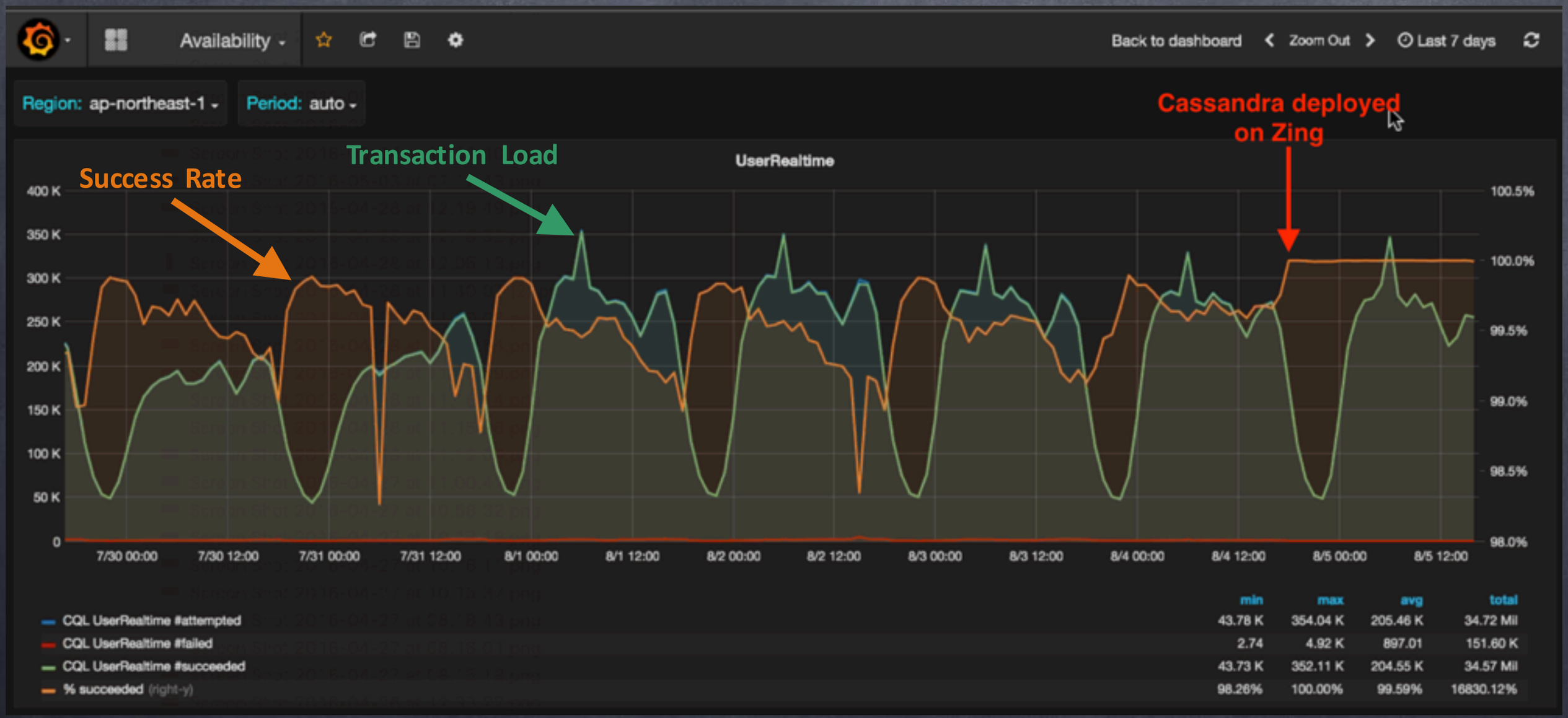
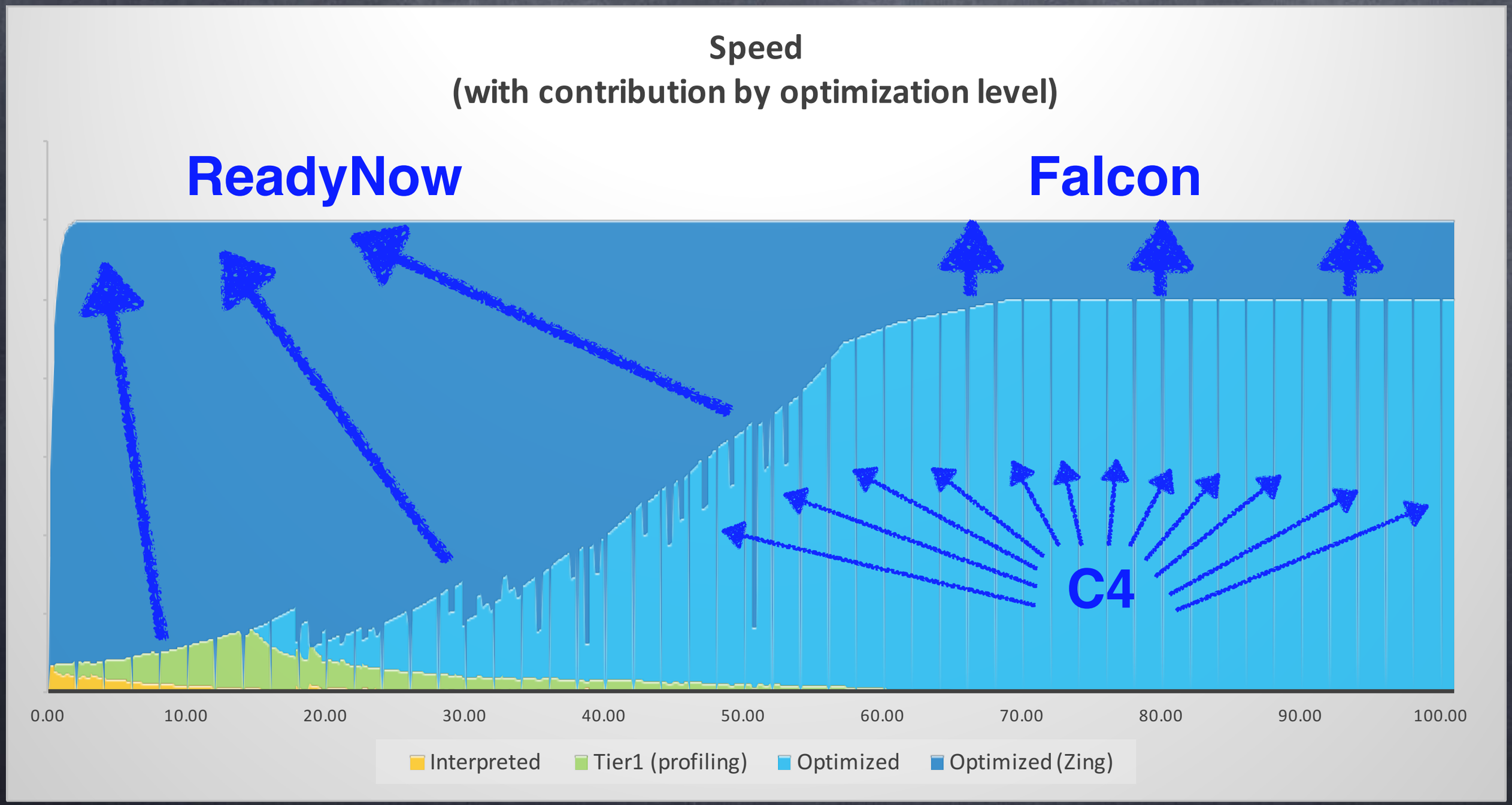
Warning: results may be too good

A practical real-world example: Improve Digital (Video Advertising)

- Cassandra cluster running on 6x AWS i3.2xlarge
  - Approx. 80/20 write/read split
  - Data read and written with quorum consistency
  - 6 client machines sending requests collocated in the same AZs
- SLA requirements for read operations:
  - 20ms at 99.9%
  - 50ms at 99.99%
  - 100ms at 99.998% (not a typo, last 9 hard to maintain on AWS)
- HotSpot w/G1: can maintain ~4K TPS before SLA breach
- Zing: can maintain ~21K TPS before SLA breach
- QED...



Start Fast, Go Fast, Stay Fast



Q & A

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